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GLACIOLOGICAL DATA

SOVIET AVALANCHE RESEARCH
AVALANCHE BIBLIOGRAPHY UPDATE: 1977-1983

World Data Center A
for
Glaciology
[Snow and Ice]

November 1984

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GLACIOLOGICAL DATA

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DESCRIPTION OF WORLD DATA CENTERS[1]

WDC-A: Glaciology (Snow and Ice) is one of three international data centers serving the field of glaciology under the guidance of the International Council of Scientific Unions Panel of World Data Centers. It is part of the World Data Center System created by the scientific community in order to promote worldwide exchange and dissemination of geophysical information and data. WDC-A endeavors to be promptly responsive to inquiries from the scientific community, and to provide data and bibliographic services in exchange for copies of publications or data by the participating scientists.

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Permanent Service on the Fluctuations of Glaciers
Swiss Federal Institute of Technology
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2. Subject Matter

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Studies of snow and ice, including seasonal snow; glaciers; sea, river, or lake ice; seasonal or perennial ice in the ground; extraterrestrial ice and frost.

Material dealing with the occurrence, properties, processes, and effects of snow and ice, and techniques of observing and analyzing these occurrences, processes, properties, and effects, and ice physics.

Material concerning the effects of present day and snow and ice should be limited to those in which the information on ice itself, or the effect of snow and ice on the physical environment, make up an appreciable portion of the material.

Treatment of snow and ice masses of the historic or geologic past, or paleoclimatic chronologies will be limited to those containing data or techniques which are applicable to existing snow and ice.

3. Description and Form of Data Presentation

3.1 General. WDCs collect, store and are prepared to disseminate raw[+], analyzed, and published data, including photographs. WDCs can advise researchers and institutions on preferred formats for such data submissions. Data dealing with any subject matter listed in (2) above will be accepted. Researchers should be aware that the WDCs are prepared to organize and store data which may be too detailed or bulky for inclusion in published works. It is understood that such data which are submitted to the WDCs will be made available according to guidelines set down by the ICSU Panel on WDCs in this Guide to International Data Exchange. Such material will be available to researchers as copies from the WDC at cost, or if it is not practicable to copy the material, it can be consulted at the WDC. In all cases the person receiving the data will be expected to respect the usual rights, including acknowledgement, of the original investigator.

[1]International Council of Scientific Unions. Panel on World Data Centers. (1979) Guide to International Data Exchange Through the World Data Centres. 4th ed. Washington, D.C. 113 p.

[+]The lowest level of data useful to other prospective users.

This Guide for Glaciology was prepared by the International Commission on Snow and Ice (ICSI) and was approved by the International Association of Hydrological Sciences (IAHS) in 1978.

3.2 Fluctuations of Glaciers. The Permanent Service is responsible for receiving data on the fluctuations of glaciers. The types of data which should be sent to the Permanent Service are detailed in UNESCO/IASH (1969)*. These data should be sent through National Correspondents in time to be included in the regular reports of the Permanent Service every four years (1964-68, 1968-72, etc.). Publications of the Permanent Service are also available through the WDCs.

3.3. Inventory of Perennial Snow and Ice Masses. A Temporary Technical Secretariat (TTS) was recently established for the completion of this IHD project at the Swiss Federal Institute of Technology in Zurich. Relevant data, preferably in the desired format**, can be sent directly to the TTS or to the World Data Centers for forwarding to the TTS.

3.4. Other International Programs. The World Data Centers are equipped to expedite the exchange of data for ongoing projects such as those of the International Hydrological Project (especially the studies of combined heat, ice and water balances at selected glacier basins***), the International Antarctic Glaciological Project (IAGP), and Greenland Ice Sheet Project (GISP), etc., and for other developing projects in the field of snow and ice.

4. Transmission of Data to the Centers

In order that the WDCs may serve as data and information centers, researchers and institutions are encouraged:

4.1. To send WDCs raw+ or analyzed data in the form of tables, computer tapes, photographs, etc., and reprints of all published papers and public reports which contain glaciological data or data analysis as described under heading (2); one copy should be sent to each WDC or, alternatively, three copies to one WDC for distribution to the other WDCs.

4.2 To notify WDCs of changes in operations involving international glaciological projects, including termination of previously existing stations or major experiments, commencement of new experiments, and important changes in mode of operation.

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*UNESCO/IASH (1969) Variations of Existing Glaciers. A Guide to International Practices for their Measurement.

**UNESCO/IASH (1970a) Perennial Ice and Snow Masses. A Guide for Compilation and Assemblage of Data for a World Inventory; and

Temporary Technical Secretariat for World Glacier Inventory. Instructions for Compilation and Assemblage of Data for a World Glacier Inventory.

***UNESCO/IASH (1970b) Combined Heat, Ice and Water Balances at Selected Glacier Basins. A Guide for Compilation and Assemblage of Data for Glacier Mass Balance Measurements; and

UNESCO/IASH (1973) Combined Heat, Ice and Water Balances at Selected Glacier Basins. Part II, Specifications, Standards and Data Exchange.

+The lowest level of data useful to other prospective users.

FOREWORD

Our first issue of Glaciological Data, published in 1977, contained articles on avalanche research and data problems and a bibliography. This issue provides an updated bibliography covering the period 1977-1983 and makes available, in English, a series of important Soviet papers on work conducted at the Problem Laboratory of Snow Avalanches, Moscow State University. The translations were prepared by Kevin J. McKenna, currently a faculty member at the University of Vermont, with the assistance of Misha Plam. We acknowledge the permission of the Export and Import Department of Social and Scientific Publications, Moscow, to publish these papers in English. Funding support for the translation work was provided through the Mountain Snow and Avalanche Research Project, Rocky Mountain Forest and Range Experiment Station, U.S. Department of Agriculture, Forest Service. We are grateful to Dr. M. Martinelli, Jr. for his collaboration and encouragement of this activity. The typing of the articles was done by Irene Butler and Barbara Sloan; data entry work for this issue was undertaken by Carol Pedigo, and the bibliography was edited by Ann Brennan, of the Data Center staff.

R.G. Barry
Director
WDC-A for Glaciology (Snow and Ice)
and National Snow and Ice Data Center

CONTENTS

Introduction

Misha Plam

In 1964 the Snow and Ice Laboratory, of the Geographical Department, Moscow State University was upgraded to the Problem Laboratory of Snow Avalanches under the leadership of Professor G. Tushinskii. As Scientific Secretary of the Laboratory I set up its physical-mathematical section to address the following problems:

Mechanics of snow avalanches;

Theory of avalanche impact on and flow around obstacles;

Air waves associated with avalanches;

Mechanical and physical processes in the snow;

Avalanche forecasting;

Snow slope stability.

This wide range of problems could be addressed thanks to help from Professor S. Grigoryan and Dr. Yu. Yakimov of Moscow State University's Institute of Mechanics. Mathematicians invited to work in the laboratory included Irina Shurova (avalanche impact), Aleksander Bozhinskii (snow slope stability), and Lidiya Ushakova (metamorphism of snow).

In 1965 two lecturers of the Mechanics/Mathematics Faculty, Margarita Eglit and Elena Shveshnikova, joined the group to work on the theory of avalanche motion, a line of research further strengthened in 1966 by Professor Nikolai Bakhvalov. The work of all these scientists appeared in various Soviet publications and was briefly described by Professor Grigoryan at the Grindelwald Symposium of the International Commission of Snow and Ice in 1974 (IAHS Publ. 114). However, much of the work accomplished between 1965 and 1974 has not become known and therefore is presented here in full translations of eight key papers, together with a ninth paper analysing and restating the mathematics of the Soviet avalanche model.

Synopsis

Snow slope stability

In a 1968 review paper (No. 1 in this collection) Bozhinskii evaluated existing criteria derived from continuum mechanics for the formation of snow avalanches. Several authors had addressed this problem in terms of stationary snow blocks on an inclined rough surface, without regard to the rheological properties of the snow. This is permissible only for short-duration avalanches produced by heavy snowfall. Bozhinskii instead treats the avalanche release as a breakdown of the snowpack. This requires specifying a snow stability characteristic such as shear resistance, which depends on the temperature, density, and structure of the snow and cannot readily be measured in the avalanche release zone. As a way around this difficulty, Bozhinskii examined the small perturbations which arise when the snow moves down an infinite inclined plane under the influence of gravity. The mathematical solution then describes the snow slope stability in terms of basal sliding. These results need to be checked by remote measurements of snow velocity profiles. However, when the model was applied to the problem of locating snow-retaining structures it suggested smaller spacings than had been derived with a partly rheological argument by R. Haefeli.

The optimal arrangement of snow-retaining gates on a mountain slope is established by Bozhinskii in the second paper of this collection which gives solutions for a linear viscous medium that develops plastic rheology while moving down a channel with rigid curved walls. In the third paper, Bozhinskii discusses the snow load on a gate and the shear stress between the snow and the gate.

Avalanche motion

In the fourth paper of this collection, Margarita Eglit compares the independent and parallel work of Voellmy (Switzerland) and Kozik (Soviet Union) on avalanche runout distances and loads. She shows that both these authors treated the avalanche as a material point with variable mass (although Voellmy started out from hydraulic concepts). The limitation is that in their approach the form of the avalanche must be specified. Eglit instead develops a hydraulic model that predicts the main avalanche parameters (velocity, shape) for given slope profiles and snow pack characteristics (snow density and thickness of the snow layer that is entrained by the avalanche). In a further paper (No. 5 in this collection) Bakhvalov and Eglit consider the avalanche motion along finite non-uniform slopes and obtain algebraic solutions that are checked with a computer model. All these results are critically analyzed in the last paper (No. 9) of this collection.

Avalanche impact and air pressure waves (eddies) created by the avalanche

The problem of avalanche impact received its first hydraulic formulation in terms of the leading-edge height in 1955 by Voellmy, but this explained only one half of the pressures actually measured by B. Salm. In paper No. 6 of this collection, Shurova develops a new model in which the snow is represented by a continuous two-phase medium (ice crystals and air pores). This model gives results in better agreement with Salm's measurements, even though it does not make allowance for the air flow through the snow during impact.

In the next paper (No. 7) Yakimov and Shurova describe the air pressure wave created by an avalanche and model it as a vortex ring governed by the characteristics of the avalanche. The same authors review the full range of continuum-mechanics avalanche models as a basis for experimental determination of the avalanche impact on structures in a further paper (No. 8).

In the final paper of this collection (No. 9) Plam, Radok, and Taylor take the Soviet avalanche model of Eglit and others apart and put it together again in detailed mathematical terms commonly employed by Western glaciologists. This is considered valuable in view of the fact that to date, Soviet avalanche work has been largely ignored outside the Soviet Union.

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appearing in the upper cross section of the block was simulated by a small cable which supported the block. The cable had strength equal to the tensile strength of the snow. The balance of forces for the block was given by the equation for the critical width of the snow layer

$$h^* = \frac{\tau^* l}{\rho g l (\sin \psi - f \cos \psi) - \sigma_+^*}. \quad [1]$$

Here σ_+^*, τ^* are the limiting tensile and shear stresses respectively, ψ is the slope angle, ρ is the mass density of the snow, g is gravity acceleration, and f is the coefficient of internal friction.

The problem of the snow "slab" flow of finite length on a slope has not been solved at the present time, even for the simplest of media. Therefore, computing the limiting state seems justified in certain situations. Let us analyze equation [1] in more detail. We will suppose that the snow block represents an ideal rigid plastic medium. We will assume that the shear stresses in the underlying surface and the tensile stresses in the upper end are distributed equally along the cross sections. We will also use a condition of a yield rectangle in a stress plane, σ, τ (fig. 2a). Then if the length l such that, $\sigma < \sigma^*$, the snow block will be represented for a certain thickness, h, in plane σ, τ by rectangle ABCD. The overall load, Q, on the block will grow in proportion to h. Since the problem is not statically determinate, we will assume that the loads, P (from the action of normal tensile stresses) and T (from the action of shear stresses in the underlying surface), are also proportional to h. Then stress, σ, will remain constant with the increase of height, h, since the load and the area of the end section depends linearly on h. At the same time, the shear stress increases in the underlying surface. In the diagram, this corresponds to the "elongation" of rectangle ABCD to the right until AD coincides with the flow boundary. This moment represents block AB'C'D (fig. 2b). The problem becomes statically definable after the formation of this plastic "slippage" plane. Henceforth, the force caused by the action of shear stress in the underlying surface will remain constant. Shear stresses in any cross section parallel to the slope continue to grow but with lesser speed. The remaining part of the load from the block weight increases the

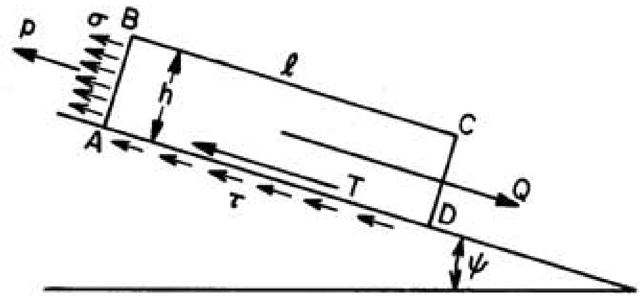

Figure 1. The investigation of slippage along a rough slope of a heavy snow block with dimensions l (length) and h (height).

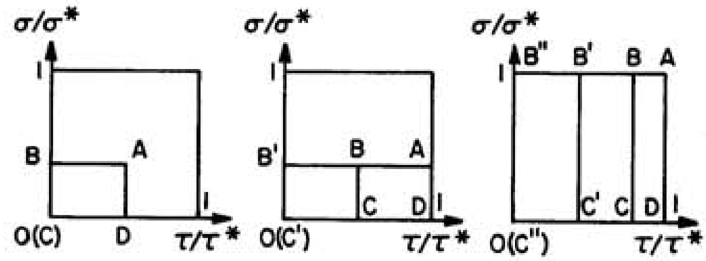

Figure 2. A yield rectangle in a stress plane, σ, τ showing progressive stages of block creep leading to avalanche release.

stress, σ, since force, P, will not grow faster than the area of the cross section. Straight lines in the diagram, parallel to AD, shift clockwise, but do not reach AD (they condense) and simultaneously stretch until the flow boundary is reached for σ (at this instant the snow block corresponds to rectangle AB"c"D (fig. 2c), as a result unlimited block creep on the slope becomes possible. According to Saatchan (1936), this is equivalent to the release of an avalanche. Thus, one can support equation [1] with specific allowances on the basis of a model of an ideal rigid-plastic body.

Attempts were made in subsequent investigations, in the analysis of limiting balance conditions, to take into account snow block resistance to creep on the lateral surfaces (Sulakvelidze, 1949), snow compressive strength from the side of the lower end of the section (Handbook of Snow-Avalanche Studies, 1965), and also forces acting as a result of linear temperature decrease of the snow layer during abrupt temperature drop (Akkuratov, 1960). Consideration of the additional forces acting on the block contour led, naturally, to an increase of the critical height of the snow cover, upon which snow avalanche release was possible (Tushinskii, 1949).

Losev (1963) extended the equations of static balance of the snow layer on the slope suggested earlier. In this work, the snow model, as before, is a solid block, stationary on a rough slope due to frictional force caused by shearing strength with the underlying surface. Furthermore, shear stresses of the lateral faces of the block are taken into account as well as limit tensile and compressive stresses of the respective upper and lower ends of the block faces. The equation for the critical snow height has the form:

$$h^* = \frac{\tau^* b l}{\rho g b l (\sin\psi - f\cos\psi) - \sigma_+^* b - \sigma_-^* b - 2\tau_1^* l}. \qquad [2]$$

Here, σ_-^* is the limit of compressive stress, τ_1^* is the limit of snow shear stress in the plane, oxz.

If we introduce the dimensionless height of the snow cover, $h_o = \frac{h\rho g}{\tau^*}$, then [2] will be written in the form:

$$h_o^* = \frac{1}{(\sin\psi - f\cos\psi) - \frac{\sigma_+^*}{\rho g l} - \frac{\sigma_-^* b}{\rho g l} - \frac{2\tau_l^* l}{\rho g b}} . \qquad [3]$$

It is easy to show for real densities, ρ, limit strengths, σ_+^*, σ_-^*, τ_l^*, slope angles, ψ, coefficient, f, and the characteristic block sizes, l, b, that the term in parenthesis in the denominator is of an order of 10^{-1}; whereas, the remaining terms are of an order of 10^{-2}. Thus, only the first term in the denominator needs to be considered, since the remaining terms give a smaller contribution and can be neglected. It has been demonstrated that equation [7] is derived without taking into account the rheological properties of the snow cover.

An attempt was made later to introduce an average stress, σ, in the layer contour and a certain derived radius, R, with the goal of computing the shape of the fracture line (Moskalev, 1965). However, since the influence of the contour forces is inconsequential and the fracture line shapes are determined very roughly, such a complication of the calculation seems unwarranted. Moskalev (1965, 1966) also examined the effect of gravitational water on the critical slope angle; he carried out his investigation similar to the known methods of soil mechanics. As was expected, the action of the water filtering down the slope is equivalent to the reduction of the coefficient of internal snow friction. In another paper, (Moskalev, 1965) examined the balance of the snow layer (as an absolutely solid body) in concave and convex slope sections and analyzed the possibility of layer creep on a cylindrical surface. Krasnosel'skii (1964) and Shcherbakov (1966) discuss other proposed snow avalanche formation criteria which amount to a simple rephrasing of a single criterion which lies at the base of all the investigations without exception; specifically, the criterion of static balance of the snow block on the whole which is gravitationally stable on a rough slope (various modifications of this model were mentioned above).

Analysis of a limiting balance of snow layer of infinite length results in a condition superimposed on the height of the snow cover. The rheological properties of the medium are not considered here. As a result, one can use the criterion, based on a condition of limiting balance, in practical applications when it is possible to disregard the rheological properties.

For example, such a situation can occur in intense snowfalls of short duration (direct action avalanches).[1] There is considerable snow cover settlement after a snowfall which, in turn, results in stabilization. From the beginning of the snowfall, the avalanche-danger period is determined for a given slope by the intensity of the snowfall and the measured values of the limit of shear strength, τ^*, of the freshly fallen snow and its density, ρ (Losev, 1960). Use of the equation for critical height,

$$h^* = \tau^* / \rho g \sin \psi , \qquad [4]$$

for prediction of avalanches from freshly fallen snow provided good results. Shcherbakov (1966) cites experimental points which correspond to the release of 41 avalanches, for which the limit of shear strength was determined by an empirical curve of the dependence of τ^* on the density.

Rheological Approach

Before moving to a discussion of the studies which have computed the rheological properties of the snow cover, let us make several comments pertaining to the selection of stability criteria. Let us consider a snow cover on a slope in the form of a layer of a certain continuous medium, flowing due to gravity on an inclined plane (fig. 3). Then the balance equations of an infinitely small volume element, dx, dy, dz (the z axis is oriented normal to the sketch plane to the reader) have the form:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} + X = 0 ,$$

$$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} + Y = 0 ,$$

$$\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + Z = 0 . \qquad [5]$$

Here, σ_{xx}, σ_{yy}, σ_{zz}, σ_{xy}, σ_{yz}, σ_{xz} are the stress tensor components, and X, Y, Z are the body force components per unit volume. It is assumed that the medium is in a quasi-static state so that

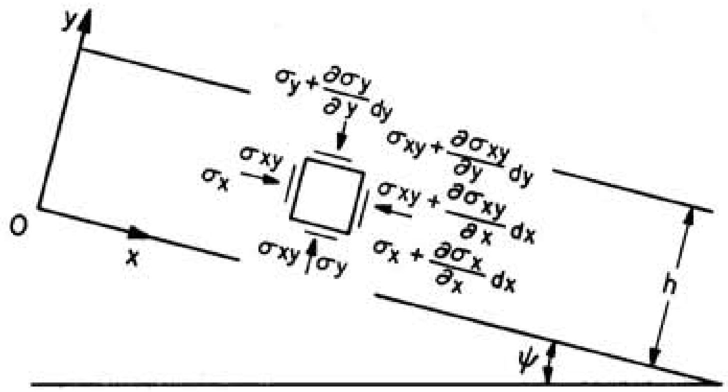

Figure 3. Body force components exerted on a continuous inclined snow layer.

the inertia forces may be disregarded. Assuming that the flow of the continuous medium is steady, we will write the equation of continuity as

$$\frac{\partial \rho v_x}{\partial x} + \frac{\partial \rho v_y}{\partial y} + \frac{\partial \rho v_z}{\partial z} = 0 , \qquad [6]$$

where v_x, v_y, v_z are the components of the velocity vector of the medium point, and ρ is the mass density of the medium. The system of four equations [5-6] includes 10 unknown quantities, ρ, v_x, v_y, v_z, σ_{xx}, σ_{yy}, σ_{zz}, σ_{xy}, σ_{yz}, σ_{xz}. For closing the system, it is necessary to supplement these four equations with six rheological relationships characterizing the medium,

$$R(\sigma_{ij}, \dot{\sigma}_{ij}, \varepsilon_{ij}, \dot{\varepsilon}_{ij}) = 0; \; i, j = x, y, z , \qquad [7]$$

where ε_{ij} are the tensor components of deformation, and the point, $(\cdot)$, indicates time differentiation. The relationships of [7] are written out for an isothermal process and are not the most general, but they are sufficient for purposes of our investigation. In the homogeneous layer of constant thickness under consideration, the vector components of the gravitational forces are

$$X = \rho g \sin \psi , \; Y = -\rho g \cos \psi , \; Z = 0 . \qquad [8]$$

Here, μ is a viscosity coefficient, and m is Poisson's ratio, which, generally speaking, is variable. We note that equations [14] correspond to the model of certain compressible, linearly viscous, fluids. We assume that the hydrostatic pressure is equal to zero and the average pressure is equal to the product of the coefficient of dilatational viscosity times the velocity of the relative change of volume. In this case, for the general relations of a linear-viscous fluid, the so-called dilational coefficient of viscosity does not appear (as for the incompressible fluid), and there is total analogy with Hooke's law. In the relations cited, μ is the viscosity of tension (Young's module analog), and m is Poisson's ratio of the fluid (analog of the Poisson's ratio of an elastic body).

Haefeli also investigates plane strain. From Cauchy's balance equations [5], we formally derive (since ρ is an unknown function depending on y and time t)

$$\sigma_{xy} = g \sin \psi \int_0^y \rho dy; \quad \sigma_{yy} = g \cos \psi \int_0^y \rho dy \ . \qquad [15]$$

The constants of integration are equal to zero since the plane, y = 0, is free from stresses. Unlike fig. 2, the origin of the coordinates is selected on the surface and the y axis is directed downward normal to the slope. In using the rheological relations of [14], we derive

$$\sigma_{xx} = \sigma_{zz} = \frac{\sigma_{yy}}{m-1} = \frac{g \cos \psi}{m-1} \int_0^y \rho dy \ . \qquad [16]$$

Thus, the stress field is known at any instant of time. We have the following for the principle stresses:

$$\sigma_{1,2} = \left[\frac{m}{2(m-1)} \pm \qquad \frac{1}{4}\left(\frac{m-2}{m-1}\right)^2 + \tan^2\psi \ \right] g \cos \psi \int_0^y \rho dy \ , \qquad [17]$$

$$\sigma_3 = \sigma_{zz} \ .$$

We can see that for some conditions, the second principle stress approaches zero. This condition has the form

$$\tan \psi = (m-1)^{1/2} \ , \qquad [18]$$

which, according to Haefeli is the avalanche formation criterion. For incompressible material, $m = 2$, and instability occurs for all angles corresponding to the the condition $\psi \geq \pi/4$.

This problem is time dependent. The author suggests that the density increases with depth and time. It is postulated that Poisson's ratio, m, decreases with increase in density, reaching a limiting value, $m = 2$ (incompressible material - ice in this case). On the other hand, if the slope angle is known, then, according to condition [18], m is fixed. One can assume with a considerable degree of accuracy that the density is uniform at the initial time following a heavy snowfall. Then $m = m^* = \text{const}$; $\psi = \psi^* = \arctan(m^* - 1)^{-1/2}$. During creep and settlement, the density increases with depth and time; therefore, m decreases and consequently, ψ increases. It follows from this that if the avalanche does not release at the initial moment, then it never will, since there will not be any tensile stresses on the second principle area for that slope angle. Therefore, Haefeli's criterion, $\sigma_2 = 0$, is suitable only for avalanches of freshly fallen snow when the density is uniform and $\rho = \rho_{min}$, $m = m_{max}$. He uses the result of the increased snow stability on a slope in the following manner: if the fresh snow is cohesive and has a limiting shear strength, τ^*, then, as was shown above, one can always write the strength condition according to Coulomb (linear dependence on the normal pressure) in an area parallel to the slope,

$$\tau^{**} = \tau^* + \sigma_{yy} \tan \alpha \ . \qquad [19]$$

Hence,

$$h^* = \frac{\tau^*}{\rho g \cos \psi (\tan \psi - \tan \alpha)} \ . \qquad [20]$$

However, according to Haefeli only the slopes for which $\sigma_2 = 0$ are critical. We derive the following after making elementary conversions taking this condition into account:

$$\hat{h}^* = \frac{2\tau^*}{\rho g} \tan \left[\frac{\pi}{4} + \frac{\alpha}{\pi}\right] , \qquad [21]$$

in which $\frac{\pi}{4} + \frac{\alpha}{2} = \psi$, $\hat{h}^*$ is the snow layer height vertically (thickness). Jaccard (1966) attempted to establish a dependence of the critical slope angle of Poisson's ratio, m, describing the compressibility of the medium using rheological relations suggested by Haefeli (Handbook of Snow-Avalanche Studies, 1965). The condition for strength on an area parallel to the slope is written

$$\tan^2\psi = (1 - M)^2 \sin^2\alpha - M^2 \ , \qquad [22]$$

where

$$M = \frac{m - 2}{2m - 2} .$$

It is easy to show, however, by means of identity transformation, that the shearing stress, τ_1, in the area, found from the principle stresses, equals

$$\tau_1 = g \int_0^y \rho dy \cdot \cos\psi \left[\frac{1}{\cos\alpha} \sqrt{M^2 + \tan^2\psi} - (1 - M) \tan\alpha \right] =$$

$$= \tau^{**} - \sigma_{yy} \tan\alpha \ . \qquad [23]$$

Condition [22] corresponds to $\tau_1 = 0$. Thus, the author first determined the stress components and then found the principle stresses and areas; he then wrote out the stresses on the area, parallel to the slope, after which he formulated a Coulomb equation. Instead of this procedure, one can write out the Coulomb condition immediately since the stresses on the slope are determined from balance equations. Furthermore, it was shown earlier that the stability criterion for a snow layer on a slope does not depend on the rheological conditions of the medium (for a definite type of medium, in using the Mohr strength condition). The present type of media is included in the relations of [14]; therefore, it was possible to confirm the dependence beforehand of the critical slope angle on the parameters of the snow.

Ziegler (1963) also used techniques of the theory of plasticity in snow mechanics. the snow cover on the slope was treated as a layer of an ideal, rigid-plastic, incompressible material subjected to a condition of Mises flow,

$$(\sigma_{xx} - \sigma_{yy})^2 + 4\sigma_{xy}^2 = 4k^2 \ , \qquad [24]$$

where k is the yield stress in pure shear. The kinematic relations have the form (for plane strain)

$$\dot{\epsilon}_{xx} = -\dot{\epsilon}_{yy} = \lambda(\sigma_{xx} - \sigma_{yy}) \; ; \; \dot{\epsilon}_{xy} = 4\lambda\alpha_{xy} \; . \qquad [25]$$

Here $\dot{\epsilon}_{xx}$, $\dot{\epsilon}_{yy}$, $\dot{\epsilon}_{xy}$ are the deviator components of the rate of deformation, and λ is a positive coefficient of proportionality. In assigning the relations of [25] (constitutive equations), the stress field is statistically definable. Taking into account the boundary conditions, $\sigma_{yy} = \sigma_{xy} = 0$ with $y = 0$ (here the origin is transferred to a free surface, see fig. 3), we derive

$$\sigma = -k\left[\frac{y}{h}\,\text{cotan}\,\psi \pm 2 \qquad 1 - \left[\frac{y}{h}\right]^2\ \right] . \qquad [26]$$

$$\sigma_{yy} = -k\,\frac{y}{h}\,\text{cotan}\,\psi \; .$$

$$\sigma_{xy} = k\,\frac{y}{h} \; ;$$

$$h = \frac{k}{\rho g \sin\psi} \; .$$

This equation corresponds to the critical depth of a completely plasticized layer; it coincides with equation [4]. It is later shown that the statistically defined stress field is compatible with a kinematically compatible field of velocities. The construction of the creepage lines results in a network of characteristics portrayed in fig. 4. The curves approach the free surface at an angle, $\pi/4$ or $3\pi/4$. We locate the pressure on the obstacle by integrating the equation for σ_{xx} over the height

$$-N_{xx} = \int_0^h \sigma_{xx}dy = k\,\frac{h}{2}\,(\text{cotan}\,\psi + \pi) \; . \qquad [27]$$

The ordinate line of the pressure is derived from the condition of zero pressure for all times with respect to the origin. The limiting shear strength is equal to:

$$N_{xy} + \int_0^h \sigma_{xy}dy = k\,\frac{h}{2} \; .$$

This solution makes it possible to conclude when obstacles of height, h, are unsuitable, since a rigid area, G, appears in front of the obstacle and the snow can overflow it. The critical line of the layer, at which overflow is possible, is determined from the balance condition of forces of the internal pressure and gravity,

$$l^* = \frac{h}{2}(\cot an\,\psi + \pi) \ . \qquad [29]$$

If we take into account the region containing the rigid zone, then the distance between successive obstacles should be equal to

$$l^{**} = \frac{h}{2}(\cot an\,\psi + 3\pi) \ . \qquad [30]$$

For example, for $\psi = \pi/4$, the obstacles should be arranged at a distance of 5 h from one another. One should be careful in applying these equations in practice since a purely plastic state of snow is found only in exceptional cases.

Stability of a Quasi-Static State of Equilibrium

The criteria discussed above (static and rheological) are based on physical concepts, according to which the avalanche starts when the strength of the snow cover disintegrates. In defining these criteria, the determination of parameters of the critical state are linked to some strength characteristics, for example, snow shearing strength. However, for avalanche prediction for other than new snow avalanches, the use of strength specification, in practice, is complicated by difficulties in defining long-term snow strength. For this depends to a considerable extent on structure, temperature, moisture, and other factors. Thus, it is impossible to estimate with much accuracy the limit of long-term strength and the lead time for its formation. Furthermore, direct measurement of avalanche defense-structure stresses is difficult at best. Therefore, attempts of a different nature have been adopted recently for dealing with the question of predicting the release of avalanches.

One of the new approaches pertaining to snow stability consists of investigating the stability of the creep and/or glide process with respect to small disturbances (Bozhinskii, 1967).[2] When a disturbance that perturbs an otherwise steady flow dissipates in time, the flow is considered stable; whereas, when a perturbation results in an unrestricted increase of disturbance amplitude, this implies instability. With respect to instability, flow parameters are established which correspond to approach to a critical condition. The physical process connected with this critical condition of the increase in disturbance amplitude in time will lead to the formation of compression and tensile zones. The appearance of cracks in tensile zones is unavoidable. This may serve as a basis for snow failure and the release of an avalanche. Bozhinskii (1967) examines the simplest problem of stability. Snow cover on a slope is portrayed as a layer of incompressible, linearly viscous, continuous medium that flows at constant velocity on an infinite inclined plane due to gravity (fig. 5). The stability of the flow is investigated with respect to small disturbances of the free surface. A principle or disturbance solution (in dimensionless form) is derived using the relation of an incompressible, linearly viscous, continuous fluid, Cauchy balance equations, and the continuity equation, namely:

$$v_x^o = \frac{3}{2}\left[1 - (1 - y)^2 + 2\beta\right] ,$$

$$p_x^o = (1 - y) \text{ cotan } \psi ; \; s_{xy}^o = 1 - y . \qquad [31]$$

$$s_{xx}^o = s_{yy}^o = v_y^o = 0 ,$$

where p is the average pressure, s_{xx}, s_{xy}, s_{yy} are the deviator components of stress, and β is a parameter depending on conditions in the underlying surface. Dimensionless parameters are also introduced (the dimensional variables are noted by an asterisk):

$$x = \frac{x^*}{h} ; \; y = \frac{y^*}{h} ; \; s_{xx} = \frac{s_{xx}^*}{\rho g h \sin \psi} ; \; s_{yy} = \frac{s_{yy}^*}{\rho g h \sin \psi} , \qquad [32]$$

$$s_{xy} = \frac{s_{xy}^*}{\rho g h \sin \psi} ; \; p = \frac{p^*}{\rho g h \sin \psi} ; \; v_x = \frac{v_x^*}{V_x} , \; V_x = \frac{\rho g h^2 \sin \psi}{3\mu} .$$

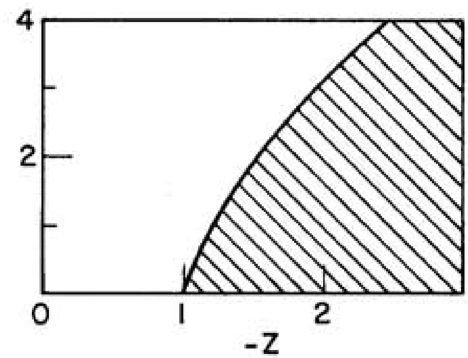

Figure 6. The graph of the neutral curve separating stationary and nonstationary states. The region of instability is shaded.

the snow cover, a sharp change or disintegration of the snow structure occurs which causes considerable slippage. The conclusion about the effect of slippage on the stability of the snow flow on a slope, made on the basis of a strict theoretical solution as well a the mechanism of instability cited above, require experimental confirmation (Bozhinskii, 1967). Thus, the possibility of the onset of avalanche danger in the proposed approach is tied in with the establishment of definite velocity profiles of the flow on the slope. It seems that one can obtain the information about the velocity distribution of runoff as a function of thickness using fairly simple remote-acting devices arranged in a series of avalanche paths along the slope.

Empirical Criteria

Some studies have cited empirical criteria for the release of snow avalanches based on observations in specific mountain regions. For example, avalanches in the Khibiny Mountains which are associated with snowstorms are predicted by the following empirical equations [1,2,3]:

$$t_1 = \frac{m + 38}{m + 2}\ ;\ t_2 = \frac{6,8\ m + 95}{m - 1,86}\ . \qquad [36]$$

where t_1 is the beginning time of avalanche danger in hours; t_2 is the end time of the danger period in hours; m is the intensity of snow deposition in $g/cm^2 \cdot min$. Practice has shown the acceptability of using these empirical dependencies in the Khibiny region.

A number of empirical criteria are associated with avalanche prediction on the basis of meteorological factors. The empirical dependence of the amount of precipitation necessary for the initiation of avalanches of fresh fallen snow on the depth of the previous snow layer has ben established (Tsomaia and Abdushelinshvili, 1965),

$$H = 55 - 2,8\sqrt{h_{75}}\ . \qquad [37]$$

where H is the amount of precipitation and h_{75} is the thickness of the previous layer of snow at the time of the stable drift of daily mean relative humidity per level, 75%. It was found over the course of a number of years from observations of avalanche stations in the United States that a water content of about 10% in the snow cover corresponds to critical conditions. Atwater (1954) gives an empirical relation between the starting time of the avalanche danger, the free water content of the snow cover before the rain began, the critical percent of water content in the snow cover, the water reserve in the snow cover and the intensity of the rain. Tsomaia and Abdushelinshvili (1965) made an attempt to consider the dependence of the limit of snow strength on time. One can then derive the degree of avalanche danger by using equation [4] for the critical thickness of the snow cover and the empirical relations, $\tau^*(t)$, where t is the time. However, the empirical coefficients are still difficult to estimate; therefore, the practical application of this dependence is difficult.

One could continue this list of empirical criteria pertaining to the prediction of snow avalanches, but we will limit ourselves to the above-mentioned studies. It seems that the majority of empirical criteria have effect only for definite geographic regions having various climatic conditions, relief, slope exposure, etc. Their application for other mountain regions is not always supportable. Thus, from the standpoint of a general approach to the problem of avalanche formation, empirical criteria apparently will have a secondary significance.

Conclusions

This analysis of the principal studies devoted to the criteria of snow avalanche formation shows that the problem of predicting avalanche danger has been only slightly developed. There are encouraging results only for predicting avalanches from freshly fallen snow. It would be helpful for a number of mountain regions to perform systematic observations for the onset of avalanches during intensive snowfalls with the hope of finally being able to recommend equation [4] for use in practical applications.

The problem of predicting indirect action avalanches is more difficult. As is apparent from the above, the proposed rheological criteria are reduced in a number of cases to a static criterion of which Haefeli's (1966b) is a certain modification. The slippage effect (Bozhinskii, 1967) has still not been confirmed by experiments which would be very helpful to perform. Furthermore, the problem of stability of a layer of incompressible linear, uniformly viscous fluid on an inclined slope is in a certain sense standard. It is necessary to evaluate the influence of factors such as the heterogeneity of density with thickness, temperature, and viscosity on stability. It seems logical to limit ourselves to initial consideration of linear viscous nonuniform media since nonlinear, viscous behavior of snow is found only at high stress levels (Haefeli, 1965). Furthermore, we should try to include the influence of edge effects in all of these problems even if it can only be done roughly. *In situ* experiments, making it possible to develop more accurate factors leading to avalanche release, take on an important role in the development of criteria for predicting snow avalanches. In connection with this, it would be helpful to perform experimental studies on the determination of the velocity profiles of the flow of a snow cover on a slope for developing a limit condition at the underlying surface (adhesion or slippage), and for estimating the effect of the structure on slippage. Systematic observations are helpful for determining the distribution of density, viscosity, and temperature as a function of snow thickness. At the present time, mortar shells and explosions are used for reducing avalanche danger. It is important to evaluate the effect of explosions on avalanche flow velocity, density distribution, shear strength, etc. It is necessary to set up systematic experiments for determining the long-term strength of snow in shear and in complex tensile conditions. It is also necessary to clarify the nature of snow failure as a function time (brittle or viscous) under a constant shear load and the role of the deformation process in the change of snow structure. Finally, observations of the release of hard slab avalanches have acquired primary importance. Only in the careful computation of all the above-mentioned factors will it be possible to formulate sound rheological criteria for the release of hard slab avalanches.

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Footnotes

[1]Unlike avalanches of short-term or direct action, avalanches not directly connected with snowfall but being essentially the result of complex processes occurring in the snow over the course of the whole winter, are designated as long-term or indirect avalanches. The following terms are used in foreign literature: "direct action avalanche", indirect action, or climax avalanche" (Jaccard, 1967).

[2]We will apply this approach not only for analyzing snow stability on the slope and avalanche prediction, but for similar slope processes; for example, for studying solifluction and catastrophic movements of glaciers.

The Prevention of Avalanches with Arrangements of Snow Supporting Structures on Mountain Slopes

A.N. Bozhinskii

In recent years, avalanche-prone mountain slopes have been fortified with avalanche supporting structures (fig. 1) most often represented by a regular system of reinforced concrete (sometimes wood) structures. Such construction requires considerable financial investment (1 hectare in Switzerland is estimated at $60,000); therefore, the question of a rational arrangement of supporting structures is very timely.

Construction on avalanche-prone mountain slopes should be performed in such a way that it is possible to completely eliminate avalanche impact on the defense structures. Moreover, the snow-supporting structures affect the redistribution of the snow cover in a specific manner. As a result of the structures, the nature of the snow deposit changes, and the thickness of the snow cover on the whole becomes more normal since the snow does not discharge from the slopes as a result of the construction development.

The problem of arranging supporting structures on mountain slopes is a very difficult one because of the necessity of complicated calculation of a number of natural factors. "Instructions for Developing Avalanche Supporting Structures", published in Switzerland 10 years ago (Eidgenossisches Institut für Schnee und Lawinenforschung, N 15, 1961) was based on semi-empirical equations. There is very useful information in the "Instructions" pertaining to the designation and effect of structures, plans for their arrangement on a real slope, the thickness of the snow cover and height of the structure, as well as regional factors and snow type upon which the pressure on the structure depends. There is also considerable information relating to specific calculations and operation. The problem of determining the structure interval along and across the slope is solved in the following manner.

In the evaluation of the longitudinal interval (fig. 2), the tangential component of Q mass forces is balanced by the effect of the shearing stresses, T, in the underlying surface (only the forces of dry friction are taken into account; the cohesion is assumed equal to zero) and

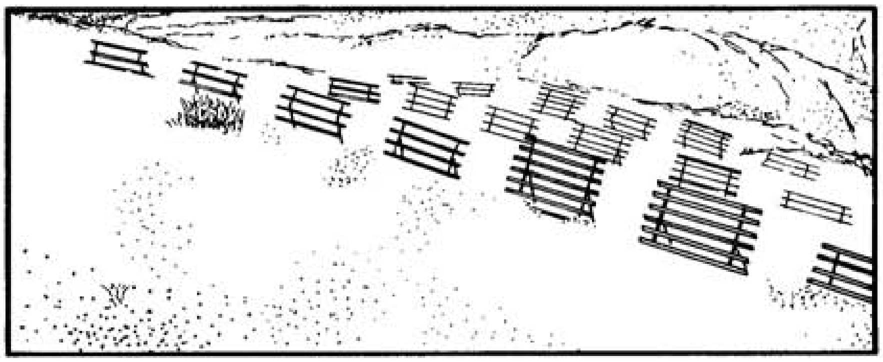

Fig. 1. A typical arrangement of structures on slopes in the Alps.

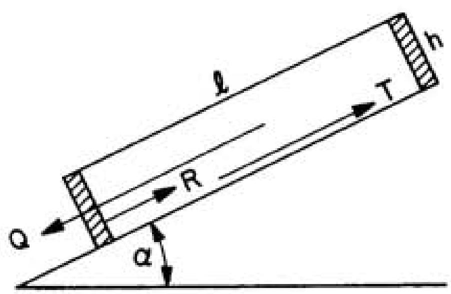

Fig. 2. Equilibrium of snow block on a slope.

by the reaction, R, of the structure. The latter is deduced from empirical relations. As a result, the equation is obtained for the distance, l, between the structures on the slope

$$l/h = \frac{K_1 K_2 \tan \alpha}{(\tan \alpha - \tan \varphi)\cos \alpha}, \qquad [1]$$

where h is the height of the snow cover perpendicular to the surface, α is the slope incline angle, $\tan \varphi$ is the coefficient of internal snow friction, K_1 and K_2 are empirical coefficients depending on the snow type and slippage conditions. In the recommendations (Eidgenossisches Institut für Schnee und Lawinenforschung, N 15, 1961) $K_1K_2 = 2$ was adopted. For real avalanche-prone slopes and friction coefficients, $3.5 \leq l/h \leq 17$.

The lateral interval is determined on the basis of experiment and intuition according to which the gaps should be overlapped by the defense structure. The recommendation for the distance between the structures laterally has the form $\beta \leq 2$ m. In deriving equation [1], the avalanche collapse is identified from the moment when the forces of dry friction will be overcome in the subsurface and the strength of the structure on the shearing is surpassed. Thus, the primary idea of the Swiss recommendations is to maintain the snow cover on the mountain by the defense structures. Small gaps are allowed in the lateral direction excluding the possibility of the formation of movements of loose snow.

Of the other studies, it is necessary to point out work (Ziegler, 1963) in which an analysis of the layer equilibrium is performed on the basis of a model of an ideally plastic body. The existence of a thickness, h_{crit} was established as being critical for a possible avalanche collapse in the sublayer. Slippage lines were plotted having a cycloid shape for which the sublayer is the boundary line. The solution shows that a rigid obstacle with a height, h_{crit}, which prevents avalanche collapse in the sublayer, does not exclude the possibility of shearing along the slippage line when the avalance passes over the upper point of the obstacle.

Sometimes, in estimating the longitudinal interval, Goff and Otten's equation is recommended for use for a snow block with dry friction and cohesion along the sublayer (Handbook on Snow-Avalanche Studies, Gidrometeoizdat, 1955). However, in this case the relation l/h is not actually established since the pressure on the structure is unknown, and should be determined from the solution of the appropriate problem of the limiting equilibrium or be assigned empirically as was done in the Swiss recommendations.

The results of the experiments for determining the pressure of sliding snow on supporting structures are given in a study by Anfilop'ev, and Lokhin (1970). It turned out that these pressures can be fairly great (with snow thickness of 1 m, and density $\gamma = 0.3$ t/m^3 on an order of 2 t/m^2). Nearly the same pressure values for the flow of snow over the structure were obtained in a study (El'mesov, 1970); however, we cannot accept the theoretical calculations of the viscous flow in this study as being satisfactory since the formulation of the problem is incorrect. Finally, there is an article (Losev, 1970), which presents geographic considerations relating to supporting structures on mountain slopes.

This paper will examine two problems: that of terracing mountain slopes by parallel rows of supporting structures, and the more general problem associated with the "checker board" arrangement of the structure.

Analysis of scholarly literature shows that it is necessary to combine the statements of the Swiss recommendations and Ziegler's paper. In fact, it is advantageous to distribute the structures on a slope in this manner in order to take into account all possible slippage lines. In order to show the possible slippage lines (in a planar problem on a three-dimensional surface) as opposed to slippage lines along the base, it is necessary to accept the fact that the obstacles have very high shearing strength (being in theory infinitely rigid). In this case, snow collapse will result in the formation of an avalanche not in the sublayer but along some curve passing through the upper point of the obstacle (fig. 3). We will use a simplified method well known in soil mechanics for obtaining engineering appraisals for the task of terracing slopes by parallel rows of supporting structures. We will assume that the shape of the slippage line, along which the strength condition breaks down, is known beforehand.

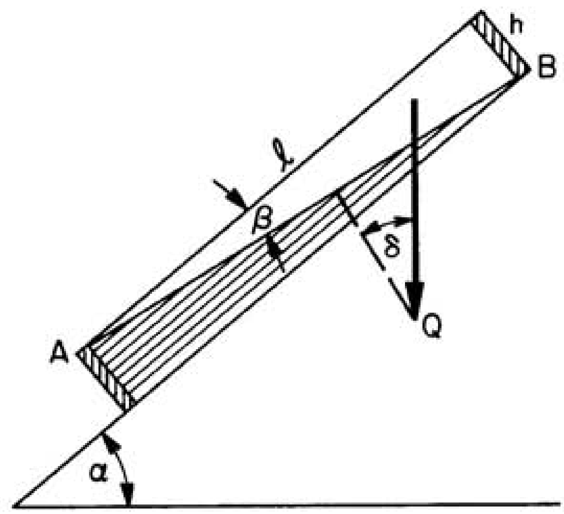

Fig. 3. Snow prism shearing.

Since we are considering the shearing of the snow block as a whole, these lines can be a straight line and a circular arc. We will consider the straight line in the first approximation (fig. 2). Inasmuch as the slippage line passes through line A,B, its location is known. It should be pointed out that in a case when the position and shape of the slippage line are known, problems of the arrangement of the structures and their pressure are linked. In other words, the problem of the distribution of structures is independent; proceeding from the solution of this problem, one can solve the problem of determining pressure on the structures.

By definition, the condition of instability requires that the upper nonshaded triangular prism (fig. 3) shear along the slippage plane, when the shear strength condition breaks down along this plane. This condition can be adopted from Coulomb in a fairly general form $\tau = C + \delta \tan \varphi$, where C is the cohesion, $\tan \varphi$ is the coefficient of internal snow friction, and δ is normal pressure. The following forces act along the shear lines:

Force of gravity $Q_g = 1/2lhb\gamma \sin(\alpha - \beta)$;

Force caused by cohesion $Q_s = cbl/\cos\beta$

Force of dry friction $Q_\varphi = 1/2\ l\ h\ b\gamma \cos(\alpha - \beta) \tan\varphi$.

So, b here is the block cross-section (perpendicular to the sketch), $\delta = \alpha - \beta$ is taken from geometric relations. From the equilibrium conditions we have

$$1/2\,h\,\gamma\,\frac{\sin\alpha - (h/l)\cos\alpha}{1 + (h/l)^2} = C \qquad 1 + (h/l)^2$$

$$+\,1/2h\,\gamma\,\frac{\cos\alpha\tan\varphi + (h/l)\sin\alpha\tan\varphi}{1 = (h/l)^2} \tag{2}$$

when $l \to \infty$, the result is

$$h_{crit} = \frac{2C}{\gamma(\sin\alpha - \tan\varphi\cos\alpha)}\,. \tag{3}$$

The obtained value h_{crit} is two times greater than the corresponding value for the problem without an obstacle (see for example [10]). This is associated with the fact that the slippage line is fixed in the simplified formulation under consideration, whereas in actuality the shape of the slippage line responds to each value, l/h. In the limiting case $l \to \infty$, the slippage line changes to a straight line parallel to the slope. With the reduction of the ratio l/h (when the obstacles converge from infinity), the slippage line differs all the more from the limiting case and for moderate l/h apparently approximates the straight slippage line over the obstacle which is under examination.

After the conversions from [2], we have the following

$$l/h = \frac{1}{\frac{h}{2h_{crit}}K + \qquad \frac{1}{4}\left(\frac{h}{h_{crit}}\right)^2 K^2 + \frac{h}{h_{crit}} - 1}, \tag{4}$$

where

$$K = \frac{\cos\alpha + \tan\varphi\sin\alpha}{\sin\alpha - \tan\varphi\cos\alpha}$$

The limiting change at $h \to \infty$ gives

$$l/h \to K \qquad [5]$$

which complies to equilibrium in the presence of only a dry, friction force. Thus, for $h \gg h_{crit}$, the forces caused by the cohesion are suppressed, and the dry, friction forces dominate. This is easy to explain since the force of gravity and, consequently, also the dry, friction force are proportional to h^2, whereas the forces caused by cohesion are proportional to h.

If $\varphi = 0$; that is there is a medium having only cohesion forces $C \neq 0$, then for $h \to \infty$ we have $l/h \to \cot\alpha$; that is, the slippage will be horizontal.

The relation l/h as a function of h/h_{crit} is represented in figure 4 by a continuous line ($\alpha = \pi/4$; $\tan\varphi = 0.5$), in which a value corresponding to the solution of the problem without obstacles is taken as h_{crit}. It is evident that the vertical asymptote for the solution obtained complies to $h/h_{crit} = 2$. The real solution must have an asymptote $h/h_{crit} = 1$. This nonconformity is explained by the fact that with the change of l/h the shapes of the slippage lines change. In this case, the horizontal asymptote, complying to $h >> h_{crit}$, heaves upward, and the vertical asymptote -- to the left to $h/h_{crit} = 1$. All the curves of this type intersect. The true solution is represented as an enveloping curve of intersecting points (fig. 4 schematically shows this curve by a dashed line). It is apparent, however, from figure 4 that the continuous and the dashed curves are a little different, primarily in the area $h/h_{crit} \approx 1$. We can use the obtained dependence for practical purposes if h/h_{crit} or h_{crit} is known. The latter quantity varies greatly. Therefore, one can recommend the asymptotic estimate [5] when the relation l/h does not depend essentially on h_{crit}. Thus, a more precise solution is required with respect to making our knowledge of h_{crit} more precise.

Solution [1] is plotted by a dot-dash line in figure 4. It is evident that it too is a certain asymptotic estimate, empirically obtained (a simple modification [1] in taking into account the cohesion forces in the sublayer shows this). Thus, equation [1] also can be used only for $h >> h_{crit}$. The comparison of [1] and [4] in general is not strictly valid since lesser friction coefficient values are possible in slippage of the sublayer. Nevertheless, it is apparently possible to confirm that the relation [5] will be a lower estimate for l/h. Generally speaking for optimum designing, an equality of the values of l/h is necessary which respond to the shear on the surface and the shear together with the obstacles along the sublayer.

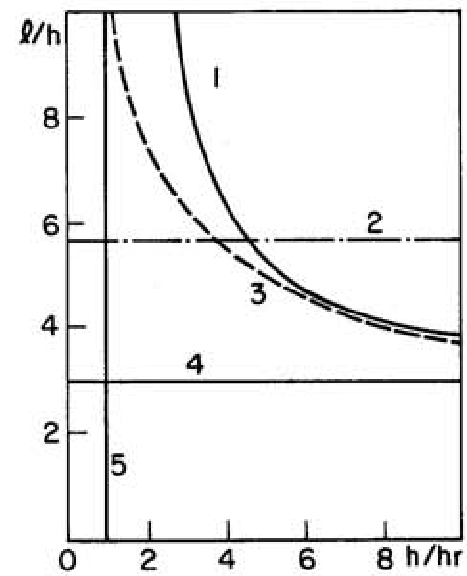

Fig. 4: Dependence of the distance between the structures along the slope on the snow cover thickness ($\tan\alpha = 1$; $\tan\varphi = 0.5$).
1--the solution of (4),
2--recommendations (1),
3--schematic real solution,
4--asymptote (5),
5--asymptote of the real solution.

This imposes a definite connection on the internal friction angles during sublayer and surface shearings. If the internal friction angle near the sublayer is somewhat less than the internal friction angle during surface shear, then equations [1] and [5] will give similar results for $h \gg h_{crit}$. Solution [1] is unsuitable for $h/h_{crit} \approx 1$ and equation [4] should be used in the first approximation. This conclusion, evidently, occurs also for the zone. The fulfillment of these connections in natural conditions for internal friction angles obviously is not always possible; therefore, one can make an optimum design in the sense of arranging the structures in the following manner: a) determine the mean value $\tan\varphi$ for surface shear and for sublayer shear; b) assign a calculated thickness of the snow cover; c) compute the structure interval from equation [5]; d) determine the total pressure on the structure using the values of l/h and $\tan\varphi$ along the base; e) assign the shear strength of the structure taking account of the obtained pressure.

It is not difficult to make a comparison of the pressures on the structure according to the distances between them, defined in this paper and already existing in the Swiss norms. In general the pressure will be written in the form

$$p = \gamma h^2 \frac{l}{h}(\sin\alpha - \tan\varphi\cos\alpha)(1 - \frac{h_{crit}}{h}) \qquad [6]$$

The power expansion of [4],

$$(1 - \frac{h_{crit}}{h}) \text{ gives } l/h(1 - \frac{h_{crit}}{h}) \approx K\,.$$

We then obtain

$$\frac{P}{p_s} = \frac{(l/h)}{(l/h)_s} = \frac{(1 + \tan\varphi + \tan\alpha)\cos\alpha}{K_1 K_2 \tan\alpha}\,, \qquad [7]$$

where the subscript, s, refers to the Swiss standards. Equation [7] shows that for $\tan\varphi = 0.5$, $\alpha \approx \pi/\partial$ and $K_1 K_2 = 2$; $p/p_s \approx 1$. With the increase of the slope angle, the distances between the structures according to equation [5] should be less than the Swiss recommendations; accordingly, lesser pressures will also act on the structures.

In a more general formulation, the problem of arranging snow-supporting structures on mountain slopes becomes three-dimensional and considerably more complicated. It is evident that foreseeable results can be obtained only as a result of simplified schematizations, reflecting only the most essential aspects of such a little-studied natural phenomenon as the formation of a snow avalanche.

Let us examine a fairly long slope in comparison with snow cover thickness with an approximately identical slope angle. Mathematically this corresponds to an infinite slope of constant steepness. We will assume that there is a critical thickness h_{crit} for the snow layer deposited on this slope such that for $h < h_{crit}$ the snow cover on the slope is stable, and for $h \geq h_{crit}$ snow collapses in the form of an avalanche. The problem consists of being able to the collapse of the snow layer in the form of an avalanche is identified at the moment of attaining a limiting value by maximum shearing stress.

Equations, describing the slow stationary flow of an incompressible, uniform, linearly viscous medium along a slope channel with curvilinear rigid walls, have the following form (Bozhinskii, 1967)

$$\left.\begin{array}{l} -\frac{\partial p}{\partial x} + \frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} + \frac{\partial s_{xz}}{\partial z} + \rho g \sin \alpha = 0 , \\ -\frac{\partial p}{\partial y} + \frac{\partial s_{xy}}{\partial x} + \frac{\partial s_{yy}}{\partial y} + \frac{\partial s_{yz}}{\partial z} - \rho g \cos \alpha = 0 , \end{array}\right] \quad [8]$$

$$\frac{\partial p}{\partial x} + \frac{\partial s_{xz}}{\partial x} + \frac{\partial s_{yz}}{\partial y} + \frac{\partial s_{zz}}{\partial z} = 0 , \quad [9]$$

$$\left.\begin{array}{ll} s_{xx} = 2\mu \frac{\partial \mu_x}{\partial x}, & s_{xy} = \mu \left[\frac{\partial \mu_x}{\partial y} + \frac{\partial \mu_y}{\partial x}\right], \\ s_{yy} = 2\mu \frac{\partial \mu_y}{\partial y}, & s_{yz} = \mu \left[\frac{\partial \mu_y}{\partial z} + \frac{\partial \mu_z}{\partial y}\right], \\ s_{zz} = 2\mu \frac{\partial \mu_z}{\partial z}, & s_{xz} = \partial \left[\frac{\partial \mu_z}{\partial \mu} + \frac{\partial \mu_x}{\partial z}\right], \end{array}\right] \quad [10]$$

where x,y,z are the coordinates of the orthogonal Cartesian system, the x axis is located along the slope, the y axis is perpendicular to the slope, the z axis is across the slope, the origin of the coordinates is on two channels (fig. 6); S_{ij} are the stress deviator components, u_{ij} are the vector components of the rate of displacement (i, j = x, y, z,); P is the hydrostatic pressure; μ the viscosity coefficient; ρ is the mass density; g is the gravity acceleration; α is the slope angle.

In addition to the equations of quasi-static equilibrium [8], the equations of discontinuity [9] and relations between the stresses and rates of deformation [10] must satisfy the following boundary conditions: on the bottom of the channel y = 0 is the condition of particle adhesion

$$u_x = u_y = u_z = o ;$$

On the side walls of the channel,

$$z = z_+, \quad z = z_-, \quad z_+(x) = \frac{b}{2} - \frac{a}{2} - \frac{a}{2} \sin \frac{\pi x}{l},$$

$$z_-(x) = -\frac{b}{2} + \frac{a}{2} - \frac{a}{2} \sin \frac{\pi x}{l},$$

(the equations of curvilinear walls) the condition of particle adhesion: $u_x = u_y = u_z = 0$; on the free surface $y = \eta(x, z)$ is the condition of equality to zero vectors of normal and shearing stresses, and also the kinematic condition for normal velocity

$$s_{xy} = s_{yz} = \delta_{yy} = 0, \quad u_y = u_x \frac{\partial \eta}{\partial x} + u_z \frac{\partial \eta}{\partial z}.$$

In a general way, finding the solution of the equations of the three-dimensional problem [8] - [10], satisfying all boundary conditions, involves many problems. Therefore, let us examine some individual cases which make it possible to delineate definite effects caused by the flow over obstacles. An analysis shows that in a broad channel having a weak undulation of walls (analogous to the considerable spacing of obstacles both along as well as across the slope; the width of the obstacle is on the order of the snow cover thickness), equations [8] - [10] agree, with an accuracy up to the terms of the first order of smallness, with the equations for a slope of infinite length without obstacles. In other words, it is not advisable to widely disperse obstacles (at least to a distance exceeding snow cover thickness) since the defense role of the structures turns out to be negligibly small.

Let us examine in detail a narrow channel with a weak undulation of walls having considerable dispersion of obstacles along the slope and small (on an order of snow cover thickness) intervals between them. It follows from the general relations of [10] that in the given case the pressure and shearing stresses in planes xy, xz have a zero order; the remaining stresses are of a higher order of smallness. This means that in the zero-approximation, the problem under examination corresponds to the problem of the flow of a viscous fluid in a planar rectangular channel. It is known (Slezkin, 1955) that a slow stationary runoff of uniform viscous incompressible fluid in a sloping channel of an open rectangular cross-section, under the effect of gravity is reduced to the integration of the Poisson equation

In substituting the variables

$$Y_1 = \left[1 - \frac{y}{h}\right]^2, \quad z_1 = \left[\frac{z}{d}\right]^2,$$

we reduce the equation of the slippage surface to the form

$$k_y^2 y_1 \left[1 - z_1\right]^2 + k_z^2 z_1 \left[1 - y_1\right]^2 - 1 = 0 . \quad [19]$$

The intersection of curve [19] with the axis $z_1 = 0$ (or $z = o$) gives

$$\frac{y}{h} = 1 \pm \frac{1}{k_y} .$$

The curve touches the rectangle at $k_y = 1$. With the increase of $k_y (k_y > 1)$, the curve approaches the rectangle from the side of point A (fig. 8), tightening occurs by the curve along the y-axis. With the decrease of k_y a stretching by the curve occurs along the y-axis, the curve recedes from the rectangle. Similarly, with $k_z = 1$, the curve touches the rectangle at points B, B^1 .

Proceeding from the breakdown conditions of the strength $k_y = k_z = 1$, we obtain a function of the critical thickness (h_{crit}) of the snow cover on the distance 2d between the structures. Figure 9 graphically portrays this dependence (the nonrealized arms/sides are noted by the dashed line). It is evident that the curve has a vertical $d = 4/5$ and horizontal $h = 4/5$ asymptotes. Actually, the horizontal asymptote refers to the critical thickness of the snow with an infinitely large interval between the structures. The difference of the value 4/5 from one is due to the fact that in solving the problem the approximate method of Galerkin was used. The solution shows that not only h_{crit} exists but also d_{crit}. In other words, an interval exists between the structures, in the attaining of which no avalanche takes place no matter how great the snow cover thickness. This is caused by the fact that in the narrowing of the channel, the primary role in the snow containment belongs not to the bottom but to the edges of the channel.

The curve in figure 9 very closely envelopes the angle formed by the horizontal and vert-

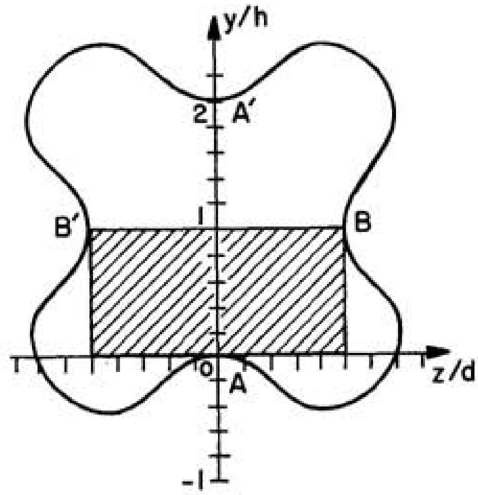

Fig. 8. Intersection of the slippage surface by the plane y_z.

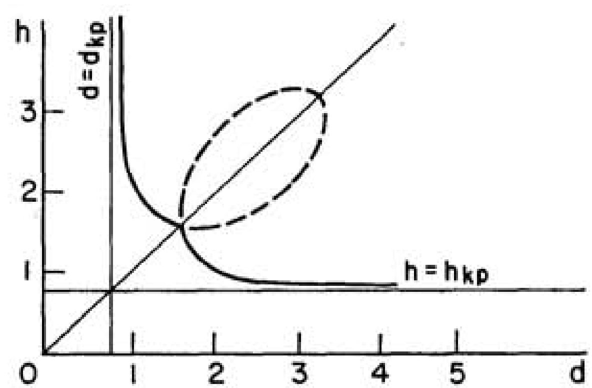

Fig. 9. Dependence of the snow cover thickness on the interval between the structures in a lateral direction.

ical asymptotes. Hence, it follows that the effect connected only with the viscous friction when the snow flows over the obstacles is not very great. The maximum effect responds to the interval between the structures of about four times the critical thickness of the snow cover, computed in the absence of structures.

The obtained results make it possible to roughly evaluate the reaction when the snow flows over the structures. This reaction will accumulate from two components. First, a force, caused by the pressure of the condensated snow in front of the structure, will act on the structures. Once can roughly compute the value, R_g from equation [6]. Secondly, shearing stresses will act on the structure as a result of the viscous flow past the structure. In the limiting case of a rectangular channel in question, these stresses, due to viscosity forces, will be transmitted only to the lateral edges of the structure as concentrated loads, being the integrals of the shearing stresses s_{xa} along the sides of the channel

$$R_m = \frac{5}{3} \gamma \frac{l h d}{1 + (d/h)^2} \sin \alpha . \qquad [21]$$

Thus, the total reaction of the structure is

$$R = 2 R_m + R_g . \qquad [22]$$

This estimate of the reaction when snow flows over the structure, refers only to the rough model under study. For final conclusions, it is necessary to compare it with the data of natural experiments.

It is evident that the obstacle intervals should be interconnected in longitudinal and lateral directions. In principle there should be a certain limiting surface $h = h(l, d)$, connecting the snow cover thickness with the whole set of geometric parameters for the structure. Therefore, it follows that in the future an attempt should be made to remove those rough assumptions according to which the problems of determining the longitudinal and lateral intervals have been independent. On the other hand, the constructed solutions have been based on the knowledge of h_{crit} (or c, $\tan \varphi$). These parameters must be defined in different physical-geographical conditions.

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Sliding of a Snow Slab Past a Retaining Structure

A. N. Bozhinskii

This paper will consider the problems associated with the arrangement of snow supporting structures on mountain slopes (Bozhinkii, 1972; Isaenko, 1975). The existing recommendations of the Swiss Federal Institute for Snow and Avalanche Research (Lawinenverbau, 1968) on this question, which were developed for the Alps, are hardly applicable in different physical-geographical regions of the U.S.S.R. Furthermore, in evaluating the distance between retaining structures, it is necessary to give consideration to two possible slippage lines, shearing along the base of the snow pack and shearing above, (Bozhinskii, 1972) which improves estimations of distances between structures on the building of avalanche-prone slopes.

The problem of the snow as a unit overflowing the retaining structure is very complex. The difficulties are caused by the physical-mechanical nature of the snow, complex rheological relations, as well as by the mathematical formulation of the problem, free surface, non-stationary natures. Therefore, this paper will examine a condition of Coulomb boundary equilibrium for the snow cover between two retaining structures along the slope. We will primarily consider an instance in which there is a layer of deep rime (depth hoar) in the sub-layer and in which the sliding line partially coincides with the horizon of deep rime during snow slippage over the structure, and for which the conditions of bed stability are impaired.

This paper will show computations of the distance between the snow-retaining structures as a function of the slope angle, horizon length of the thickness of depth hoar, and snow strength features.

Let us examine a snow cover with thickness, H, confined between two supporting structures located a distance, L, apart along the slope (fig. 1). We will limit ourselves to a planar problem. We will investigate the possibility of snow cover slippage as a unit over the lower supporting structure. We will assume that a layer of depth hoar has formed in the sublayer as a result of snow metamorphosis. As is known, such a layer has a very slight resistance to shear. Therefore, it is natural to adopt a straight line, coinciding with the sublayer, as the line of snow cover slippage. However, if the lower structure possesses sufficient resistance to shearing, then snow cover slippage from above over this structure is possible. In connection with this, it is appropriate to represent the slippage line in the form of a straight line BC and an arc AB with the center at O_1 which are joined at point B (see fig. 1).

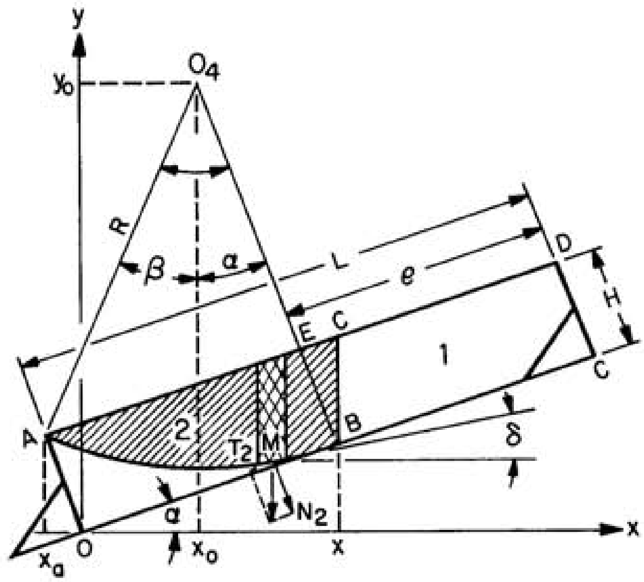

Fig. 1. Snow bed slippage over a supporting structure.

We have the following from geometrical relationships:

$$R = \frac{H}{2}\left[1 + \left(\frac{L - l}{H}\right)^2\right], \ \breve{AB} = \vartheta R, \qquad [1]$$

where R is the radius of the circle of which AB is a part, 1 is the length of the rectilinear part of the slippage line, $\breve{AB}$ is the length of the arc of the curvilinear part of the slippage line, ϑ is the center angle AO_1B.

We will introduce the dimensionless variables:

$$r = \frac{R}{H}; \quad \lambda = \frac{L}{H}; \quad \mu = \frac{l}{H}; \quad S = \frac{\breve{AB}}{H}. \qquad [2]$$

Then,

$$r = \frac{1}{2}\left[1 + (\lambda - \mu)^2\right]; \quad \vartheta = \text{arc sin}\,\frac{\lambda - \mu}{r}; \quad S = \vartheta r. \qquad [3]$$

There are two limiting cases: a) the radius of the arc is equal to the thickness of the snow cover $\lambda - \mu = 1$, and b) the snow cover length considerably exceeds its thickness, $\lambda \to \infty$. Equations [3] have the form:

a) $r = 1; \quad \vartheta = \pi/2; \quad s = \pi/2;$ [3a]

b) $r \to \lambda^2/2; \quad \vartheta \to 0; \quad S \to \lambda$. [3b]

Next we will introduce a Cartesian system of coordinates x0y as is shown in fig. 1. We will supply the coordinates of points A, B, O_1 with subscripts a, b, o respectively. The circumference equation in system x0y will be written in the form:

$$(x - x_o)^2 + (y - y_o)^2 = R^2. \qquad [4]$$

Hence

$$y = y_o - \left[R^2 - (x - x_o)^2\right]^{1/2}. \qquad [5]$$

The minus sign is taken here before the root since the lower half of the circumference is being considered.

Differentiating [5], we will obtain the following:

$$y' = \tan\delta = (x - x_o)\left[R^2 - (x - x_o)^2\right]^{-\frac{1}{2}}, \qquad [6]$$

where δ is the angle formed tangential to the circumference (arc) with the x axis in a random point M.

From analytic geometry formulas we have:

$$\sin\delta = \frac{(x - x_o)\left[R^2 - (x - x_o)^2\right]^{-\frac{1}{2}}}{\left\{1 + (x - x_o)^2\left[R^2 - (x - x_o)^2\right]^{-1}\right\}^{\frac{1}{2}}}.$$

$$\cos\delta = \frac{1}{\left\{1 + (x - x_o)^2\left[R^2 - (x - x_o)^2\right]^{-1}\right\}^{1/2}}. \qquad [7]$$

$$x_a = -H\sin\alpha;\ \ y_a = H\cos\alpha;\ \ x_o = R\sin\beta - H\sin\alpha;\ \ y_o = R\cos\beta + H\cos\alpha;$$

$$x_a - x_o = -R\sin\beta;\ \ y_a - y_o - -R\cos\beta;\ x_g - x_o = R\sin\alpha;\ \ \beta = \vartheta - \alpha.$$

The equation of the straight line AE in system x0y will be

$$y = y_a + (x - x_a)\tan\alpha. \qquad [8]$$

We will then introduce the difference h(x) between the ordinates of the straight line AE and arc AB.

$$h(x) = y_a - y_o + (x_a - x_o)\tan\alpha + \left[R^2 - (x - x_o)^2\right]^{1/2} \qquad [9]$$

Let us move on to a consideration of the boundary equilibrium of the element of the snow layer ABCD. Following the methods of soil mechanics (Tsytovich, 1963), we will break down the whole element ABCD into two elements ABG (2, shaded) and BCDG (1, non-shaded). The equilibrium condition of the element BCDG (1) will be

$$P + C_1 l + N_1\tan\psi_1 - T_1 = 0, \qquad [10]$$

where P is the reaction (creep pressure from element 2); C_1 is the bonding along the slippage line at a rectilinear segment; N_1 is the normal specific stress (to the slippage line); ψ_1 is the angle of inner snow friction at segment BC, T_1 is the tangential specific stress. We obtain the following from [10]:

$$P = \rho g H(l - \frac{H}{2}\tan\alpha)\sin\alpha - C_1 l - \rho g h(l - \frac{H}{2} - \tan\alpha)\cos\alpha\cdot\tan\psi_1. \qquad [11]$$

where ρ is the mass snow density and g is the friction acceleration.

In examining the equilibrium of element 2, we will set up an equation of moments with respect to point O_1. A force, equal to the creep pressure having an opposite sign, acts on element 2 from the side of element 1.

We have

$$P\cdot R + T_2\cdot R - N_2 \tan\psi_2\cdot R - C_2\breve{AB}\cdot R = 0 . \quad [12]$$

N_2, T_2 here are respectively the normal and the tangential integral components of the mass forces

$$N_2 = \int_{x_a}^{x_b} \rho g \cos\delta\cdot h(x)\, dx ; \quad T_2 = \int_{x_a}^{x_b} \rho g \sin\delta\, h(x)\, dx , \quad [13]$$

C_2, ψ_2 are respectively the bonding along arch AB and the angle of internal snow friction of element 2.

Equilibrium condition [12] is based on the assumption that, first, all forces act along the shearing line and, secondly, a lateral contraction of the vertically cut elements in ABG is absent. Figure 1 shows a small element (double shaded) and the elementary mass forces which are acting. The latter assumption is widely used in soil mechanics and is known as Fellens Hypothesis (Tsytovich, 1963).

We will write equation [12] in the form:

$$\rho g H(l - \frac{H}{2}\tan\alpha)\sin\alpha - C_1 l - \rho g(l - \frac{H}{2}\tan\alpha)\cos\alpha\tan\psi_1 + \rho g H^2 I_s - \rho g h^2 I_c \tan\psi_2 - C_2 H\cdot S = 0 , \quad [12']$$

where

$$I_s = \int_{x_a}^{x_b} h(x)\sin\delta a x , \quad I_c = \int_{x_a}^{x_b} h(x)\cos\delta\, a x . \quad [14]$$

Having divided equation [12'] into $\rho g H^2$, we obtain:

$$\left(\mu - \frac{\tan\alpha}{2}\right)\sin\alpha - \frac{C_1}{\rho g h}\mu\cdot\sin\alpha - \left(\mu - \frac{\tan\alpha}{2}\right)\cos\alpha\cdot\tan\psi_1 + I_s - I_c\tan\psi_2 - \frac{C_2}{\rho g H}\cdot S = 0 . \quad [15]$$

We will consider the bonding of the snow cover along the layer of depth hoar to be small, that is, $C_1 = 0$. If we fix μ, then we will obtain the following from [15] for a limitless increase of the distance between obstacles ($\lambda \to \infty$):

$$H_{crit} = \frac{C_2 \cdot S_\infty}{\rho g (I_{S_\infty} - I_{c_\infty} \cdot \tan \varphi_2)} \quad , \qquad [16]$$

where the subscript, ∞, refers to the limiting values of the quantites for $\lambda \to \infty$. In using the limiting values from [16] we will find

$$H_{crit} = \frac{3C_2}{2\rho g(\sin\alpha - \tan\psi_2 \cos\alpha)} \, . \qquad [17]$$

Equation [17] provides an expression of the critical thickness of the snow cover for an infinite distance between structures (without actually having been built) for the adopted shear line. The equation is the same for shearing in the sublayer, but the coefficient is not equal to 3/2 but to 1; in the case of shearing along a straight line passing from the base of the upper structure over the top of the lower structure, the coefficient is equal to 2 (Bozhinskii, 1972).

In introducing the limitless thickness of snow cover $h = H/H_{crit}$, we will obtain the following from the equation for boundary equilibrium [15]:

$$h = \frac{2}{3} - (\sin\alpha - \tan\psi_2 \cos\alpha) \cdot S \cdot \left[\left(\mu - \frac{\tan\alpha}{2} \right) (\sin\alpha - \tan\psi_1 \cos\alpha) + I_s - I_c \tan\psi_2 \right]^{-1} . \qquad [18]$$

Calculations for equation [18] were performed on a "Mir-2" computer. The following parameter values were adopted: the slope angle, a = 30°, 35°, 40°, 45°; the coefficient of internal friction for element 1 was equal to $\tan\psi_1 = 0.1; 0.5$; the coefficient of internal snow friction of element 2 was equal to $\tan\psi_2 = 0.5$; the relative length of the rectilinear segment of the shear line equaled $\mu = 1, 2, 3, 5, 10$. Curves were plotted for the function of the relative spacing between structures λ on the relative thickness, h for the values of the slope angles under consideration, as well as the snow strength conditions and μ parameter.

Figure 2 gives the typical curves $\lambda(h)$ for $\mu = 1$. They illustrate the decrease of interval λ between the structures with an increase of the relative thickness of snow cover h. It is important to note the considerable role of the coefficient of internal snow friction for element 1, that is, along the rectilinear segment of the shear line. Thus, for h = 4 the distance between the structures can be increased 1.5 times if we increase the coefficient of internal friction $\tan \psi_1$ from 0.1 to 0.5.

Figure 3 shows the transformation of curves $\lambda(h)$ as a function of parameter μ. With $\mu > 2.5$, the values of h, which correspond to the boundary equilibrium of the bed, are less than one. This indicates the deterioration of the conditions of equilibrium. In other words, the creep pressure is great, and the length of the curvilinear segment of the slippage line is small, h approaches one with the increase of λ for μ = const.

Figure 4 shows the change of the distances between the structures as a function of the slope angle. It is seen that with the increase of the slope angle; the distances between the structures are reduced (all conditions being equal).

It is interesting to compare the results we obtained with the recommendations of the Swiss National Institute of Snow and Avalanches (Lawinenverbau, 1968). In its recommendations, a snow cover thickness is used for a vertical $H_K = H/\cos a$; the relation L/H_k is indicated by f_L. The relationship between the relative interval λ and f_L has the form:

$$f_L = \lambda \cos\alpha . \qquad [19]$$

Figure 5 shows a comparison of the results. The shaded line represents the recommendations of (Lawinenverbau, 1968); the dashed-shaded curve represents the solution of a study (Bozhinskii, 1972) for a straight slippage line (h = 5, $\tan \psi_2 = 0.5$); the solid lines represent the solution which was obtained for $\mu = 1$, fig. 2.; h was adopted as a parameter. We must admit that the values of h depend on many factors and are susceptible to snow, structure, and temperature type. It is also seen from fig.2 that for h >> 1, the solution does not depend essentially on h. The graphs show that even the curve h = 5 can be considered as a lower apparaisal of the distances between the structures. A comparison with the

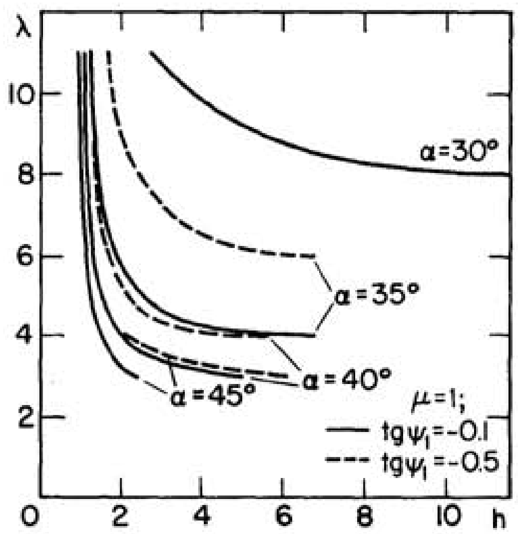

Fig. 2. The dependence of the relative interval between structures (λ) on the snow strength features (h) for various slope angles (α).

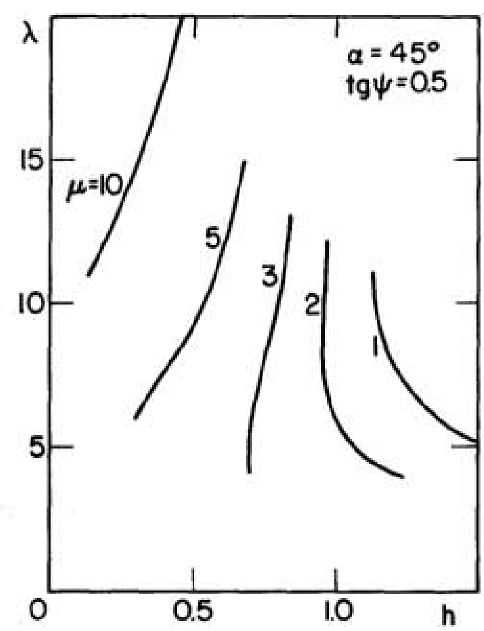

Fig. 3. The effect of the length of the horizon of rime (h) on the relative structure interval (λ).

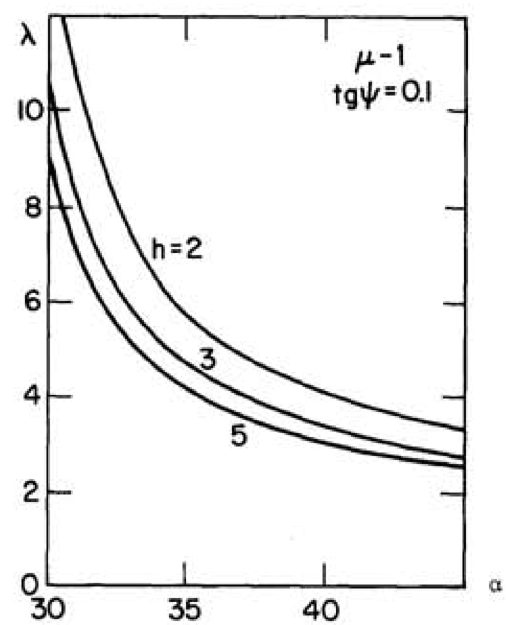

Fig. 4. Dependence of the relative structure interval (λ) on the slope angle (α).

recommendations of the Swiss Institute (Lawinenverbau, 1968) shows that the results are relatively close for $\alpha < -35°$. For greater steepness this solution results in a denser arrangement of structures on the slopes, however, the pressure on the structure will be less in this case. We will note that the solution of Bozhinskii's study (1972) will better agree with the recommendations of the Swiss Institute in a slope angle range $\alpha > 35°$.

The solution which we have obtained should be considered as an extension of the result of Bozhinskii's study (1972) where a straight line, passing from the base of the upper structure and over the top of the lower structure, was adopted as the slippage line. The theoretical solution of the problem of placing retaining structures on mountain slopes according to boundary equilibrium can apparently be considered completed. An analysis of other slippage lines would scarcely lead to a substantial change of results. Further improvements will be due to taking into account snow rheology and a consideration of the whole problem of snow flowing over a retaining structure. The latter will require the use of equations for continuous medium mechanics. Moreover, an experimental determination of the long-term snow strength in various physical-geographical conditions is necessary in transferring from the solutions which have been obtained to practical recommendations.

In conclusion, the author expresses gratitute to Professor IU. G. Simonov and to senior engineer I.M. Zeidis for their help in making the computer calculations.

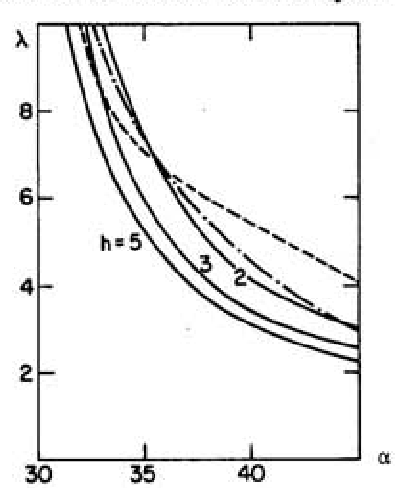

Fig. 5. Comparison of the obtained solutions with the Swiss recommendations.

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Theoretical Approaches to Avalanche Dynamics

M.E. Eglit

At the present time a number of theoretical studies exist in which the dynamics of snow avalanches are considered and velocities and runout distance for various types of avalanches are suggested (Kozik, 1962; Goff and Otten, 1939; Gongadze, 1954; Sulakvelidze, 1949; Grigorian et al., 1967; Voellmy, 1955; Laboudigye, 1958; Salm, 1966). In all the studies, very idealized schemes are proposed, which are capable of describing a moving avalanche only in general terms. This is tied to the complexity of the phenomenon as well as the paucity of quantitative data about the properties of moving snow. The approximate nature and lack of information from the proposed theories lies, first, in the selection of a highly simplified model of the moving medium itself, second, in the use of approximate equations of motion and, third, in the approximate and simplified assumptions which are made in the solution of these equations. In all three of these features, the theories under consideration can be made more accurate and can be developed further.

Model studies of moving medium and computation methods used can be divided into two groups: (1) the moving snow is viewed as a liquid, and hydraulic methods are used for computation (Voellmy, 1955; Laboudigye, 1958; Salm, 1966; Grigorian et al., 1967); (2) the avalanche is viewed as a material point (with, generally speaking, a variable mass), and the motion within the avalanche is not taken into account at all (Kozik, 1962; Goff and Otten, 1939; Gongadze, 1954; Sulakvelidze, 1949; Barban, 1962; Moskalev, 1966; Tushinskii, 1960; Goff and Otten, 1938). The latter theories represent the simplest quantitative approximation of the complex phenomenon studied. Many questions, particularly important in practice, related to the motion of avalanches are not considered. Thus, within the limits of this theory, it is impossible to study the velocity distribution of snow in an avalanche (the velocities of snow, as a rule, are not the same as the velocity of the leading edge of the avalanche), the change of avalanche form and size as it moves, and the load distribution in the avalanche flow around a barrier. The theory which considers the avalanche to be a material point may be considered essentially finished at this time. Of course, new examples of the calculation of avalanche motion may appear with the help of this theory; however, it is difficult to expect substantially new information about avalanches in comparison to that obtained in (Kozik, 1962; Goff and Otten, 1939; Gongadze, 1954; Sulakvelidze, 1949; Barban, 1962; Moskalev, 1966).

The theory that views avalanche motion as the movement of a continuous medium is in a position to describe much more fully the phenomena associated with the motion of avalanches along a slope and their interaction with an obstacle. In particular, only this theory can provide the sufficiently detailed information about the forces acting on structures from avalanche impact. At present, there exist a small number of studies in which attempts are being made to use methods of continuum mechanics for theoretical study of avalanche dynamics (Voellmy, 1955; Laboudigye, 1958; Salm, 1966; Grigorian et al., 1967). The hydraulic scheme being used in all these studies calculates the motion of the snow inside the avalanche only in general terms. It is possible and, in the future it may be necessary, to use more intricate models, with internal stresses, anisotropy, stratification, etc. However, even the simplified hydraulic theory is far from comprehensive. Furthermore, in essence there is a complete lack of the necessary mathematical formulation of the problem of avalanche motion within the framework of a hydraulic scheme (Voellmy, 1955; Laboudigye, 1958; Salm, 1966). Only part of the necessary relationships has been derived; therefore, the solution of the problem seems possible only with a number of highly arbitrary assumptions which, in essence, lead to the supposition that the avalanche moves as a rigid body. This, of course, loses all the advantages of such a theory.

The studies of A. Voellmy (1955), and S. M. Kozik (1962), which represent the two existing viewpoints on avalanches, are analyzed in detail below. Analysis and comparison of the basic assumptions used in the formulation and solution of the problem were made to clearly formulate the basic assumptions of the two approaches and to make it possible to select from the existing methods, and to formulate a direction for the future development of the theory.

A complete mathematical formulation of the problem of steady-state movement of the avalanche along a constant slope within the framework of a hydraulic scheme is also cited. The solution of this problem makes it possible to find the velocity of the avalanche front moving along a constant slope, the distribution of snow velocity in the avalanche, the shape of the longitudinal section of the avalanche, and the height of its leading edge. Let us begin the survey of studies in which hydraulic methods are applied to the study of avalanches with Voellmy's article (1955). It describes a series of observed avalanches and the destruction caused by them. Data are given on the size and weight of the damaged objects and on the type and magnitude of the forces necessary to create the damage observed. Avalanche dynamics considered. Motion equations are derived and the maximum velocity developed on slopes with a constant gradient is computed. Formulas are given for the change of the flow height of the avalanche and avalanche velocity during passage through a change in slope gradient. The air wave is also considered. The runout distance of the avalanche and the snow debris cone height which remained are computed as well as the pressure of the avalanche when it is stopped by an obstacle. Various computations are performed from the equations which were obtained and comparisons are made with on-site observations. Certain recommendations are also made for building defense structures. Numerous logical omissions, the lack of necessary drawings, and misprints in the equations hinder the reading of this work and make it necessary to analyze it in detail.[1]

Voellmy considers moving snow to be a viscous fluid. Turbulent movement is considered to begin at a velocity of $v_{cr} \simeq 1$ m/sec. Let us evaluate the viscosity coefficient, ν, of snow. We will accept that the transition to a turbulent regime takes place at Re = 2000, ($Re = \frac{vh}{\nu}$ -- Reynold's number). We have

$$\frac{v_{cr}h}{\nu} = 2000 .$$

With $h \simeq 2$ m (avalanche flow height) and $v_{cr} \simeq 1$ m/sec, we obtain $\nu = 10$ cm^2/sec; that is, 1,000 times greater than the viscosity of water (water viscosity = $\nu_w \simeq 0.01$ cm^2/sec).

Voellmy also gives an equation for the velocity profile in the movi..g measurements in a sandstorm),

$$v = v_{mean}\left[\frac{4}{3} - \left(\frac{y}{h}\right)^2\right].$$

Here, h is the flow height of the moving layer of snow, and y is the depth measured from the top of the avalanche. Therefore, unlike the usual viscous liquid, the condition of adhesion to the solid boundary is not assumed for snow; slippage of the moving layer along the wall (slope) is postulated. In connection with this, the equation of motion, which is derived by Voellmy for a one-dimensional hydraulic system, has the form (fig. 1):

$$\frac{dv}{dt} = g\left(1 - \frac{\rho_L}{\rho}\right)(\sin\psi - \mu\cos\psi) - \frac{g}{kh}v^2 . \qquad [1.1]$$

where v is the velocity parallel to the slope, ψ is the slope angle; ρ_L is air density; ρ is snow density; and h is the vertical height of the layer of moving snow; k is a constant coefficient; μ is the coefficient of Coulomb friction; g is the acceleration of gravity; and t is time. Thus, the Coulomb friction and the hydraulic resistance due to the viscosity of snow are simultaneously taken into account. The numerical values of μ are $\mu = \frac{\rho g}{c}$ where c = 1,000 to 2,000 kg/m^3 for ground avalanches and c = ∞ for wet and loose snow.

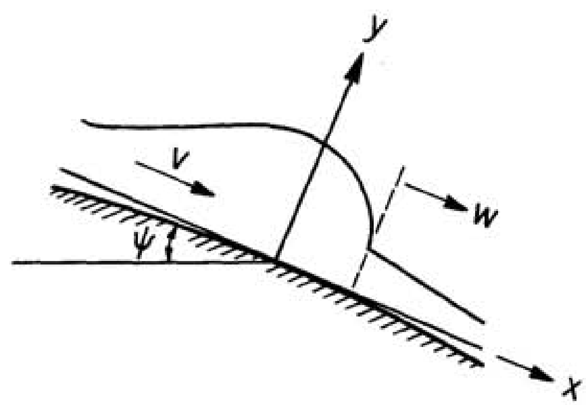

Fig. 1. Diagram of avalanche movement along the slope.

Let us make some observations with respect to equation [1.1]. For comparison, we will write out the equation of motion of the usual viscous fluid on a slope with a slightly changing slope angle in a one-dimensional hydraulic system (Arkhangel'skii, 1936),

$$\frac{dv}{dt} g \sin \psi - g \frac{\partial h}{\partial x} \cos \psi - \frac{g}{C^2 R} v^2 .$$

Here, x is the coordinate along the slope; C is the Chézy coefficient linking the friction loss with the square of the velocity ($i_{friction} = v^2/C^2R$) when velocities are large enough; R is the hydraulic radius of the flow section (for a two-dimensional problem, R = h-- the thickness of the flow measured perpendicular to the slope). This equation does not include the force associated with Coulomb friction. Also included in it is the second term on the right side of the equation connected with the gradient of the pressure force along the slope. It is assumed that on the flow surface the pressure is constant everywhere and is equal to p_{atm}, and in depth the pressure, p, is distributed according to the hydrostatic law, $m = p_{atm} + \rho g(h - y)\cos \psi$. In this case, the pressure acting on the cross section is not constant for x if the thickness of the moving layer is variable and a corresponding term appears in the equation of motion. Therefore, it is apparent that (a) Voellmy considers a plane problem; that is, cases when either the avalanche is indefinitely wide or when it is possible to disregard lateral spreading and change of width, since [1.1] uses h instead of R; (b) Voellmy does not take into account forces due to the variability of h; (c) the designation of the quantity, h, (the vertical thickness of the moving layer of snow) is apparently incorrect because it follows from hydraulics that if k is considered constant and independent of slope, then h should be the thickness measured perpendicular to the slope.

In equation [1.1], additional inertia forces, which result from the curvature of the path, were not taken into consideration (only the change of the velocity module is taken into account).

Equation [1.1] is a partial derivative equation containing three unknown functions: $v = v(x,t)$, $h = h(x,t)$ and $\rho = \rho(x,t)$ for which the equation dv/dt has the form

$$\frac{dv}{dt} = \frac{\partial v}{\partial t} + v\,\frac{\partial v}{\partial x} \ .$$

(x is the coordinate along the slope). In Lagrangian coordinates, x_o, t, equation [1.1], is written out in the form

$$\frac{\partial v(x_o,t)}{\partial t} = g\left[1 - \frac{\rho_L}{\rho}\right](\sin\psi - \mu\cos\psi) - \frac{g}{kh}\,v^2 \ . \qquad [1.1']$$

In this equation, v, ρ, h, and ψ are the unknown functions of x_o and t. Therefore, additional relationships are still necessary in order to determine all the unknown functions. Voellmy, however, integrates this equation,, considering h = const, ρ = const, and ψ = const. In the solution of equation [1.1'], the following equation for v is derived in which

$$v = v_{max} \mathrm{th}\ \frac{v_{max}}{K}\,t \ . \qquad [1.2]$$

$$v_{max} = \quad kh\left[1 - \frac{\rho_L}{\rho}\right](\sin\psi - \mu\cos\psi)\ , \quad K = \frac{k}{g}\,h \ . \qquad [1.3]$$

Equation [1.2] is derived from [1.1'] if one makes the additional assumption that the slope is sufficiently steep so that $\sin\psi - \mu\cos\psi > 0$, and that with t = 0, $v(x_o) = 0$ for all x_o. Therefore, the velocities of all the particles are found to be equal to each other for any $t \geq 0$; that is, in such a system the avalanche can be represented as a rigid body. The major assumption that ρ and h are constant in all cross sections of the avalanche and that all the snow particles begin to move simultaneously has led to the fact that the relative movement of snow inside the avalanche has been rejected from consideration. Furthermore, in such a case, it is impossible, without contradictions, to introduce concepts of the leading edge of the avalanche (since all the snow on the slope according to [1.2] begins to move simultaneously).

Movement, according to [1.2], occurs with acceleration and is not steady-state. The graph of v(t) is shown in fig. 2. The travel distance, S, is derived by integrating [1.2] to get

$$S = k\ \ln\ \mathrm{ch}\left[\frac{v_{max}}{k}\,t\right], \qquad [1.4]$$

in which $S(x_o) = 0$ with $t = 0$ for all x_o. The quantity, S, increases with time and tends toward infinity with $t \to \infty$ (fig. 3). From equation [1.2], it is apparent that v rapidly tends toward v_{max} with the increase of time. Thus, the quantity, $v^* = 0.8v_{max}$, is attained in the expansion of path, $S^* \simeq 25h$, (if k is accepted as = 500 m/sec^2). Therefore, the velocity on a slope of the angle, ψ, is considered constant and equal to v_{max}; that is,

$$v \simeq v_{max} = \quad kh\left[1 - \frac{\rho_L}{\rho}\right](\sin\psi - \mu\cos\psi)\,. \qquad [1.5]$$

We will observe that if the snow particle enters at the moment, $t = t_0$, onto the slope with $\psi = \psi_1$, where $\sin\psi_1 - \mu\cos\psi_1 > 0$, with a non-zero initial velocity $v_o \neq v_{1max}$, then [1.1'] gives

$$v = v_{1max}\,\frac{c\exp\left[2v_{1max}t/K_1\right] - 1}{c\exp\left[2v_{1max}t/K_1\right] + 1}\,. \qquad [1.6]$$

in which

$$c = c(x_o) = \frac{v_{1max} + v_o}{v_{1max} - v_o}\,\exp\left[-2v_{1max}t_0/K_1\right].$$

and then again, $v \to v_{1max}$ with time (fig. 4). This equation is not contained in Voellmy's study. Therefore, on all segments of the slope, where $\sin\psi_1 - \mu\cos\psi_1 > 0$, and ψ_i = const, it is possible to roughly consider $v_i = v_{imax}$, if the length of the segment is sufficiently great. In such a consideration, it is also possible to compute the velocity from equation [1.5] in the case of movement along a slope with a slowly changing slope angle. Let us consider that the slope angle changes substantially only at distances noticeably greater than the quantity S^* calculated in the maximum velocity for the given slope. Then it is possible to consider, with the same accuracy as for the slope with a constant gradient, that the velocity everywhere reaches the values given by equation [1.5].

In general, Voellmy does not consider the part of the path where $\sin\psi - \mu\cos\psi < 0$. In this region, the snow will slow down and equation [1.11] (formerly where h = const, ρ = const, ψ = const)[2] yields

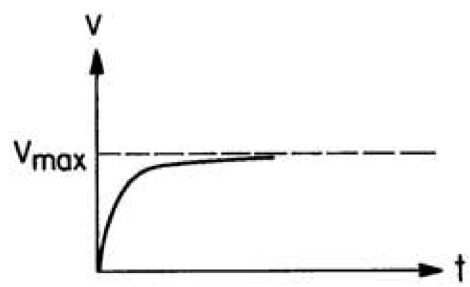

Fig. 2. Dependence of snow velocity in the avalanche on time according to [1.2].

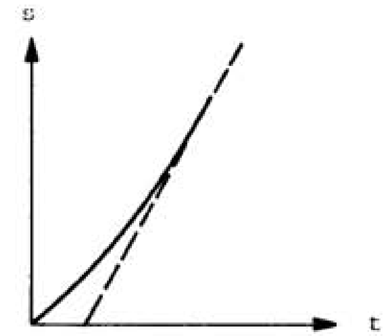

Fig. 3. Dependence of the distance of the snow's travel upon time, according to [1.4].

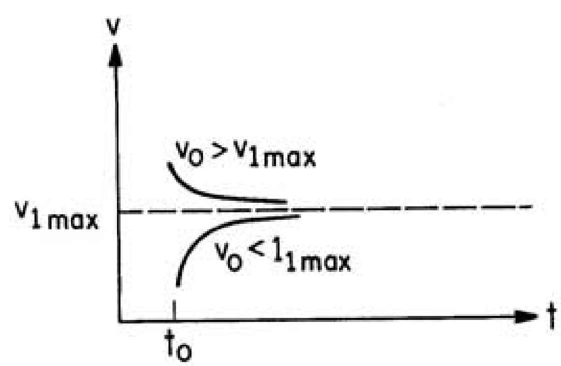

Fig. 4. Change of velocity with time according to [1.6].

$$v = A \tan\left[\arctan \frac{v_o}{A} - \frac{A}{K}(t - t_o)\right]. \qquad [1.7]$$

where

$$A = \quad kh\left[1 - \frac{\rho_L}{\rho}\right](\mu \cos \psi - \sin \psi). \qquad [1.8]$$

At the moment, $t = t_{final} = t_o + \frac{K}{A} \arctan \frac{v_o}{A}$, the snow particles stop, and the velocity is converted to zero. By virtue of the inequality of $[\sin \psi - \mu \cos \psi < 0]$, the component of the force of gravity directed along the slope is insufficient to overcome the Coulomb force of friction and support the movement. In this case, there is a maximum runout distance. By S_{max}, let us designate the slope distance from the last major change in slope gradient to the end of the debris. Let v_o represent the velocity which the particles have at the start of the runout zone. Then, from [1.7] we obtain

$$S_{max} = \frac{hk}{2g} \ln \left[1 + \frac{v_o^2}{kh\left[1 - \frac{\rho_L}{\rho}\right](\mu \cos \psi - \sin \psi)}\right]. \qquad [1.9]$$

If

$$v_o^2 \ll hk\left[1 - \frac{\rho_L}{\rho}\right](\mu \cos \psi - \sin \psi),$$

then [1.9] is approximated as

$$S_{max} \simeq \frac{v_o^2}{2g\left[1 - \frac{\rho_L}{\rho}\right](\mu \cos \psi - \sin \psi)}. \qquad [1.10]$$

Let us examine another instance when the particle with a velocity of v_o reaches the slope where $\sin \psi - \mu \cos \psi = 0$. Then, from [1.1'] we obtain

$$v = K/(t - t_o + k/v_o) \qquad [1.11]$$

and

$$S = K \ln \left[1 + v_o(t - t_o)/K\right]; \qquad [1.12]$$

that is, $S = K \ln \frac{v_o}{v}$.

It is apparent that with $t \to \infty$, $S \to \infty$; that is, the avalanche does not stop. Coulomb friction on the runout slope is equalized exactly by the component of gravity parallel to the slope. However, its velocity falls rather fast. In fact, let $v_o \simeq 20$ m/sec, $h \simeq 2$ m, and $K \simeq 50\,h \simeq 100$ m, then with $(t - t_o) \simeq 245$ sec, and $S \simeq 400$ m, the magnitude of v is equal to 2% of the original velocity; $v \simeq 0.4$ m/sec. These are the formulae for the velocity and runout distance, obtained from [1.1], assuming ρ = const, ψ = const, and h = const. In Voellmy's study, equations [1.6 - 1.12] are not cited.

The equation of continuity which should be used here is in the form

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho h v}{\partial x} = 0, \text{ or } \frac{\partial \rho h}{\partial t} + \rho h \frac{\partial v}{\partial x} = 0,$$

with movement along a constant slope satisfied automatically since ρ and h in the volume are assumed constant, and $v = v(t)$ does not depend upon x.

Voellmy does not consider the quantities ρ, v, and h constant for the entire slope; rather, the slope is divided into segments in which ρ, v, and h can be considered constant. In the transition from one such segment to another, the quantities ρ, v, and h change abruptly. Instead of calculating this change using the usual conditions in shock waves, Voellmy accepts (1) that the velocity and the thickness of the snow layer changes when the slope angle changes, but the density does not change; (2) that the velocity for each rectilinear segment, i, is computed independently of the other segments from the equation,

$$v_i = v_{imax} = \quad kh\left[1 - \frac{\rho_L}{\rho}\right](\sin\psi - \mu\cos\psi);$$

and (3) that at the change in slope angle from segment "1" to segment "2", the equation of the conservation of mass is fulfilled in the form:[3]

$$v_1 h_1 = v_2 h_2 \ . \qquad [1.13]$$

Then, when $\rho_1 = \rho_2$ and $\mu \cos \psi_1 \ll \sin \psi_1$, the following is obtained:

$$\frac{v_1}{v_2} = \frac{h_2}{h_1} = \frac{\sqrt{h_1 \sin \psi_1}}{\sqrt{h_2 \sin \psi_2}} \, ;$$

that is,

$$h_2 = h_1 \sqrt[3]{\frac{\sin \psi_1}{\sin \psi_2}} \, ; \quad v_2 = v_1 \sqrt[3]{\frac{\sin \psi_2}{\sin \psi_1}} \, . \qquad [1.14]$$

Voellmy confirms that equations [1.14] are well-supported by avalanche observations. In equation [1.13], h_1 and h_2 indicate, apparently, the height of the snow layer not vertically, as Voellmy assumes, but perpendicular to the slope. Furthermore, (and this is very essential), the equations of [1.14] are derived only for slopes on which the avalanche does not slow down; that is, [$\sin \psi_1 - \mu \cos \psi_1 > 0$]. Meanwhile, it is very important to know how the velocity changes at the abrupt transition at the upper end of the runout zone. This question is neither formulated nor resolved in Voellmy (1955).

The conditions of [1.14] describe the change of the flow height and the velocity of the moving avalanche in the transition from one segment of the slope to another. However, even on the part of the slope where the avalanche originates, ρ_1 and h_1 in the avalanche do not coincide with the density, ρ_o, and height, h_o, of the snow cover on the slope before the avalanche ran. For determining ρ_1 and h_1 from ρ_o and h_o, it is necessary to examine the leading edge of the avalanche (cross section AB in fig. 5). Voellmy obtains snow density and flow height of the moving layer in the following manner: for powder avalanches, a relationship is derived from which the density, ρ_1, is determined by

$$g\left(\rho_1 - \rho_L\right) h_1 = \frac{\rho_L v^2}{2} = \frac{\rho_L}{2} k h_1 \left[1 - \frac{\rho_L}{\rho_1}\right] \sin \psi \, . \qquad [1.15]$$

This relationship can be considered as a condition of the equality of the pressures for both sides of the leading edge at a point A (fig. 5), if it is assumed that (a) the velocity of the front coincides with the velocity of the snow particles in the avalanche and is computed according to [1.5] with $\mu = 0$; (b) snow cover is absent in from of the avalanche; (c) it is possible to neglect Coulomb friction in calculating the velocity; (d) quantity h_1 is the difference of the heights of points A and B$'$ (fig. 6). From equation [1.15] ρ_1 is found

$$\rho_1 = \frac{\rho_L}{2g} k \sin \psi \ . \qquad [1.16]$$

Thus, ρ_1 is obtained independent of ρ_o, the density of the original snow cover. We will note that since it is necessary that $\rho_1 > \rho_L$, then from [1.16] it follows that $\sin \psi > 2g/k$. For the flow height of the moving layer, h_1, the formula is written

$$h_1 = \frac{\rho_o}{\rho_1} (1 + m) \, h_o = \frac{\rho_o h_o (1 + m) \cdot 2g}{\rho_L k \sin \psi} \, , \qquad [1.17]$$

in which m is the quantity not being determined, but assigned; for example, for the surface from hardened snow, $m = 0$ is accepted, but for a dry powder avalanche, $m = 1$. The method of selecting m does not yield to explanation. But, from the reliable ratio, $h_o \rho_o w = h_1 \rho_1 (w - v)$, expressing the law of the conservation of mass at the leading edge of the avalanche, it follows that $m = \frac{v}{w - v}$, where w is the velocity of the leading edge. It is also unclear how to combine equations [1.15] and [1.17] since in [1.15] it is assumed that $h_o = 0$, but in [1.17] it is essential that $h_o \neq 0$. In assuming that [1.16] and [1.17] are correct, the expression for avalanche velocity is obtained in the form:

$$v = \quad 2gh_o \frac{\rho_o}{\rho_L} (1 + m) \left[1 - \frac{2g}{k \sin \psi} \right] . \qquad [1.18]$$

If one disregards the term $2g/k \sin \psi$ in this equation, then it will be found that the velocity of the powder avalanche does not depend upon the incline of the slope. This conclusion was also made by Voellmy. Let us carry out the corresponding evaluation with $\psi = 30°$, $k = 500$ m/sec^2, $g = 10$ m/sec^2; we have $2g/k \sin \psi \simeq 0.08$. We will note that [1.17] is in contradiction with [1.14] since, according to [1.17], $h = c_1/\sin \psi$, where c_1 does not depend upon ψ, and, according to [1.14], we have $h = c_2/\sqrt{\sin \psi}$, where c_2 also does not depend upon ψ.

For ground avalanches, other ratios are used for determining h_1 and ρ_1 in a moving avalanche. Using w to indicate the velocity of the avalanche front, Voellmy writes

$$\frac{\rho_1}{2}(v - w)^2 = \frac{\rho_L}{2} w^2 \qquad [1.19]$$

and

$$w = v\left[1 - \frac{\rho_o h_o}{\rho_1 h_1}\right] \qquad [1.20]$$

and, as a result of [1.19] and [1.20],

$$\rho_1 h_1 = 2.6 \rho_o h_o \,. \qquad [1.21]$$

However, equations [1.19] and [1.20] do not yield to interpretation, and [1.21] can in no way be obtained from [1.19] and [1.20].

It is further considered that for ground avalanches $\rho_1 = \rho_o$ and then

$$h_1 = 2.6 h_o \,, \qquad [1.22]$$

which is independent of the slope angle as well as the velocity and density of the original snow cover.

Finally, Voellmy proposes that ρ_1 and h_1 in the moving avalanche be:

(1) $h_1 = h_o$, $\rho_1 = \rho_0$ for surface avalanches and snow slabs;

(2) $h_1 = \frac{\rho_o h_o}{\rho_1}$, $\rho_1 = \frac{\rho_L}{2g} k \sin \psi$ for powdered avalanches; and

(3) $\rho_1 = \rho_o$, $h_1 = 2.6 h_o$ for ground avalanches.

In computing the runout distance, Voellmy changes over to another point of view. He writes a relation for an avalanche as a material point, coinciding with the avalanche center of gravity (fig. 7). It is assumed that in the runout zone the flow height of the moving layer increases, with the increase of this flow height being proportional to the distance the avalanche has traveled into the runout zone. (We will note that this is a completely arbitrary condition and not the result of the laws of mechanics.) The mass of a unit width of avalanche,

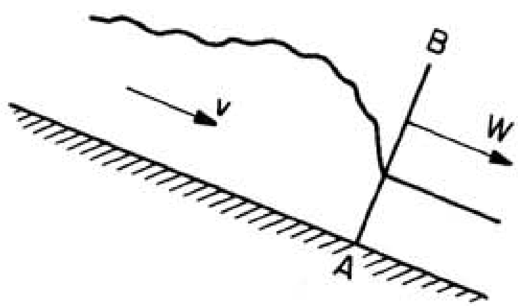

Fig. 5. Leading edge of the avalanche -- cross section AB.

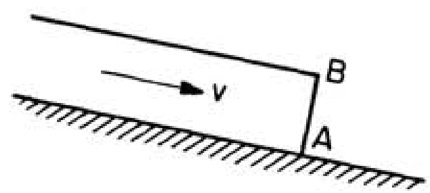

Fig. 6. Diagram explaining [1.15].

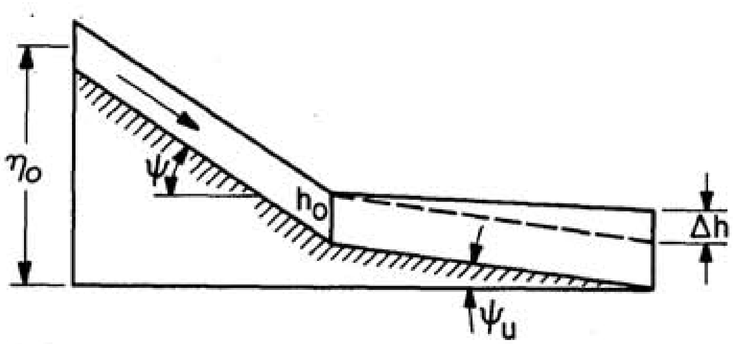

Fig. 7. Sketch of the formation of the "cone" in the stopping of the avalanche (according to [1.]).

flowing out onto the runout zone, in this instance, is equal to

$$M = S\,\frac{2h_o + \Delta h}{2}\,\rho\,. \qquad [1.23]$$

Its kinetic energy at the top of the runout zone is equal to $E_k = 1/2 \cdot Mv_o^2$, after the avalanche stops, $E_k = 0$. The energy equation for a point with mass, M: located in the center of gravity of the avalanche, is

$$E_k = E_p + A_R + A_v + A_S\,. \qquad [1.24]$$

Here, E_p is the change of the potential energy of mass, M:

$$E_p = Mg\eta_1 - Mg\eta_o = Mg\,\frac{3h_o + 2\Delta h}{2h_o + \Delta h}\left(\frac{\Delta h}{6} + \frac{S}{3}\tan\psi_u\right), \qquad [1.25]$$

where $(\eta_o - \eta_1)$ is the difference of the heights of the center of gravity of mass M in the beginning and at the end of the runout zone. A_R is the work of the Coulomb force of friction,

$$A_R = \mu \cdot Mg\cos\psi_u \cdot \xi\,, \qquad [1.26]$$

where ξ is the path of the avalanche's center of gravity and

$$\xi = \frac{S}{3}\,\frac{3h_o + 2\Delta h}{2h_o + \Delta h}\,. \qquad [1.27]$$

From [1.27], it is apparent that ξ is the projection of the avalanche's center for gravity to the horizontal. A_v is the work of hydraulic friction,

$$A_v = \frac{\rho g}{k}\,\frac{v_o^2}{2}\,S\,. \qquad [1.28]$$

In general, the hydraulic resistance per unit of area is equal to $\rho\, gv^2/k$ (this quantity has a dimension of pressure); $v_o^2/2$ is the mean square value of the velocity in the runout zone; the quantity $\frac{\rho g}{k} \cdot \frac{v_o^2}{2} \cdot S$ is approximately equal to the full force of the hydrodynamic friction acting on the area, $S \cdot 1$, (and not to the work of this force). Therefore, the equation for A_v is written with an error. It apparently should be written:

$$A_v = \frac{\rho g}{k} \frac{v_o^2}{2} S \cdot S\,, \tag{1.29}$$

or

$$A_v = \frac{\rho g}{k} S \cdot \xi \cdot \frac{v_o^2}{2}\,;$$

however, these expressions are also rough approximations. The quantity A_S is given in the form

$$A_S = \zeta \frac{Mg}{\gamma_P} \frac{\gamma_L v^2}{2g}\,, \tag{1.30}$$

where γ_P is the specific weight of snow lacking air inside it, γ_L is the specific weight of air, and ζ is the dimensionless coefficient. The origin of this term is unclear, apparently this is the term taking into account the force of air resistance.

Equation [1.24] makes it possible to compute S if Δh is given. Voellmy proposes that $\Delta h = \frac{v_o^2}{2g}$. This can be true only when *friction is absent*. Thus,

$$S = \frac{v_o^2}{2g\left[h_o + \frac{2}{3}\Delta h\right]} \; \frac{\frac{3}{2}h_o + \frac{2}{3}\Delta h - \frac{2g}{k}}{\mu\cos\psi_u - \tan\psi_u + \frac{\gamma_L}{\gamma_P}\frac{v_o^2}{2g}}\,. \tag{1.31}$$

However, the equation [1.31] cannot be obtained from [1.24]. Instead of [1.31], the following equation for S is obtained, assuming that $\Delta h = v_o^2/2g$ and using A_v as given in the equation [1.29].

$$S = \frac{v_o^2\left[\frac{3}{2}h_o + \frac{2}{3}\Delta h\right] - \zeta(2h_o + \Delta h)\frac{\gamma_L}{\gamma_P}}{2g\left[h_o + \frac{2}{3}\Delta h\right](\mu\cos\psi_u - \tan\psi_u) + \frac{2g}{k}v_o^2}\,. \tag{1.32}$$

Voellmy suggests replacing this equation with an approximate one, assuming $h_o = 0$, $k = \infty$, and $\zeta = 0$; that is, disregarding energies A_v and A_S and considering $h_o \ll \Delta h = \frac{v_o^2}{2g}$. Let us evaluate the values of A_v and A_S. Let $v_o = 20$ m/sec, then $\Delta h = 20$ m, $h_o = 2$ m,

$k = 500\ m/sec^2$; $\zeta \simeq 1$, $\gamma_L \simeq 1\ kg/m^3$, $\gamma_F \simeq 600\ kg/m^3$, $\frac{3}{2} h_o \simeq 3$ m, $\frac{2}{3} \Delta h \simeq 13$ m, and $\zeta(2h_o + \Delta h)\,\gamma_L/\gamma_F \simeq 0 \simeq 0.04$ m. Thus, under these conditions $\frac{3}{2} h_o + \frac{2}{3} \Delta h \gg \zeta(2h_o + \Delta h)\,\frac{\gamma_L}{\gamma_F}$, and it is possible to disregard the energy of A_S. On the other hand,

$$2g\left[h_o + \frac{2}{3}\Delta h\right](\mu \cos \psi_u - \tan \psi_u) \simeq 90\ \frac{m^2}{sec^2}$$

with $\mu = 0.3$ and $\frac{2g}{k} v_o^2 \simeq 1.6\ \frac{m^2}{sec^2}$, that is, the role of A_v in the given assumptions is also not large. Consequently, with large μ it is possible to disregard the energy of A_S and A_v in comparison with the energy of A_R. However, disregarding h_o in comparison with Δh raises doubt. The approximate equation for S, with $A_v = 0$, $A_S = 0$, and $h_o = 0$, has the form:

$$S = \frac{v_o^2}{2g(\mu \cos \psi_u - \tan \psi_u)}. \qquad [1.33]$$

Such a equation is also obtained by disregarding the energy of A_v and A_S and, if one considers that, $\Delta h \ll h_o$. This later condition means that one does not take into account the formation of a debris cone as the avalanche slows down and stops.

The analysis just performed makes it possible to make the following observations concerning a equation for runout distance:

1. It is not only illogical but also unjustified, other than for avoiding the difficulties of solving the nonstationary problem, to switch to a consideration of avalanche motion as movement of a material point. This makes it necessary to make rather rough approximations, especially in computing the mass of the material point and the work of hydrodynamic friction. Equation [1.10] for the runout distance, which was obtained by us with the help of the integration of the differential equation of motion [1.1'], is close to the approximate equation [1.33]; however, it does not coincide with it. The difference becomes even more noticeable if one takes into account that in [1.10] S represents slope distance and in [1.33], horizontal distance. This

difference is slight if the runout occurs on a gentle slope (ψ_u is a small angle).

2. The use of horizontal distance for computing the work of A_R, A_ψ, and A_S, and not the slope distance, raises doubt.

3. It is wrong to consider that $\Delta h = v_o^2/2g$, if the deceleration takes place due to friction.

4. It is also unclear what is meant by v_o and h_o in equations [1.32] and [1.33]. The author apparently considers v_o and h_o as that which were formed on the preceding slope; that is, he considers that in the break of the slope from ψ to ψ_u, the velocity and flow height of the moving layer do not change. This, however, does not agree with the preceding theory.

Therefore, the equation developed by Voellmy for the runout distance of an avalanche [1.31] is incorrect. Although equation [1.32], obtained in exchange for [1.31], contains no formal errors, its applications were made in its derivation.

Voellmy also makes some assumptions concerning the computation of the air wave. It is proposed that the increase of pressure be computed from the equation

$$\Delta p = \rho_L wa , \qquad [1.34]$$

where w is the velocity of the avalanche front, and a is the speed of sound in air. It is known that this equation computes the increase of pressure in a weak shock wave formed when a stationary, infinite plane suddenly begins to move perpendicularly with velocity, w. Then, from the back side of the plane, the wave begins to move backwards with the same decrease of pressure. If a three-dimensional body suddenly begins to move with velocity, w, then equation [1.34] is incorrect and can be used only for estimates which will be exaggerated. Air behind such a wave moves with velocity, w.

It is interesting to estimate the increase of static pressure, Δp, as a result of the air shock wave and stagnation pressure, p_s, in the air flow behind the shock wave. Let

$\rho_L = 0.125 \frac{kg \cdot sec^2}{m^4}$,

$w = 50$ m/sec,

$a = 330$ m/sec,

then

$\Delta p = 2062.5$ kg/m$^2 \simeq 2$ t/m$^2 \simeq 0.2$ atm,

$p_s = 1/2\, \rho_L\, w^2 \simeq 0.16$ t/m^2.

Therefore, in these conditions, the dynamic pressure, p_s, is 13 times less than the increase of the static pressure behind the wave, Δp. Further assumptions by Voellmy with respect to p_s and Δp are clearly incorrect.

Let us now sum up the analysis performed here of Voellmy's study (Voellmy, 1955). This study traces the following theoretical approach to avalanche movement:

1. Selection of a model of moving snow and construction of equations describing the movement of such a medium for sections of the slope where the slope angle is continuously changing.

2. Deduction of the necessary boundary conditions for the system of equations, in particular, at the leading edge of the avalanche and at breaks in the slope profile. These are places where all the avalanche parameters appear to experience a sharp change.

3. Integration of the system of equations and calculation of all the characteristics of avalanche movement.

4. Development of the methods for computing the forces acting on obstacles of prescribed shape and size hit by an avalanche.

In the proposed theory, the properties of snow can enter into the solution only through the coefficients μ and k and through the density, ρ and, in general for calculating the whole movement, it is necessary to know (1) coefficients μ and k, (2) the density, ρ_o, and the thickness, h_o, of the snow on the slope just prior to the avalanche, (3) air density ρ_L, and (4) slope angle, that is, the function, $\psi(x)$ [4].

As far as the coefficients k and μ are concerned, they are k = 400 to 600 m/sec^2; $\mu = 0$ (for wet and powder avalanches); $\mu = \frac{\gamma}{c}$ (for the other avalanches in which c = 1000 to 2000 kg/ cm^3 (also depending upon the properties of the underlying surface)).

Criticisms of the study concern, first of all, the internal contradictions and faults of this theory and, secondly, the approach itself, the very postulation of the problem which, unquestionably, can be made more precise.

Let us enumerate here, once again, what can be considered as the internal weaknesses of the study;

1. A complete system of equations was not developed even for one-dimensional movement of the medium examined. Only an equation of motion and an equation of continuity for steady-state motion were developed. Therefore, instead of deriving a solution for the entire system of equations, an integration is performed separately for the equation of motion using major and incorrect assumptions that amount to a condition whereby the avalanche moves as a solid body. The fact is, from the solution obtained from these assumptions, all the snow on the whole slope (with ψ = const) begins to move simultaneously, all the particles move with identical velocity, and the flow height of the moving layer on all points of the avalanche is identical.

2. In such an investigation, in particular, it is impossible to logically introduce the conception of the leading edge of the avalanche. Only examination of the conditions at the leading edge can yield the necessary connections between the parameters of the snow lying on a slope, in particular h_o and ρ_o, and the snow parameters in a moving avalanche. The equations proposed to make these connections, derived by a method not yielding to interpretation, contradict each other and, conse-

quently, are quite doubtful. At the same time, equations of this type are very important since without them it is impossible to calculate avalanche movement.

3. Integration of the equation of movement in performed with very simplified assumptions and only for the condition that the angle of slope, ψ, satisfies the condition $\tan \psi > \mu$.

4. Avalanche runout distance is found not be means of integrating the derived equation of motion, but with the help of a still more approximate relationship replacing a theorem on the change of mechanical energy.

All these shortcomings can be eliminated, and then it will be possible to construct an orderly theory even though relying upon the rather major assumption that moving snow can be considered as a liquid (true, with somewhat unusual properties).

Laboudigye's study (Laboudigye, 1958) is the only review of the studies of a number of Swiss authors. In particular, that part which concerns avalanche dynamics is almost a word for word translation into French of the study considered above by Voellmy. Some of Voellmy's misprints are eliminated, but new ones were made. Therefore, it is impossible to rely upon the equation of study (Laboudigye, 1958) without careful checking.

Salm (1966) developed Voellmy's ideas somewhat. He expresses the equation of motion in a one-dimensional approximation; however, the avalanche is not considered as infinitely wide (lateral spreading out is taken into account). Furthermore, in the equation of motion, additional things are taken into account: (1) the force connected with hydraulic friction, proportional to the first power of velocity; (2) the force connected with aerodynamic resistance of the leading edge of the avalanche; (3) the force necessary to break off new layers of snow entrained by the avalanche; and (4) supplementary force of Coulomb friction appearing if additional pressure, S, is rendered from above onto the moving layer of snow. The corresponding equation of motion has the form:

$$\frac{dv}{dt} = g\left[\sin\psi - \mu\cos\psi - \mu\frac{S}{F}\right]\left(1 - \frac{\rho_L}{\rho}\right) - \frac{g}{kR}v^2 - \frac{\eta}{\rho\delta R}U - C_w\frac{\rho_L v^2}{2}\frac{1}{\rho s} - \omega\frac{\beta}{\rho s}. \qquad [1.35]$$

Here, F is the area of the avalanche cross section; R is the hydraulic radius of the cross section ($R = F/U$, U is the perimeter of the cross section); δ is the thickness of the boundary layer; η is the coefficient of viscosity; C_w is the coefficient of avalanche snow entrainment; and β is the rupturing stress on the area parallel to the snow surface such that the resistance of the snow moved by the avalanche is equal to $\omega F \beta$. All these coefficients are unknown beforehand. No relationships from which it would be possible to theoretically find coefficients, entering into equation [1.35], are cited. The inclusion of the forces $C_w \rho_L v^2 / 2\rho S$ and $\omega\beta/\rho S$ into the equation of motion is incorrect. These forces should be included in conditions at the leading edge of the avalanche which the author, however, does not consider. The solution of equation [1.35], that is, the equation for avalanche velocity, was written out with a condition that all the parameters entering into it are constant, except for velocity. An equation was also developed for avalanche runout distance, correct in certain suppositions.

This work also lacks a full mathematical postulation of the problem about avalanche movement within the limits of a hydraulic scheme. The viewpoint of the avalanche as a moving, continuous medium is not carried out to conclusion. An equation of motion was derived [1.35], outwardly rich in contrast, but other continuum equations are not written out. Equation [1.35] is solved on the assumption that the avalanche does not change with movement and the velocities in all points of the avalanche are identical.

In the survey of studies that use point mechanics methods for the study of avalanche motion, we should dwell on S. M. Kozik's (1962) study in which: (1) a description and criticism of the methods of computing avalanche movement, proposed at the Tbilisi Construction Institute (TNIIS) and by G. K. Sulakvelidze, are given (Goff and Otten, 1939; Gongadze, 1954; Sulakvelidze, 1949); (2) an equation of avalanche motion is developed with a detailed analysis of the value of the coefficients for various types of avalanches, as well as equations for the velocity and runout distance which were derived by the integration of this equation using different means of assigning coefficients; (3) the velocity change is examined separately where the avalanche flows over sharp and smooth changes in gradient; and (4) a simplified equation is given for the maximum runout distance of the avalanche. Some of the ideas of this study are contained also in the works of other authors (Goff and Otten, 1939; Gongadze, 1954; Sulakvelidze, 1949; Barban, 1962; Moskalev, 1966; Tushinskii, 1960; Goff and Otten, 1938); however, S.M. Kozik's study is distinguished by its greater completeness and clarity. It is also characterized by the accuracy of the formulations and by the logic of the conclusions. Therefore, a comparison is given below of the premises and the results of the theory discussed in it with those discussed in Voellmy's study (Voellmy, 1955). An exchange of symbols (Kozik, 1962) was performed for this purpose:

	Here	In S.M. Kozik
Slope angle	ψ	α
Coefficient of Coulomb friction	μ	r
Air density	ρ_L	ρ
Density of moving snow	ρ	δ_1
Flow height of avalanche	h	H

S. M. Kozik looks at the avalanche as a material point, with a variable mass, M. The avalanche moves under the force of gravity and resistance forces of a diverse nature--Coulomb friction force, air resistance, and cohesion with the underlying surface. The equation of motion for such a material point in projection to the tangent to the slope is written in the form

$$\frac{dv}{dt} = g \sin \psi - f_1 - f_2 \ , \qquad [2.1]$$

where f_1 is the Coulomb force of friction,

$$f_1 = \mu \quad (g \cos \psi)^2 + \left(\frac{v^2}{R}\right)^2 + \frac{2v^2 g \cos \psi \cos \omega}{R} \qquad [2.2]$$

where ω is the angle between the osculating plane of the avalanche path and the vertical; R is the radius of curvature of the path; and f_2 is the sum of the other resistance forces, including the reaction force due to the variability of the mass,

$$f_2 = \frac{q_1}{M} v^2 \pm \frac{q_2}{M} (v - u)^2 + \frac{cB}{M} . \qquad [2.3]$$

In the last equation, the first term determines the force due to entrainment of snow and rock by the avalanche; q_1 can be treated as the mass of snow accelerated by the avalanche per unit of width. Consequently, q_1 depends upon the state of the slope the moment before the passage of the avalanche (upon the density and thickness of the snow cover, the amount of rocks located in it, etc.), and upon the width of avalanche B, which can be variable and unknown beforehand. The second term is connected with the air resistance which depends also upon the wind velocity, u, along the direction of avalanche movement. The value of the coefficient q_2 depends upon the thickness and width of the avalanche, and also upon the air density in which the avalanche is moving. The third term which defines the cohesion force with the underlying surface, coefficient c, apparently can be considered as known if the properties of the slope surface are known. Finally, the equation includes mass, M, of the avalanche, a quantity unknown beforehand and changing in the process of movement. It is possible in certain assumptions to write an additional equation controlling the change of mass; for example,

$$\frac{dM}{dt} = q_1 v . \qquad [2.4]$$

Equation [2.4] together with [2.1] indicates that: (1) capture of mass per unit time is proportional to the velocity of the avalanche and to the amount of snow and rock per unit area of the slope, and (2) the avalanche center of gravity does not shift from the addition of mass. The additional mass is distributed uniformly along the avalanche (that is, the avalanche accumulates snow like a snowball rolling down a hill). This last supposition is equivalent to the assumption that the velocity of the avalanche front coincides with the velocity of the particles (which is precisely true only when there is not any snow or rock entrained by it).

Let us compare the described statement of the problem with that of Voellmy (1955):

1. In spite of the fact that Voellmy considers an avalanche as the flow of a continuous medium and S. M. Kozik as the movement of a material point, the equations for determining velocity turned out to have the same form. This is due particularly to the fact that the primary forces acting here--weight and Coulomb friction per unit mass--depend upon neither mass nor upon the shape of the moving body. The discrepancy of the equations of [1.1] and [2.1] consists, first of all, in the fact that in [1.1], v signifies the velocity of the element of the avalanche; different velocities can be in different points of the avalanche; the velocity of the center of gravity can be computed in addition. Equation [1.1] itself is a partial derivative equation for the function v(x,t). Contrary to this, equation [2.1] is an ordinary differential equation for the velocity of the center of gravity of the avalanche, v(t). We will note, however, that assumptions which were adopted in solving equation [1.1] were no more accurate than those of equation [2.1].

2. Equations [1.1] and [2.1] contain unknown and, generally speaking, variable coefficients. In particular, equation [1.1] includes unknown h and ρ. In examining the avalanche as a moving continuous medium it is possible to use also an equation of continuity (the conservation or change of the mass of the element) and to derive a system of equations in partial derivatives with reference to v, h, ρ. The coefficients of equation [2.1] in principle cannot be determined if left in the theoretical limits of the movement of a material point. However, S. M. Kozik shows how it is possible to assign these coefficients if they are given a definite mechanical meaning and the avalanche is considered no longer as a point, but as a body changing its dimensions and shape in a definite manner in the process of movement. Of course, it is necessary to make assumptions and thus certain arbitrariness enters into the theory. These suppositions are rather major. For example, the assumption that a moving avalanche has the shape of a parabolic cylinder with a ratio of maximum flow height to the width and length equal to 1:3:10. In return, the consideration of the

avalanche of a finite and changing width does not introduce any additional difficulties here; whereas, for Voellmy's theory it is essential to assume the problem to be two-dimensional (that is, the avalanche has an infinite width or that one may disregard the lateral spreading out).

3. Let us compare the coefficients in equations [1.1] and [2.1]:

   a. Equation [1.1] includes a factor $1 - \frac{\rho_L}{\rho}$, which is the buoyant effect due to the fact the avalanche element is embedded in air, connected with a consideration of the effect on the avalanche element of buoyant force. This factor is absent in [2.1]. However, in that part of Kozik's study where powder avalanches are considered, this correction for buoyant force is taken into account. Apparently, in practice it is advisable to take this correction into account only for powder avalanches. In fact, estimations of ρ_L/ρ are $\rho_L/\rho \simeq 0.083$ for powder avalanches, since $\rho g \simeq 15 \frac{kg}{m^3}$, $\rho_L g \simeq 1.25 \frac{kg}{m^3}$, and $\rho_L/\rho \simeq 0.0062$ for other avalanches $\left(\rho g \simeq 200 \frac{kg}{m^3}\right)$. Therefore, factor $1 - \frac{\rho_L}{\rho}$ in many cases can be considered = 1.

   b. In equation [2.1] the influence on the amount of Coulomb friction is caused by centrifugal force and the curvature of the path is computed. Depending upon the slope profile, this can have practical significance. In equation [1.1], the centrifugal force is not taken into account, apparently, for simplicity. It is not difficult to make the appropriate correlation in [1.1]. S. M. Kozik suggests calculating the correction for centrifugal force only for segments of the path with sharp curvature and performs the appropriate computations for the loss or gain of velocity in the passing of such sections.

   c. Equation [2.1] takes into account the wind effect which is not included in [1.1].

d. Finally, equation [2.1] also contains a force, cB/M, for the coupling of the moving snow with the underlying surface; this force is not included in [1.1]. However, the necessity for entering this force is not substantiated.

Let us now compare the interpretation and order of magnitudes for identical terms of equation [1.1] and [2.1]. These terms represent the force of Coulomb friction on a straight segment of the path and the resistance force proportional to velocity squared (disregarding wind effect).

1. Voellmy suggests considering $\mu = 0$ for wet and powder avalanches and $\mu = \gamma / c$ for the other avalanches where γ is the specific weight of the snow just prior to the avalanche (which approximately coincides in these cases with the specific weight of moving snow), and c is a coefficient $\simeq 1000 - 2000$ kg/cm^3. Therefore, the coefficient of Coulomb friction is a function only of specific weight of snow.[5] In this case, the estimates for the coefficient of the friction are:

	Full Depth Avalanches-- Running on the Ground (Bodenlavine)	Avalanches That Run on Snow (Oberlavine)
γ	150 kg/m^3	150 kg/m^3
c	1000 kg/m^3	2000 kg/m^3
μ	0.15	0.075

S. M. Kozik uses higher values of the friction coefficient, specifically $\mu = 0.2$, 0.3, 0.4, and 0.5. As a mean value, it is recommended to take $\mu = 0.3$ since it is said that this number is, as a rule, too low, although sometimes μ also can be significantly less (if sliding friction is replaced by rolling friction).

The term of equation [1.1], representing the resistance force and proportional to the velocity squared, has the form,

$$\frac{g}{kh} v^2 , \quad [2.5]$$

where k is a constant, with limits $400\ m/sec^2 \le k \le 600\ m/sec^2$; the mean value of $k = 500\ m/sec^2$. Since this value is taken from experiments on hydraulics, it follows that k depends upon the roughness of the slope. The quantity, h, is considered a constant in the integration of equation [1.1] and is the linear function of the runout distance.

In Kozik's study (Kozik, 1962), the corresponding coefficient for the velocity squared term is signified by b which is dependent upon avalanche mass, M, and also upon q_1 and q_2, respectively, the masses of snow and air put into motion by the avalanche during the passage of a unit length of path,

$$b = \frac{q_1 + q_2}{M} . \qquad [2.6]$$

The assumptions about the character of the resistance force, which is the basis of equations [2.5] and [2.6], are considerably different, and are associated with the different points of view of the type of motion by the two authors. S. M. Kozik considers that ground friction is completely taken into account by the Coulomb force, (air friction can be disregarded) and the appropriate resistance needs to be connected only with the resistance experienced by the leading edge of the avalanche due to the snow and air masses displaced by it. Roughly speaking, the quantity $q_1 + q_2$ is proportional to the cross section area of the avalanche (but not to the complete surface area as occurs when the friction is considerable). It is possible to present the quantity of [2.5] in the form b_1v^2 in the following manner: let us assume

$$b_1 = \frac{g}{kh} = \frac{g}{k}\frac{Q}{m} , \qquad [2.7]$$

where

$$Q = \rho l \ , \ m = \rho l h \ .$$

Here, m is the mass of an avalanche element with length l and width 1, but Q, in contrast to $q_1 + q_2$, is proportional to the area of the lower and upper surface of the element (along which friction forces act on the element making its velocity distribution diminish toward the boundaries). Therefore, equation [2.5] computes a purely hydraulic resistance and is not directly connected with the presence of snow in front of the avalanche (the appropriate dependence still exists since, according to Voellmy, h is found from conditions at the leading edge of the avalanche). The force [2.5] differs also from zero when snow is absent in front of the avalanche, and it is possible to disregard air resistance. Coefficient b, in this case, would be considered equal to zero. In concrete examples of computations, S. M. Kozik considers the quantity b constant for a channelized avalanche and considerably variable for an unconfined avalanche slab. In channelized avalanche computations, width and length are considered proportional to the maximum height, h. The relationship between the maximum flow height, maximum width, and maximum length of an avalanche are 1:3:10. The area of the mid-section is $2h^2$ and the volume is $10\ h^3$. From these relations the following is derived:

$$b = \left(0.3\ \frac{h_o}{h} + 0.1\ \frac{\rho_L}{\rho}\right) \cdot \frac{1}{h}\ ,$$

where h_o is the thickness of the snow cover in front of the avalanche, ρ_L is the density of air, and ρ is the density of the moving snow. In numeric examples, the following values of b are derived (we emphasize once more that these values are intrinsically connected with assumptions about the shape and dimensions of the avalanche).

	Value of b			
	According to Kozik			According to Voellmy $k = 500\ m/sec^2$
h	$h_o = 0$	$h_o = 10$ cm	$h_o = 100$ cm	Independent of value of h_o
17 m	$35 \cdot 10^{-6}\ \frac{1}{cm}$	$137 \cdot 10^{-6}\ \frac{1}{cm}$	$1060 \cdot 10^{-6}\ \frac{1}{cm}$	$12 \cdot 10^{-6}\ \frac{1}{cm}$
35 m	$16 \cdot 10^{-6}\ \frac{1}{cm}$	$38 \cdot 10^{-6}\ \frac{1}{cm}$	$237 \cdot 10^{-6}\ \frac{1}{cm}$	$25 \cdot 10^{-6}\ \frac{1}{cm}$

In examples of computations for unconfined avalanches, b is taken in the following form as functions of runout distance S:

$$b = \frac{1}{S} + \frac{\gamma}{\sqrt{S}}\ ;\ b = \frac{1}{S} + \frac{\beta}{1 + \beta S}\ ;\ b = \frac{c}{1 + cS}\ ,$$

where γ, β, and c are constants depending upon air and snow density, the thickness of the snow cover on the slope etc., and also upon the shape of the avalanche. Such a form of the functions for coefficient b is connected with concrete suppositions about the size of the change of M, q_1, and q_2 as the unconfined avalanche moves along the slope. When ω and u are small, equation [2.1] can be written in the form

$$\frac{dv}{dt} = a - bv^2 , \text{ or } \frac{1}{2}\frac{dv^2}{dS} = a - bv^2 , \qquad [2.8]$$

where a and b do not depend upon the velocity, and S is the coordinate along the slope (path). Integration of equation [2.8] is performed for various special assignments of a and b as functions of the path. In particular, S. M. Kozik considers that in the movement of an avalanche along a channelized path its mass is roughly preserved. If it is accepted that, in this case, the shape of the avalanche also does not change, the snow and rocks are distributed uniformly along the path, then it follows that coefficients a and b will be constant on a straight segment of the path. The solution of equation [2.8] is written in the form

$$v^2 = \frac{a}{b} + \left(v_o^2 - \frac{a}{b}\right) \exp^{-2bs} , \qquad [2.9]$$

or

$$S = \frac{1}{2b} \ln \frac{a - bv_o^2}{a - vb^2} . \qquad [2.10]$$

Equation [2.9] gives the same values for velocity as [1.2], if one considers

$$a = g\left(1 - \frac{\rho_L}{\rho}\right)(\sin\psi - \mu\cos\psi) , \text{ and } b = g/kh ,$$

in a condition of $a > 0$, $v_o > 0$. In particular, from [2.9], it is apparent that v rapidly strives toward $v_{max} = \sqrt{a/b}$. Equations [2.9] and [2.10], in contrast to [2.1], are correct also with $a < 0$, and then they agree with [1.7], which was not written by Voellmy. With $a < 0$, that is, if the incline of the slope is not great, the avalanche can stop on the slope. The runout distance is determined from the equation

$$S = \frac{1}{2b} \ln\left(1 - \frac{b}{a} v_o^2\right) . \qquad [2.11]$$

agreeing with [1.9], not written by Voellmy and not agreeing with [1.2].

In contrast to the channelized avalanche, the unconfined avalanche should be viewed (according to S. M. Kozik) as an avalanche with a considerably variable (growing) mass. If one considers, as the author does, that the shape of the avalanche preserves a geometric similitude during the time of its movement, then all its parameters also increase with the increase of the mass. This results in a lowering of the resistance per unit mass, so much so that, for the unconfined avalanche on the slope with $a > 0$, the idea about the maximum velocity ceases to exist (the velocity grows to infinity on an infinitely long slope). If $a \le 0$, then the unconfined avalanche with a width, B, an initial mass, M_o, entering onto a flat slope with a constant thickness, h_o, and with a snow density, ρ_o, has the from

$$S = \frac{1}{c}\left[\sqrt[3]{1 - \frac{3}{2}\frac{cv_o^2}{a}} - 1 \right], \qquad [2.12]$$

where

$$c = \frac{h_o \rho B}{M_o}.$$

If one defines S roughly, then in the capacity of the first approximation, S. M. Kozik recommends adopting

$$S \simeq \frac{v_o^2}{-2a + cv_o^2}, \qquad [2.13]$$

since, if c is small and S is small, then $b \simeq c$ = constant and, in effect equation [2.13] is roughly correct. Let us note, however, that this equation does not follow directly from [2.12]. Equations for the velocity and runout distance are also presented in Kozik's study which are derived from computing air resistance, variability of the slab width, and the nonuniformity of the snow cover in front of the avalanche. It is considered that as the avalanche passes the break in the avalanche profile, its shape does not change (the thickness, in particular, does not change). The velocity, however, changes so that the component of the velocity in front of the break, parallel to the new path direction, is maintained, and the component perpendicular to it completely dies out; that is,

$$v_2 = v_1 \cos(\psi_1 - \psi_2)\,. \qquad [2.14]$$

If the transition from the segment with slope ψ_1 to a segment with a different average slope angle, ψ_2, takes place over a curvature, then the evaluation of the loss or the gain of velocity is performed by S. M. Kozik in the following manner. Let us look at the case when there is uniform movement between points 1 and 2 on a straight path. Then, considering that the velocity changes, $\Delta v = v_2 - v_1$, due to the effect of centrifugal force, is small in comparison with the velocity, one can derive the following equation for Δv:

$$\Delta v \simeq \mu v \Delta\psi\,, \qquad [2.15]$$

in which $\Delta\psi = \psi_2 - \psi_1 < 0$ on a concave slope. (In deriving this equation, it is also considered that the internal energy of the snow does not change on this path.) Let us note that a certain imprecision is allowed here: (1) in computing the work of the additional force of friction, the fact that the additional force itself changes in the transition from 1 to 2 owing to the change of velocity is not taken into account; (2) in general, the effect of the work of the resistance force, f_2, on the effect of the velocity change is not considered. Meanwhile, even in the more precise computation of the work of the additional friction force (the exchange of the velocity squared by its mean value, and not by the value in the initial point, 1, a different equation is derived instead of [2.15],

$$\Delta v \simeq \mu v \,\frac{\Delta\psi}{1 - \mu\Delta\psi}\,. \qquad [2.16]$$

The basic assumptions of equations [2.14] and [2.15], or [2.16], seem sensible; at any rate, they can be subjected to experimental verification. However, apparently, in passing the break in the profile, the snow density in the avalanche and the thickness of the moving layer should change abruptly. In this case, additional relationships are necessary for determining the change of these quantities.

Let us draw some conclusions from S. M. Kozik's study. It contains a model of moving snow (an absolutely rigid body); equations of motion are written as well as conditions where the slope angle changes; and solutions are found. In connection with the fact that the avalanche is viewed as an absolutely rigid body; that is, the motion of the medium inside the avalanche is completely ignored, the equations describing the phenomena are much simpler (one ordinary differential equation instead of a system of equations in partial derivatives of the mechanics of the deformed continuous medium). However, the equations of motion for the material point seem insufficient to describe the movement of the avalanche from the initial conditions of the snow on the slope. It is also necessary to assign to the mass, dimensions, and shape of the avalanche, the coefficient of entrainment by it of the snow lying on the path, and the aerodynamic resistance (which depends upon the dimensions and shape of the avalanche). In general, with certain additional plausible assumptions adopted by Kozik for computing the movement of avalanches, it is necessary to know (1) the coefficient of friction, μ, (2) the density of the moving snow, ρ, and the flow height of the moving layer, h, (3) the density ρ_o, and the thickness, h_o, of the original snow cover on the slope, (4) the initial width of avalanche, B, and the way it changes, (5) air density, and (6) profile of the slope.

The principal difference between the studies of Voellmy and Kozik, in our view, consists in the different treatment of the coefficient in the velocity squared term for the resistance force. According to Voellmy, this force is related only to the internal friction, and, according to Kozik, it is associated with the presence of aerodynamic resistance of the snow displaced by the avalanche. The question of which type of resistance is more important can be subjected to experimental analysis. For example, the role of aerodynamic resistance can be explained by wind tunnel tests of solid bodies having a typical avalanche shape. Apparently, the experiment is also absolutely necessary in resolving the question about the shape of conditions which are different in Kozik and Voellmy's studies at the break in slope and the conditions linking the parameters of the original snow cover and the parameters of the moving avalanche.

Let us now make several observations about various studies (Goff and Otten, 1939;

Gongadze, 1954; Sulakvelidze, 1949; Barban, 1962; Moskalev, 1966). All the authors of these works consider the movement of the avalanche to be the movement of a material point. In several studies (Gongadze, 1954; Barban, 1962; Moskalev, 1966) the primary equation of motion is close to equation [2.1]; however, in it certain terms are not taken into account which are in [2.1]. In two studies (Goff and Otten, 1939; Sulakvelidze, 1949) the primary equation of motion differs considerably from [2.1] (the air resistance force and velocity dependent frictional drag of (f_2) of the surface of the slope are considered proportional to the first power of the velocity, not to its square). We know that the force of hydraulic resistance (due to internal friction) and aerodynamic resistance of a body in air turns out to be proportional to the first power of velocity for low velocities or small dimensions of the moving bodies. Then, with the increase of velocity, the resistance is represented well by the sum of two forces, one of which is proportional to v and the other to v^2. With increasing velocity, the first of these forces becomes negligibly small in comparison with the second. The velocities and dimensions of most avalanches are such that it is more correct to adopt the quadratic law of resistance; that is, to consider the force of resistance proportional to v^2 (Voellmy, for example, considers that turbulent movement in the avalanche has already begun with velocity ~ 1m/sec). However, for fairly slow moving avalanches, the movement equation adopted in studies (Goff and Otten, 1939; Sulakvelidze, 1949) appear to be more correct.

The above-selected formulation of the problem of avalanche movement along a slope possesses the essential fault that they make it possible to find the velocity of snow in an avalanche only when the shape and dimensions of the avalanche are known beforehand. Meanwhile, it is clear that all the characteristics of the moving avalanche should be determined by conditions on a slope and should be evaluated in the process of solving the problem.

An example is given below of the most simple statement of the problem of the movement of a snow avalanche along a slope, the solution of which makes it possible to find all the parameters of the moving avalanche if the profile of the slope and the characteristics of the snow cover on it are known (Grigorian et al., 1967). The leading edge of the avalanche, moving with velocity, W, is viewed as a front of destruction extending along a stationary snow cover. For describing the movement of the snow beyond the front, as in Voellmy, a hydraulic scheme is adopted. This signifies, first of all, that only the average velocity of snow, v, along the longitudinal profile of the avalanche is considered (see fig. 1). If only fairly broad avalanches are examined, then the lateral spreading of snow can be disregarded. Then v and h are functions of x', t, which are necessary to find in the process of solving the problem. Within the limits of a hydraulic scheme, the system of equations, describing the movement of snow in an avalanche, can be taken in the following form (where the density of the moving snow is considered constant and equal to the density of the undisturbed snow cover):[6]

$$\frac{\partial v}{\partial t} + v\,\frac{\partial v}{\partial x'} = f_1 - \frac{g}{kh}\,v^2 - \frac{1}{2}\,\frac{g}{h}\,\frac{\partial h^2 \cos\psi}{\partial x'}\ ,$$

$$\frac{\partial h}{\partial t} + \frac{\partial hv}{\partial x'} = 0\,. \qquad [3.1]$$

Here, the coordinate is signified by x', and f_1 is linked to that part of the force acting on the moving particle of snow which does not depend upon its velocity. In Voellmy's study (Voellmy, 1955), for example, the following expression is accepted for f_1:

$$f_1 = g\left[1 - \frac{\rho_L}{\rho}\right](\sin\psi - \mu\cos\psi)\,.$$

For further investigation, it is essential only that f_1 does not depend upon v.

Let us consider a smooth and fairly long slope with uniform snow cover. In these conditions, it is possible to assume that in a short time after the beginning of motion a steady state is established in the sense that the velocity of the leading edge of the avalanche, w, becomes constant.[7] One may set up the problem to find steady-state solutions of the equations [3.1]. In this case, the equations [3.1] are essentially simplified if they are written in a system of coordinates moving with the leading edge.

$$u\,\frac{du}{dx} = -\,\frac{g}{kh_o}\left[K_o^2 - \frac{h_o}{h}\,(w-u)^2\right] - g\cos\psi\,\frac{dh}{dx} \qquad [3.2]$$

$$uh = wh_o .$$

Here, $x = wt - x'$ is the coordinate measured upward from the slope in a moving system of coordinates, $u = w - v$ is the snow velocity with reference to the moving system of coordinates, and

$$K_0^2 = \frac{kh_o}{g} f_1 .$$

From the equations [3.2], it is possible to derive one equation for $h(x)$,

$$F(h) \frac{dh}{dx} = \frac{gw^2}{k} \Phi(h) , \qquad [3.3]$$

where

$$F(h) = g \cos \psi \frac{h_o^2 w^2}{h^3} ,$$

$$\Phi(h) = \frac{(h - h_o)^2}{h^3} - \frac{K_o^2}{h_o w^2} .$$

Equation [3.3] contains an unknown constant, w. Equation [3.3] is a differential equation and boundary conditions are necessary for its solution (i.e., for finding the function $h(x)$).

For deriving boundary conditions, general conditions of the conservation of mass and impulse in the leading edge of the avalanche are considered. The snow velocity directly behind the front is indicated by $\overline{u}$. The flow height of the moving layer immediately beyond the front by $\overline{h}$. Then the conditions in the leading edge can be written in the form,

$$h_o w = \overline{hu} ,$$

$$h_o w(w - \overline{u}) = \frac{g}{2} \overline{h}^2 \cos \psi - \frac{\sigma_*}{\rho} h_o . \qquad [3.4]$$

Here, h_o is the height of that layer of undisturbed snow cover which is set in motion by the avalanche. In writing these conditions, it is taken into account that the snow in front of the leading edge is in a stressed state, and a critical value, σ_*, is reached at the leading edge.

The quantity, σ_*, apparently should always satisfy the condition $\sigma_* \geq \frac{1}{2}\rho g h_o \cos\psi$, since otherwise the snow cover being overrun would turn out to have a lower resistance to disaggregation than water. Air resistance is not included in [3.4]. From the two equations [3.4], it is possible to derive one condition for $\overline{h}$, which is a necessary boundary condition for equation [3.3]:

$$(\overline{h} - h_o)\left[\overline{h}(\overline{h} + h_o) - \frac{2\omega^2 h_o}{g \cos\psi}\right] = \frac{2h_o\overline{h}\left[\sigma_* - \frac{1}{2}\rho g h_o \cos\psi\right]}{\rho g \cos\psi}. \qquad [3.5]$$

However, this condition also contains an unknown constant, ω. Study of condition [3.5] makes it possible to conclude that if $\sigma_* > \frac{1}{2}\rho g h_o \cos\psi$, then at the leading edge there is always an abrupt change in the velocity and thickness of the snow layer. Condition [3.5], in general for each ω, yields three possible values for $\overline{h}$, from which $\overline{h}$ should be selected so that $\overline{h} \geq h_o$. (This is a condition in which the avalanche moves downward along the slope.) Furthermore, it always turns out that $\overline{h} > h_{crit}$. The quantity, h_{crit}, plays a significant role in the further investigation. It is determined in such a manner that with $h = h_{crit}$, the velocity of the snow movement, u, would be equal to the velocity of the propagation of small disturbances of the surface of moving snow by snow particles; that is, the quantity,

$$c = \sqrt{gh \cos\psi},$$

when

$$h_{crit} = h_o \;\; {}^{3} \;\; \frac{\omega^2}{g h_o \cos\psi}.$$

with

$$u = \sqrt{g h_{crit} \cos\psi} = \sqrt[3]{\omega g h_o \cos\psi} = u_{crit}.$$

Equation [3.3], with condition $h = \overline{h}$ with $x = 0$, where $\overline{h}$ is determined from [3.5], makes it possible to find h(x), if only h_o, ψ, K_o^2, σ_* are known (the quantities assigned by the external conditions), as well as ω. The method of selecting ω will manifest itself as a result of studying all the solutions of equation [3.3] corresponding to all the possible values of ω. Equation [3.3] can be presented in the form:

$$\frac{dh}{dx} = \frac{gw^2}{k} \frac{\Phi(h,w)}{F(h,w)} .$$

There are three types of behavior of $\frac{dh}{dx}$ (h), depending upon the value of ω. The first type corresponds to the condition $\omega^2 < 27K_o^2/4$; the second corresponds to the condition $w^2 = 27K_o^2/4$; and the third to the condition that $w^2 > 27K_o^2/4$. In the study of Grigorian et al. (1967), only instances are investigated of fairly fast avalanches; that is, of those when $w > \sqrt{gh_o \cos\psi}$. Graphs of the function $\frac{dh}{dx}$ (h) are shown in figures 8, 9, 10 for this instance. In these figures, the line $h = h_{crit}$ is shown by the dotted line.

From the graphs shown in figures 8, 9, and 10, it is apparent that in instances, I, IIa (only if $\overline{h} < 3h_o$), IIb, IIIa (only if $\overline{h} < h_2$), and IIIc, the function h(x) has the form shown in fig. 11; that is, it is not single valued and, consequently, a steady-state solution having physical sense does not exist in these cases. In the remaining cases, a unique solution exists that satisfies all the above-stated conditions. All these solutions, with the exception of those which are derived in cases IIc and IIIe have $h > h_{crit}$ throughout the whole avalanche and, consequently, $u < u_{crit}$ or $u < c$ (fig. 12). If $u_\infty < c(u_\infty = x \to \infty)$, then possible small disturbances of the surface (lowering of the level) in the tail part of the avalanche can be transmitted ahead and, generally speaking, weaken the leading edge, decreasing $\overline{h}$, and that means also the velocity of the leading edge, w. This process can occur until a cross section arises inside the avalanche in which $u = c$ and $h = h_{crit}$. Therefore, only the solutions are studied in detail in which points exist with $h = h_{crit}$. They correspond to cases IIc and IIIe. In these instances, the following ratios should be fulfilled:

$$K_o^2 - \frac{h_o\omega^2}{h_{crit}^2}\left(h_{crit} - h_o\right)^2 = 0 , \qquad K_o \geq 2\sqrt{gh_o \cos\psi} . \qquad [3.6]$$

The condition, $w^2 \geq \frac{27}{4} K_o^2$ is fulfilled automatically. The equations of [3.6] make it possible

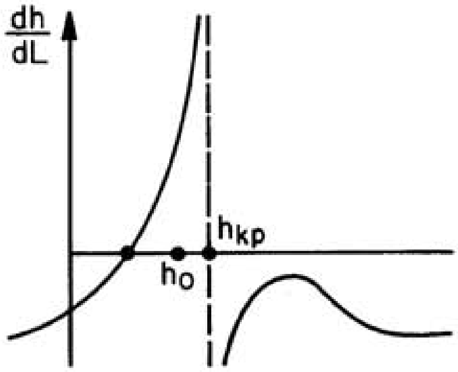

Fig. 8. Graph of the function of $\frac{dh}{dx}(h)$ in a condition of $c_o^2 < w^2 < 27K_o^2/4$. (Type 1).

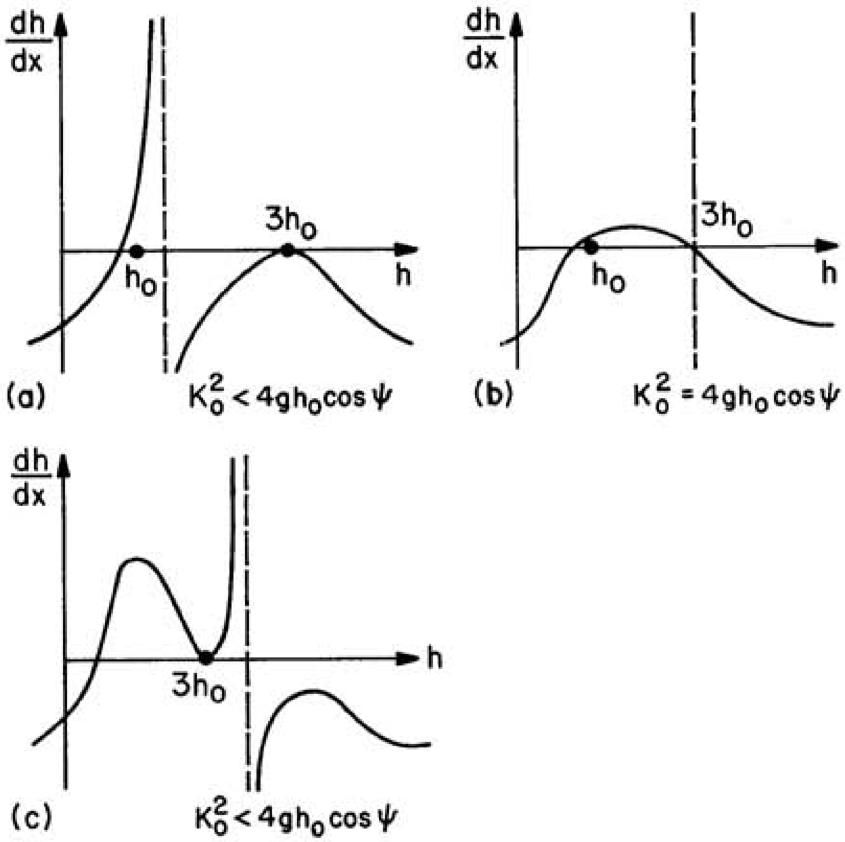

Fig. 9. Graphs of the function of $\frac{dh}{dx}(h)$ when $w^2 = 27K_o^2/4$ (Type II).

to define, unambiguously, w and h_{crit} as well as the shape of the avalanche; that is, the function $h(x)$, and the velocity distribution of $u(x)$ in the avalanche points from the leading edge ($x = 0$) to the point $x = x_{crit}$, where $u = u_{crit}$, and $h = h_{crit}$. With $k_o = 2\sqrt{gh_o \cos\psi}$, that is in the instance of IIc, $x_{crit} = \infty$. With $k_o > 2\sqrt{gh_o \cos\psi}$ beyond the point $x = x_{crit}$, the solution can be lengthened by various methods. In the condition that the external parameters satisfy the inequality, $k_o => 2\sqrt{gh_o \cos\psi}$, the equation for w and h_{crit} can be written in the form,

$$w = c_o \left[1 + \frac{K_o}{c_o}\right]^3,$$

$$h_{crit} = h_o \left[1 + \frac{k_o}{c_o}\right], \qquad [3.7]$$

$$c_o = \sqrt{gh_o \cos\psi}\,,$$

in which these equations are correct for both the fulfillment of the conditions of IIIe as well as IIc. It should be remembered that if the avalanche does not flow along the ground, but over snow, then h_o is the thickness of that layer of snow lying on the slope which is set in motion by the avalanche, and h is the thickness of the moving layer (avalanche) perpendicular to the slope above the layer over which the avalanche is flowing.

The expression for the function $\eta(x) = \dfrac{h(x)}{h_{crit}}$ has the form,

$$\eta - \bar{\eta} + 1n \left[\frac{\eta - \eta_1}{\bar{\eta} - \eta_1}\right]^{\alpha_1} \left[\frac{\eta - \eta_2}{\bar{\eta} - \eta_2}\right]^{\alpha_2} = -\lambda \frac{s}{h_{crit}}\,. \qquad [3.8]$$

Here

$$\bar{\eta} = \frac{\bar{h}}{h_{crit}}\,,\quad \eta_1 = \frac{h_1}{h_{crit}}\,,\quad \eta_2 = \frac{h_2}{h_{crit}}\,.$$

$$\alpha_1 = \frac{1 + \eta_1 + \eta_1^2}{\eta_1 - \eta_2}\,,\quad \alpha_2 = \frac{1 + \eta_2 + \eta_2^2}{\eta_2 - \eta_1}\,.$$

$$\lambda = K_o^2 / kh_o \cos\psi = f_1 / g \cos\psi\,.$$

(For the meanings of h_1 and h_2 see fig. 10.)

The coordinate, $x = x_{crit}$, of the cross section of the avalanche in which $u = u_{crit}$ can be computed from the equation

$$x_{crit} = \frac{h_{crit}}{\lambda}\left[\bar{\eta} - 1 - \ln\left(\frac{1-\eta_1}{\bar{\eta}-\eta_1}\right)^{a_1}\left(\frac{1-\eta_2}{\bar{\eta}-\eta_2}\right)^{a_2}\right]. \qquad [3.9]$$

The distribution of the velocity of v(x) in the avalanche points is found with the help [3.7] from the equation

$$v = w\left(1 - \frac{h_o}{h}\right). \qquad [3.10]$$

The form of the function h(x) is shown in fig. 13. Thus, if the properties of the snow cover are known, as well as the profile of the slope thickness, then from equations [3.7-3.10], it is possible to determine the longitudinal profile of the steady-state avalanche, the velocity distribution in the avalanche, and the velocity of the leading edge of the avalanche. The solution derived can describe the characteristics of the movement only of the front part (nucleus) of the avalanche. The processes occurring in the tail of the avalanche cannot be described within the confines of the statement of the problem examined here, since the motion in the tail part is essentially nonsteady state.

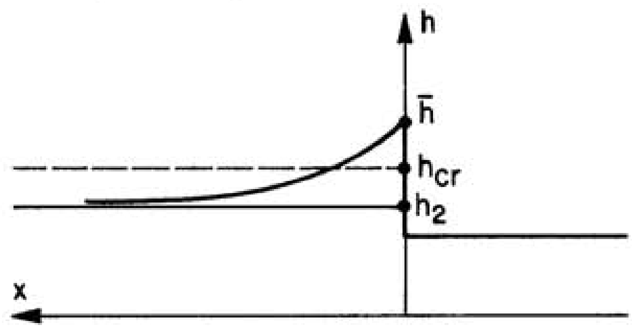

Fig. 13. Shape of the longitudional cross section of the avalanche (stationary solution).

The derived solution is easily generalized in the instance when the snow density in the absence of a snow cover, or a snow slab moving over the snow cover, are not avalanches in the full sense of the word because in such a movement, new portions of snow are not entrained.[8] The derived solution is not applied to avalanches of this type since it is essential in it that $h_o \neq 0$.

Apparently, powder avalanches require special consideration since in their movement the interaction with air, not taken into account in the above described statement of the problem, plays an essential role. As far as dry and wet avalanches flowing over the snow are concerned, if the external parameters satisfy the above indicated conditions, the essential features of the movement of the leading part of such avalanches should be described, to a certain degree, by the solution which was derived. The difference between dry and wet avalanches arises in the different value of the coefficients entering into the solution. This conclusion is partially supported by observations of avalanches carried out during 1965-1966 (Briukhanov, 1966). It should be emphasized that the solution obtained in (Grigorian et al., 1967) is not a simple reformulation of the hydraulic results in the instance of snow movement. The stated problem differs, essentially, from the problem of hydraulics; primarily, in that the properties of snow in front of the leading edge of the avalanche and behind the leading edge are considered to be different. Snow, lying on the slope, is not described by the hydraulics equations, and the basic equations of [3.1] become ineffective in the region in front of the leading edge of the avalanche. The leading edge of the avalanche is viewed as a front of disaggregation in which the properties of the medium change abruptly. In connection with this, the conditions themselves at the leading edge have a different form than the conditions used in hydraulics. They include a critical stress, σ_*, in which the destruction of the snow cover on the slope takes place.

Recalling the results of Voellmy's study (Voellmy, 1955), we see that in using all the necessary equations, and not just one equation of motion, it becomes possible to derive a complete solution of the problem. Voellmy's assumption, regarding the fact that in all points of the avalanche on a uniform slope, h is identical, is not justified. The velocities of snow in different cross sections of the avalanche are different, and the velocity of the leading edge of the avalanche does not coincide with the velocity of the snow behind it and does not coincide with the velocity, v_{max}, derived by Voellmy [1.5].

In conclusion, let us note also that equations [3.7-3.10] derived on the assumption that the slope is uniform and the angle of the incline, ψ = const, can be applied with only a small error in the case when the slope angle changes fairly smoothly such that the motion at each moment of time in the moving coordinates can be considered as quasi-steady state. The amount of the error derived in using equations [3.7-3.10] can be evaluated only after obtaining a solution of the problem of the nonsteady-state movement of the avalanche in an exact statement of the problem.

In the simplest statement of the problem of avalanche movement examined above, many very important facts of the phenomenon turned out to be excluded from consideration. In the future development of the theory, they should and can be taken into account. Let us enumerate here some of the problems of avalanche dynamics which can be stated mathematically on the basis of already existing information on the nature of snow movement or after the additional study of the processes occurring in this phenomena.

1. Problems of the Movement of Slow Avalanches. Avalanches exist (particularly wet ones) that have a very low velocity. For such avalanches apparently, it is more correct to consider that the force linked with the hydraulic resistance is proportional to the first power of velocity. The equation of motion [5.1], in this case, should be replaced by the equation

$$\frac{dv}{dt} = f_1 - \frac{v}{k_1 h^2} - \frac{1}{2}\frac{g}{h}\frac{\partial h^2 \cos\psi}{\partial x},$$

and the type of the motion changes substantially. Appropriate investigations (at least of steady-state movements) can be performed, and, apparently, will be of practical interest since slow avalanches can also produce much destruction.

2. Study of the Disaggregation Mechanism of the Structure of the Snow Cover at the Leading Edge of the Avalanche. Such a study is important for a more accurate description of

the conditions at the leading edge and, primarily, for deriving additional conditions which would make it possible to compute the snow density in the avalanche from the known density of the original snow cover. Knowing the density of the moving snow is very necessary for computing the forces acting on an object hit by an avalanche. Apparently, in many cases in front of the leading edge of destruction, elastico-plastic waves propagate in which the snow is condensed and its density is increased. At the leading edge of destruction and then in the avalanche, subsequent complex processes occur which result in the mean density of the moving snow being both larger and smaller than the mean density of the snow cover on the slope. These processes can be studied partially in natural observations as well as by means of laboratory investigations of the disaggregation of snow specimens in compression under the effect of impact load. At the same time, it is now possible, using certain schemes developed in the theory of plasticity and in hydrodynamics, to try to describe, in more detail and theoretically, the process of disaggregation. It will be possible to study the shape of the leading edge of the avalanche which can be very important in the collision of an avalanche with an obstacle.

3. On the Interaction of the Moving Avalanche with the Surrounding Air. The definite shape of the leading edge of the avalanche is produced under the influence of the action of the surrounding air. The problem of the joint movement of the snow cloud and the surrounding air can be stated mathematically. Questions can be resolved here of the shape of the leading edge, the size and effect of the resistance force of the air on the velocity of the avalanche, on the effect of the mixing of snow and air on the snow density in the avalanche and, finally, on the "air wave" accompanying the descent of the avalanche. It should be pointed out, however, that this problem exceeds the limits of hydraulic schemes, although in a rough form, computation of the air resistance in the simplest hydraulic consideration can be performed; the appropriate force should be included in the conditions at the abrupt change at the leading edge.

4. Problems of the Non-steady State Movement of Avalanches. The steady-state solution

(Grigorian et al., 1967) describes in a precise sense only the behavior of the developed avalanche on an infinitely long, uniform slope. Finding nonsteady-state solutions is an incomparably more complicated and interesting problem. The nonsteady-state solution, describing the behavior of the avalanche on a slope with a variable slope angle and a variable snow cover thickness, if derived even for only one concrete selection of parameters, would make it possible to evaluate the error which is made when the simple equations (Grigorian et al., 1967) are used for calculating avalanche velocity on such a slope. It is apparent that deriving such an evaluation is very important for practice. However, the derivation of nonsteady-state solutions also has an independent interest. In particular, without computing nonsteady-state types of motion, it is impossible to answer the following important questions of avalanche dynamics:

(1) What is the maximum runout distance of avalanches in a given slope?

(2) How does the avalanche interact with an obstacle of a given shape and dimension?

(3) Will the beginning movement of a certain mass of snow, caused by some kind of external cause (for example, an explosion), develop or die down?

Within the limits of a hydraulic scheme, the nonsteady-state movement of the avalanche is described by equations [3.1], which have been satisfied in the area occupied by moving snow. Since snow begins to behave as a liquid only after disaggregation at the leading edge of the avalanche, the equations of [3.1] are not satisfied for snow lying in front of an avalanche. At the leading edge, if it represents an abrupt change, the conditions of type [3.4] should be fulfilled. In the zone in front of the avalanche leading edge, all the parameters of the snow cover should be given. Furthermore, conditions should be assigned for the rear of the avalanche. Apparently, obtaining nonsteady-state solutions is such a complicated problem that the only real means of theoretical investigation of nonsteady-state snow movement is by computer. The study of nonsteady-state movement also includes the following question requiring special individual study. Observational data of Briukhanov (1966) show that even on a fairly long and uniform slope the velocity of the leading edge of the avalanche

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Footnotes

[1]Almost all the numerical evaluations and the drawings, cited below, are absent in Voellmy's (1955) article. In some instances, new formulas are proposed.

[2]Generally speaking, in the runout zone it is necessary to take into account the variability of h (formation of the cone). Therefore, subsequent equations [1.7 - 1.12] can only describe the behavior of the avalanche very roughly, on the whole.

[3]This condition is true, if $\rho_1 = \rho_2$ and if there is no snow accumulation the slope break.

[4]In actuality, only the instance was considered when $\psi(x)$ = const.

[5]From measurements, coefficient μ decreases with the increase of γ (Goff and Otten, 1938).

[6]All the following assumptions and calculations are easily generalized in the case when snow density in the avalanche is not equal to the density of the undisturbed snow covered, but is known and is constant.

[7]This assumption is further justified by the fact that the steady-state solution of system [3.1] actually exists.

[8]Editor's note.--This highly restrictive definition of an avalanche is not used in many countries, including the United States and most western European countries.

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Investigation of the Solutions to Snow Avalanche Movement Equations

N.S. Bakhvalov and M.E. Eglit

This paper, as well as the investigations of Grigoriian (1967) and Briukhanov (1955), assume that snow movement in an avalanche may be considered to be a turbulent movement of a continuous medium and may be roughly described by the following equations:

$$\frac{\partial h}{\partial t} + \frac{\partial hv}{\partial s} = 0 , \quad \frac{\partial v}{\partial t} + V\frac{\partial v}{\partial s} = f - K\frac{V^2}{h} - \frac{g}{2h}\frac{\partial h^2 \cos\psi}{\partial s} . \qquad [1]$$

Here, v is the mean downslope velocity of the snow along the slope averaged for a transverse cross-section of the avalanche, h is the thickness of the moving snow layer measured perpendicular to the slope from the surface along which the avalanche moves, t is time, s is the coordinate along the slope, g is the acceleration of gravity, ψ is the slope angle, K is the coefficient of "hydraulic" friction, and f is associated with the gravitational and possibly frictional forces which act on the snow and which do not depend on velocity (fig. 1). In actual computations, we used the following equation for f (Voellmy, 1955):

$$f = g(\sin\psi - \mu\cos\psi) , \qquad [2]$$

where μ is the coefficient of Coulomb friction.

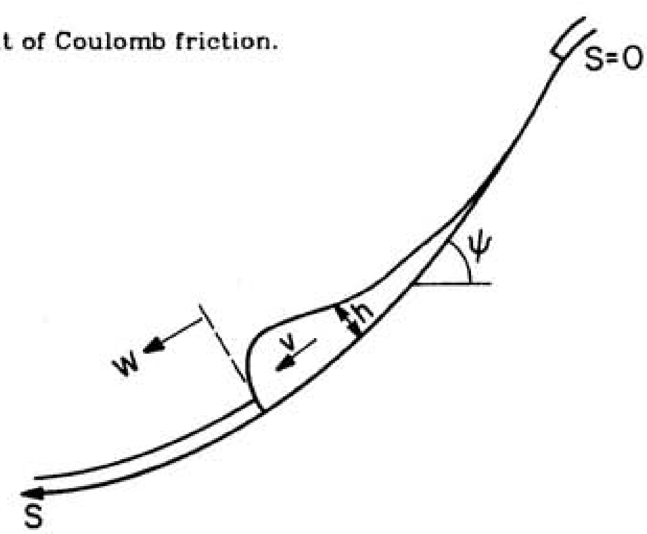


Fig. 1. Diagram of a moving avalanche.

Equations [1] are written for a wide channel or slope for which one may disregard the effects of channel edges on air on the lateral boundaries of the avalanche. We consider these equations to be useful for describing the mechanical behavior of snow inside the avalanche. One should treat the undisturbed snow cover lying in front of the avalanche as a medium with different properties. We will assume that the condition of the snow in front of the avalanche is known; specifically, the velocity will be equal to zero. We designate the leading edge of the avalanche as the boundary which separates it from snow which has not yet started to move. Continuity (mass discharge rate per unit of time) should be maintained at the leading edge. Thus, the continuity equations are

$$\rho h(w - v) = \rho_o h_o w \,, \quad \rho_o h_o w v = \frac{1}{2} \rho g h^2 \cos \psi - \sigma^* h_o \,. \qquad [3]$$

Here, w is the velocity of the leading edge, ρ and ρ_o are the snow densities in the avalanche and in the undisturbed snow cover, respectively, (we will subsequently assume that $\rho \cong \rho_o$). h_o is the thickness of that layer of snow cover entrained by the avalanche, and σ^* is the critical stress at which disaggregation (failure) of the snow cover takes place. We can write the equation of the leading edge in the form

$$s = \int_0^t w(t)dt \,, \qquad [4]$$

in which the position of the crown face is adopted as the origin of s.

With the functions ψ (s), h_o (s), sigmao* (s), and μ (s) given, one can determine the distributions of the snow velocities, v (s, t), and the flow height, h (s, t), in the avalanche for any moment of time by integrating equations [1] with the conditions of [3] and [4]. Certain "initial" conditions, as well as conditions in the trailing edge of the avalanche (in the crown face), should also be assigned. We adopted the following:

$$v = 0, \quad h = 0 \quad \text{with } s = 0 \,. \qquad [5]$$

In this paper, we will cite some of the results of numeric solutions of equations [1] through [5] using a computer and qualitative investigation of the solutions of this system.

The latter was performed for the purpose of obtaining approximate analytical equations for the velocity of the avalanche leading edge and the distribution of v and h inside the avalanche for certain types of slopes.

Let us investigate the avalanche movement along a long, uniform slope (ψ = const) with a homogeneous snow cover (σ^* = const, h_0 = const, and ρ_0 = const). In this case, it is convenient to introduce dimensionless variables of T, S, H, V, and W from the equations

$$t = T\sqrt{\frac{gh_0 \cos \psi}{f}}, \quad s = S\,\frac{gh_0 \cos \psi}{f}, \qquad [6]$$

$$h = Hh_0, \quad v = V\sqrt{gh_0 \cos \psi}, \quad w = W\sqrt{gh_0 \cos \psi}.$$

Then, equations [1] through [4] become

$$\frac{\partial H}{\partial T} + \frac{\partial HV}{\partial S} = 0, \qquad [1']$$

$$\frac{\partial V}{\partial T} + V\frac{\partial V}{\partial S} + \frac{\partial H}{\partial S} = 1 - \beta\,\frac{V^2}{H}.$$

$$\left.\begin{aligned} H(W - V) &= W \\ WV &= \frac{1}{2}H^2 - \alpha \end{aligned}\right\} \quad \text{for} \quad S = \int_0^T W(T)dT, \qquad [3']$$

where

$$\alpha = \frac{\sigma^*}{\rho g h_0 \cos \psi}, \quad \beta = \frac{kg \cos \psi}{f}.$$

If $f = g(\sin \psi - \mu \cos \psi)$, then $\beta = \dfrac{k}{\tan \psi - \mu}$.

The system of equations transformed in this manner contains two dimensionless parameters, α and β, which determine conditions of avalanche motion. In this paper the condition $\alpha \geq 1/2$ is always assumed. The limiting value ($\alpha = 1/2$) corresponds to the condition when the snow in front of the avalanche behaves like a fluid. With respect to the values of β, it is impossible to indicate any kind of limits (without special experiments). However, subsequent arguments in this section are useful only when $\beta > 0$ or, if equation [2] is adopted, $\tan \psi > \mu$.

We will attempt to construct an asymptotic solution of [1'], [3'], and [5] (i.e., to construct functions V (S, T), H (S, T), and W to which the solutions tend when $T \to \infty$). We will use the following concepts: we naturally assume that in avalanche motion along a long, sufficiently steep ($\beta > 0$), a uniform slope with homogeneous snow cover, the frontal velocity will tend toward a certain limiting velocity, W_a, and the distribution of the characteristics in the "head" zone, bordering on the leading edge, will tend toward some steady-state distribution. Then one can describe the velocities and thickness of the snow layer in the "head" by one of the steady-state solutions of [1'] through [3'] which [1] and [3] investigated, (i.e., of the form $V = V(S - W_a T)$, $H = H(S - W_a T)$. Table 1 gives a more detailed classification of the steady-state solutions. On the other hand, one can exclude the derivatives $\frac{\partial V}{\partial T}, \frac{\partial V}{\partial S}, \frac{\partial H}{\partial S}$ from equation [1'] for the area not bordering on the leading edge, since with time (i.e., with the increase of temporal and spatial scale of the phenomena) these derivatives tend toward zero in a continuous solution. Consequently, one can disregard them by comparison with the other terms not containing derivatives. Thus, one can assume that equations [1] can be replaced by [8] everywhere outside the relatively narrow area immediately adjacent to the leading edge,

$$1 - \beta \frac{V^2}{H} = 0 , \quad \frac{\partial H}{\partial T} + \frac{\partial HV}{\partial S} = 0 . \qquad [8]$$

We note that all the steady-state solutions of equations [1'] and [3], when the distance from the leading edge increases, tend rapidly toward the (following) constants ($H \to H_\infty$, $V \to V_\infty$, $H_\infty = \beta V_\infty^2$) which also satisfy equations [8]. In connection with this, it is interesting to investigate the stability of the solutions of [1'] in which the derivatives are so small that one can disregard them in comparison with the finite terms. One can conduct this investigation similarly to that which Grigoriian (1967) made in studying the question of the stability of the solution, $h = h_{crit}$, $v = v_{crit}$. We find that for $\beta < 1/4$, small perturbations of the solution will increase with time for any solution which satisfies the condition

$$1 - \beta \frac{V^2}{H} \cong 0 .$$

Therefore, small disturbances which occur randomly and extend along the body of the avalanche, in sufficiently steep and homogeneous slopes where $\beta < 1/4$ (that is, $\tan \psi > \mu + 4K$), will grow and with time can disaggregate and approach smooth distribution of parameters in the avalanche and change the frontal velocity. However, this does not mean that a stable value of the limiting velocity of the leading edge is nonexistent for $\beta < 1/4$. Small disturbances, in solutions of the type 1.1 and 1.2 (tab.1), which appear in the region of instability, will grow with time but will settle away from the "head" of the avalanche since the velocity of their dispersal is less than the frontal velocity (Grigoriian, 1967). Therefore, under the influence of such disturbances, only the avalanche tail changes, and the steady-state head, corresponding to the limiting velocity of the leading edge,

$$W_a = \left(1 + \frac{1}{\sqrt{\beta}}\right)^3 . \qquad [9]$$

is not changed in shape and in this sense may be called stable.

The dissolution of the continuous distribution of characteristics in the tail part of the avalanche causes secondary waves to arise in the body of the avalanche, and equations [8] become unsuitable for describing the movement in this part of the avalanche. This phenomenon is similar to the formation of so-called roll waves in super-critical water flows in canals (Stoker 1967). Figure 2a shows a possible steady-state shape of the avalanche head on a slope with $\beta < 1/4$. We emphasize that both the continuous and discontinuous distributions of characteristics correspond to the same velocity, W_a, determined by equation [9].

Investigation of the stability of the solutions close to the constants which satisfy the condition,

$$1 - \beta \frac{V^2}{H} = 0 ,$$

for less steep and rougher slopes where $\beta > 1/4$; that is, where ($\tan \psi < \mu + 4K$) leads to the

TABLE I

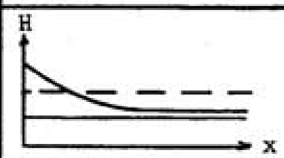
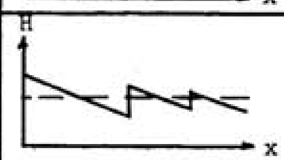
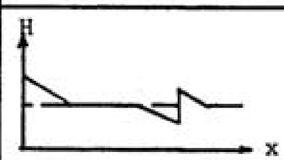
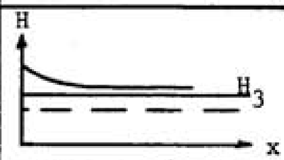
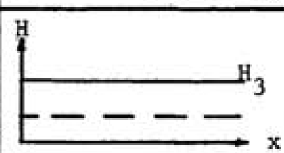
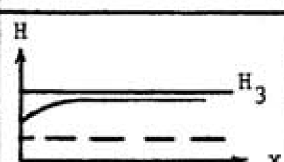
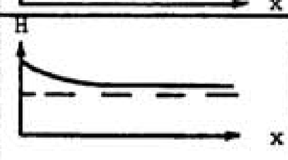
CLASSIFICATION OF UNIVALUE STATIONARY SOLUTIONS OF SYSTEM(I') WITH THE CONDITIONS OF (3) WHEN $\beta>0$, $\alpha>\frac{1}{4}$.

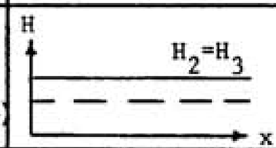
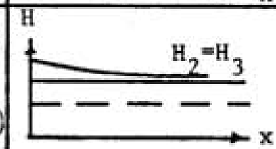
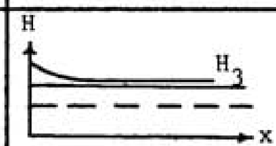
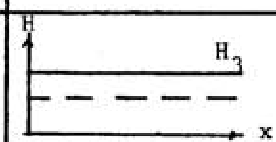
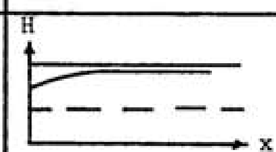
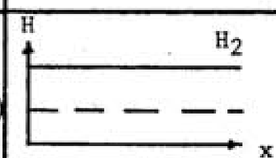
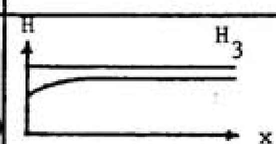
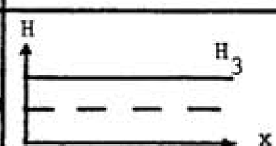
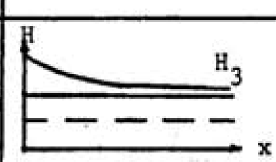
The following values are used in the table:
$H_1<H_2<H_3$ are the roots of the equation $H^3=\beta w^2(H-1)^2$; $H_{cr}=\sqrt[3]{w^2}$ is the value of H, with $w=v+\sqrt{H}$;

$$A(H)=\frac{1}{2}H^2-w^2\,\frac{H-1}{H};$$

$$B(\beta)=(1+\sqrt{\beta})^2\left[\frac{(2+\sqrt{\beta}+\sqrt{\beta+4\sqrt{\beta}}\,)^2}{8}+\frac{2}{\beta\sqrt{\beta}(2+\sqrt{\beta}+\sqrt{\beta+4\sqrt{\beta}})}-\frac{1+\sqrt{\beta}}{\beta\sqrt{\beta}}\right];$$

x is the distance from the leading edge.

β	w	α	A view of function H(x). The line $H=H_{cr}$ is shown by ----.
Type 1 $\beta<\frac{1}{4}$	$\sqrt{\left(1+\frac{1}{\sqrt{\beta}}\right)^3}$ with $w^2=H_3^3$	I.1 any	
		I.2 any	
		I.3 any	
	any that satisfies the inequality $27<w^2<H_3^3$	I.4 $\alpha>A(H_3)$	
		I.5 $\alpha=A(H_3)$	
	moreover $w=\frac{\sqrt{\beta}H_3\sqrt{H_3}}{H_3-1}$	I.6	
Type 11 $\beta=\frac{1}{4}$	$\sqrt{27}$	II.1	

β	w	α	A view of function H(x). The line $H=H_{cr}$ is shown by---
Type 111 $\beta>\frac{1}{4}$	$\sqrt{\frac{27}{4\beta}}$	III.1 $\alpha=\frac{9}{2}\left(1-\frac{1}{\beta}\right)$	
		III.2 $\alpha>\frac{9}{2}\left(1-\frac{1}{\beta}\right)$	
	$\sqrt{\left(1+\frac{1}{\sqrt{\beta}}\right)^3}$	III.3 $\alpha>B(\beta)$	
		III.4 $\alpha=B(\beta)$	
		III.5 $\alpha<B(\beta)$	
	$w=\frac{\sqrt{\beta}\,H_2\sqrt{H_2}}{H_2-1}=\frac{\sqrt{\beta}\,H_3\sqrt{H_3}}{H_3-1}$	III.6 $\alpha=A(H_2)$	
		III.7 $A(H_2)<\alpha<A(H_3)$	
		III.8 $\alpha=A(H_3)$	
		III.9 $\alpha>A(H_3)$	

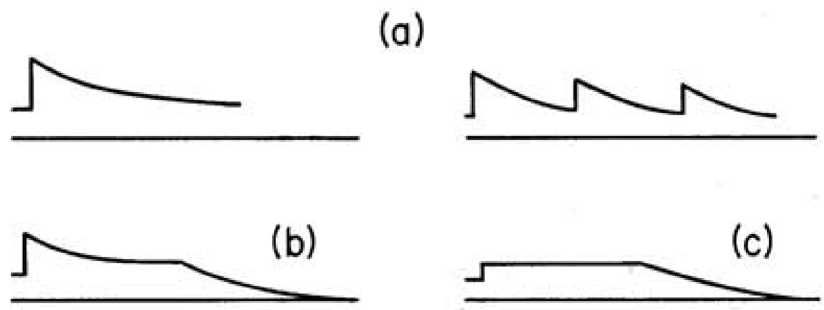


Fig. 2. Terminal avalanche shapes on various steep slopes.

conclusion that small perturbations superimposed on these solutions damp out rapidly. Therefore, all these solutions are stable in spite of the fact that the velocity of the leading edge is less than the velocity of the propagation of small perturbances in all the steady-state solutions in which $\beta > 1/4$, and random small perturbations overtake the front.

The condition of stability for $\beta > 1/4$ does not determine the velocity of the leading edge unambiguously. In this case, apparently, one can not determine the velocity of the leading edge without taking into account the boundary condition in the trailing part of the avalanche. Using equations [8], one can construct an asymptotic solution (with $T \to \infty$) for the trailing part of the avalanche using the boundary conditions in [5]. This enables one to find the maximum velocity, W_*, by combining the solution of equations [8] with the corresponding steady-state solution. We can reduce equations [8] to one equation, for example, for $V(S, T)$

$$\frac{\partial V}{\partial T} + \frac{3}{2} V \frac{\partial V}{\partial S} = 0 . \qquad [10]$$

The characteristics of the equation are determined by the relationships

$$\frac{dS}{dT} = \frac{3}{2} V , \quad \frac{dV}{dT} = 0 ;$$

that is,

$$S = S(0) + \frac{3}{2} VT . \qquad [11]$$

Apparently, with a sufficiently large T, one can replace equations [11] by the equation

$$S = \frac{3}{2} VT , \qquad [12]$$

and, consequently, the solution of equations [8] is represented by

$$V = \frac{2S}{3T} , \quad H = \beta V^2 = \frac{4}{9} \beta \frac{S^2}{T^2} . \qquad [13]$$

The equations of [13] describe the distribution of V and H in the avalanche in the region between the fracture face, (S = 0), and a certain characteristic, S = 3/2 VT. Thus, the leading boundary of this region propagates along the body of the avalanche with a velocity $W_1 = 3/2\ V$ (here V is the velocity of snow at the site where the boundary is at a given moment of time).

If solution [13] must adhere to a certain steady-state solution, then it should be

$$W_1 = \frac{3}{2} V_- ,$$

where V_- is the steady-state, snow velocity fairly close to the leading edge. The velocity of W_1 should not be more than the velocity of the leading edge of the avalanche, W_a, i.e., the steady-state solution which describes the movement of the avalanche should satisfy the condition:

$$\frac{3}{2} V_- \leq W_a . \qquad [14]$$

It is not difficult to show that this condition makes it possible to select a single steady-state solution for any $\beta > 1/4$ and $\theta > 1/2$ and thus, to indicate the equation for maximum velocity of the leading edge of W_a ; that is, with $B > 1/4$ and $\alpha > 9/2\ (1 - 1/\beta)$ (if α, which is associated with the strength of the snow cover, is sufficiently large), then the solution of type III.2 (tab. 1) where

$$W_a = \sqrt{\frac{27}{4\beta}} \qquad [15]$$

satisfies condition [14]. Figure 2b shows the limiting shape of the avalanche in this case.

If $\alpha \leq 9/2\ (1 - 1/\beta)$ (the strength of the snow cover is low), then the velocity of the leading edge for this β is greater and can be found as the root of the following equations;

$$\frac{H^2}{2} - \alpha = W_a^2\ \frac{H-1}{H},$$

$$\frac{H^3}{(H-1)^2} = W_a^2\,\beta\,. \qquad [16]$$

The steady-state solution of type III.6 corresponds to this value of W (tab. 1). Figure 2c shows the limiting shape of the avalanche in this instance.

We can propose equations [9], [15], and [16] as approximate equations for computing the velocities of the leading ledge of an avalanche along a sufficiently steep ($\beta > 0$) slope with a slowly changing curvature.

Only with the use of modern computers can one (using equations [1] through [5]) determine the character of avalanche movement along a slope with substantially varying parameters, as well as along a slope with constant angle having homogeneous snow cover. Selection of a suitable scheme of calculation poses significant problems, particularly with respect to the instability of the continuous solution for $\beta < 1/4$ which has been described.

The computations we performed on the BESM-4 computer had the goal, on the one hand, of verifying the conclusions made in the second section of this paper on the basis of a qualitative analysis of equations [1] through [5]. On the other hand, we wanted to investigate the possibility of determining avalanche parameters during movement along a variable slope, in particular the determination of run out distance. Numeric integration was performed by a method of finite differences in a grid with a constant spacing for X = ($dX = dS \cos \psi$) moving with the leading edge of the avalanche. The computations confirm that for a movement along a steep, uniform slope velocity, W_a, tends, accordingly, toward the value given by one of the equations [9], [15], or [16], and the distribution of the characteristics over time begins to coincide with the corresponding limiting (asymptotic) distributions described above with great accuracy. The speed of the establishment of the limiting distribution with constant β depends upon α as well as upon the initial conditions which are the avalanche parameters at the moment of its runout onto the slope in question. In computing the movement along slopes $\beta < 1/4$, we noted the appearance of secondary waves in some instances, over a short period of time. We determined them to be (within limits of given accuracy, 0.1%) at definite distances from the leading edge of the avalaynche (i.e., they began to move with the velocity of the leading edge). We found the distance between these waves to vary depending upon the state of the slope when movement began.

Table 2 gives examples of some of the results of the computations for movement along a uniform slope. Table 3 shows results of the computation of runout zone on a parabolic slope of decreasing curvature and acceleration on a parabolic slope of increasing curvature.

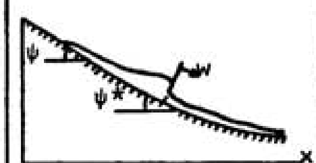
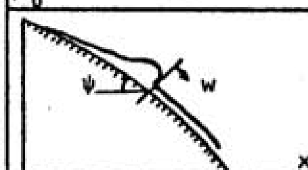
Table 2

Change of the velocity of the leading edge w in movement along a slope of constant angle (x is the projection of the path passed by the leading edge onto the horizontal, t is the time from the beginning of the movement).

Movement Conditions	t sec	x meters	w m/sec	w_a m/sec
$\tan\psi=0.5$, $\psi=26°36'$, $K=0.02$, $\mu=0.3$, $h_0=0.3m$, $\frac{\sigma^*}{\rho_0}=100\ \frac{m^2}{sec^2}$, $\alpha=37.6$; $\beta=0.1$	24.9	166.5	10.1	$w_a=\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=13.7$
	42.6	342.5	11.9	
	58.5	517.5	12.9	
$\tan\psi=0.35$, $\psi\approx19°18'$, $K=0.02$, $\mu=0.3$, $h_0=0.3m$, $\frac{\sigma^*}{\rho_0}=60\frac{m^2}{sec^2}$, $\alpha=21.7$; $\beta=0.4$	23.7	41.5	0.68	$w_a=\sqrt{\frac{27}{4\beta}gh_0\cos\psi}=6.84$
	95.5	182.1	3.86	
	189.2	528.	5.76	
$\tan\psi=0.35$, $\psi\approx19°18'$, $K=0.1$ $\mu=0.3$, $h_0=0.3m$, $\frac{\sigma^*}{\rho_0}=25\frac{m^2}{sec^2}$, $\alpha=0.9$; $\beta=2$	4.7	17.2	3.93	$w_a=W_a\sqrt{gh_0\cos\psi}=3.15$ W_a is determined by formula (16)
	22.8	76.8	3.27	
	43.6	139.7	3.16	

Table 3

Velocity change of the leading edge w during the avalanche's movement along a slope of variable slope angle (x is the projection of the path, passed by the leading edge, onto the horizontal, t is the time from the beginning of the movement).

Movement Conditions	t sec	x met.	ψ^*	w m/sec	w_a m/sec
 $\tan\psi=0.5$ for $x<200$; $\tan\psi=0.5-0.001(x-200)$ for $x>200$; $K=0.02$, $\mu=0.3$, $h_0=0.3m$, $\frac{\sigma^*}{\rho_0}=100\ \frac{m^2}{sec^2}$	16.6	97.5	26°36'	8.68	$\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=13.7$
	28.7	202.5	25°12'	10.4	$\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=12.6$
	40.9	310.5	19°54'	8.21	$\sqrt{gh_0\cos\psi\frac{27}{4\beta}}=8.60$
	59.4	399.5	15°18'	1.62	
	79.7	404.5	15°	0	
 $\tan\psi=0.5$ for $x\leq200$; $\tan\psi=0.5+0.001(x-200)$ for $x>200$; $K=0.02$, $\mu=0.3$, $h_0=0.3m$, $\frac{\sigma^*}{\rho_0}=100\frac{m^2}{sec^2}$	16.6	97.5	26°	8.68	$\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=13.7$
	28.7	202.5	28°	10.8	$\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=14.9$
	38.3	303.5	32°12'	14.0	$\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=18.3$
	45.9	401.5	36°12'	17.0	$\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=21.2$
	52.3	494.5	39°24'	19.6	$\sqrt{gh_0\cos\psi(1+\frac{1}{\sqrt{\beta}})^3}=23$

where ρ_1 is the snow density in the avalanche before impact, ρ_2 is the snow density after impact, v is the velocity of the avalanche at the moment of approaching the obstacle. Khristianovich based his equation on the use of the most general mechanics laws: the law of conservation of momentum and the law of conservation of mass. Unfortunately, it is difficult to use Khristianovich's equation since there is no information about the real values of

the snow density after impact.

The impact effect of the avalanche on an immovable obstacle as a function of the height of the avalanche front has been investigated in Switzerland using an hydraulic analogy. Voellmy (1955) compared these theoretical results with observations of damage caused by catastrophic avalanches in the Swiss Alps in 1954.

For describing the interaction of avalanches with an obstacle, it has been proposed that snow be considered a linear-elastic body. Such a model is valid only for avalanches with an undisturbed structure. Equations were derived for determining pressure during avalanche impact on an elastic obstacle using this model. Comparison of the computations from these equations with experimental data, which I have made, shows that the maximum impact pressure exceeds that which was calculated more than two times (Salm, 1964).

Experimental investigations were performed along with the theoretical studies which basically can be broken down into two groups. One group of studies was aimed at determining the dependence of the density following impact upon the initial snow density (Gongadze et al., 1955; Sulakvelidze, 1951). Snow density some time after impact was measured in experiments. It would be possible to use the results of these experiments if one assumes that the density, ρ, following impact remains unchanged for a fairly long time. In fact, this assumption is too imprecise since the discharge wave disaggregating the snow mass, arrives at the run out zone after some time. Furthermore, some of the air escapes from the snow which also leads to a change of density.

The second group includes investigations which measured the pressure during the snow avalanche impact (naturally or artificially made) on an immovable obstacle (Goff et al., 1939; Vollemy, 1955; Roch, 1955; Kuroda, 1956). Not all the experiments, however, produced satisfactory results since not all the instruments used to measure the pressure were suitable for this. Salm (1964) for the first time examined problems of the modeling of the impact of a snow avalanche on a structure.

I have taken some new positions to attempt to solve the question of snow avalanche impact.

One can consider the avalanche to be a continuous medium with a porous structure consisting of ice crystals and air. The snow and air particles move in the primary mass of the avalanche without shifting their relative positions significantly. During the impact of the avalanche mass on the obstacle, there is no escape of air from the snow-air mass due to the short duration of the process. Therefore, the composition of the small snow-air particle is assumed to maintain continuity during the course of impact in the theoretical schematization of the problem. In this case (Gongadze and Papinashvili, 1955), the movement of the snow-air mass in the avalanche can be described by hydrodynamic equations for a continuous medium (Landau and Lifshitz, 1965)

$$\rho \frac{d\bar{v}}{dt} = \rho \bar{F}^e + \operatorname{div} \sigma_{ij} \quad ,$$

$$\operatorname{div}(\rho \bar{v}) = \frac{\partial \rho}{\partial t} \quad , \qquad [1.1]$$

$$p = F(\rho) \quad .$$

where ρ is the mean snow density in the avalanche, v is the mean velocity, F^e is the body force, σ_{ij} is the stress tensor component. This will be a closed system if one disregards the strength properties of the ice structure (in this case, the stresses amount to pressure p), and if it is known that $p = F(\rho)$.

In fact small loads, acting on the snow, are absorbed by the ice structure. In large dynamic (impact) loads, however, the ice structure disintegrates and a significant density increase takes place, leading to increased pressure in the entrapped air. In this case, one can expect that the air absorbs the primary load and the strength properties are no longer important. Than the stresses are reduced to the pressure and it is sufficient to know the connection between the pressure and remaining parameters for closing the system of equations [1.1].

For the simplest model of snow, let us consider first a continuous medium consisting of equally mixed ice crystals and air. In this case, we will disregard the compressibility of the ice crystals, the strength properties of the structure formed from these crystals, and air filtration through the structure. Then the equation for the mean density of the snow-air mass will have the following form:

$$\rho = \frac{M_i + M_a}{\Omega_i + \Omega_a} = \frac{m + 1}{m \dfrac{RT}{p} + \dfrac{1}{\rho_1}} \qquad [1.2]$$

where $m = \frac{M_a}{M_i}$ is the ratio of the air mass to the ice mass in the snow element under consideration, R is the gas constant for air, T is the absolute temperature, p is pressure, ρ_i is the ice density. This equation includes the air temperature which can be determined on the basis of two limiting suppositions: (1) heat exchange between air and ice is not present and the air condenses according to the adiabatic law; and (2) the heat exchange is so intense that the air temperature does not differ significantly from that of ice.

Having made either of the above mentioned assumptions, we derive a relationship between the density of the snow-air mass and its pressure:

$$p = \frac{RT_\rho}{1 + \dfrac{1}{m} - \dfrac{1}{m}\dfrac{\rho}{\rho_i}} \quad . \qquad [1.3]$$

The velocity of sound c is determined by the equation

$$c = \quad \frac{dp}{d\rho} = \frac{RT\left[1 + \dfrac{1}{m}\right]}{1 + \dfrac{1}{m} - \dfrac{1}{m}\dfrac{\rho}{\rho_i}} \quad . \qquad [1.4]$$

The dependence of the velocity of sound, c, on density ρ for $\rho = p_{at}$ is shown in Fig. 1. It is apparent from the graph that the velocity of the sound does not exceed 30 m/sec for a density on the order of 0.15 / 0.35 g/cm^3. Similar investigations were performed for other mediums, in particular for water-saturated soils (Liakhov, 1959). Thus, the velocity of sound in a snow avalanche can be less than the velocity of the movement of the avalanche itself, that is, the movement in the avalanche can be supersonic. It follows from this that the nature of the flow past an obstacle will be similar to the flow in a supersonic gas flow, that is, with the presence of impact waves. According to this analogy, a simple method can be proposed for calculating loads on obstacles of a simple shape (planes, wedges, etc.) using the solution of the thoroughly studied problems of gas dynamics.

Let us consider the problem of the flow past a wedge-shaped obstacle in the path of a snow avalanche when the propagation velocity of small disturbances in the snow is less than the velocity of the avalanche movement. Let the snow avalanche move with a velocity V_o (Fig.2). There is an obstacle in the avalanche path in the form of a wedge with an angle ψ toward the direction of the velocity vector. This problem has no characteristic linear size in either the motion equations or in the boundary conditions, therefore, the course will contain a rectilinear impact wave issuing from the peak of the wedge at an angle β, and will consist of two progressive flows in front of and behind the impact wave. The flow velocity behind the impact wave is parallel to the surface of the wedge. The impact wave in this case will have the following conditions:

a. $v_n = v_o \sin(\psi + \beta)$;

b. $v_{n_1} = v_o \cos(\psi + \beta) \tan \beta$;

c. $\rho_o v_n = \rho_1 v_{n_1}$;

d. $P_o + \sigma_o + \rho_o v_n^2 = p_1 + \sigma_1 + \rho_1 v_{n_1}^2$; [2.1]

e. $$\rho_o = \frac{1 + m}{\frac{RT}{p_o} m + \frac{1}{\rho_1}}$$

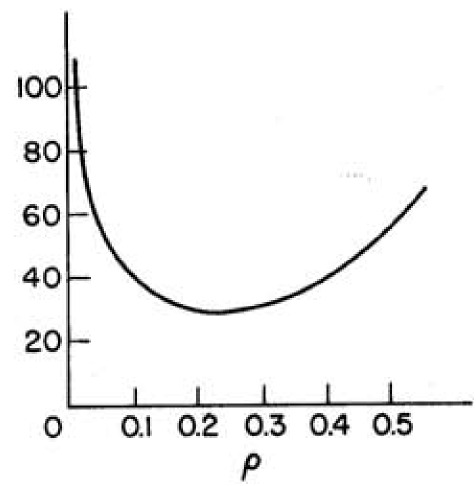


Fig. 1. Dependence of the sound velocity "c" on density ρ for $p = p_{at}$.

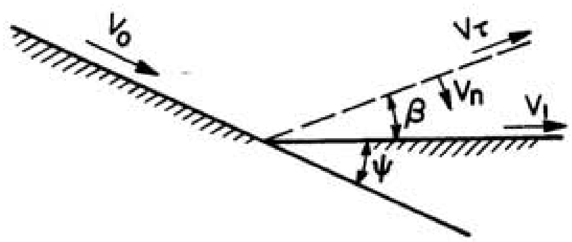


Fig. 2. Flow of snow against a wedge-shaped obstacle standing in the snow avalanche path.

f. $\rho_1 = \dfrac{1 + m}{\dfrac{RT}{p_1}m + \dfrac{1}{\rho_i}}$.

Here equation 2.1.a and equation 2.1.b are the equations for the normal velocity components for the impact wave taking into account that the tangential component will not tolerate a gap in the impact wave; 2.1.c is the discontinuity equation; 2.1.d is the equation for the conservation of momentum; 2.1.e and 2.1.f are the equations of state written for particles in front of and behind the impact wave.

We derive the following equation for p_1 by solving these algebraic equations with respect to p_1, that is, the pressure behind the impact wave (pressure on the surface side of the wedge):

$$p_1 = \frac{V_o^2\, a^2\, m\,(1 + m)\, RT}{P_o\left(m\dfrac{RT}{p_o} + \dfrac{1}{\rho_i}\right)^2} \qquad [2.2]$$

Here $a = \sin(\psi + \beta)$, $m = \dfrac{M_a}{M_i}$. After elementary transformations, taking into account that

$$\frac{RT}{p_o} = \frac{1}{\rho_a} \; ,$$

we derive

$$P_1 = v_o^2\, \rho_i a^2\, \frac{800m(1 + m)}{(800m + 1)^2} \; . \qquad [2.3]$$

One can assume a = 1 for evaluating the maximum pressure. One can use this equation only with supersonic flow, that is, when $v_o > c$, where c is the velocity of sound in the snow avalanche.

Using this model, let us consider the simplest problem of the impact of snow against a fixed obstacle (III). We can consider the obstacles (dams, houses, anti-avalanche reinforced-concrete structures) as being rigid since we can disregard the pliability and compressibility of the undisturbed obstacle compared to the compressibility of the snow-air mass flowing against it. The snow moves with a constant velocity perpendicular to its boundary and at a certain moment in time its entire front edge collides with the fixed object. In subsequent moments, a flat front (impact wave) will propagate deep into the snow from the obstacle against which the snow will compact and stop resulting in increased pressure on the obstacle. The statement contains two similar problems (Sedov, 1967). Their solutions reduce to the resolution of the following algebraic ratios at the front of the impact wave:

$$\text{a.}\quad \rho_o(v_o + d) = \rho_1 D;$$

$$\text{b.}\quad p_o + \rho_o(v_o + D)^2 = p_1 + \rho_1 D^2 \qquad [3.1]$$

Here equation 3.1.a is the law of conservation of mass; equation 3.1.b is the law of conservation of momentum, ρ_o , ρ_1 are the density of snow before and after impact; v_o is the velocity of snow against the obstacle; D is the velocity of the propagation of the impact wave; p_o, p_1 are the snow pressure before and after impact. In order to close this system, it is necessary to add the equation of state (1.2) to the conditions of conservation (3.1).

Let us examine the solution of the entire problem for the two assumptions noted above concerning the nature of the change of air temperature during compression.

First of all, an adiabatic condition should be used for the solution of the problem, that is

$$T_1 = T_o\left(\frac{p_1}{p_o}\right)\frac{\gamma - 1}{\gamma}$$

where T_o is the air temperature before impact, equal to the temperature of ice; T_1 is the air temperature after impact, $\gamma = 1.4$ is the adiabatic exponent for air.

Secondly, it is necessary to consider that the air temperature for the whole time of the impact is equal to the temperature of ice, that is, to assume $T_1 = T_o$ in the equation of state.

The equation of state taking into account the adiabatic conditions:

$$\frac{P_o}{\rho_o^\gamma} = \frac{P_1}{\rho_1^\gamma} \qquad [3.2]$$

will have the following form:

$$\rho = \frac{1 + m}{\dfrac{mRT_o}{p_o^{1-\frac{1}{\gamma}}\, p_1^{\frac{1}{\gamma}}} + \dfrac{1}{\rho_i}} \quad . \tag{3.3}$$

Due to analogous parts, the solution of the problem will consist of two progressive flows separated by the impact wave. The flow adjacent to the obstacle has a velocity equal to zero, density ρ_1, and pressure p_1. The velocity of the impact wave, propagating backward along the flow is equal to D. The problem will then be reduced to determination of ρ_1, p_1, and D from (3.1) and (3.3), that is, from

$$\rho_o(v_o + D) = \rho_1 D \; ;$$

$$p_o + \rho_o(v_o + D)^2 = p_1 + \rho_1 D^2 \; ; \tag{3.4}$$

$$\rho_1 = \frac{1 + m}{\dfrac{mRT_o}{p_o^{1-\frac{1}{\gamma}}\, p_1^{\frac{1}{\gamma}} + \dfrac{1}{\rho_i}}} \quad .$$

In solving these algebraic relationships we will derive a formula for determining the snow density after impact:

$$p_o^{1-\frac{1}{\gamma}}\left[\rho_1 - \rho_i(1 + m)\right]\left[p_o(\rho_1 - \rho_o) + v_o^2\rho_1\rho_o\right]^{\frac{1}{\gamma}} + \tag{3.5}$$

$$+ \, mRT_o\, \rho_1\rho_i(\rho_1 - \rho_o)^{\frac{1}{\gamma}} = 0 \quad .$$

We write this equation in a dimensionless form:

$$\left(1 + m - \frac{\rho_1}{\rho_i}\right)\left[\frac{p_o}{\rho_i v_o^2}\left(\frac{\rho_1}{\rho_i} - \frac{\rho_o}{\rho_i}\right) + \frac{\rho_1}{\rho_i}\cdot\frac{\rho_o}{\rho_i}\right]^{\frac{1}{\gamma}} =$$

$$= \frac{mRT_o\rho_i}{p_o\left(\dfrac{v_o^2\rho_i}{\rho_o}\right)^{\frac{1}{\gamma}}}\cdot\frac{\rho_1}{\rho_i}\left(\frac{\rho_1}{\rho_i} - \frac{\rho_o}{\rho_i}\right)^{\frac{1}{\gamma}} \; ; \tag{3.6}$$

Finding $\frac{\rho_1}{\rho_i}$ from this equation and inserting it into the equation for determining pressure p_1:

$$p_1 = p_o\left[\frac{RT_o\rho_1}{p_o\left(1 + \frac{1}{m} - \frac{1}{m}\rho_1/\rho_i\right)}\right]^{\gamma} \quad . \qquad [3.7]$$

we will derive the pressure behind the impact wave, or the pressure against the obstacle. When $T_1 = T_o$, the following conditions will exist in the impact wave:

$$p_o\left(v_o + D\right) = \rho_1 D\ ;$$

$$p_o + \rho_o\left(v_o + D\right)^2 = p_1 + \rho_1 D^2\ ; \qquad [3.8]$$

$$\rho_1 = \frac{1+m}{\frac{mRT_o}{p_1} + \frac{1}{\rho_i}} \quad .$$

After conversions, we derive the quadratic equation with respect to density $\frac{\rho_1}{\rho_i}$:

$$\left(\frac{\rho_1}{\rho_i}\right)^2\left(1 + \frac{mRT_o\rho_i}{v_o^2\rho_i} + \frac{\rho_o}{v_o^2\rho_o}\right) - \frac{\rho_1}{\rho_i}\left[1 + m + \frac{mRT_o}{v_o^2} + \frac{\left(1 + m\right)p_o}{v_o^2\rho_o} + \frac{\rho_o}{v_o^2\rho_i}\right] +$$

$$+ \frac{(1 + m)p_o}{v_o^2\rho_i} = 0 \quad . \qquad [3.9]$$

This equation contains two solutions: one for the compaction wave, another for the expansion wave. The coefficients of this equation do not depend on the sign v_o . Due to the fact that we are interested only in the root of the equation pertaining to the compaction wave, we can discard the lesser root for the expansion wave which does not have any physical meaning according to the second law of thermodynamics (Landau and Lifshitz, 1965).

Finding the value of $\frac{\rho_1}{\rho_i}$ from this formula and inserting it into the formula for pressure, we will derive a value for the impact pressure p_1:

$$p_1 = \frac{RT_o\rho_1}{1 + \frac{1}{m} - \frac{1}{m}\frac{\rho_1}{\rho_i}} \qquad [3.10]$$

Figures 3 and 4 show the results of computing pressure on an obstacle as a function of the initial snow density and velocity of its movement for the two instances examined above.

There is much snow packing during the impact of high velocity avalanches and the question arises about the need for computing these interactions in determining the load on the obstacle.[1] For large snow densities, for example, powder avalanches, the effect of the interaction between ice particles is unimportant, even during much snow compaction in the process of impact. The relationship in the impact wave in the snow-air mass allowing for the interaction of ice particles have the form:

$$\rho_o(v_o + D) = \rho_1 D\,;$$

$$\sigma_o + p_o + \rho_o(v_o + D)^2 = \sigma_1 + p_1\,\rho_1 D^2\,; \qquad [4.1]$$

$$p_1 = \frac{mRT\rho_1}{1 + m - \frac{\rho_1}{\rho_i}} \quad .$$

These equations will be closed if the function $\sigma = \sigma(\rho, T)$ is known. It follows from [4.1] that:

$$\bar{p} = p_o + \frac{v_o\rho_o\rho_1}{\rho_1 - \rho_o} \quad . \qquad [4.2]$$

where $\bar{p} = p_1 + \sigma_1 - \sigma_o$. Let us assume that the stresses caused by the interaction of the ice particles with one another in the moving avalanche differ little from the stresses in the snow in static conditions. Apparently, some density $\rho^* \cong 0.2$ exists so that for snow densities of small ρ^* the snow is not a solid body and, therefore, does not absorb static loads. The qualitative form of the function $\sigma = \sigma(\rho)$ is represented in Fig. 5. We will consider below only densities smaller than ρ^*. For these densities, $\sigma_o = \sigma_o(\rho_o) = 0$. Let us examine the function:

$$\bar{p} = p_1 + \sigma_1 \quad . \qquad [4.3]$$

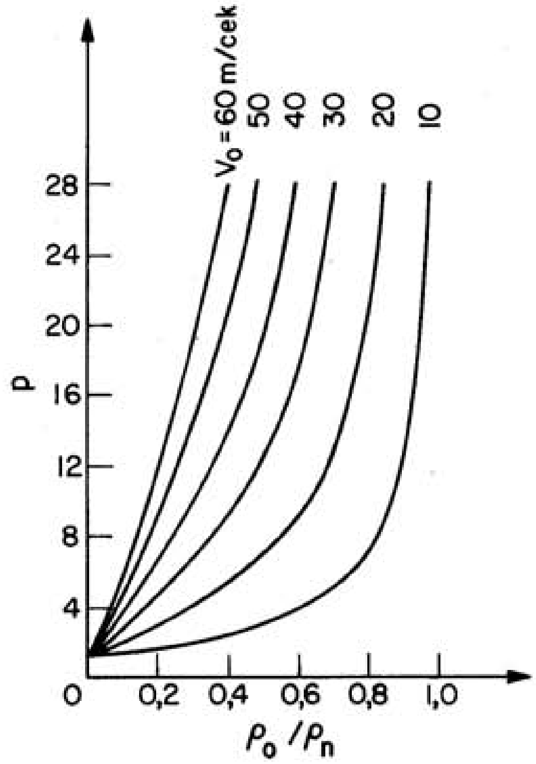


Fig. 3. Dependence of pressure on time and density for an adiabatic problem.

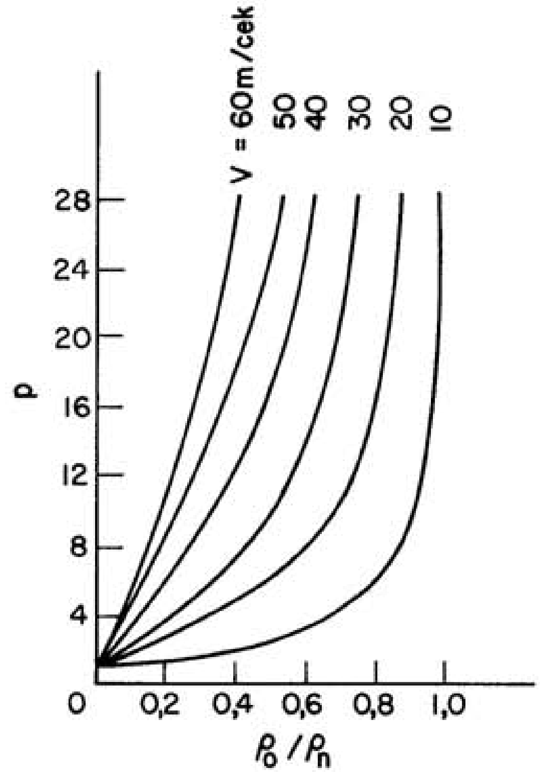


Fig. 4. Dependence of pressure on speed and density for an isothermal problem.

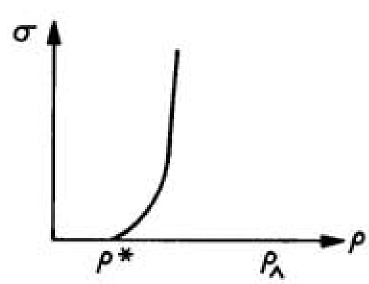


Fig. 5. Qualitative view of the dependence $\sigma = \sigma(\rho)$.

Figure 6 shows the qualitative function $p_1 = p_1(\rho)$ by a continuous line. The form of the curve $\bar{p} = \bar{p}(\rho)$ is represented by a dashed line. It is apparent that curves 1 and 2 coincide for densities less than ρ^*.

Let us examine the right part of equation (4.2) for densities, ρ_1, after an impact larger than the initial density, ρ_o, (Fig. 7). The graph in Fig. 7 has a vertical asymptote $\frac{\rho_1}{\rho_o} = 1$ and a horizontal $\bar{p} = p_o + \rho_o v_o^2$.

The value $\bar{p}$, which determines the full load on the obstacle, corresponds to the point of the intersection of the curve (Fig. 7) and the dashed curve (Fig. 6).

Two instances of the curves 1 and 2 (Fig. 8) can occur: One case, $\frac{\rho_1}{\rho_o} < \frac{\rho^*}{\rho_o}$ (the intersection of curves 1" and 2, (Fig. 8)). The second case: $\frac{\rho_1}{\rho_o} > \frac{\rho^*}{\rho_o}$ (intersection of curves 1" and 2, Fig. 8). In the first case, computing the strength is not important since $\rho_1 < \rho^*$ and $\sigma = \sigma(\rho_1) = 0$. Therefore, the values of the impact loads will be determined in conformity with the problem described above. In the second case, the value $\bar{p}$, corresponding to the point of the intersection of curves 1" and 2 (Fig. 8), will differ little from the horizontal asymptote ($\bar{p} \cong p_o + \rho_o v_o^2$), since we assume that the initial density of the snow-air mass is small, that is, $\frac{\rho^*}{\rho_o} \gg 1$, and curve 2 (Fig. 8) is already close to its horizontal asymptote. Thus, in the second case the value $\bar{p}$ generally does not depend on the form of curve 1" (Fig. 8). For example, one could take the curve $p_1 = p_1(\rho_1)$ as the curve (1"). Only the value of the density ρ_1 after impact depends on the form of the dependence $\bar{p}(\rho)$. Thus, one can use relationships that disregard the stresses which appear in the interaction of ice crystals with one another in determining impact loads for $\rho_o < \rho^*$.

In studying the phenomenon of snow impact on a fixed obstacle with a terminal velocity of heat-exchange between air and ice, one can imagine that the adiabatic scheme will be valid at the initial moment of time. In time the air temperature will become equal to the temperature of ice for all particles, excluding those which just passed through the impact wave.

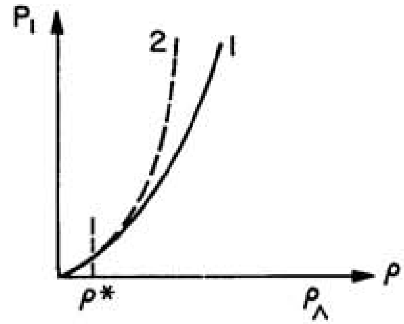


Fig. 6. Qualitative dependence of $p = p(\rho)$.
1 -- $p_1 = p(\rho)$.
2 -- $\bar{p} = \bar{p}(\rho)$

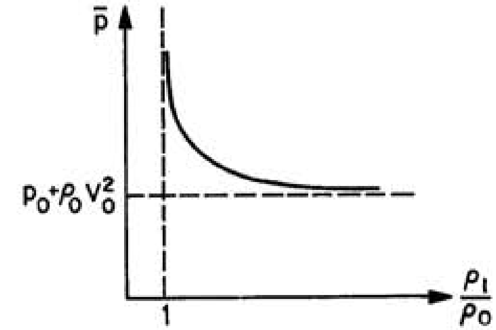


Fig. 7. Qualitative dependence of the right part of formula (4.2).

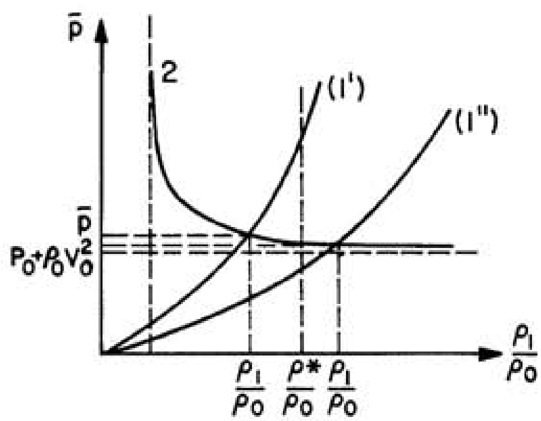


Fig. 8. Values of $\bar{p}$ for $\frac{\rho_1}{\rho_0} < \frac{\rho^*}{\rho_0}$ (intersection of curves 1' and 2), and for $\frac{\rho_1}{\rho_0} > \frac{\rho^*}{\rho_0}$ (intersection of curves 1" and 2).

The air in these particles has still not managed to cool. The heat exchange between air and ice is very intense, therefore, one can expect that the width of the zone, in which the heat-exchange has not yet occurred, will be very small. Let us consider the laws of conservation for this layer bordered by two reference surfaces. One can do this for moments of time when the impact wave has already moved away from the obstacle to considerable distances compared to the thickness of the layer. One can use an isothermic scheme in this case for determining the pressure in the obstacle and outside the transition layer. Thus, the qualitative picture of the change of pressure in the obstacle during snow impact on an obstacle, according to the analyzed schemes, will have a form shown by the solid line in Fig. 9. Here p_1 is the pressure for intense heat exchange.

Let us now consider the result of the limited nature of the length of the flowing snow mass with calculation of the strength. The propagation velocity of the disturbance for the ice structure is greater than (1000 to 1500 m/s) the velocity of the propagation of impact waves in the schemes cited above (36 to 100 m/s). Therefore, a zone with stresses in the structure, changing from the maximum value σ_m which the structure can hold up to zero in a free end point, will exist in front of the impact wave. Since the structure in this zone is still not deformed and the snow is moving as a solid body, all the particles there will move with the same acceleration a, depending only on time ($a = \frac{\sigma_m}{\rho \cdot l}$, where l is the length of the non-deformed part of the "snow" sample, and ρ is snow density). This acceleration is due to the fact that the slowing of the snow particles begins before the impact wave approaches it. As a result, a certain lowering of the intensity of the impact wave will occur in the process of its motion which leads to the decrease of pressure in the obstacle. Figure 9 shows this by a dashed curve. A discharge wave will begin to extend along the snow after the impact wave reaches a free terminus moving along the structure which unloads stresses in the structure almost immediately and then after a little while the discharge wave will approach disaggregating the air-snow mass (see sections 4-6 in Fig. 10). The snow flow of the obstacle begins after this (section 7, Fig. 10), for which one can estimate the pressure from the equation

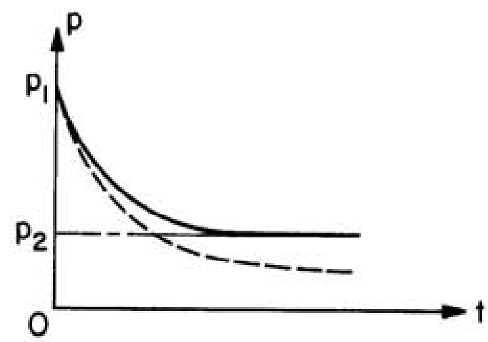


Fig. 9. Qualitative picture of the dependence of the snow pressure against an obstacle with time.

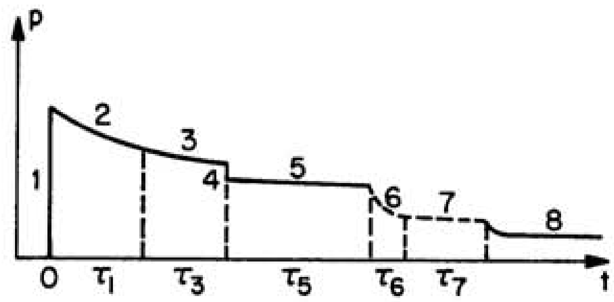


Fig. 10. Change of snow pressure on the obstacle in time.

$p = \frac{\rho v^2}{2}$ (where v is the velocity of the flowing snow against the obstacle). One can then determine the pressure by the weight of the remaining snow. Fig. 10 shows the qualitative picture described above of the change of the snow pressure on the obstacle with time: (1) the moment of impact; (2) the section of cooled air; (2) and (3) the motion of the impact wave along the snow "sample"; $\tau_2 + \tau_3 \cong \frac{l_o}{c}$ where c is the velocity of the propagation of the impact wave along the snow, l_o is the length of the snow "sample"; (4) the discharge wave of the structure from stresses, (5) the disaggregation wave movement along the "sample" $\tau_5 \cong \tau_2 + \tau_3$, (6) the disthickening wave has reached the obstacles; (7) the obstacle flowed-over by snow, $\tau_7 \cong \frac{l_o}{v_o}$, (the velocity of the snow flow on the obstacle); (8) the static load from the lying snow. In essence, this diagram is only a rough approximate scheme calculating the primary phenomena during snow impact on an obstacle. Furthermore, this scheme does not consider such features as the presence in the sample of lateral surfaces free from stress, air filtration over the ice structure, the presence of cracks in the snow "sample", irregularity in the initial density distribution, etc. Therefore, one can show only separate elements in the experimental oscillograms, common with the diagram in Figure 10.

A series of experiments was carried out for determining the impact pressure of a snow sample on a fixed obstacle. Snow samples representing a cylinder with a diameter of 41.8 cm and a height of 40 cm were dropped from different heights, 12 m, 7 m, and 4 m, onto a fixed steel plate (700 × 800 × 30 mm). Piezoelectric pressure gauges with an output to a cathode ray oscillograph were mounted onto the plate lying on the ground. A very high input impedance 10^{13} ohms) made it possible to obtain a practically undistorted signal during the entire experiment and to statically calibrate the gauges. The natural frequency of the measuring system, including the plate vibration, was about 2 khz.

The natural structure of the snow was deformed in preparing the snow samples and the mean density was determined by weighing the samples. The initial density, ρ_o, in the experiment changed from 0.212 g/cm^3 to 0.809 g/cm^3. The experiments were performed with snow of a diverse structure (freshly-fallen, dry coarse-grained, wet coarse-grained, and water-saturated). The initial temperature of the snow changed from −7°C to 0°C. The quantities of the maximum pressures were taken from the oscillograms which correspond to the first peak and were compared with the theoretical curves plotted for the problem examined above for the absence of heat-exchange (Figs. 11-13, curve 1). Comparison of the experimental data with the theoretical shows that the theoretical curves correspond well with the maximal values in the first peak. The horizontal segment of the oscillogram following the first peak was compared with theoretical values computed from the isothermal scheme. This comparison shows (Figs. 11, 12, and 13) that as a rule the experimental points lie somewhat above the theoretical curve which can perhaps be explained by the presence of the structure strength which was not allowed for in the theoretical computation. Furthermore, Fig. 12 shows experimental points derived by B. Salm (1964). One can distinguish segments in several of the oscillograms which correspond to the discharge waves (segments 4 and 6 in Fig. 10). The amount of the discharge in wave 4 lies in limits up to 1 kg/cm^2 which agrees with the data about snow strength obtained in static conditions. Separate characteristic segments in several experiments, for example 2 and 4 in Fig. 10, are not able to be distinguished. This can be explained, perhaps, by the presence of cracks in the snow sample or by glancing collision of the sample on the obstacle. Thus, the comparison of the experimental results and theoretical calculations, as well as the qualitative behavior of the oscillograms, agrees with the theoretical concepts about snow impact described above.

The results obtained in the model experiment have a more general nature than those obtained by computation since only the most general information about the snow and construction properties is sufficient for formulating dimensionless numbers. It is known that certain dimensionless combinations (dimensionless numbers) should be the same for scaling the measured results from model experiments to nature (Sedov, 1957). In order to form these numbers, we will write out the basic parameters determining snow avalanche impact on a structure: d is the characteristic linear size, for example, structure height or the height of

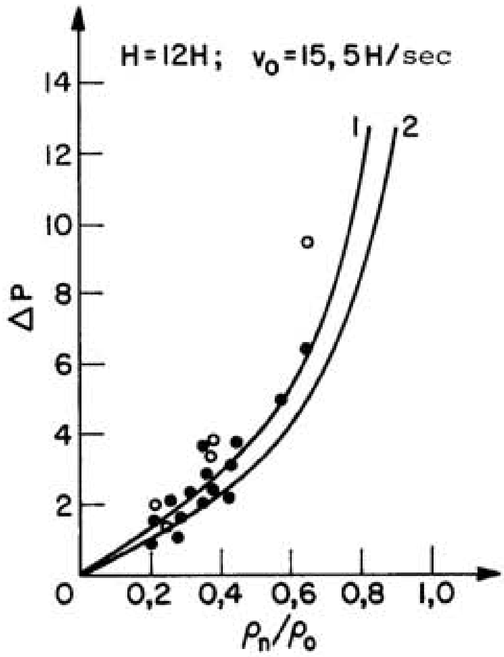


Fig. 11. Comparison of theoretical and experimental results.

1) -- adiabatic problem.
2) -- isothermal problem.

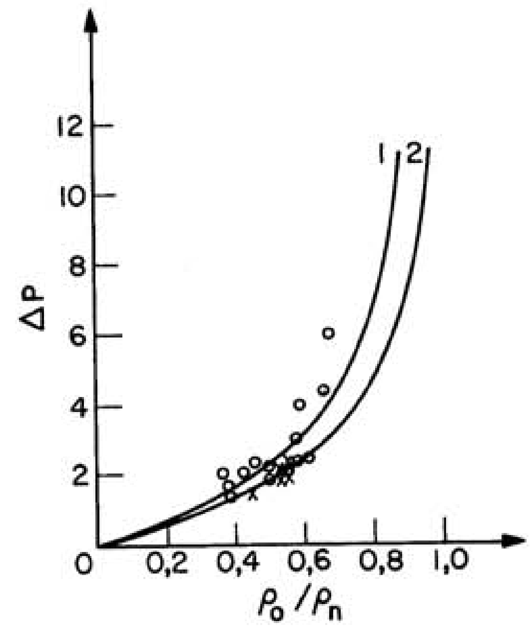


Fig. 12. Comparison of theoretical and experimental results.

1) -- adiabatic problem.
2) -- isothermal problem.
x -- experimental points derived by Sal'm

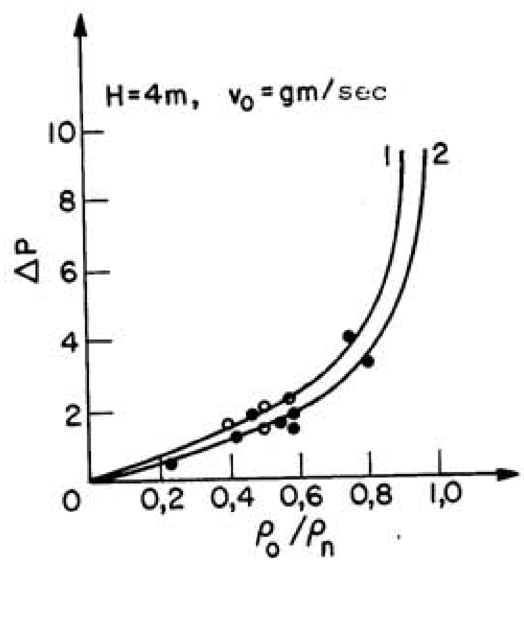


Fig. 13. Comparison of theoretical and experimental results.

1) -- adiabatic problem.
2) -- isothermal problem.

the avalanche front. (In geometrical simulation this parameter completely determines all the geometrical sizes); g is the acceleration of gravity; p_o is the atmospheric pressure; R is the gas constant for air; T is the absolute temperature of air; ρ_i is the ice density; ρ is the density of snow in the avalanche; v_o is the avalanche velocity at the time of its approach to the structure; σ_i are the stresses which dimensionally characterize the elastic properties of the snow, E_i are the stress values with dimensions which characterize the elastic properties of the structure. One can form six dimensionless numbers from these ten quantities which have four independent dimensions (length, mass, time, temperature):

$$\frac{gd}{v_o^2}, \frac{\rho}{\rho_i}, \frac{\rho_i RT}{p_o}, \frac{\sigma_i}{p_o}, \frac{E_i}{p_o}, \frac{\rho_i v_o^2}{\rho_o} \quad .$$

Let us consider modeling in ordinary conditions in which we will use snow as the modeling material. In this case p_o, ρ_i, and RT are practically identical for the model and for nature; σ_i depends primarily on density ρ and the snow structure; and E_i can be identical if the elastic properties of the model material and nature are the same. Therefore, if we take snow of the same density and identical structure for the model as for nature, then the second, third, fourth, and fifth dimensionless numbers will automatically be the same in the model and in nature. One can satisfy the equality of each of the two remaining numbers

$$\frac{gd}{v_o^2} \text{ and } \frac{\rho v_o^2}{p_o}$$

by the selection of velocity in the model experiment. However, in order to satisfy the first of the remaining numbers, the velocity v_o should be proportional to the square root of the ratio of the linear dimensions of nature and the model, and for ensuring the last number the velocities should be identical. Thus, it is not possible in ordinary conditions to simultaneously satisfy all the dimensionless numbers in the model.

It seems advisable to consider approximate modeling. In fact, the pressure during snow impact against an object is much more than the hydrostatic pressure and, consequently, the force of gravity is not important here. The force of gravity was considerable in the acceleration of the avalanche but not in the process of impact. Therefore, one can drop parameter g in analyzing impact and perform the modeling from the remaining five numbers. We will note that the times, including the periods of natural oscillations of the construction, during the modeling are reduced proportionally to the ratio of the linear sizes from the determining parameters discussed above (excluding g). For example, if a snow sample is thrown onto a structure, the linear size of which is an order of magnitude less than the linear size of the avalanche, then it is necessary to assign the model structure with a frequency of natural oscillations, an order larger than the natural structure for determination of load. This requirement is important. If one uses a low-frequency structure in a model experiment for determining equivalent load, for example a beam, the parameters of which are close to the parameters of a natural structure for which the impact of the snow sample occurs over a time less than the period of natural oscillations of the structure, then the load will have an impulsive character. Consequently, all the sags/depressions of the model structure and, thereby, the equivalent load will be proportional to the impulse of the sample. It follows from considerations of the dimensionality that:

$$P_{equiv} = \frac{d^3 \rho_i v_o}{\tau} f\left(\frac{\rho}{\rho_i}, \frac{\rho_i RT}{p_o}, \frac{\sigma_i}{p_o}, \frac{\rho_i v_o^2}{p_o}, \ldots\right),$$

where τ is the period of the structure's natural oscillations. The area of this sample is proportional to d^2. Now if one considers that the equivalent load is

$$\sigma_{equiv} = \frac{P_{equiv}}{S},$$

where S is the area of the sample, we will derive:

$$\sigma_{equiv} = \frac{P_{equiv}}{S} = d \cdot \rho_i \cdot v_o \cdot \frac{1}{\tau} \cdot f \cdot \left[\frac{\rho}{\rho_i}, \frac{\rho_i RT}{p_o}, \frac{\sigma_i}{p_o} \frac{\rho_i V_o^2}{p_o}, \cdots\right].$$

Additionally, the equivalent load σ_{equiv}, determined in this manner, will be proportional to the size of the snow sample and can not be used for computing avalanche-defense structures. In the above-described method of modeling, the pressures in the model will be the same as in a natural structure.

The results obtained from computing pressures arising in snow avalanche impact against an obstacle can be taken into account in the building of avalanche-defense structures. The greatest pressures are attained at the initial moment of impact, however, the duration of these pressures is small and depends only on the rate of heat-exchange in the snow, that is, on the physical properties of the snow. The duration of these pressures for natural avalanches will be the same as for small snow samples. It is apparent from the experiment that this time does not exceed 3 μ sec which, as a rule, is considerably less than the period of the natural oscillations of avalanche defense structures. Consequently, these pressures will be absorbed by the structures as impulsive loads. The primary loads which the structures should withstand will be determined by the pressures computed from an isotherm scheme. Deviations of the experimental points from theoretical curves (Fig. 11-13) are not important for the practical computation of the structures. The duration of these pressures is proportional to the dimensions of the moving snow-air mass and can be commensurate or even greater than the period of natural oscillations of the natural construction. Therefore, it is necessary to allow for these pressures in the design of avalanche-defense structures. As a rule, these pressures in real conditions as a rule will be less than those computed due to the following reasons: 1) the avalanche front actually is not flat. Therefore, the object will absorb the snow impact gradually depending on the shape of the leading edge of the avalanche; 2) avalanche velocity, as a rule, is aimed at a certain angle toward the obstacle. Therefore, it is advisable to design structures specially oriented at a certain angle to the direction of avalanche motion.

The results obtained show that pressures during impact depend on the velocity of the moving snow and its density. At the present time, various methods exist for computing the velocity of snow avalanches. However, knowledge about the density of avalanche snow is practically non-existent. Therefore, the problem of determining the density of snow in an avalanche is one of great importance. In particular, one can use data from measuring the pressure of natural avalanches for determining density and then derive density ρ as a function of pressure and velocity.

In the future it will be important to evaluate more accurately the duration of pressures. One can do this with the help of an approximate solution of the spatial problem of the diffusion of compression and discharge waves in snow.

In describing the impact of snow avalanche on structures, it is necessary to allow for the strength of the ice structure since a significant part of the load can be absorbed by the structure. Unfortunately, the strength properties of snow have been studied very little in dynamic problems.

Air filtration through the ice structure was disregarded in the snow model which was presented above. Apparently, these processes are important for the formation of a zone of residual density near the obstacle. In solving such problems, the snow model discussed must be perfected.

The simplest statements of the problem of the interaction of moving snow with an obstacle have been considered in this paper. The presence of a connection $p(\rho)$ makes it possible to describe more complex movements of snow air mass as well (Riemann waves). It is worthwhile to describe the interaction of a snow avalanche with a flexible obstacle using the solution of the type of Riemann waves.

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The Nature of an Air Wave Caused by Snow Avalanche

Iu. L. Iakimov and I. E. Shurova

A strong air wave occurs in certain types of snow avalanches. As a rule this air wave follows an avalanche of loose snow and is one of the most dangerous phenomena. This is explained, first of all, by the snow's unusually low strength and, secondly, by the fact that the snow descends along the same paths, whereas the path of the air wave can be completely unexpected. Observers note that the air wave frequently occurs far ahead of the avalanche. We quote from V. Fliaig's book *Vnimanie, Laviny* (Fliaig, 1960), "The track becomes bad when powder from the trees suddenly begins to fall to the ground far ahead of the cloud and branches, whole trees, and debris fly high up into the air." Whirlwind-type air motions and a sucking action which accompanies the air wave are also noted.

We should note that there can be no discussion about shock waves in the air similar to those which accompany a supersonic jet flight since the rate of avalanche motion on the slope, as a rule, does not exceed 100 m/sec, which is considerably less than the speed of sound in the air. Nevertheless, some authors consider that the nature of the air wave is connected with the presence of these shock waves.

Also invalid is the viewpoint that the air wave is an area of increased pressure in front of the avalanche. Such a zone can exist only during the movement of a body and stretches for a very short distance in front of the body. It is also known that the air wave which accompanies a snow avalanche is observed after the avalanche itself has stopped.

Also untenable is the assumption that the air wave, like the shock wave, forms during avalanche descent over cliffs. We know that such a wave stretches in the shape of a spherical impact wave with a center in the rupture. This circumstance contradicts the observed directional propagation of the air wave.

Thus, the existing viewpoints on the nature of the air wave contradict observed phenomena.

We think the formation and motion of an air wave is analogous to the formation and motion of a vortex ring. Such rings are frequently demonstrated using a box filled with smoke and having a round opening. A vortex ring occurs when the body of the box, which can move inward a distance of tens and hundreds of ring diameters, is sharply contracted. If we cut across this ring at right angles to the plane of symmetry, then we obtain a model of an air wave representing a semi-circle moving above the surface.

There are a sufficient number of detailed mathematical descriptions of such vortex rings (Kochin et al., 1963). In particular, if we examine the motion of an infinite vortex line along a plane (two-dimensional problem), we find that the speed near the plane is four times greater than the rate of motion of the vortex line.

Conditions may arise during the descent of an avalanche of loose snow which are favorable for the formation of a powerful vortex. In reality, snow avalanches entrap air lying along the slope. An intense displacement of snow with air adjacent to the avalanche front contributes to this in loose snow avalanches, whereas air lying somewhat above is not entrapped. As a result we find a circulation of velocity diferent from zero and vortex lines encircling the avalanche front rest against the slope which is a plane of symmetry. The vortex semi-rings continue to move down the slope during avalanche runout causing damage in its path similar to those described above.

One can observe phenomena, where the vortex line touches the slope, which are similar to the action of a tornado. Such phenomena have been noted in snow avalanches by many observers. Additional increase of the air flow energy can occur due to the potential energy of snow particles carried down the slope by the vortex. Other mechanisms of vortex formation can also be cited.

With avalanche speed at the moment of vortex formation in the order of 100 m/sec, the pressure of the air on the obstacle will reach 500 kg/m^2 due to velocity head or kinetic energy.

Let us examine the modeling rules in Sedov (1965) to explain the various possible formation mechanisms of a vortex in labortory conditions.

The determining parameters are the characteristic linear size, for example, the height of the slope, H, and parameters characterizing them, such as the kinematic viscosity, v, and the air density, ρ.

We have not included the parameters which describe the motion of snow on a slope and air compressibility since, in the phenomenon under consideration, the air movement is subsonic and we can disregard compressibility.

In this problem, we are interested in the air motion caused by an avalanche. Therefore, we can use only the law of motion for determining the parameters of the avalanche movement,

$$V(t) = V_o f\left(\frac{t}{t_o}\right);$$

that is, V_o and t_o.

One can set up two dimensionless numbers from the enumerated parameters H, ν, ρ, V_o, t_o which describe the air movement

$$R_e = \frac{HV_o}{\nu} \quad \text{and} \quad \frac{V_o t_o}{H}.$$

Since we know from observations that the avalanche moves with a speed in the order of 100 m/sec and the same rate for air entrapped by the avalanche, then $R_e \sim 10^9$. The air movement will be turbulent for these R_e numbers.

Let us consider turbulent viscosity according to Prandtl'. We have the following equation for turbulent shearing stress:

$$\tau = \left\{\mu + \rho l^2 \left|\frac{d\overline{V}_x}{dy}\right|\right\} \frac{d\overline{V}_x}{dy}, \qquad [1]$$

where $\overline{V}_x$ are the average speeds, and

$$l = \frac{a\overline{V}_x}{1 + b\,\dfrac{dV_x}{dy}} \qquad [2]$$

is the length of the displacement path.

The relationship of the displacement path length to the characteristic size according to experimental data in a tunnel with radius r_o has the form

$$\frac{l}{r_o} = \frac{a\,\dfrac{\overline{V}_x}{V_{max}}}{1 + b\,\dfrac{r_o}{V_{max}} \cdot \dfrac{d\overline{V}_x}{dy}}, \qquad [3]$$

where a = 0.166, b = 0.26.

Having substituted into the equation

$$V_x \sim V_{max} \sim 100\,\frac{m}{sec}, \quad \frac{dV_x}{dy} \sim \frac{V_{max}}{h},$$

where h is the height of the layer of air entrapped by the avalanche, $r_o \sim h$, we obtain $l \sim 0.1h$.

We then obtain an estimate for turbulent viscosity from equation [1],

$$\mu_t = \mu + \rho l^2 \left| \frac{d\overline{V}_x}{dy} \right| .$$

On the other hand, knowing the estimate for turbulent viscosity, we will find the number

$$Re_{turb} = \frac{hV_o}{\mu_t}\rho \sim 100 .$$

In connection with the fact that the length of path displacement, l, decreases during the approach to a solid wall, the turbulent viscosity also decreases, returning at the wall to a very small value equal to the air viscosity.

One of the possible methods of modeling the phenomenon under consideration consists in the fact that turbulent air movement is modeled by the movement of a viscous fluid in which the equality of the Reynolds numbers is provided by $Re_t = Re_m$, where

$$Re_m = \frac{\rho_m h_m V_o}{\mu_m}.$$

In this regard, in an experiment one can roughly circumvent the difficulties connected with the substantial decrease of the μ_t at the wall when the boundary is a free surface. In this case, the viscous friction in the boundary decreases practically to zero.

The experiments which have been carried out show that avalanche motion, as a rule, is accompanied by a vortex motion of the surrounding medium which also continues after the avalanche stops. Since the nature of the vortex propagation should depend under natural conditions on the slope relief, then it is necessary in practical observations to use a classification of avalanche-hazard slopes according to geomorphological criteria (Tushinskii, 1960).

The modeling discussed above has shown that the vortex can propagate after the avalanche stops for a distance exceeding the characteristic size of the avalanche.

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Determining Snow Avalanche Load on a Structure by Physical Modeling

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The problem of determining the design load on engineering structures built in avalanche-hazard areas is one of the main concerns in avalanche mechanics. At the present time, however, the theoretical solution of this problem is difficult.

A method of determining loads on structures based on a technique of physical modeling is presented below. Natural structural loading can be determined from models by a method of appropriate scaling. In order to do this scaling, dimensionless numbers should be properly selected in the modeling; that is, certain combinations of determined parameters of natural conditions and the model should be identical.

The question about the structure and number of dimensionless parameters is trivial if there is mathematical formulation of the problem or if a snow model is selected. After this, the dimensionless numbers can be found on the basis of dimensional analysis (Sedov, 1972).

Snow is a fairly complex material. Various models of snow are known today from which we may calculate its different properties depending upon the type of problem. For example, a model of incompressible viscous fluid is applicable to define flow or creep of snow along a slope (Grigoriian et al., 1967), or a model of heavy gas may be applicable for representing two-dimensional frontal impact of a snow mass against a two-dimensional obstacle (Shurova, 1968; Shurova and Iakimov, 1969; Shurova and Iakimov, 1970).

In the interaction of a natural avalanche with obstacles, the flow has a very complex nature. The probability of direct frontal impact is very low, and the process of non-steady-state flow of the snow mass becomes the primary process which determines the load. As computations show, these loads are considerably less than the loads occurring from direct frontal impact.

A model of flowing snow depends upon the acceleration of gravity, g, characteristic linear dimension, L, the snow velocity in front of the obstacle, v, and other parameters.

These parameters form the dimensionless Froude number,

$$Fr = \frac{v}{\sqrt{gL}}. \qquad [1]$$

In order for this number to be the same in nature and in the model, it is necessary to reduce the velocity, v, when decreasing the characteristic dimension, L.

Let us examine a class of snow models for which the velocity of the snow movement is determined only by the Froude number [1].

Model 1 is an ideal, incompressible fluid. Snow compressibility and shearing stresses are disregarded in this model. Then, the mean density, ρ_o, is also added to the number of determining parameters, g, L, and v. This model appears to describe fairly well the interaction of wet avalanches and mud flows (with a negligible content of stones) with an obstacle.

Model 2 is an ideal heavy gas representing a mixture of an incompressible component (ice crystals) and a compressible ideal gas (air). This model is studied in detail in papers (Shurova, 1968; Shurova and Iakimov, 1969; Shurova and Iakimov, 1970).

The relationship between the mean density and pressure has the form

$$\rho = \frac{1 + m}{\frac{mRT}{p} + \frac{1}{\rho_i}} \qquad [2]$$

where $m = \frac{M_a}{M_i}$ - the ratio of air mass to ice mass per unit volume; ρ_i is the density; R is the universal gas constant; T is the absolute temperature of air; p is the pressure.

For the state of the avalanche before impact we have

$$\rho_o = \frac{1 + m}{\frac{mRT}{p_o} + \frac{1}{\rho_i}} \qquad [3]$$

where p_o is the pressure before impact, which is near atmospheric, and ρ_o is the mean density of the snow-air mass before impact.

Eliminating m from expressions [2] and [3], we have

$$\rho = \frac{p}{p\,\dfrac{\rho_o RT - p_o}{\rho_o(\rho_i RT - p_o)} + \dfrac{(\rho_i - \rho_o)RTp_o}{\rho_o(\rho_i RT - p_o)}} \qquad [4]$$

Coefficients from equation [4], which are additional dimensionless numbers, are denoted by $A\rho_o$ and $\frac{B}{gL}$, where A and B are parameters. The explicit definition of each is defined as follows: Defining the equation of state for air as

$$p_o = \rho_{oa} RT \,. \qquad [5]$$

(where ρ_{oa} is the initial density), the first dimensionless number acquires the form

$$A\rho_o = \frac{1}{\dfrac{M_a}{\rho_{oa}} \cdot \dfrac{p_i}{M_i} + 1} = \frac{1}{\dfrac{\Omega_{oa}}{\Omega_i} + 1} \,. \qquad [6]$$

We note that this number depends only upon the relative volumes Ω_{oa} and Ω_i, taken as components, and does not depend upon their densities.

The second number has the form

$$\frac{B}{gL} = \frac{(\rho_i - \rho_o)RTp_o}{\rho_o(\rho_i RT - p_o)gL} = \frac{(\rho_i - \rho_o)p_o}{\rho_o \rho_i gL\left[1 - \dfrac{\rho_{oa}}{\rho_i}\right]} \cong \frac{(\rho_i - \rho_o)p_o}{\rho_o \rho_i gL} \,. \qquad [7]$$

This criterion can be met if either the initial pressure, p_o, (experiments on models are performed with reduced atmospheric pressure), or (which is apparently more convenient) the density of the ice component, ρ_i, is modified, consistent with change of the linear dimension, L. For example, increase in ρ_i in a model simulation may be attained by the addition of heavy particles (lead shot) to the snow.

This model can describe the impact of dry avalanches in which compression of the snow-air mass is significant.

Model 3 is a mixture of ideal fluids or gases of different densities or of solid bodies. It is a complicated variant of the preceding model and a number of criteria of the type

$$\frac{\rho_i}{\rho_o}, \quad \frac{d_i}{L} \,, \qquad [8]$$

are added to criterion [1], where ρ_i is the density of different fractions, and d_i are the characteristic linear dimensions of solid particles.

This model can describe the impact of (1) an avalanche containing snow and ice blocks, (2) rock moving in a powder avalanche, (3) loose snow, or (4) a mud flow.

Model 4, in an effort to further complicate the snow model, takes into account the presence of complex force interactions between various fractions contained in the avalanche. Let us assume that the force acting on the rigid fraction depends upon (1) the velocity of the particle with respect to the fluid phase, (2) the acceleration of the particle, (3) fluid density, (4) the characteristic linear dimensions, and (5) dimensionless coefficients. The last may include coefficients of particle resistance and interaction between masses. The velocity of the fluid phase is determined proceeding from the mean value of the forces per unit volume. In this case, to the already-described dimensionless numbers are added only dimensionless coefficients depending upon the shape of the particles.

Model 5. As a rule, in the flow of snow against an obstacle, a zone of more dense snow forms in front of the obstacle. In models 3 and 4, one may predict the formation mechanism of these zones, since movement of fluid and solid phases relative to each other is possible in these models, and, consequently, the solid phase can accumulate near the obstacle. These models should be supplemented by the assumption that if the concentration of a solid phase in a given zone reaches a certain critical value (for example, density near the density of ice), then further consideration of movement in this zone is removed.

Different mechanisms of interaction between solid particles, for example, resilient and non-resilient impacts, may also be predicted in these snow models.

If one assumes that snow, in its interaction with an obstacle, is described by any of the above mentioned models, then experiments for determination of obstacle load involve the following steps. A model of a structure or an obstacle is prepared which we want to test. This model is suspended on sensing devices which record the forces acting on the model. A model avalanche is dropped on the structural model, which satisfies the criteria of [1], [2],

[6], and [7]. Scaling of the forces to those acting on the natural structure are then determined according to the equation

$$F_N = F_m \left(\frac{L_N}{L_m}\right)^3 \left(\frac{\rho_{oN}}{\rho_{om}}\right) . \qquad [9]$$

where F_N and F_m are the forces acting in nature and on the model, respectively.

It is apparent that we have included almost all the snow models which have been conceived based on the mechanics of a continuous medium, if we compute the viscosity of separate components, μ_i, and the stable properties of ice and snow blocks, σ_i. The following additional dimensionless numbers will then appear:

$$\frac{\mu_1}{\rho g^{0.5} L^{1.5}} , \frac{\sigma_1}{\rho g L} . \qquad [10]$$

We see that the structure of these dimensionless numbers is such that in experiments with the same kind of snow and by increasing the linear dimension, L, the values of these numbers tends toward zero. Therefore, one may expect that if a fairly large L is used, then these numbers are unimportant. Experiments with models of various scales and with wet spring snow show that these numbers are insignificant if the characteristic linear dimension of a structure model is greater than 0.1 meters since scaling of the forces acting in nature from different models larger than 0.1 meters provides the exact same result. It is also apparent that these numbers are unimportant in the modeling of extremely loose, dry avalanches.

We have analyzed almost all types of snow models that are based on continuous medium mechanics, including models for which the appropriate mathematical equations are known and certain problems solved, and models for which there is still lacking a mathematical formulation, but or which certain mechanisms and determining parameters can be identified. However, by the use of experimental models, structural load estimates and a picture of avalanche movement near an obstacle can be determined independent of the mathematical description of an actual avalanche. In a variety of cases (wet avalanches, mud flows) the requirements for these experiments are easily fulfilled and amount to merely a proportional reduction of the velocity and modeling of the shape of the avalanche body prior to the impact provided that the characteristic size of the model is not less than 0.1 meters. Additional measures are needed in cases which involve fulfillment of criteria [2] and [7].

In all experimental modeling, lower velocities are needed which are selected according to criterion [1]. Besides velocity, the shape and structure of the avalanche body prior to the impact should be known. The appropriate shape and structure of the avalanche body prior to impact should be selected in experimental modeling in agreement with the criteria of [2] and [7].

At the present time, an installation for snow sample impact with a given structure is being tested at Moscow State University.

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The Soviet Avalanche Model - Exegesis and Reformulation

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Introduction

In the Soviet Union the modern study of avalanche dynamics was initiated by Margarita Ernestovna Eglit, whose pioneering paper is included in this collection of translations. It will be quoted here as "ref. 1". A condensed version of the Eglit's results (Grigorian et al., 1967) has been previously translated. A second paper presented here for the first time in translation (Bakhvalov and Eglit, 1970) gave the same theory in non-dimensional form and developed a computer procedure for its application. Here it will be referred to as "ref. 2". An expanded version of that paper appeared in the Soviet Academy of Sciences' Izvestiya series (Bakhvalov and Eglit, 1972) and exists also in an English translation.

Misprints and unstated arguments in these papers have made it desirable to attempt in the first place an exegesis, using in addition to Bakhvalov and Eglit (1970), the papers by and by Bakhvalov and Eglit (1972, ref. 3) and by Grigorian et al (1967, ref. 4). This part of our work was prepared by Misha Plam and Uwe Radok. The computer model developed by Bakhvalov and Eglit (1970, 1972) cannot be fully reconstructed and adequately described from the published information. It probably has historical interest only, in view of newer computer models now available, such as that of Brugnot and Pochat (1981). The algebraic solutions of the Soviet researchers, on the other hand, have remained unique in this field and therefore it seemed worthwhile to give their coherent and complete derivation. This part of our paper, prepared by Karl Taylor, constitutes Part II.

It must be emphasized that any claims to "exact" theoretical solutions in avalanche dynamics deserve a liberal sprinkling of salt. As has been pointed out by Mellor (1978, p. 776), the variations and complications of real avalanche situations (and especially the

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changes in mass properties with velocity) make it somewhat futile to seek a completely general solution to this dynamic problem. The solutions achieved by the Soviet workers should however be used for comparisons with those of others and, of course, with real avalanche data.

Part I. An exegesis of the Soviet avalanche model.

1. The dynamic problem.

We consider a wide (two-dimensional) avalanche moving down a slope of angle ψ and impacting a resting snow cover which is being entrained down to a depth h_0 with a leading-edge velocity w. Behind the leading edge the avalanche has the thickness $h(x')$ and the vertically averaged velocity $v(x')$; these quantities are to be determined. (Figure 1).

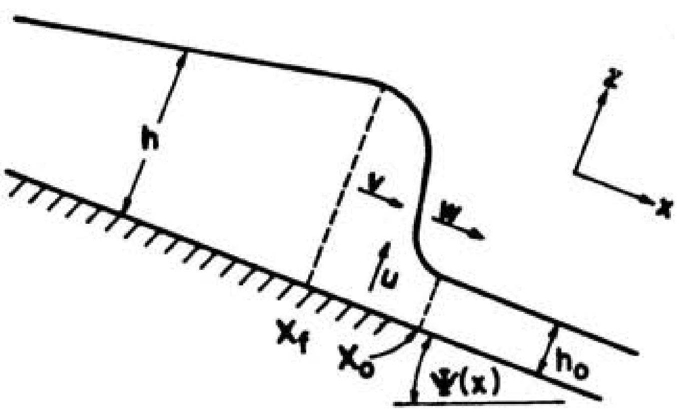

Figure 1. Symbols used in the avalanche equations.

Taking (for simplicity only) the density of the avalanche snow, ρ, to be the same as that of the undisturbed snow, ρ_0, the equations of motion and continuity are (ref. 3)

$$h\frac{\partial v}{\partial t} + h v\frac{\partial v}{\partial x'} = hf_1 - (g/k)v^2 - gh\frac{\partial h}{\partial x'}\cos\psi \qquad (1a)$$

$$\frac{\partial h}{\partial t} + \frac{\partial (hv)}{\partial x^1} = 0 \,. \qquad (1b)$$

For consistency equation (1a) has here been multiplied by h to make it relate, like (1b), to a vertical column of unit cross section area extending through the avalanche.

Interpretation:

i) hf_1 is the force of Coulomb friction which is independent of the velocity and assumed, following Voellmy (1955), to be proportional to the normal force:

$$hf_1 = hg(1 - \rho_{air}/\rho)\,(\sin\psi - \mu\cos\psi)\,.$$

ii) The second term on the r.h. side of equation (1a) is a hydrodynamic friction force of the form $F = C\,v^2$. Since all terms in (1a) have the dimension $[cm^2\ sec^{-2}]$ it can be seen that the factor k (nowhere explained in any of the Soviet papers) must be an acceleration: $[gv^2/k] = [cm/sec]^2$ or $[k] = [cm/sec^2]$. This shows that the usual friction factor C has been scaled in (1a) by the acceleration of gravity; ref. 3 uses the letter K for C, making K five hundred times as large as the k of the earlier paper.

iii) The final term on the r.h. side of (1a) is the slope-parallel component of the pressure gradient force per column mass, $(P/\rho)\cos\psi$ where P is the total pressure on a vertical plane of unit width and height h:

$$P = \frac{g\rho h}{2}h = \frac{g\rho h^2}{2}$$

$$\cos\psi\frac{\partial p}{\partial x'} = \rho g h\frac{\partial h}{\partial x'}\cos\psi$$

To complete the mathematical formulation the following boundary conditions are specified: at the line of rupture

$$v(0) = 0 \quad h(0) = 0 \; ;$$

At the leading edge of the avalanche, moving with a velocity $w \neq v$, conservation of mass and momentum requires that in steady state

$$\rho h(w-v) = \rho_o h_o w \tag{2a}$$

$$\rho_o h_o v w = (1/2)\rho g h \cos\psi - \sigma^* h_o \, . \tag{2b}$$

In ref. 4 the first term on the r.h. side of (2b) appeared in the somewhat more precise form

$$\frac{1}{2}\rho g(h^2 - h_o^2)\cos\psi = \rho g \, \frac{h + h_o}{2}\,(h - h_o)\cos\psi$$

which will be used here. The left hand side of (2b) is the extra momentum ($\rho_o h_o v$) which the undisturbed snow ahead of the avalanche requires to become part of it. σ^* is the (compressive) stress at which the snow pack ruptures; for a fluid this is the mean normal stress $g\rho_o h_o/2$.

2. Analytical solutions

The analytical solutions presented in refs. 1 and 3 (which elaborate on the treatment of ref.2) follow two different approaches. Both define a coordinate system (with abscissa now called x or s) moving with the avalanche leading edge. In ref. 1 the reformulated equations are used directly, whereas in refs. 2 and 3, they are transformed to become non-dimensional, using a "critical" velocity $v_{crit.} = (g h_o \cos\psi)^{1/2}$ as scaling parameter. This velocity corresponds to the velocity of sound in a gas and sets the limit to the rate at which density and other disturbances can be signaled ahead. It follows immediately from the conservation of mass continuity in the steady-state that

$$(h - h_o)w = hv$$

or

$$h(w - v) = h_o w = hu, \quad \text{say}$$

$$h_{cr}^2 u_{cr}^2 = h_o^2 w^2 = h_{cr}^2(g\, h_{cr} \cos\psi) = h_{cr}^3 g \cos\psi = h_o^3\, w^2 / h_o\,.$$

Hence the critical thickness in the body of the avalanche, $h_{cr}(x') = h_o w / u_{cr}$, is related to that of the undisturbed snow pack ahead of the avalanche by

$$h_{cr} = h_o (w^2 / h_o g \cos\psi)^{1/3}\,. \tag{3}$$

The first approach is then to establish a single equation for dh/dx and determine the ranges in which a solution h(x) is physically and mathematically realistic. This leads to formulae permitting the longitudinal profile, velocity distribution, and leading-edge velocity of the avalanche to be computed. The second approach is to use non-dimensional quantities (time, distance, velocity, thickness) in a discussion of asymptotic solutions which are approached after a long time of steady-state motion. Both approaches assume long slopes of constant inclination; that condition is later relaxed in the numerical version of the second approach.

2.1 Approach #1.

The first step is to rewrite equations (1) for the case of steady-state motion in a coordinate system moving with the constant speed w of the avalanche leading edge. In that system (abscissa $x = x' - wt$) the avalanche snow has the velocity $u = w - v$, and only the last term in the expansion $dv/dt = dw/dt - \partial u/\partial t - u\partial u/\partial x$ differs from zero. Hence in the steady state we get

$$-hu(du/dx) = -(hg/kh_o)\left[K_o^2 - \frac{h_o}{h}(w-u)^2\right] + gh\frac{dh}{dx}\cos\psi \tag{1a'}$$

$$uh = wh_o\,. \tag{1b'}$$

The Coulomb friction here has been replaced by $K_o^2 = h_o k f_1 / g$ in order to combine the two friction terms:

$$-hf_1 + (w-u)^2 g/k = -(hg)/(kh_o)[K_o^2 - (h_o/h)(w-u)^2] \ .$$

From (1') a single equation is derived for h. Since both h_o and w are constant

$$\frac{d(wh_o)}{dx} = \frac{d(hu)}{dx} = 0$$

$$\text{i.e. } hdu/dx = -udh/dx \ .$$

Thus,

$$-du/dx = -(u/h)dh/dx$$

and (1a') becomes

$$-u^2 dh/dx + hg\cos\psi dh/dx = (hg/kh_o)\left[K_o^2 - \frac{h_o}{h}(w-u)^2\right].$$

Next from (1b') $u = wh_o/h$, whence

$$(-w^2h_o^2/h^2 + hg\cos\psi)dh/dx = (hg/kh_o)\left[K_o^2 - \frac{h_o}{h}w^2\left(1-\frac{h_o}{h}\right)^2\right]$$

$$= -h\frac{w^2g}{k}\left[\frac{1}{h}\left(1-\frac{h_o}{h}\right)^2 - \frac{K_o^2}{h_o w^2}\right].$$

This is written finally as

$$F'(h)\frac{dh}{dx} = \frac{hgw^2}{k}\phi(h) \qquad (4)$$

with

$$F'(h) = hg\cos\psi - w^2h_o^2/h^2$$

$$\phi(h) = -\frac{1}{h}\left(1-\frac{h_o}{h}\right)^2 + \frac{K_o^2}{h_o w^2} \ .$$

Note: ref.1 uses $F(h) = F'(h)/h$.

The boundary condition for integrating (4), a first-order ordinary d.e. follows from equation (2) as rewritten for the moving coordinate system. Neglecting density differences and denoting $h(x=0)$ by h' and $u(x=0)$ by u'

$$h'u' = h_o w \tag{2a'}$$

$$h_o w(w - u') = (1/2)\, g(h'^2 - h_o^2)\cos\psi - \frac{\sigma^*}{\rho} h_o \,. \tag{2b'}$$

Elimination of $u'(= w\, h_o/h')$ from (2b') gives as boundary condition

$$(h' - h_o)\left[h'(h' + h_o) - \frac{2w^2 h_o}{g\cos\psi}\right] - \frac{2h_o h'}{\rho g \cos\psi}\sigma^* = 0 \,. \tag{5}$$

Ref. 4 discusses this equation in terms of the "critical" thickness and velocity (cf. Part II) but the equation can evidently be rendered more transparent, by bringing it to the form

$$h'^3 - h'h_o^2\left\{1 + \frac{2(w^2 + \sigma^*/\rho)}{c_o^2}\right\} + \frac{2w^2h_o^3}{c_o^2} = 0 \tag{5'}$$

where $c_o = (gh_o \cos\psi)^{1/2}$ is the critical velocity in the undisturbed snow.

Note that since $(w/c_o)^2 = (h'_{crit}/h_o)^3$ the last term is simply $2h'^3_{crit}$.

Equation (5') has the standard "reduced" cubic form:

$$y^3 - 3py + 2q = 0$$

where

$$-p = (h_o^2/3c_o^2)(c_o^2 + 2w^2 + 2\sigma^*/\rho) > 0$$

$$q = (w/c_o)^2\, h_o^3 = h'^3_{crit} > o$$

and $q^2 - p^3 < 0$ (since the bracket in p will be in general > 3). The roots of (5') are then those for the "casus irreducibilis" and can be written in terms of p and q as follows:

defining

$$\cos\varphi \equiv -q/(-p)^{3/2} = -\sqrt{27}\, c_o w^2\left[c_o^2 + 2w^2 + 2\sigma^*/\rho\right]^{-3/2}$$

the three real roots are

$$h'_1 = 2\sqrt{-p}\,\cos(\varphi/3)$$

$$h'_2 = 2\sqrt{-p}\,\cos(\varphi/3 + \pi/3)$$

$$h'_3 = 2\sqrt{-p}\,\cos(\varphi/3 - \pi/3)\,.$$

The main part of these roots is

$$(-p)^{1/2} = \left[h_o/c_o\sqrt{3}\right]\left[c_o^2 + 2(w^2 + \sigma^*/\rho)\right]^{1/2}$$

and they can be evaluated numerically, as a relationship between h' or w and the remaining parameters, which could be checked against observations.

Ref. 4 proceeds instead to discuss the possible solutions of (4) with the boundary condition (5) and the physical constraint that $h' > h'_{crit} > h_o$. Specifically the discussion turns on the condition

$$0 = dh/dx = (gw^2/k)\dot{\phi}/F \tag{6}$$

$$= -(gw^2/k)\frac{\frac{1}{h}(1 - h_o/h)^2 - K_o^2/h_o w^2}{g\cos\psi - w^2 h_o^2/h^3}\,.$$

The righthand side can be simplified as follows:

$$-\frac{gh^3}{k}\,\frac{(h_o/h)(1-h_o/h)^2 w^2 - K_o^2}{h_o g\cos\psi\, h^3 - w^2 h_o^3}$$

and since

$$h_o^3 w^2/c_o^2 = h'^3_{crit}$$

where

$$c_o^2 = gh_o\cos\psi$$

this becomes

$$-(g/k)\frac{h^3}{c_o^2}\,(h^3 - h'^3_{crit})^{-1}\left[\left(h_o^3 - 2h_o^2 h + h_o h^2\right)w^2/h^3 - K_o^2\right]. \tag{6'}$$

The zero gradients $dh/dx = 0$, therefore, are found from

$$\left(\frac{h_o^3 - 2h_o^2 h + h_o h^2}{h^3}\right)w^2 = K_o^2\,. \tag{7}$$

Ref. 1 does not show this development but simply states that three ranges can be distinguished according to the condition

$$4w^2 \gtreqless 27K_o^2 . \tag{8}$$

The equality sign implies that

$$h = 3h_o . \tag{9}$$

The origin and meaning of that condition will emerge from the non-dimensional analysis of the problem (see 2.2) below). Here we note furthermore that (6') corresponds to vertical asymptotes for dh/dx as $h \to h'_{crit}$.

The discussion of the full range of solutions that can be assumed by dh/dx for different w identifies several double-valued ones which are discarded (perhaps too readily) as physically unreal. Some of the remaining solutions imply specific parameter values and therefore cannot have general validity. In another group the relative velocity u is everywhere smaller than the critical velocity c_o in the undisturbed snow ahead of the avalanche, which, therefore, requires a driving force in addition to gravity. That leaves as a plausible solution only that with $4w^2 > 27K_o^2$ and the condition that (6') is valid for $h = h'_{crit}$. Using the zero-gradient condition found earlier,

$$w^2\left(h_o^3 - 2h_o^2 h'_{crit} + h_o h'^2_{crit}\right)/\, h'^3_{crit} = K_o^2 . \tag{10}$$

(Ref. 1 mistakenly makes the h' exponent in the denominator 2 instead of 3).

From (10) it is possible to derive explicit expressions for w and h'_{crit} in terms of h_o and $c_o = (gh_o \cos\psi)^{1/2}$, using the relationship

$$h'^3_{crit} = h_o^3 w^2 / c_o^2 .$$

Substitution in (7) gives

$$K_o^2 = c_o^2\left[(w^2/c_o^2)^{2/3} - 2(w^2/c_o^2)^{1/3} + 1\right] = c_o^2\left[\left(\frac{w^2}{c_o^2}\right)^{1/3} - 1\right]^2$$

$$\therefore\ w^2 = c_o^2\left(1 + \frac{K_o}{c_o}\right)^3$$

so that

$$w = c_o\sqrt{1 + K_o/c_o^3)}\,.$$

(The translation of ref. 4 erroneously makes this $w = c_o\sqrt{1 + (K_o/c_o)^3}$ but the correct form appears in the Russian paper and is used in refs. 2 and 3.) Next we find for the critical thickness

$$h'_{crit} = h_o\left[w^2/c_o^2\right]^{1/3} = h_o\left[1 + K_o/c_o\right].$$

These expressions can be checked by substitution in (7) and satisfy that equation (in contrast to the expressions in the translation of ref. 1).

The remainder of the paper deals with the corresponding avalanche profile $h(x)/h'_{crit}$ under stationary conditions and will not be discussed here further. We turn instead to the non-dimensional treatment which points the way to a numerical solution of the problem.

2.2 Approach #2: Non-dimensional analysis.

The model becomes more transparent when the different variables are cast into non-dimensional form using the critical velocity $c_o = (h_o g \cos\psi)^{1/2}$, h_o, and the Coulomb friction $f_1 = g(\sin\psi - \mu\cos\psi)$ as scaling parameters for:

time	$T = tf_1/c_o$
height	$H = h/h_o$
distance	$S = x'f_1/c_o^2$
snow velocity	$V = v/c_o$
avalanche front velocity	$W = w/c_o$.

Multiplication of equation (1a) by f_1^{-1} and equation (1b) by $c_o/h_o f_1$ gives their non-dimensional forms (assuming $\rho_{air} \ll \rho_{snow}$)

$$\frac{\partial V}{\partial T} + V\frac{\partial V}{\partial S} = 1 - \frac{\partial H}{\partial S} - \beta\frac{V^2}{H} \qquad (1a'')$$

$$\frac{\partial H}{\partial T} + V\frac{\partial H}{\partial S} + H\frac{\partial V}{\partial S} = 0 \qquad (1b'')$$

where

$$\beta = (g/k)g\cos\psi/f_1 = g/K(\tan\psi - \mu)^{-1} = c_o^2/K_o^2 .$$

Actually both refs. 2 and 3, without saying so, use the symbol k for what previously was called g/k. We shall here denote this by k'.

The corresponding transformation of the leading-edge boundary conditions (2a) and (2b) is achieved through division by c_o and c_o^2, respectively:

$$H(W - V) = W \tag{2a''}$$

$$WV = \frac{1}{2}\,\frac{1\rho h_o g h^2 \cos\psi}{\rho_o c_o^2 h_o^2} - \frac{\sigma^* h_o}{\rho_o c_o^2} = \frac{1}{2}H^2 - \alpha \tag{2b''}$$

where $\alpha = \sigma^*/\rho_o c_o^2$.

The first solutions sought are again asymptotic with a constant W and steady-state conditions in a coordinate system moving with velocity W. In order to obtain such solutions, ref. 3 argues that at some distance from the front the derivative terms on the lefthand side in equation (1a'') all are negligible in comparison to the terms on the righthand side, so that approximately

$$1 - \beta\frac{V^2}{H} \approx 0 . \tag{1a'''}$$

On the other hand, equation (1b'') consists entirely of derivative terms and cannot be simplified.

Ref. 3 next combines equation (1a '''), in which the derivative terms have been omitted, with (1b'') in which they are retained. With $H=\beta V^2$ and $HV=\beta V^3$ equation (1b'') becomes d.e.

$$\frac{\partial H}{\partial T} + \frac{\partial (HV)}{\partial S} = 2\beta V\frac{\partial V}{\partial T} + 3\beta V^2\frac{\partial V}{\partial S} = 0 \tag{1b'''}$$

or simply,

$$-\frac{\partial V}{\partial T} + \frac{3}{2}V\,\frac{\partial V}{\partial S} = 0$$

which implies that at the coordinate origin

$$-\frac{\partial S}{\partial T} = W = (3/2)V .$$

This implies, with (2a''), that $H = 3$, corresponding to the equality sign in Eq. (8) of ref. 3. The physical significance of that condition will be shown in Part II to be that it separates two regimes in the form of the transition from the interior of the avalanche to the avalanche front. For the moment we note that for consistency the substitution of (1a''') might also have been made in (1a''). This gives

$$\frac{\partial V}{\partial T} + \frac{V\partial V}{\partial S} + 2\beta V\frac{\partial V}{\partial S} = 0 \qquad \text{(1a.iv)}$$

which can be exactly reconciled with (1b''') by giving β a definite value, viz.

$$\beta = 1/4 .$$

This can also be written in the forms

$$f = 4k'g\cos\psi \quad \text{or} \quad \mu = \tan\psi' = -4k' + \tan\psi .$$

The approximation (1a''') is strictly valid for this special case only but is adequate more generally for the asymptotic solutions.

An alternative result is obtained by combining (1a''') with the boundary condition (2a''), $H(W - V) = W$ giving a standard-form cubic equation for $V' = (V + W/3)$, viz. $V'^3 - (W^2/3)V' - 2(W/3)^3 + W/\beta = 0$, equivalent to the dimensional form (5') above.

Ref. 3 also provides a fully valid combination of equations (1a'') and (1b'') in the form

$$\frac{dH}{dS} = \frac{H^3 - \beta W^2(1 - H)^2}{H^3 - W^2} . \qquad \text{(6''')}$$

This evidently should be equivalent to (6) or (6'):

$$\frac{dh}{dx} = -\frac{g}{k}\frac{h^3}{c_o^2}(h^3 - h'^3_{crit})^{-1}\left[\left(h_o^3 - 2h_o^2h + h^2h_o\right)w^2/h^3 - \frac{h_of_1}{g/k}\right]$$

where the last term defined the parameter K_o^2. To convert the left-hand side into the form dH/dX requires multiplication by c_o^2/h_of since $c_o^2 = h_og\cos\psi$, $H = h/h_o$ and

$X = S - WT = x'f_1 / c_o^2 - (w/c_o)\, tf_1/c_o$; also $k' = g/k$.

Moreover,

$$\beta = k' g \cos\psi / f_1$$

$$\therefore h_o f_1 / k' = c_o^2 / \beta .$$

Hence,

$$dH/dX = -\frac{\beta}{k'} k' \frac{h^3}{c_o^2} \frac{c_o^2 (h_o/h)^3 (1 - h/h_o)^2 - c_o^2/\beta}{h_o^3 \left[(h/h_o)^3 - (w/c_o)^2 \right]}$$

$$= -\frac{\beta W^2 (1-H)^2 + H^3}{H^3 - W^2} .$$

In addition the boundary conditions (2'') show directly that

$$H(X) = W/(W - V(X))$$

$$2W^2 \leq H(o) + H^2(o) .$$

These relationships are used in ref. 3 to group the possible asymptotic solutions of (6''') in ranges defined by $\beta \gtreqless \frac{1}{4}$. This will be discussed in Part II. Here we follow refs. 2 and 3 by disregarding next not the lefthand side of (1a'') but the righthand side and finding a numerical solution of the homogeneous form of (1'') (or its dimensional equivalent) which can describe the conditions both near the leading edge and at some distance from it.

3. A numerical solution

Ref. 2 mentions a numerical solution of equations (1) and quotes actual results obtained for slopes with constant curvature. The numerical results are claimed in ref. 3 to have reproduced some of the analytical results with 1 percent accuracy, but no detailed comparisons are shown. The numerical method was not described in ref. 2 and only a few hints to its nature are given in ref. 3.

The equations to be integrated have the form

$$\partial u/\partial t + v\frac{\partial U}{\partial s} = G\left[h, v^2, \psi, k'_1 \ldots\right] \qquad (14a)$$

$$\frac{\partial h}{\partial t} + v\frac{\partial h}{\partial s} + h\frac{\partial v}{\partial s} = 0\,. \qquad (14b)$$

The right hand side of (14a) is a complicated function of s containing in addition to the variables v and h the slope angle ψ. On the other hand, h, is not a variable on the left-hand side since the equation relates to a vertical column through the avalanche. The basic approach, presumably has been to solve the homogeneous equivalent of equations (14) and then use an iterative adjustment to satisfy (14a) more closely. In this way arbitrary slope profiles and even different assumptions regarding the friction parameters could be handled.

Writing next the homogeneous system in the form

$$U + \frac{\partial}{\partial S} F(U) = 0 \qquad (14')$$

where

$$U = \begin{Bmatrix} v \\ h \end{Bmatrix} \quad F(U) = \begin{Bmatrix} v^2/2 \\ hv \end{Bmatrix}.$$

it is clear that the Jacobian matrix

$$\left[\frac{\partial F_i}{\partial U_j}\right] = \begin{bmatrix} v & 0 \\ h & v \end{bmatrix} \equiv A(U)$$

is not a constant in this case. For this reason the two-step Lax-Wendroff algorithm then seems likely to have been used by the Soviet workers, on the grounds that it is strictly valid for a constant matrix and might work if its value were held constant for several time steps. This could be the meaning of the reference to a "principle of frozen coefficients" in ref. 3.

A further development that might have been made is the addition of pseudo-friction terms to smooth and stabilize any shocks that might arise. Lax and Wendroff (1960) showed that these should take the form

$$\frac{1}{8} A(\Delta s)^2 + A^2 \Delta t^2 \frac{\partial^3 U}{\partial s^3} + \frac{1}{8} A^2 \Delta t (\Delta s)^2 - (A\Delta t)^2 \frac{\partial^4 U}{\partial s^4} .$$

For further details see Richtmyer and Morton (1976), section 12.14. The pseudo-viscosity of the numerical scheme is hinted at in ref. 3, but there is no clear indication of whether or not the additional terms were used.

Ref. 3 did state the difference form of the v^2 term on the right hand side of equation (11a), viz.

$$(hv)^{n+1}_{j+1/2}(v^n_j + v^n_{j+1}) / h^n_j h^n_{j+1}$$

for the first step, and

$$(hv)^{n+1}_j v^n_j / h^n_j$$

for the second step of the Lax-Wendroff scheme. A "movable grid" with origin at the avalanche leading edge and constant grid spacing was used. The integration extended back to the break in the snow cover, and the leading-edge speed and height were found from the boundary conditions (2) and " a linear combination of equations (14) defining a characteristic entering the leading front of the avalanche" - i.e. solutions of equation (1b'''). The time interval was chosen to be two thirds of the maximum allowed by the stability condition of the process, $(u + c_o)\Delta t / \Delta s < 1$.

In this manner the results in tables 2 and 3 of ref. 2 were produced. Both tables give computed leading-edge velocities w as functions of the distance x and time t from the start of the avalanche. The results were obtained numerically for different slope angles ψ and values of $k_1, \mu, h_o, \frac{\sigma^*}{\rho_0}$, which in turn determine the parameters

$$\alpha = (\sigma^* / \rho_o) / c_o^2$$

$$\beta = (c_o / K_o)^2 = k'g \cos\psi / f_1 .$$

For comparison the asymptotic leading edge velocities w_a, obtained by substituting for $\left[K_o / c_o^2\right] = 1/\beta$ in the formula derived from equation (10), viz.:

$$w_a = c_0\sqrt{(1 + K_o/c_o)^3} = \sqrt{h_o g \cos\psi(1 + 1/\sqrt{\beta})^3}$$

are also given in the tables. Here we note merely that in one case the limiting condition $4w^2 = 27K_o^2 = \frac{27c_o^2}{\beta}$, giving $W_a = \sqrt{27/4\beta}$ was exactly realized; this evidently requires the special combination of parameters noted in section 3 for $\beta = 1/4$, so that in reality $w_a = 3^{3/2}c_o$ or alternatively

$$\frac{1}{2}\rho_o w_a^2 = 4.5 g\rho_o h_o \cos\psi\ .$$

This equates the kinetic energy acquired by the entrained snow to a certain multiple of the normal force - a mathematic relationship without clear physical content.

A numerical model makes it possible to examine the approach of the theoretical solutions and their asymptotic force. The Soviet model appears to be constrained to the theory by its use of characteristics for the calculation of the snow velocity near the leading edge of the avalanche. As a consequence, the numerical scheme must be expected to produce the theoretical results. A better use for numerical methods would be to solve directly the "primitive" equation (1) of the problem. This has been done more recently by Brugnot and Pochat (1981) and obviates the need for further probing into the obscurities of the numerical procedures used by the Soviet workers. On the other hand, their algebraic solution remains unique in the field and deserves a more coherent and complete exposition. Such an exposition has been prepared by Karl Taylor and is given in the second part of this paper.

Part II. A complete restatement of the Soviet avalanche model.

1. Dynamical equations

We consider a wide (two-dimensional) avalanche moving down a slope of angle ψ and impacting a resting snow cover of uniform depth. The depth h_o is the depth of snow that is entrained into the avalanche as it moves down the slope and will be presumed to be constant. The leading edge or avalanche "front" moves at speed w and behind the front, the avalanche has the thickness h(x,t) where x is the coordinate along the slope. The down-slope velocity $\left[v \equiv \frac{dx}{dt}\right]$, the normal velocity $\left[u \equiv \frac{dz}{dt}\right]$ and the density ρ of the snow are in general functions of position and time. Note that $w \geq v$ near the front because snow is continually being entrained into the avalanche ahead of its leading edge. This causes the front to move faster than the snow itself in the frontal zone.

The equations*) of motion for the avalanche may be written under the assumptions that:

1) The slope $\psi(x)$ is slowly varying so that the curvature effects are unimportant in most of the inertial terms. We shall retain only the centrifugal acceleration which, however, vanishes as the radius of curvature R of the slope increase (i.e., as the slope angle ψ approaches a constant).

2) The air density is much less than the snow density.

3) All variations perpendicular to the x–z plane are negligible (i.e., no variations are permitted across the avalanche).

The down-slope and normal components of the momentum equation and the continuity equation are:

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho v^2}{\partial x} + \frac{\partial \rho uv}{\partial z} = -\frac{\partial p}{\partial x} + \rho g \sin\psi - \frac{\partial \tau_x}{\partial z}, \tag{1}$$

$$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho uv}{\partial x} + \frac{\partial \rho u^2}{\partial z} + \frac{\rho v^2}{R} = -\frac{\partial p}{\partial z} - \rho g \cos\psi - \frac{\partial \tau_z}{\partial x}, \tag{2}$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial x} + \frac{\partial \rho u}{\partial z} = 0, \tag{3}$$

where ρ is density, p pressure, g the gravitational acceleration and τ_x and τ_z are the most important components of stress. The cross-slope component of the momentum equation is trivial since variations are neglected in this direction.

*) All equation numbers that follow refer exclusively to part II of the paper.

Along the upper interface between the avalanche and the air where the coordinate normal to the slope has the value $z = h$, a free surface boundary condition applies:

$$p = \text{const.} \quad \text{and} \quad \tau_x = 0 \, .$$

Along the base of the avalanche where $z = 0$, the velocity normal to the surface must vanish:

$$u = 0 \quad \text{and} \quad \tau_x = -\rho \frac{|\bar{v}|}{\bar{v}} \left[h\mu \cos\varphi + k'\bar{v}^2 \right] .$$

Two friction coefficients μ and k' appear above because we have assumed that the stress at the avalanche base is the sum of two components: a fixed component or "yield stress" and a viscous component. The viscous component is presumed to be proportional to the square of the avalanche velocity ($\bar{v}^2$) where the overbar indicates that the down-slope velocity has been averaged through the depth h of the avalanche. The static friction is assumed to be large enough to keep the undisturbed snow pack at rest. Once the snow begins to move, however, μ decreases to a smaller value associated with kinetic friction. It is the kinetic friction coefficient that applies throughout the avalanche except perhaps its leading edge.

To remove the details of the internal structure, (1)-(3) are now averaged through depth h. Defining

$$\bar{\zeta} = \frac{1}{h} \int_0^h \rho dz \, ,$$

$$\zeta' = \zeta - \bar{\zeta}$$

and representing the "hydrostatic defect" by

$$\bar{\varepsilon} = \bar{p} - (g \cos\psi - \bar{v}^2 / R) h^{-1} \int_0^h \int_z^h \rho \, dz' \, dz$$

$$= h^{-1} \int_0^h \int_z^h \left[\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u v}{\partial x} + \frac{\partial \rho u^2}{\partial z'} + \frac{\partial \tau_{x'}}{\partial x} + \frac{(\rho v^2 - \bar{\rho} \bar{v}^2)}{R} \right] dz' \, dz \, ,$$

we reduce (1)-(3) to

$$\frac{\partial \bar{\rho} \bar{v} h}{\partial t} + \frac{\partial \bar{\rho} \bar{v}^2 h}{\partial x} = -g \frac{\partial}{\partial x} \left[\cos\psi \int_0^h \int_z^h \rho \, dz' dz \right] - \frac{\partial}{\partial x} \left[\frac{\bar{\rho} \bar{v}^2 h^2}{2R} \right]$$

$$- \frac{\partial h\bar{\varepsilon}}{\partial x} + \bar{\rho} g h \left[\sin\psi - \mu \cos\psi \, \frac{\bar{v}}{|\bar{v}|} \right] - \bar{\rho}\, k' \, \bar{v} |\bar{v}| \tag{4}$$

$$\frac{\partial \bar{\rho} h}{\partial t} + \frac{\partial \bar{\rho} \bar{v} h}{\partial x} = 0 \tag{5}$$

where we have used all the boundary conditions given earlier.

To simplify the equations further we assume $\bar{\rho} = \rho_0$ = constant (uniform density) which reduces (4) and (5) to

$$\frac{\partial \bar{v} h}{\partial t} + \frac{\partial h \bar{v}^2}{\partial x} = - g \, \frac{\partial}{\partial x} \left[\cos\psi \, \frac{h^2}{2} \right] + hg \left[\sin\psi - \mu \cos\psi \right] \tag{6}$$

$$- k' \bar{v} |\bar{v}| - \frac{\partial}{\partial x} h \left[\frac{\bar{\varepsilon}}{\rho_o} + \bar{v}'^2 + \frac{\bar{v}^2}{R} \, \frac{h}{2} \right],$$

$$\frac{\partial h}{\partial t} + \frac{\partial h \bar{v}}{\partial x} = 0 \, . \tag{7}$$

Except for the last three terms in parenthesis in (6) (which are differentiated with respect to x), (6) and (7) are equivalent to Eqs. 1.1 of Ref. 3.

2. Equations for the avalanche front

The frontal equations are derived from (6) and (7) by integrating them with respect to x. We define $x_f(t)$ as a position somewhere behind the sharp gradients of the of the frontal region, and $x_0(t)$ as the position of the leading edge (where the snow is at rest but accelerating). (See Figure 2). These definitions of x_0 and x_f imply

$$v = 0 \, , \; h = h_0 \; \text{ at } \; x = x_0 \, ,$$

$$v = v_f \, , \; h = h_f \; \text{ at } \; x = x_f \, .$$

Defining the velocities,

$$w_f = \frac{dx_f}{dt} \qquad\qquad w_0 = \frac{dx_0}{dt}$$

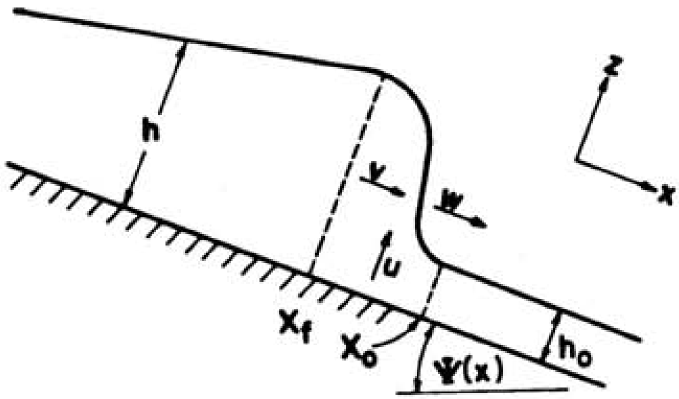

Figure 2. (Repeating Figure 1). Symbols used in the avalanche equations.

and integrating down the slope through the front, we find from (6) and (7)

$$\frac{\partial}{\partial t}\int_{x_f}^{x_0} h\bar{v}dx + h_f\bar{v}_f(w_f - \bar{v}_f) = g\cos\psi_f\,\frac{h_f^2}{2} - \frac{h_o\sigma^*}{\rho_0}\,, \tag{8}$$

$$\frac{\partial}{\partial t}\int_{x_f}^{x_0} h dx + h_f(w_f - \bar{v}_f) - h_0 w_0 = 0\,, \tag{9}$$

where

$$\frac{h_0\sigma^*}{\rho_0} = g\cos\psi_0\,\frac{h_0^2}{2} - \int_{x_f}^{x_0}\left[hg(\sin\psi - \mu\cos\psi) - k'\,\bar{v}|\bar{v}|\right]dx$$

$$- h_f\left[\frac{\bar{\varepsilon}_f}{\rho_o} + \overline{v'^2_f} + \frac{\bar{v}_f^2}{R}\,\frac{h_f}{2}\right].$$

It is not clear whether σ^* should be larger or smaller than $.5\,\rho_o\,g\cos\psi_o$ in the avalanche itself. In Ref. 3 it is argued that $\sigma^* = .5\,\rho_o g\cos\psi_o$ corresponds to a critical stress that is needed to keep the undisturbed snow ahead of the avalanche from immediately sliding down the slope like a liquid. But σ^* is a parameter that applies to the avalanche not the undisturbed snow. A distinction should be made between kinetic and static coefficients of friction.

If μ and k' are small enough in the frontal zone, then $\sigma^* < .5\rho_o g \cos\psi_o$ since the other terms contribute negatively to σ^*. (Note that the hydrostatic defect $\bar{\varepsilon}_f$ is probably positive and small.) In contrast to Ref. 3, then we shall not constrain σ^* in any way.

We proceed by imposing a steady state condition on the front and choose x_f such that $x_o - x_f$ = constant. Then $w_f = w_o$ and

$$\frac{\partial}{\partial t}\int_{x_f}^{x_0} h\bar{v}\, dx \to 0$$

$$\frac{\partial}{\partial t}\int_{x_f}^{x_0} h\, dx \to 0 .$$

The steady-state frontal equations can then be obtained directly from (8) and (9):

$$h_f(w_f - \bar{v}_f) = h_0 w_f \tag{10}$$

$$h_0 w_f \bar{v}_f = g\cos\psi\,\frac{h_f^2}{2} - \frac{h_0\sigma^*}{\rho_o} . \tag{11}$$

The equations are equivalent to eqs. 1.3 of Ref. 3 under the assumptions given above.

3. Non-dimensional equation

Further analysis is facilitated by recasting the equations in non-dimensional form. We assume in what follows that the slope is constant, $\psi = \psi_0$. Let

$$T = tf_1/c_0 \qquad S = xf_1/c_0^2 \qquad H = h/h_0$$

$$V = \bar{v}/c_0 \qquad W = w/c_0 \qquad c_0 = \left[h_0 g\cos\psi_0\right]^{1/2}$$

$$f_1 = g(\sin\psi_0 - \mu\cos\psi_0) \qquad \beta = k'\,(\tan\psi_0 - \mu)^{-1} \qquad \alpha = \frac{\sigma^*}{\rho_0 c_0^2}$$

$$\gamma = \left[\frac{\bar{\varepsilon}_f}{\rho_o} + \bar{v}'^2\right]\Big/\bar{v}^2 + \frac{h}{2R} .$$

The interior equations (6) and (7) (for the main body of the avalanche) become:

$$\frac{\partial HV}{\partial T} + \frac{\partial}{\partial S} H(1 + \gamma) V^2 = H - \frac{\partial}{\partial S} \frac{H^2}{2} - \beta |V| V \tag{12}$$

$$\frac{\partial H}{\partial T} + \frac{\partial HV}{\partial S} = 0 \,. \tag{13}$$

The steady-state equations for the front, (10) and (11), become:

$$V_f W_f = \frac{H_f^2}{2} - \alpha \tag{14}$$

$$H_f(W_f - V_f) = W_f \,. \tag{15}$$

Eliminating v_f from (14) and (15), we obtain

$$W_f^2 = \frac{\frac{1}{2} H_f^2 - \alpha}{1 - H_f^{-1}} \,. \tag{16}$$

Alternatively, elimination of W_f yields,

$$V_f^2 = (1 - H_f^{-1}) \left[\frac{1}{2} H_f^2 - \alpha \right] . \tag{17}$$

These expressions are useful as diagnostic equations for V_f and W_f if H_f is known. In Section 5 we shall show how H_f can be determined by connecting a solution for the avalanche interior with its leading edge (front).

4. Asymptotic solution for the avalanche interior

Away from the frontal region of the avalanche, (12) and (13) describe the motion. A consistent asymptotic solution can be obtained in which the gravitational acceleration is exactly balanced by frictional retardation. In the limit as $T \to \infty$,

$$H = B |V| V \tag{18}$$

and from the continuity equation,

$$V = \frac{2}{3} \frac{S}{T} \quad \text{as } T \to \infty. \tag{19}$$

5. Solutions in the "connecting" region

We have found relationships (16) and (17) that govern the frontal region. Three variables, (W_f, V_f and H_f) appear so that a complete determination of the frontal profile and speed is impossible using only these two equations. This should not be surprising since the front must be attached to the body of the avalanche. A complete asymptotic solution (for $T \to \infty$) can only be found when the solution at the front is matched to the solution for the avalanche interior through a connecting region. Figure 3 indicates schematically three possible profiles of the avalanche that will be of particular interest.

Region I in the figure is the body of the avalanche where the solutions discussed in Section 4 apply. The frontal region between S_f and S_0 is governed by the relationship given at the end of Section 3. In sections 6 and 7 we shall discuss solutions for the connecting region II.

The motion of the avalanche in the connecting region is governed by (12) and (13). The boundary conditions are that V and H at S_i and S_f should match solutions for the interior and the frontal region, respectively. The assumption is that both H and V are continuous except in the region between S_f and S_0. In general analytic solutions to (12) and (13) cannot be found. We shall consider here two special cases for which complete solutions can be obtained.

6. Discussion of case A

In the connecting region II we first seek solutions under the assumption that all derivatives vanish in the region (i.e., V and H are independent of S and T). Thus

$$H = H_f = H_i \tag{20}$$

and

$$V = V_f = V_i \,. \tag{21}$$

For this case (12) implies that in region II

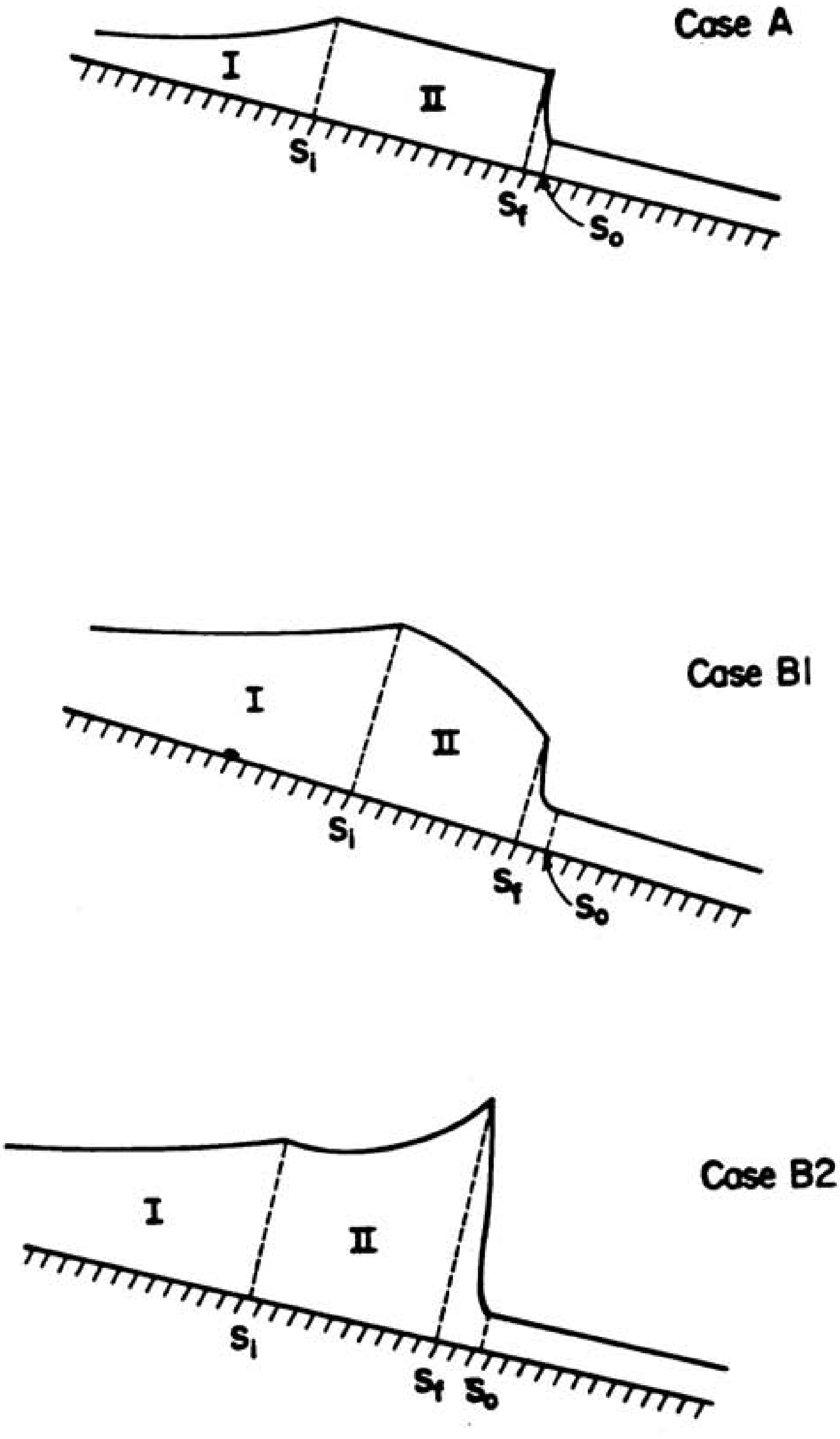

Figure 3. The three avalanche profiles for which solutions are given.

$$H = \beta V^2 . \tag{22}$$

The set of equations (20) - (22) and (17) can now be reduced to a single cubic equation that determines the height H in region II:

$$\frac{1}{2} H^3 - \left(\frac{1}{2} + \frac{1}{\beta}\right) H^2 - \alpha H + \alpha = 0 . \tag{23}$$

Once H is found, V is given by (22) and W_f is given by (16) with $H_f = H$.

The solution for case A is not complete until the velocity of the interface between the interior and the connecting region is determined by matching the velocity for region II with that of region I at this interface. Assuming that as $T \to \infty$ the interface velocity,

$$W_i \equiv \frac{dS_i}{dt}$$

approaches a constant, then we find according to the solution for the interior that

$$V_i = \frac{2}{3} \frac{S_i}{T} = \frac{2}{3} \frac{W_i T + S'_i}{T}$$

and in the limit as $T \to \infty$,

$$V_i = \frac{2}{3} W_i . \tag{24}$$

But from (21) we find

$$W_i = \frac{3}{2} V_i = \frac{3}{2} V = \frac{3}{2} \sqrt{H/\beta} \tag{25}$$

where H satisfies (23).

This completes the formal solution for case A, but only when α and β are in a certain parameter range are physically realizable solutions possible. It is clear that if $W_i > W_f$ the connecting region would grow smaller and smaller and eventually vanish. Thus for an asymptotic solution to exist as $T \to \infty$, the following condition must hold:

$$W_f \geq W_i > 0 \tag{26}$$

Eqs. (16), (20), (23) and (25) can be reduced to form the expression

$$\frac{W_f}{W_i} = \frac{\frac{2}{3}}{1 - H^{-1}}. \tag{27}$$

In order to satisfy (26) we require

$$1 < H \leq 3.$$

This in turn implies that according to (23),

$$\alpha \leq \frac{9}{2}(1 - \beta^{-1}).$$

Case A can be realized whenever α and β satisfy the above inequality. When the inequality is not satisfied, a different asymptotic solution must be found for region II.

7. Discussion of case B

For this case we simplify the system of equations by assuming that the width of the connecting region $(S_f - S_i)$ approaches a constant as $T \to \infty$. Unlike case A we no longer require H and V to be constants in region II. (See the figure given earlier showing the avalanche profile.) The assumption that the width of the connecting region is constant along with the steady-state assumption for the avalanche's interior solution imply that the height profile and velocity profile in region II remain invariant as the region propagates down the slope. The local change in height must then be equal to its "advective" change as the region moves down the slope at velocity $W = W_i = W_f$:

$$\frac{\partial H}{\partial t} = -W \frac{\partial H}{\partial S}. \tag{28}$$

This relationship and the continuity equation (13) imply that

$$\frac{\partial}{\partial S}(V - W)\,H = 0.$$

The constant of integration is determined by matching the values of V and H across the interface at S_f. According to (15),

$$(W - V)\,H = \text{const.} = (W_f - V_f)H_f = W_f\,.$$

and remembering that $W_f = W$, we find

$$V = W(1 - H^{-1}) \, . \tag{29}$$

Matching this solution with the interior solution given by (24), we obtain the depth H_1 of the avalanche at S_1:

$$H_1 = 3 \, .$$

According to (18) and (24), we also find that

$$V_1 = \sqrt{\frac{3}{\beta}}$$

$$W = W_1 = W_f = \frac{3}{2}\sqrt{\frac{3}{\beta}} \, . \tag{30}$$

The height profile throughout region II can now be found by reducing the momentum equation (12) to a simpler form using (28) and (29).

$$\frac{\partial H}{\partial S} = \frac{H^3 - \beta W^3 (H-1)^2 + W^2 H^2 \dfrac{\partial}{\partial S}\left[\dfrac{\gamma}{H}(H-1)^2\right]}{H^3 - W^2} \, .$$

If we assume γ is small (i.e. assume $(\bar{\varepsilon}_f/\rho_o + \overline{v'^2})/\bar{v}^2$ is small) and use (30) to eliminate W, then

$$\frac{\partial H}{\partial S} = \frac{H^3 - \dfrac{27}{4}(H-1)^2}{H^3 - H_S^3} = \frac{(H-3)^2\left[H - \dfrac{3}{4}\right]}{(H - H_S)(H^2 + HH_S + H_S^2)} \equiv F(H) \tag{31}$$

where

$$H_S^3 = \frac{27}{4\beta} \, . \tag{32}$$

The solution to (31) is obtained through direct integration of

$$S - S_1 = \int_{H_1}^{H} \frac{dH'}{F(H')}$$

but a complicated and unenlightening expression results.

It is instructive, however, to examine (31) which will provide a qualitative understanding of the nature of the solution. First we limit our discussion to cases where $H > 1$ since these are the only solutions of physical interest. We consider two cases (B1 and B2) distinguished by whether β is greater than or less than $\frac{1}{4}$.

For case B1 we assume $\beta < 1/4$. Then according to (32) $H_S > 3$. Recalling that at the uphill edge of region II the nondimensional depth H_l of the avalanche is 3, we conclude from (31) that $\frac{dH}{DS} \le 0$ throughout the region and that therefore

$$H_f \le 3.$$

Further analysis of (32) and (16) leads to the conclusion that for this case where we have assumed $\beta < \frac{1}{4}$,

$$\frac{9}{2}(1 - \beta^{-1}) < \alpha < \frac{1}{2}.$$

For case B2 we assume $\beta > \frac{1}{4}$ (i.e., $H_S < 3$) and a similar analysis leads to the conclusion that

$$H_f \ge 3$$

$$\alpha > \frac{27}{4\beta}\left[\left(\frac{\beta}{2}\right)^{1/3} - 1\right] > -\frac{27}{2}.$$

8. Concluding remarks

We have found asymptotic solutions for the motion of an avalanche. The avalanche profile depends on the parameters α and β. For $\beta < \frac{1}{4}$ the solution is given by case A if $\alpha \le 4.5\,(1 - \beta^{-1}) \le -13.5$ and by case B1 if $4.5\,(1 - \beta^{-1}) \le \alpha \le .5$. If $\beta > 1/4$, then the solution is given by case A if $\alpha \le 4.5\,(1 - \beta^{-1}) \le 4.5$ and by case B2 if $-13.5 \le 6.75\,\beta^{-1}\left[\left(\frac{\beta}{2}\right)^{1/3} - 1\right] \le \alpha$. We see that there are apparently two possible solutions if $\beta > \frac{1}{4}$ and

$6.75\,\beta^{-1}\left[\left(\frac{\beta}{2}\right)^{1/3} - 1\right] \le \alpha \le 4.5(1-\beta^{-1})$. We should note, however, that we have no guarantee that these solutions are stable or physically possible. In fact ref. 3 contains a discussion of this matter which indicates, for example, that case A may be unstable when $\beta < \frac{1}{4}$.

We conclude that although this approach to modeling avalanches is crude and the literature describing it unclear, the basic equations can be derived rigorously as has been done here. Future work could focus further on comparisons between the simple analytical solutions obtained and the more complete numerical avalanche models. In particular numerical codes could be checked by applying them to the simplified cases discussed here.

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Avalanche Bibliography Update: 1977-1983

Introduction

This bibliography updates that published in our first issue of Glaciological Data. The listing comprises references in all languages, including Russian, published between 1977 and the end of 1983.

We have attempted to be comprehensive by searching all of the relevant machine readable data bases. The major sources searched were:

Cold Regions Bibliography
Georef
Geoarchive
NTIS (U.S. National Technical Information Service)
Dissertation Abstracts
Compendex
Meteorological and Geoastrophysical Abstracts
Citation Data Base (WDC/NSIDC).

The bibliography is presented in two sections. The primary listing is alphabetical by first author. Each citation has also been assigned one specific subject heading. The second listing is an alphabetical sort by subject. A complete listing of the subject headings used is given on p. 198 . Because we do not have all of the original material in hand, we cannot be certain of the completeness of each citation although every effort possible has been made to ensure accuracy.

We would appreciate your comments on the bibliography - on citations we have not included, sources not searched, or subject areas that were not adequately covered. We hope to continue publishing updates to the avalanche biblopgraphy and your suggestions are welcome.

Ann M. Brennan
Compiler

SUBJECT HEADINGS

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NOTES

BOOK REVIEW

Hydrological Aspects of Alpine and High-Mountain Areas, edited by J.W. Glen, Publication No. 138, International Association of Hydrological Sciences, 1982, 350 pp. $30.00, softbound.

The spatial complexity of meteorological, hydrological, and glaciological phenomena in mountainous terrain and the temporal variability of the processes involved in them have up to now greatly limited the collection of relevant data and the modelling of mountain hydrological systems. The present work is a collection of papers from a symposium that attempted to address these questions. The meeting was organized by the International Commission on Snow and Ice and convened in Exeter, England, by E.F. Roots and J.W. Glen in July 1982.

The contributions are arranged in seven groups. The first four deal with general alpine hydrology, water storage in snow; water storage and drainage in glaciers, and water storage and release by snow. The last three sections concern alpine runoff processes - their modelling, specific basin studies, and finally erosion and sediment-transport. However, the allocation of papers into particular sections is rather inconsistent. For example, glacier hydrology topics occur in sections 1 and 6; runoff modelling is in section 5 but a related paper is in section 3, and snow cover mapping is disucssed in sections 2 and 4. I will concentrate on the glaciological contributions.

The problem of precipitation and runoff estimation in central Asian mountains is approached by Kotlyakov and Krenke viz glaciological methods - directly, through expedition data, and indirectly, through accumulation measurements, empirical relationships between summer temperature and accumulation/ablation at the equilibrium-line altitude, and through temperature coefficients of snow melt related to the transient snowline progression. Papers by Young and Makarevich deal with the estimation of the sources of runoff in glacierized basins. For the Peyto Glacier in the Canadian Rockies, the firn and ice components total only 20 percent; however, in dry years glacier and firn melt may increase substantially to compensate for the lack of snowmelt. A related study by Makarevich examines the runoff changes during a 5-year arid interval in the northern Tien Shan.

Other more specific glacier runoff studies appear in the final section of the book. These include a study for the western Tien Shan in China (Kang Ersi et al.); analysis of annual runoff variation in northwestern China, where the regimes are of a mixed glacier-fed and precipitation-derived runoff (Lai Zuming); and of the general glacier ablation-runoff relations in Western China (Yang Zhenniang). An important contribution to this section by Hewitt reports on glacier dam and outburst floods in the Karakoram, where evidence is found of 35 jokulhlaups since 1826.

Contributions in sections 2 and 3 attempt to describe and model water storage in snow and glaciers, baed on detailed site-specific studies. A conceptual model of seasonal snow-cover storage is developed by Rau and Herrmann and a meltwater model for a Norwegian glacierized basin is described by Lundquist. A model for ice ablation beneath debris, which is common in the Nepal Himalaya, for example, is presented by Nakawo and Takahashi.

Several papers deal with techniques for estimating water storage and runoff. Satellite analysis of snow cover depletion is shown to be a useful tool of widespread applicability, given sufficiently repetitive coverage (Rango and Martinec; Andersen; Tarar). Adyishin et al. report on the measurement of snow-water content using cosmic ray fluxes, while Martinec et al. use tritium anlayses to determine the snowmelt content of groundwater recharge. Another interesting group of papers make inter-model comparisons. Konavalov examines models to compute glacier melting in central Asia. Morris uses sets of test data from the Cairngorms and Alps to compare three procedures for estimating snowmelt available to users of the European Hydrological System. A WMO project to compare 11 models of snowmelt runoff is described; the results of this intercomparison should be of considerable practical value to developing countries.

The volume represents a useful supplement to existing hydrological texts that usually provide little detailed treatment of glacial hydrological processes. An especially valuable feature is the presentation of data on glacial hydrology in several parts of central Asia. It is recommended for hydrologists, glaciologists, and other scientists concerned with mountain processes, as well as the specialist libraries.

R.G. Barry
WDC-A for Glaciology (Snow and Ice)
and
Secretary of the International
Mountain Society

BOOK NOTES

The volume reviewed above is one of six that proceeded from the First Scientific Assembly of the International Association of Hydrological Sciences held at Exeter, U.K., 19-30 July 1982. The other volumes in the IAHS Exeter Assembly Proceedings are:

Advances in Hydrometry (IAHS Publication 134);
Optimal Allocation of Water Resources (IAHS Publication 135);
Improvement of Methods of Long Term Predition of Variations in Groundwater Resources and Regimes Due to Human Activity (IAHS Publication 136);
Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (IAHS Publication 137);
Effects of Waste Disposal on Groundwater and Surface Water (IAHS Publication 139).

All are available from the following addresses:

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Permafrost: Fourth International Conference, Proceedings is now available for $65.00 (U.S.) prepaid from the National Academy Press, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

The 1524-page volume contains 276 papers covering a wide range of engineering and scientific topics. These include roads, embankments, airfields, excavations, frost heave, ground ice, hydrology, ecology mapping, planetary permafrost, remote sensing, periglacial features, soil mechanics, pipelines, piles, terrestrial and subsea permafrost, and others. The volume was produced in conjunction with the Conference, which was held in Fairbanks, Alaska, in July 1983.

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GLACIOLOGICAL DATA SERIES

Glaciological Data, which supercedes Glaciological Notes, is published by the World Data Center-A for Glaciology (Snow and Ice) several times per year. It contains bibliographies, inventories, and survey reports relating to snow and ice data, specially prepared by the Center, as well as invited articles and brief, unsolicited statements on data sets, data collection and storage, methodology, and terminology in glaciology. Contributions are edited, but not refereed or copyrighted. There is a $5 shelf stock charge for back copies.

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The following issues have been published to date:

GD- 1, Avalanches, 1977

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GD- 4, Parts 1 and 2, Glaciological Field Stations, 1979, Out of Print

GD- 5, Workshop on Snow Cover and Sea Ice Data, 1979

GD- 6, Snow Cover, 1979

GD- 7, Inventory of Snow Cover and Sea Ice Data, 1979

GD- 8, Ice Cores, 1980, Out of Print

GD- 9, Great Lakes Ice, 1980, Out of Print

GD-10, Glaciology in China, 1981

GD-11 Snow Watch 1980, 1981

GD-12 Glacial Hydrology, 1982

GD-13 Workshop Proceedings: Radio Glaciology; Ice Sheet Modeling, 1982

GD-14 Permafrost Bibliography, 1978-1982, 1983

GD-15 Workshop on Antarctic Climate Data, 1984

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Barry, R.G., ed. (1984) Snow and Ice. Chapter 9, CODATA Directory of Data Sources for Science and Technology, E.F. Westrum, ed. New York, Pergamon Press. (CODATA Bulletin, no. 53, 87p.)

This chapter provides an overview of the principal agencies and institutions involved in glaciological data collection. It covers information relating to all forms of terrestrial snow and ice - snow cover, freshwater and sea ice, glaciers, ice sheets, and ground ice. The information was compiled from a survey distributed by the World Data Center A for Glaciology (Snow and Ice).

Individual copies of "Snow and Ice" are available for $10.00 (US) from: Pergamon Press, Inc., Maxwell House, Fairview Park, Elmsford, NY 10523 U.S.A.; Outside North America, inquiries or orders should be addressed to Pergamon Press, Ltd., Headington Hill Hall, Oxford OX3 OBW U.K.