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# AVALANCHE DYNAMICS:

## Engineering Applications for Land Use Planning



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Voellmy's (1955) avalanche dynamics equations are reviewed and combined with more recent findings of other workers. Equations are used to estimate flow heights, velocities, specific thrust pressure, maximum specific weight of avalanche debris, and runout distance for 12 avalanche case studies from the Colorado Rocky Mountains. Suggestions are made for using this engineering approach for avalanche zoning and land use planning.

**Keywords:** Avalanche dynamics, avalanche zoning, land use planning.

## PREFACE

The reader is cautioned against a "cookbook" use of the equations presented in this Paper. The theory of avalanche dynamics is still at a stage where a good deal of judgment and experience in avalanche matters are needed, especially in the selection of avalanche flow height and the two friction coefficients. During the calculations of avalanche motion and effects, constant checks should be made on the intermediate results to be sure they are reasonable. When they are available, field indications of flow heights or impact forces should be used as checks on the calculated values.

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## INTRODUCTION

### Concerns and Objectives

In this era of rapidly increasing recreation activity and intense resource development in snow-covered mountainous areas, careful planning to insure compatibility with natural processes is essential if tragic side effects are to be minimized. Although highways and railroads are typically most vulnerable to avalanche activity, the recent trend toward development of permanent housing in the runout zone of potentially devastating avalanches invites unprecedented disaster.

In the United States, when avalanche hazards were first recognized, the tendency was to consider explosive control. More recently, serious consideration has been given to structural solutions to the problem. In many cases, structural control is the only feasible alternative (USDA FS 1975). However, as with flood plains and other hazardous areas, there are important nonstructural alternatives that must also be considered. One of the best solutions, which by its very nature provides and insures opportunities for environmental quality and efficient land use, is that of regulating the use in avalanche areas. Zoning, subdivision regulations, building codes, and similar ordinances can be enacted which will: (1) provide for open space in critical avalanche-prone areas, and (2) require that if structures must be located in avalanche areas, they be designed to withstand the dynamic loadings imposed by avalanches. Recently enacted land use legislation in Colorado (Colorado, State of, 1974) designating avalanches and certain other natural hazards as "areas of State concern" should be a great aid in preventing major avalanche problems. Fortunately, there is still time in most of the mountainous areas of North America for the recognition and zoning of avalanche areas prior to large-scale development. However, the technical and legal guidelines to do this effectively are generally unavailable.

Two technical problems associated with land use planning in avalanche-prone areas are apparent. One has to do with forecasting avalanche occurrences, and the second deals with avalanche dynamics. Avalanche forecasting permits continued use of avalanche-prone areas with evacuation and control during periods of extreme hazard. An understanding of the dynamics of avalanches permits: (1) structures to be safely located outside the limits of the largest expected avalanches, and (2) determination of impact loads that must be withstood by existing and proposed structures in the avalanche path, such as high voltage transmission towers, bridges, or buildings.

The approach and equations offered here were first modified for use in avalanche problems from classic fluid dynamics principles by Voellmy (1955). Recent changes suggested by the work of Schaerer (1973, 1975a), Salm (1966), and Mears (1975, 1976, 1977) have expanded the original work without greatly changing the underlying concepts. The basic approach, although empirical in nature, is objective and therefore easily reexamined and modified as needed. It is felt that effective avalanche zoning requires an engineering approach for the determination of avalanche runout distances and impact forces. Part II demonstrates that reasonable values can be obtained for these parameters with proper field data and equation coefficients. For zoning purposes, the first job is to identify and delineate areas of potential avalanche danger (Rogers et al. 1974, Mears 1977). Next, avalanche danger within these areas must be quantified, preferably by some objective method. Finally, the degrees of acceptable risks must be determined by consensus of the population and the local government agencies.

The objective of this report is to outline methods whereby our status of knowledge in avalanche dynamics can be used to provide a unified engineering approach from which guidelines can be developed for quantifying avalanche hazards.

## Our Approach

### Avalanche Dynamics

Part I of this report is a review of our status of knowledge of avalanche dynamics. It is not a detailed discussion of the theory, but rather, a systematic compilation of equations which, despite the limited scientific data available, appear to be adequate for engineering applications. It is based primarily on work by Voellmy (1955), who made a rigorous analysis based on observations of structural damage immediately after avalanche occurrences in Austria. Since Voellmy's work, other studies have confirmed his approach and have improved his equations. Much work is still needed, however, on the theoretical background of avalanche dynamics.

In the authors' opinion, this review is a realistic appraisal of the engineering tools available to help solve avalanche problems. These tools reduce complex avalanche phenomena to a predictable pattern of dimensions, forces, densities, and speeds that account for the release of snow in the starting zone, its concentration in the track, and its ultimate deposition in the runout zone.

The equations are mostly for large avalanches that run on unconfined slopes. Channelization of the avalanche leads to greater flow depths, greater velocities, and longer runout distances. Channelization can usually be handled by adjusting the flow height or by continuity calculations using the hydraulic radius and hydraulic depth.

### Field Verification

Many of the equations in Part I have been formulated into a computerized model that simulates the major components of avalanche dynamics. However, *because any engineering system must be formulated with a certain amount of empiricism, field calibration is extremely important in order to build confidence in its use.* The system was calibrated against published compilations of field data (Frutiger 1964, Gallagher 1967, Williams 1975) and unpublished observations.

This work, presented as Part II, accomplishes two things. First, it provides preliminary illustrations of procedures for avalanche analyses. Secondly, it focuses on the need for systematic compilation of field data on: (1) flow and frictional resistance of avalanches under a variety of conditions; (2) runout distances; (3) extent, character, and amount of debris in the runout; (4) longitudinal profiles; and (5) fracture heights or some other estimate of average slab thickness.

# PART I. AVALANCHE DYNAMICS

## Recognition of Avalanche Areas

No single group of terrain features characterizes avalanche-prone areas (Martinelli 1974). Hazardous areas vary from deeply incised gullies to broad, uniform slopes. They may be in steep terrain or on slopes with gradients less than 30 degrees. A useful indicator of avalanche activity in forested areas is the absence of trees in conspicuous strips oriented perpendicular to the contours. However, the presence of forest cover does not preclude avalanche activity. Many avalanches occur in scattered timber. Above timberline, such features as large cornices, well-defined cirques, and steep topography are potential contributors to avalanche activity.

## Avalanche Types and Classification

The dynamics of avalanches is determined by many interrelated factors, including the type and amount of snow, manner of deposition, and topography. Accordingly, an understanding of basic avalanche types is a prerequisite to any theoretical analysis of avalanche motion. Detailed discussions of avalanche types and their classification are available elsewhere (Mellor 1968, de Quervain et al. 1973, Perla and Martinelli 1976).

It is important to differentiate several types of avalanche motion. In *powder avalanches,* most of the snow swirls through the air as a snow dust cloud. In *flowing avalanches,* most of the snow moves in a turbulent, tumbling motion near the ground. In *mixed-motion avalanches,* the snow moves in a combination of these two types of motion. Large blocks and particles bounce and tumble along the ground; smaller particles are airborne. *Flowing* and *mixed-motion* avalanches may be either dry or wet, depending on moisture conditions in the snow. Also, they may run on a snow layer, or they may penetrate through the pack and run on the ground. The former are called *surface avalanches;* the latter *full-depth avalanches.*

## Fluid Analogy for Avalanche Motion

Flowing snow usually behaves much like a fluid. In reality, the avalanche medium consists of fine grains or clumps of snow which move by a combination of saltation and suspension. The most logical analogy is to assume that the principles of fluid mechanics apply, however, so that the concepts of conservation of mass, momentum, and energy can be used to study avalanche motion. This fluid analogy of avalanche dynamics has been more or less substantiated several times through study of density currents (Shen and Roper 1970, Tochon-Danguy and Hopfinger 1975). Also, Losev (1969) argued that the motion of an avalanche should not be treated like that of a solid body. Although some will argue that slab avalanches are an exception to this concept, subsequent equations will show that, once the snow gives way, speeds are sufficient to disintegrate much of the slablike structure, thus transforming the avalanche into fluidlike motion.

Moskalev's (1966) review of avalanche mechanics indicates that the study of avalanche dynamics may have originated in Russia in the 1930's. Although this work was known in some European circles, avalanche dynamics was also studied independently in Western Europe and Japan.

The most comprehensive and far-reaching treatment of avalanche dynamics is the outstanding paper by Voellmy (1955), "Über die Zerstörungskraft von Lawinen." It presents a rigorous analysis based on intensive observations of structural damage immediately after avalanches in Austria.

In the authors' opinion, Voellmy developed the most acceptable and unified approach to the solution of avalanche dynamics problems. Accordingly, this review is essentially a summary of Voellmy's work, with some minor revisions and refinements where subsequent research has improved the original equations.

Mears (1975) pointed out, however, that the assumptions required for the use of Voellmy's equa-

tions—the two friction coefficients, $\xi$ and $\mu$, and flow height, h′, discussed subsequently in this report—make it desirable to seek any field evidence of impact force or flow height to use as a check on computations.

## Fluid Properties

Calculations required in the study of the dynamics of avalanches bring up important questions about snow properties. Because flowing snow is assumed to behave as a fluid, definite distinctions must be maintained between *weight, force,* and *mass*, and between *specific weight* and *density.*

The properties of fluids are discussed in various textbooks (Binder 1955, Ference et al. 1956, Streeter 1958, Albertson et al. 1960). However, these important concepts are also discussed in appendix A, because they are essential for a clear understanding of avalanche phenomena.

## Avalanche Velocity and Flow Height

Mellor (1968) has shown that the flow of developed avalanches is decidedly turbulent, with Reynold's numbers (Re) of $10^9$ to $10^{10}$ for mean downslope velocities of between 10 and 100 meters per second (m/s). Accordingly, viscosity is an unimportant flow parameter in virtually all avalanche situations.

The velocity equations derived by Voellmy (1955) are based primarily on the assumptions of uniform open-channel flow (Chow 1959). Similar equations can also be developed using the principles of fluid resistance (Albertson et al. 1960). Shen and Roper (1970) found that Voellmy's velocity equation for powder avalanches conforms with experimental results obtained from density current studies, and that Voellmy's suggested value for the turbulent friction coefficient ($\xi$) of 400 to 600 m/s$^2$ will give a reasonable estimate of the terminal velocity of a powder avalanche flowing over a hydrodynamically smooth boundary. For engineering design, however, they proposed $\xi = 750$. More recent work (Schaerer 1975a) indicates that $\xi$ may be as high as 1800 for an avalanche moving over a smooth snow cover with no trees.

It should be emphasized that, because Voellmy's turbulent friction coefficient ($\xi$) is not a fixed value, selecting the proper value of $\xi$ requires a basic knowledge of several factors. Voellmy's turbulent friction coefficient can be related to roughness factors which affect the flow of water in open channels. These factors include the Chézy coefficient (C) and Manning's roughness coefficient (n). The factors that exert the greatest influence on Manning's n are well described by Chow (1959):

Surface roughness
Vegetation
Channel irregularity
Channel alinement and slope
Channel stability
Obstructions
Size and shape of channel
Stage and discharge
Suspended material and bedload

At the present state of knowledge, the selection of a correct value of $\xi$ involves several intangibles; thus estimates should be tempered by engineering judgment and experience. Although theoretical studies on the mechanics of open-channel flow have not yet completely explained problems (Chow 1959), these studies have shown that it is possible to interpret the empirical roughness coefficients by means of theoretical equations for uniform flow. In practice, however, even for open-channel flow in large rivers, experience and judgment are most often used rather than theoretical equations which, at best, require some difficult assumptions.

### Velocity

Several investigators have developed equations for the maximum velocity of an avalanche (Voellmy 1955, Salm 1966, Mellor 1968, Shen and Roper 1970). All of these equations are similar in spite of the fact that different approaches were used for solving the problem. The basic form of the equation for flowing avalanches is:

$$V^2_{max} = \xi h' (1 - \gamma_a/\gamma)(\sin\psi - \mu\cos\psi) \qquad [1]$$

where

$V_{max}$ = the terminal velocity, in m/s,

$\xi$ = the coefficient of turbulent friction, in m/s²,

$h'$ = the vertically measured height of flow of the avalanche, in meters,

$\gamma_a$ = the specific weight of air (approx. 1.25 kg/m³, at sea level, or 1.0 at most avalanche sites),

$\gamma$ = the specific weight of the flowing snow, in kg/m³,

$\psi$ = slope of the avalanche path, in degrees, and

$\mu$ = the coefficient of friction of motion (kinetic friction).

Equation [1] assumes: (1) no correlation between kinetic friction and speed, (2) constant avalanche mass,[3] and (3) uniform incline of the path. Voellmy assumed that the kinetic friction term ($\mu$) varied from $\gamma/1000$ to $\gamma/2000$; however, recent work by Schaerer (1975a) has shown that $\mu$ has a significant effect on avalanche speeds less than 50 m/s. This dependence can be expressed as:

$$\mu = \frac{\omega}{V_{max}} \qquad \mu \leq 0.5 \qquad [1a]$$

[3]*Perhaps one of the most obvious criticisms leveled at this assumption is that, in reality, the mass increases when an avalanche overrides snow in the track. This growth can be longitudinal, lateral, or both, depending on snow and boundary conditions. Quantification of the change in mass with distance is extremely difficult. Mellor (1968) and Moskalev (1966) derived rather complex equations, which Mellor was careful to point out: "afford little insight into the effects of the entrainment" without better definition of the relative magnitudes of the constants. In discussing nomographs based on highly detailed analyses which also took entrainment into consideration, Moskalev (1966) stated that: "the motion of avalanches is determined by rather numerous factors, most of which cannot be taken into account with satisfactory accuracy. In the computations it always is necessary to make a number of assumptions and their final result to a certain degree is conditional. Therefore, theoretically more rigorous, but complex formulas do not always have an advantage over simpler ones."*

where $\omega$ = a parameter which Schaerer found to be 5 m/s. Schaerer suggests that $\mu = 0.5$ is an upper limit for slow-moving avalanches. Although eq. [1a] is based on limited data, it provides an objective estimate of $\mu$ and is used in subsequent equations for terminal velocity in this report. When calculating runout distance, however, it is often informative to use several values of $\mu$ to get an idea of the range of runout distances to be expected with different snow conditions. For normal snow conditions, $\mu$ varies from 0.15 to 0.20 in the upper part of the runout zone, to 0.5 at the end. For very wet or powder avalanches, 0.1 may be a better value.

If the velocity dependence of kinetic friction is included, eq. [1] can be rewritten as:

$$V^2_{max} = \xi h' (1 - \gamma_a/\gamma)\left(\sin\psi - \frac{5}{V_{max}}\cos\psi\right) \qquad [1b]$$

Schaerer's work has confirmed that eq. [1], first suggested by Voellmy (1955), is adequate for determining the speeds of fully developed flowing avalanches. He points out that in addition to $\mu$ the mean velocity is a function of the turbulent friction coefficient ($\xi$), which depends on the condition of the avalanche track. Based on field observations, Schaerer (1975b) suggests the following values of $\xi$:

| | |
|---|---|
| Smooth snow cover, no trees | 1200-1800 m/s² |
| Average, open mountain slope | 500-750 m/s² |
| Average gully | 400-600 m/s² |
| Slope with boulders, trees, forests | 150-300 m/s² |

These values bracket the 500 m/s² suggested by Voellmy (1955) and the 750 m/s² proposed by Shen and Roper (1970).

The theoretical equations for uniform flow indicate that the mean velocity may be strongly dependent upon the shape of the channel. Accordingly, Voellmy's velocity equation [eq. 1], which was derived for unconfined slopes, can be modified for other cross sections to:

$$V^2_{max} = \xi(1 - \gamma_a/\gamma)\left[R\sin\psi - \frac{5}{V_{max}} D\cos\psi\right] \qquad [2]$$

in which

R = the hydraulic radius (A/P*), in meters, and

D = the hydraulic depth (A/T*), in meters,

where

A = cross-sectional area, in $m^2$,

P* = "wetted" perimeter, in meters, and

T* = top width, in meters.

The hydraulic radius and hydraulic depth can be expressed in terms of the avalanche flow height (h′) for various cross sections. Chow (1959) summarizes formulas for computing the properties of several geometric shapes. For complex natural channels, R and D can be computed from field measurements. It should be noted that, for a very wide channel (width approximately 10 times greater than flow depth), $h' \cong R$ and $h' \cong D$ and eq. [2] reduces to eq. [1b] for the rectangular and trapezoidal sections.

Voellmy found that an avalanche reaches 80 percent of its terminal velocity when it has traveled the distance $s_t$ and that:

$$s_t = 0.5\, \xi h'/g \qquad [3]$$

where

$s_t$ = the distance required for an avalanche to reach 80 percent of terminal velocity, and

g = the acceleration of gravity (approx. 10 $m/s^2$).

When the hydraulic radius, (R) is substituted, eq. [3] results in the expression:

$$s_t = 0.5\, \xi R/g \qquad [4]$$

Moreover, if $\xi$ is 500 $m/s^2$ as suggested by Voellmy:

$$s_t = 25R \qquad [5]$$

where R varies according to channel cross section. The practical significance of eqs. [3] and [5] is that terminal velocity is reached after very short initial distances. Therefore, as Voellmy points out, defense structures in the starting zone can often be subjected to loadings imposed by sliding snow rather than from creep pressure.

Equation [2] can be reduced to the familiar Chézy steady flow formula for open channels if $\gamma_a/\gamma$ and $\mu$ are neglected. In this case, the Chézy resistance coefficient, $C = \xi^{1/2}$ and $\sin \psi \cong \tan \psi = S$. Thus:

$$V = C\sqrt{RS} \qquad [6]$$

Equation [6] has significant practical value since it can be correlated with parameters easily measured in the field. Because R is some function of h′ (h′ = R for wide channels), the maximum velocity is a parabolic function of vertical fracture height in the starting zone. Powder and flowing avalanches often involve only the new snow; full-depth avalanches, on the other hand, usually fracture to the ground.

In eq. [6], Voellmy has shown when:

$S > g/\xi + \mu$ : flow is supercritical,[4]

$S < g/\xi + \mu$ : flow is subcritical.

Salm (1966) has taken issue with the concept of supercritical flow in dense (slab) avalanches, arguing that there can be no propagation of surface waves. However, Mellor (1968) showed that the flow is supercritical for both slab and powder avalanches, using data originally published by Voellmy. Voellmy suggested that for $\xi$ = 500 $m/s^2$, supercritical flow can theoretically occur on any gradient greater than approximately 2 percent. He also suggested that the Chézy coefficient (in metric units) varies between 20 and 25, which corresponds to a turbulent friction coefficient ($\xi$) between 400 and 600. Since the velocity of frictionless motion can never be exceeded, it can be shown that $\xi$ cannot exceed the upper boundary value:

$$\xi \leq (2gs)/R$$

where $s \geq s_t$ is given by eq. [4].

According to Voellmy (1955) "as a rule, the entire motion process of avalanches need not be studied in view of the short starting distances of avalanches . . ."; hence, $V_{max} \cong V$ for practical applications.

It might be helpful at this point to show the general relationship between the Chézy coefficient (C), Manning's roughness coefficient (n), and Voellmy's turbulent friction coefficient ($\xi$), since

[4] *Voellmy called subcritical flow "streaming flow" and supercritical flow "shooting flow."*

many engineers are familiar with the first two. Chow (1959) shows that, in metric units:

$$C = \frac{1}{n} R^{1/6} \qquad [7]$$

where R is hydraulic radius. If the density terms, $\gamma_a/\gamma$, and the internal friction term, $\mu$, are ignored in equation [1] for avalanche velocity (V), it becomes:

$$V = \sqrt{\xi h' \text{ (slope term)}}$$

where h′ is flow height, and equal to hydraulic radius (R) for broad slopes. This is the same form as the familiar Chézy formula (see Eq. 6) for uniform flow in open channels:

$$V = C\sqrt{RS}$$

where R is hydraulic radius, V is velocity, and S is a slope term. Thus C is proportional to $\sqrt{\xi}$. If we allow $C = \sqrt{\xi}$ and substitute in equation [7], it becomes:

$$n = \frac{R^{1/6}}{\sqrt{\xi}}$$

From this equation, values of n as a function of $\xi$ and R can be computed (table 1).

**Table 1.—Comparison of Manning's n and Voellmy's $\xi$ for R equal to 1, 2, and 3 m. (Natural streams normally have n values of 0.02 to 0.08.)**

| | Values of n for R equal to: | | |
|---|---|---|---|
| $\xi$ | 1 m | 2 m | 3 m |
| 150 | 0.082 | 0.092 | 0.098 |
| 300 | .058 | .065 | .069 |
| 400 | .050 | .056 | .060 |
| 500 | .045 | .051 | .054 |
| 600 | .041 | .046 | .049 |
| 750 | .037 | .041 | .044 |
| 1000 | .032 | .035 | .038 |
| 1200 | .029 | .032 | .035 |
| 1500 | .026 | .029 | .031 |
| 1800 | .024 | .026 | .028 |
| 2000 | .022 | .025 | .027 |
| 2500 | .020 | .022 | .024 |
| 3000 | .018 | .020 | .022 |

## Flow Height

Flow height (h′) is dependent on type of avalanche motion and fracture depth. Three types of motion—flowing, mixed motion, and powder—and one fracture depth—full depth—are considered.

**Flowing Avalanches.**—In flowing avalanches, the height of the sliding snow layer remains constant for a relatively long time. In this case, $\gamma_a/\gamma$ in eq. [2] can be neglected, and the velocity is computed by:

$$V^2 = \xi \left[R \sin\psi - \frac{5}{V} D \cos\psi\right] \qquad [8]$$

Voellmy (1955), Mellor (1968), and Losev (1969) all agree that, after exceeding a velocity of about 10 m/s, blocks of sliding snow are disintegrated. As the result of turbulent flow and dry conditions, the snow in flowing avalanches gradually becomes suspended. However, on slopes that exceed 30°, in cold, dry weather, a flowing avalanche may assume the characteristics of a powder avalanche with considerably higher velocity and destructive potential. The determination of flow height requires considerable experience. According to Voellmy, the height of flow (h′) for flowing avalanches is approximately the same as the vertically measured fracture height of the snow in the starting zone (h). In situations where there is considerable new snow in the track, h′ should be increased to account for accretion of avalanche mass.

In the *flowing avalanche,* the specific weight of the flowing snow ($\gamma$) is equal to the average specific weight of the natural snow cover ($\gamma_0$).

**Mixed-Motion Avalanches.**—Field observations indicate this is the most common type of avalanche motion. The same equations should be used for mixed-motion as for flowing avalanches. Schaerer (1975a) concluded flow height just above the runout zone was directly related to average depth of the debris. For example, $h' = 4\ h_D$ for the dense flowing part of this type of avalanche, where $h_D$ is the average depth of the avalanche debris in meters. In this case, the debris was spread over a wide front with little variation in depth. Earlier he had observed (Schaerer 1973) the specific weight of the flowing snow in mixed-motion avalanches to be approximately 30 percent of the specific weight of the deposited snow.

**Powder Avalanches.**—Powder avalanches are produced by cold, dry snow which is whirled up into an aerosol as it travels downslope. Naturally deposited snow in the channel can be completely or partially carried along in the turbulent flow. As discussed below, the amount of snow in the avalanche track can have a significant effect on the dynamics of powder avalanches.

Voellmy indicates that air entrainment of snow particles is possible as long as the avalanche velocity is greater than about twice the particle fall velocity, which is in the neighborhood of 1 or 2 m/s. On slopes of more than about 30°, powder avalanches can form from slabs or loosened snow after the velocity exceeds 15 to 20 m/s.

For powder avalanches, the terminal velocity conforms to eq. [2] with:

$$h' = (\gamma_0/\gamma)(h + h_a) \qquad [9]$$

where

$h_a$ = the height (in meters) of the natural layer of snow lying in front of and under the avalanche, and which is whirled up by the avalanche.

Few observations of the flow height (h′) of true powder avalanches are available, however.

With a densely packed or crusted snowpack, $h_a$ in eq. [9] = 0. In many cases, $h_a = h$ if the natural snow cover in the avalanche channel consists of dry powder. Powder avalanches can form when the specific weight of freshly deposited snow cover is less than approximately 150 kg/m³.

Voellmy determined that at terminal velocity:

$$\gamma = \frac{\gamma_a \xi}{2g} \sin \psi \qquad [10]$$

which can be considered as a first approximation of the specific weight of the flowing snow.

Assuming that $\gamma_a/\gamma$ and $\mu$ are negligible in eq. [1], and substituting eqs. [9] and [10] results in the expression:

$$V^2 = 2g(h + h_a)\gamma_0/\gamma_a \qquad [11]$$

for a wide channel ($h' \cong R$). Eq. [11] states that "if the slope inclination permits a disintegration of the snow, the velocity of powder avalanches is actually not dependent upon the slope inclination . . ." (Voellmy 1955). This result has been validated by field observations (fig. 1), and applies only to high-speed powder avalanches.

**Full-Depth Avalanches.**—Avalanches of compacted or wet or damp snow whose particles are held together by the surface tension of the free water content do not produce significant snow dust clouds. In such avalanches, the movement

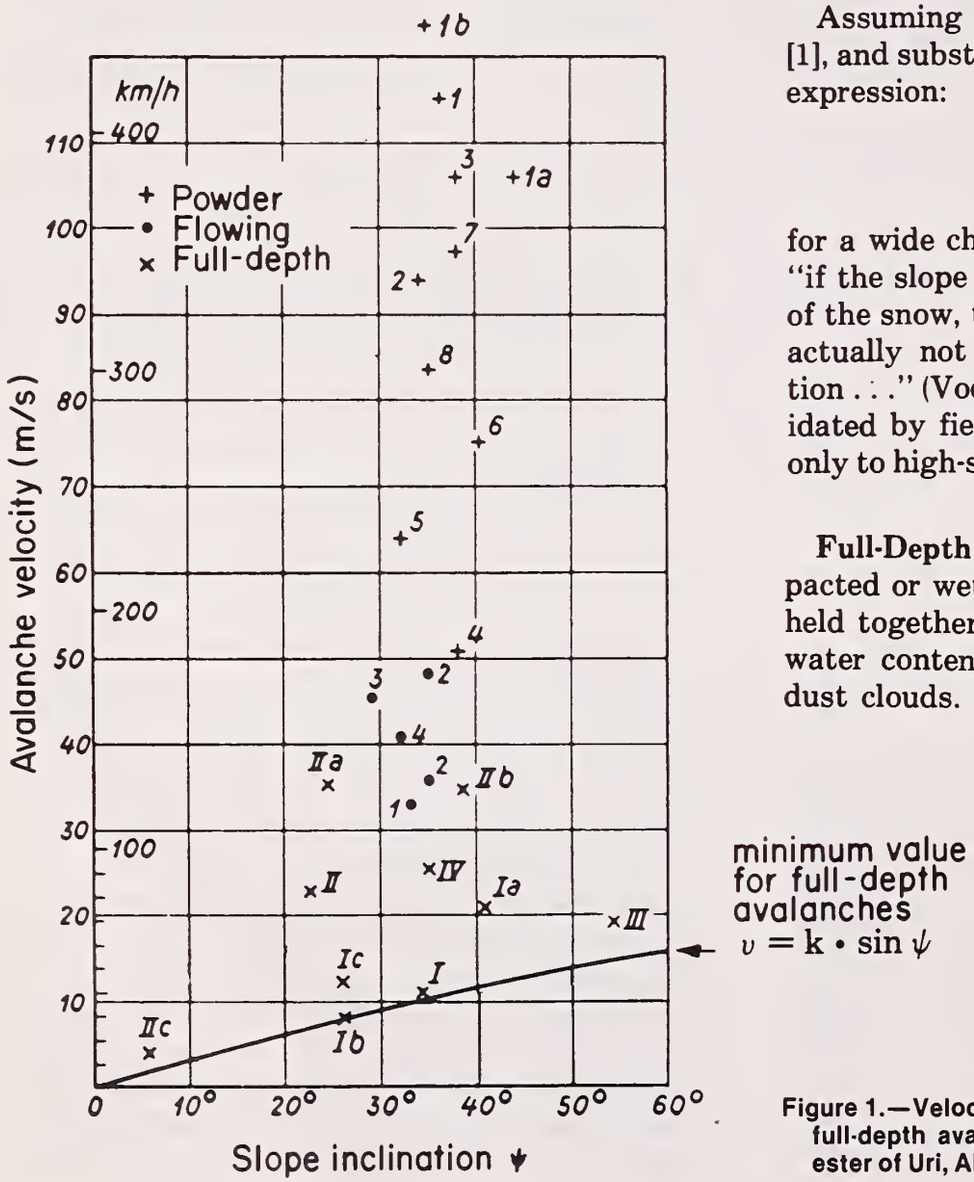



Figure 1.—Velocity measurements on powder, flowing, and full-depth avalanches, by Dr. M. Oeschlin, Canton Forester of Uri, Altdorf (adapted from Voellmy 1955).

causes densification of the snow rather than disintegration and suspension, which is characteristic of powder avalanches. A full-depth avalanche usually results, especially when wet snow is released, because the sliding snow usually works its way through the underlying snow layer to the ground. Considerable debris in the form of trees, rocks, and earth is often carried along. A straightforward method for determining the flow height of full-depth avalanches is not available. According to Voellmy (1955), the flow height, h′, can be approximated by:

$$h' \cong 2.6\,h \qquad [12]$$

which compares with an estimate of $h' = 1.5$ to 3 $h_D$, where $h_D$ is the depth of the snow in the avalanche debris, as proposed by Schaerer (1975a).

The maximum velocity of the full-depth avalanche is calculated by eqs. [1b] or [2] with $\gamma = \gamma_o$.

The fundamental correctness of eq. [8] has been validated by field studies, which indicate that the square of the velocity is a function of sin $\psi$ and h (fig. 2). In citing early observations, Voellmy suggests that, for ground avalanches, $\xi \cong 500$ and $\mu = 0.075$. However, recent work by Schaerer (1975a), although based on limited data, indicates that $\xi$ can be higher and that $\mu$ varies with speed. According to Schaerer, there is little difference between the average friction coefficients of wet and dry snow avalanches, even though the wet avalanches are slower (fig. 2). He attributes the low speed to the smaller flow depth rather than to a higher friction coefficient.

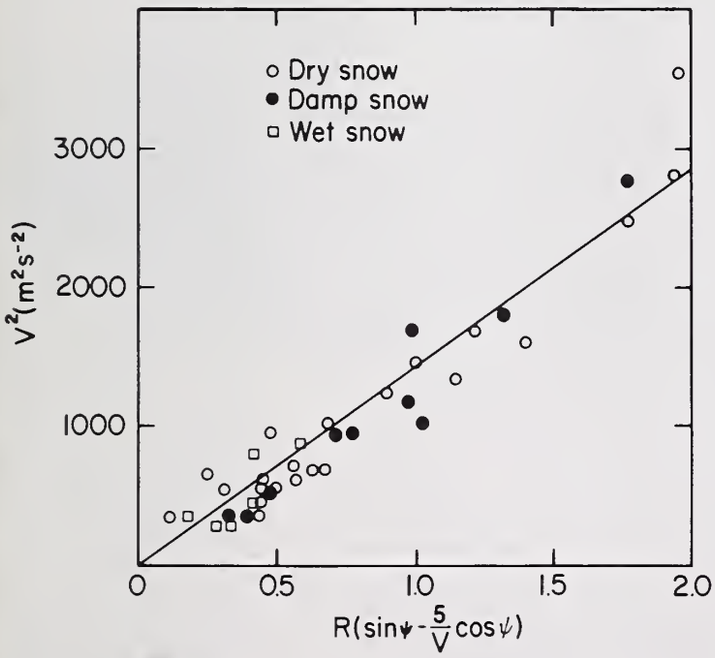



Figure 2.—$V^2$ as a function of $R(\sin\psi - \frac{5}{V}\cos\psi)$, where R is the hydraulic radius. R is approximately equal to h′ (flow depth) for avalanches on open slopes or gullies 10 h′ or more in width. Plotted points were computed by Schaerer (1975a) from observations at Rogers Pass, British Columbia.

**Gradient Changes.**—The theory and analysis of gradually varied flow (Chow 1959) have been used to compute avalanche profiles on complex slopes. At gradient changes, Voellmy (1955) proposed the approximate equation:

$$V_n/V_{n-1} = h'_{n-1}/h'_n \cong (\sin\psi_n/\sin\psi_{n-1})^{1/3} \qquad [13]$$

where

$\psi_n =$ the angle of the upper slope, and
$\psi_{n-1} =$ the angle of the lower slope.

Voellmy suggests that eq. [13] is valid for each succeeding gradient change for the determination of the basic flow height. Eq. [13] is also used to compute the flow height in the runout zone where $\psi_u$ is the gradient of the runout zone.

It should be noted that, for small values of $\psi_u$, $h'_u$ cannot exceed the velocity head, $V^2/2g$. Voellmy points out that, at a gradient change, the transition distance required to reach normal depth is less than the distance given by eq. [4] to approach terminal velocity in a given reach.

**Velocity Distribution.**—Voellmy has expressed the velocity distribution by the following parabolic equation:

$$V' = V\,[4/3 - (z/h')^2] \qquad [14]$$

where V′ is the velocity at the depth, z, below the surface of all but powder avalanches. For the case of powder avalanches, the ordinate in eq. [14] is measured above and below one-half of the flow height. Tochon-Danguy and Hopfinger (1975) observed the velocity distribution by laboratory experiments. Their work verified the form of eq. [14] with an associated backflow in the ambient air (fig. 3). Equation [14] has a significant effect on the thrust pressure of avalanches as discussed later.

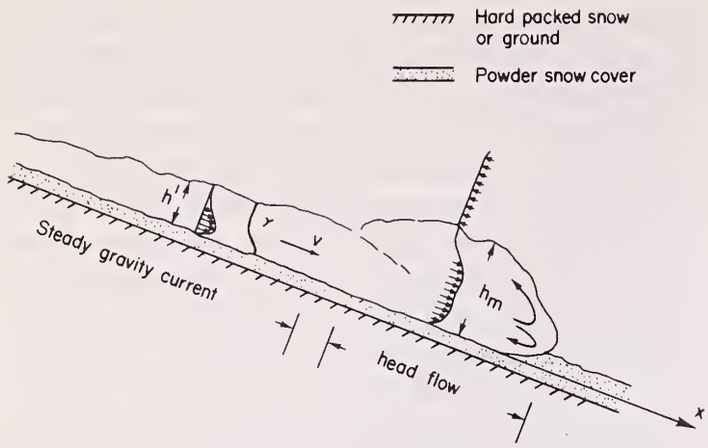



Figure 3.—Velocity distribution in a laboratory simulation of a powder avalanche (modified from Tochon-Danguy and Hopfinger 1975).

## Avalanche Winds

The previous flow equations and field observations indicate that powder avalanches can reach extremely high velocities (Voellmy 1955, Martinelli and Davidson 1966). This phenomenon has generated conflicting opinions as to the possibility of a propagated shock wave associated with high-velocity avalanches (Briukhanov et al. 1967). However, convincing arguments have been presented which show that shock is not a significant factor in avalanche dynamics (Voellmy 1955, Mellor 1968, Shen and Roper 1970).

Mellor (1968) has assumed that the flow of air around the avalanche front is incompressible and irrotational. Accordingly, it is possible to draw a flow net with streamlines and equipotential lines as shown in figure 4. If it is assumed that avalanche speed varies from 50 to 125 m/s, then Mellor (1968) suggested that the dynamic pressure is great enough

> . . . to damage or destroy lighter structures when air velocity, $u_a$, exceeds about 0.5 $u_f$ (avalanche front velocity) for the slower powder avalanches and about 0.2 $u_f$ for the fastest powder avalanches. These air velocities can be expected at about 1.25 h′ and 0.5 h′ ahead of the avalanche front, respectively, where the flow height, h′, may be in the range of 10 to 100 m for major powder avalanches. Thus, we have an explanation for the observation that structures sometimes disintegrate before the avalanche itself strikes them.

Mellor has also pointed out that air velocities, gusting, and shear forces alongside large avalanches can be destructively high due to the steep lateral velocity gradients. He has argued that the "bow wave" proposed in the Russian literature (Briukhanov et al. 1967) cannot produce true shocks and "it therefore seems unprofitable to speculate further on shock-producing mechanisms until the existence of shocks has been proven."

Mellor attributes the travel of avalanche winds, after an avalanche stops or has been deflected, to the inertia of the moving airmass. The rushing air will continue traveling in a straight line until it has dissipated its kinetic energy by boundary shear, frontal resistance, and diffusion. His equation for the deceleration of the air parcel is given by:

$$-5 \times 10^{-3} u_w^2 = H^* \frac{du_w}{dt}$$

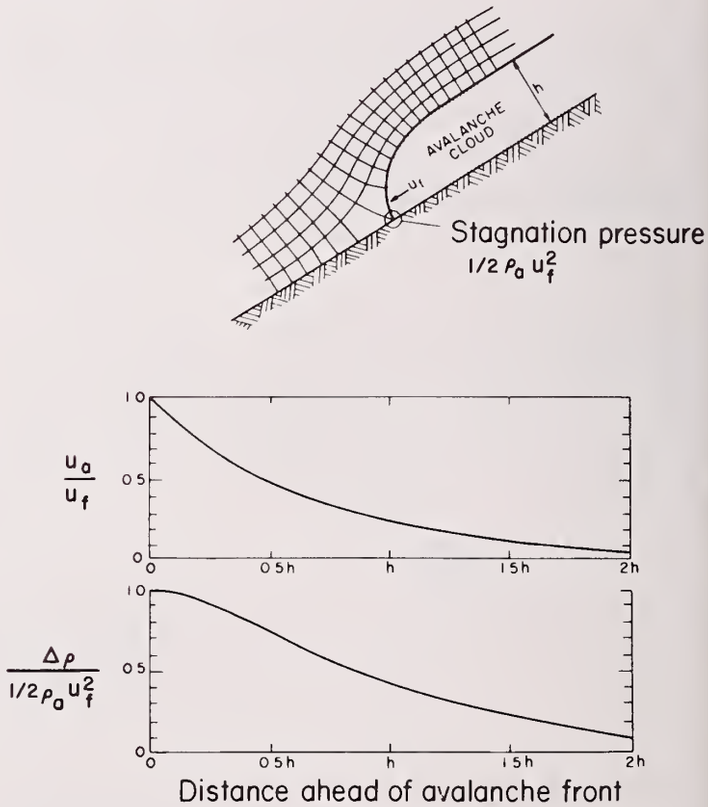



Figure 4.—Approximate distribution of velocity and pressure in air near ground level ahead of an avalanche (from Mellor 1968).

and the elapsed time for deceleration from $u_{w1}$ to $u_{w2}$ as

$$t = \frac{H^*}{5 \times 10^{-3}} \left( \frac{1}{u_{w1}} - \frac{1}{u_{w2}} \right)$$

where

$u_w$ = the wind velocity toward the center of the parcel of moving air, and

$H^*$ = the mean height.

Mellor points out that winds that precede the avalanches are sufficient to entrain snow particles from the surface "at distances of 1 to 2 h′ ahead of the avalanche front." This can be verified by figure 4, if it is considered that winds exceeding 7 to 10 m/s are sufficient to entrain snow. Moreover, observations of snow plastered to great heights on trees subjected to "air blast" is physical evidence of entrained snow (fig. 5).

Entrained snow associated with airborne avalanches behaves almost the same way as a fluid (Mellor 1968). Accordingly, equations for fluid resistance apply. When airborne snow strikes a tall obstacle, two types of drag must be considered: (1) *shear drag,* which is caused by tangential shear along the boundary, and (2) *pressure* or *form drag,* which is caused by the pressure applied normal to the surface of the boundary. When a flat plate or disk is oriented with the flow, shear drag results; when it is placed normal to the flow, pressure drag results. Most submerged objects are subjected to both pressure and shear drag. It is possible to estimate the impact loading on an obstacle immersed in the snow cloud by the equation:

**Figure 5.—Snow plastered on tree by an avalanche that ran the day before. (Parry Peak Avalanche, Twin Lakes, Colorado)**

$$F_D = \frac{C_D A \gamma_e V^2}{2g}$$

where

$F_D$ = the drag force on the obstacle, in kg,

$C_D$ = a dimensionless drag coefficient (Albertson et al. 1960),

$A$ = the projected cross-sectioned area, in $m^2$,

$\gamma_e$ = the effective specific weight of the air/snow mixture, in $kg/m^3$, and

$V$ = the velocity of the air/snow mixture, in m/s.

According to Mellor (1968) the effective specific weight of the avalanche "fluid," $\gamma_e$, can be computed by the equation:

$$\gamma_e = \gamma_s + \gamma_a - \frac{\gamma_a \gamma_s}{\gamma_i}$$

where

$\gamma_a$ = the specific weight of the air (approx. 1.25 $kg/m^3$),

$\gamma_i$ = the specific weight of ice (approx. 917 $kg/m^3$), and

$\gamma_s$ = the specific weight of snow.

Aerodynamic loading produced by airborne snow also causes lift forces on submerged objects. The lift force can be calculated by the equation:

$$F_L = \frac{C_L A \gamma_e V^2}{2g}$$

where $C_L$ is the coefficient of lift.

### Damming and Pressure Effects

If it is assumed that frictional effects are negligible in the short distance needed for the avalanche to come to rest in the runout zone, then the total energy expended can be determined from the familiar Bernoulli Equation:

$$H = Z' + \frac{V^2}{2g} + \int_{p_o}^{p_o + p^*} dp/\gamma \qquad [15]$$

where

$Z'$ = the height in meters above some reference datum,

$\int_{p_o}^{p_o + p^*} dp/\gamma$ = the pressure head, which is dependent upon the compressibility of the snow above the reference pressure head, $p_o$,

$p^* = \gamma z$ = the specific pressure at the point being considered at a depth, z, below the surface of the avalanche, and

$H$ = the total energy head, in meters.

When a powder avalanche runs out onto level terrain ($\psi_u \rightarrow 0$), eqs. [2] and [9] show that $\gamma$ can become extremely small and $h'$ extremely large. Downstream from this point, the avalanche rapidly loses its kinetic energy, which produces an increase in pressure and an associated compression of the snow to an extremely high specific weight. It is assumed that "this dynamic elastic compression is limited chiefly by the compressibility of the air in the voids; and that the ice crystal framework gives only slight compression; while the compressibility of the ice itself is negligible" (Voellmy 1955).

The air in the voids is not completely expelled during compression. For flowing avalanches of coarse-grained dry snow, the maximum specific weight ($\gamma_f$) does not exceed approximately 600 $kg/m^3$, whereas for wet snow, $\gamma_f$ can approach 1000 $kg/m^3$. An average value of $\gamma_f$ for flowing avalanche is approximately 800 $kg/m^3$ (Voellmy 1955). Voellmy assumes that the compression of air in the voids can be considered as an isothermal thermodynamic process, since the heat developed is immediately absorbed by the snow. Under this dynamic overpressure, $p_d$ (greater than $p_o$ = 1 atmosphere), the specific weight of the snow is given by:

$$\gamma_d = \gamma_o (1 + p_d/p_o) \;/\; [1 + (\gamma_o p_d / \gamma_f p_o)] \qquad [16]$$

where

$\gamma_d$ = the specific weight as a result of dynamic compression by the pressure $p_d$ over atmospheric pressure, $p_o$ = 10,000 $kg/m^2$.

The *average* specific weight during compression is given by:

$$\gamma_m = (\gamma_o + \gamma_d)/2$$
$$= \frac{\gamma_o + (\gamma_o/2)(1 + \gamma_o/\gamma_f)\, p_d/p_o}{(1 + \gamma_o p_d/\gamma_f p_o)} \qquad [17]$$

Voellmy states that the *static* compressibility of snow depends on the magnitude and duration of the pressure, the character of the snow, and degree of metamorphism. He suggests that "compression of the air in the pores first brought about by the pressure, is equalized during settlement of the snow material. Then without altering the settlement which has taken place, the air in the pores escapes."

Hence,

$$\gamma_{max} = [\gamma_o + \gamma_f(p_d/p_o)]/(1 + p_d/p_o) \qquad [18]$$

where

$\gamma_{max}$ = the maximum specific weight after compression by the overpressure $p_d$ above atmospheric pressure $p_o$.

Rapid compression of snow can cause noticeable heating of air in the pores. Voellmy notes that the maximum value of the absolute temperature can be expressed as:

$$T = T_o(1 + p_d/p_o)^{(x-1)/x} \qquad [19]$$

in which

T = temperature after compression and with no heat flow, °K,

$T_o$ = initial temperature, °K, and

x = $c_p/c_v = 1.4$ (for $\Delta Q = 0$).

where

$c_p$ and $c_v$ = the specific heat of air constant pressure and constant volume respectively, and

$\Delta Q$ = the amount of heat transfer in the system.

On the average and for the pressures involved, this process seldom heats the snow more than 0.5 °C. The initial heating and subsequent cooling of the air in the voids, however, contributes to metamorphism of the snow and results in surface melting of the ice crystals and sudden refreezing. This phenomenon accounts for the "freezing in" of objects (and people) caught up in the avalanche. According to Voellmy, the heat from friction and compression is given by:

$$W = (\gamma - \gamma_a)\,\frac{H}{427} \qquad [20]$$

where

W = K cal/m³, and

H = the total energy head given by eq. [15].

If the temperature of the snow is below 0 °C, some of the heat given by eq. [20] will be used to satisfy the energy deficit or "cold content" of the snowpack, which must be brought up to 0 °C before appreciable surface melting can take place.

Voellmy states that eq. [18] is the basic equation for computing the "damming" height in the runout zone, while eq. [17] is used in calculating the dynamic pressure effects. He further states that eq. [18] will yield a conservative estimate for powder avalanches, since in reality specific weights may be somewhat less due to deposition of part of the snow by sedimentation.

**Runout Distances**

As the avalanche reaches the runout zone, the diminishing slope inclination causes the flow height to increase according to eq. [13]. The avalanche comes to rest according to eq. [15], when the flow height plus the pressure head is equivalent to the total energy head, H. The place where the avalanche comes to rest is of primary concern to man and his activities.

By assuming that the kinetic energy is transformed into: (a) potential energy, (b) frictional work, (c) flow work, and (d) particle resistance, Voellmy developed the following equation for the runout distance:

$$s \cong V^2/[2g(\mu \cos \psi_u - \tan \psi_u) + V^2 g/\xi h_m] \qquad [21]$$

where

s = runout distance in meters measured from the break in the gradient, and

$h_m$ = $h' + V^2/4g$ when the debris is piled into a short, steep cone.

Velocity is assumed to diminish uniformly to zero in the runout zone. Hence, the average velocity is $V/2$ and its kinetic energy is $V^2/4g$.

Equation [21] is a simplistic approach that does not explain the complex flow regime in the runout zone. For example, the equation is sensitive to $\mu$, $\xi$, and $h_m$. Certainly, $\mu$ and $\xi$ are different in the runout zone than in the track, but we have no good data on their runout zone values. Also, the approximation of $h' + V^2/4g$ for $h_m$ is true only when the debris is piled in a short, steep cone.

In spite of these problems, equation [21] is useful for land use planning because it gives an estimate of the extent of the avalanche. Different workers use the equation in different ways. Some European workers prefer to keep $\xi$ between 400 and 600 m/s² for all avalanches. In this case, $\mu$ must be adjusted according to conditions in the track and runout zone to get reasonable results. Other workers prefer to use $h'$ or something between $h'$ and $h_m$ in place of $h_m$, and often select a different value for $\xi$ in the runout zone than that used in the track. Mears (1976) emphasizes the desirability of seeking field evidence of flow height and avalanche damage so it can be used to make an independent estimate of avalanche velocity and impact forces.

The approach followed in Part II of this paper is to use $5/V$ for $\mu$, select an average value of $\xi$ for the entire track based on terrain and snow conditions, use $h_m = h' + V^2/4g$ in the runout equation [21], and use equation [13] to estimate velocity and flow heights in the various parts of the path based on track gradient.

In eq. [21], the slope, $\psi_u$ is an extremely sensitive parameter which may be positive or negative. Hence, for an adverse gradient (Sommerhalder 1966):

$$s \cong V^2/[2g(\mu \cos \psi_u + \tan \psi_u) + V^2 g/\xi h_m] \qquad [21a]$$

Voellmy notes that if the term in parentheses in the denominator of eq. [21] is $\geq 0$, the avalanche comes to rest on the valley floor. If the term in parentheses is $\leq 0$, the avalanche does not come to rest in that section of the track or runout zone. In this case:

$$\sin \psi_u \geq (1/2\mu)\,[(1 + 4\mu^2)^{1/2} - 1]$$

for small values of V, or

$$\tan \psi_u \geq V^2 g / \xi(2h_o g + V^2) \text{ for } \mu \cong 0.$$

In the above situation, Voellmy states that eq. [21] for s is approximately equal to the transition distance for uniform flow where the new flow height is given by eq. [13]. Thus:

$$s_u \cong (V_o^2 - V_u^2)/2g(\mu \cos \psi_u - \tan \psi_u)$$

where

$V_o$ = velocity in a part of the track that is above a more gently sloping part, and

$V_u$ = velocity in the more gently sloping part of the track or runout zone.

For $s_u < 1$, in subcritical flow, a "backwater" curve can develop on the upper slope. If the flow is supercritical, a sudden change in height or "hydraulic jump" can develop in the vicinity of the change in gradient.

**Damming Effects**

When the avalanche loses its kinetic energy in the runout zone, the snow theoretically is deposited in a conelike configuration with an assumed maximum height of

$$h_{max} = h_o + \Delta h$$

where

$h_o$ = flow height in that section of the track just uphill from the runout zone, and

$\Delta h \cong \dfrac{V^2}{2g}$

This dimension is called the "damming height" by Voellmy, and is expressed as:

$$H' = h'\,[1 + (2\gamma_o V^2)/gh'\gamma_{max}]^{1/2} \qquad [22]$$

and

$$H' \cong (\gamma_m/\gamma_{max})\,(V^2/2g + h')$$

Because the height of the deposited snow is decreased in the runout zone, by lateral expansion, eq. [22] will overestimate the damming height.[5] If the maximum cross section of the deposition cone is geometrically similar to the flow cross section

[5] *The reader is cautioned that equation [22] can greatly overestimate the height of deposition. In most cases, the topography allows the snow to expand in a lateral direction, thus distributing it across a much broader front than assumed by equation [22]. Studies by Schaerer (1975a) showed that debris deposited in the runout was less than the flow height (h′) in those cases where topography allowed lateral spreading and uniform deposition.*

of the avalanche channel, then Voellmy suggests that:

$$H' = h' \left[1 + (2\gamma_o V^2)/gh'\gamma_{max}\right]^{1/3}$$

which can result in damming heights approximately 30 percent less than computed by eq. [22].

### Thrust Effects

Thrust effects are reviewed in some detail in order to provide the engineer with an adequate range of alternatives for design.

The specific thrust pressure is given by:

$$p = \gamma_m(h' + V^2/2g) = \gamma_m H = \gamma_{max} H' \qquad [23]$$

where

$\gamma_m$, $\gamma_{max}$, and $H'$ are given by equations [17], [18], and [22], respectively.

The expression for H in equation [23] is given by:

$$H = h' + (V^2/2g)\left[1 - (V_u/V)^2\right] \qquad [23a]$$

where

$V_u \geq 0$ = final velocity.

By combining the foregoing equations, Voellmy developed the expression:

$$p = \gamma_f \left\{ \left[(q/2)^2 + H\, p_o/\gamma_f\right]^{1/2} - q/2 \right\} \qquad [24]$$

where

$q = p_o/\gamma - (H/2)(1 + \gamma/\gamma_f)$

The maximum possible thrust pressure is given by the equation:

$$p_{max} = \gamma_m (h' + V^2/g) \qquad [25]$$

provided that the snow undergoes inelastic impact onto the obstacle without overflowing, damming up, or moving laterally around the obstacle. Equation [25] results in a highly conservative estimate of avalanche impact. Perhaps a more reasonable approximation is the specific thrust pressure given by equation [24] since most structures would probably not be required to absorb all of the kinetic energy of a given avalanche because much of the snow would flow around the ends or over the top of an obstacle. Equation [24] is used in the case studies of Part II.

It should be noted here that other investigators have also studied avalanche impacts. For example, Mellor (1968) developed the following equation for the impact pressure imparted to an obstacle:

$$\Delta p = \frac{\gamma_1\gamma_2}{\gamma_2 - \gamma_1} \cdot \frac{u_1^2}{g} = \frac{\gamma_1 u_1^2}{g}\left(1 + \frac{\gamma_1}{\gamma_2 - \gamma_1}\right)$$

where

$u_1$ = avalanche velocity, in m/s,

$\gamma_1$ = specific weight of flowing snow while still undisturbed, in kg/m³, and

$\gamma_2$ = specific weight of the snow after encountering the obstacle, in kg/m³.

Mellor (1968) suggested that errors in estimating $\gamma_2$ up to 15 percent have no significant effect on the calculation of $\Delta p$ since $\gamma_1$ is normally less than 300 kg/m³ and $\gamma_2$ always exceeds 550 kg/m³. Generally, $\gamma_2$ will lie in the range of 550 to 750 kg/m³. Mellor suggested that 650 kg/m³ is perhaps a reasonable estimate for $\gamma_2$. Figure 6 was taken from Mellor (1968) to show maximum thrust pressures on an unyielding large obstacle for various specific weights of flowing snow, assuming a constant value of 650 kg/m³ for $\gamma_2$.

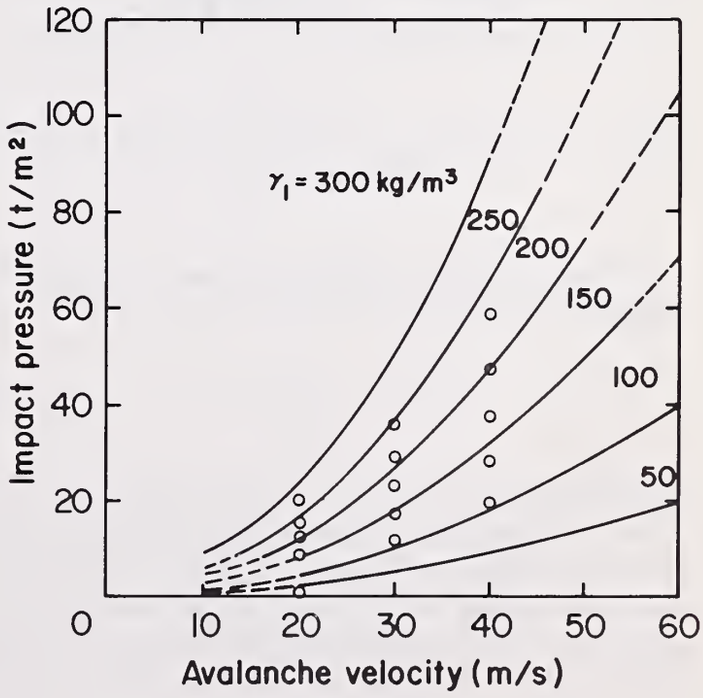



Figure 6.—Avalanche impact pressure on a wide, rigid obstacle (Mellor 1968). The plotted points were calculated by Gongadze (1954), assuming a constant value, $\gamma_2$, of 650 kg/m³. The parameter, $\gamma_1$, is the specific weight of the flowing snow prior to encountering the obstacle.

Other significant studies of avalanche impacts include those made by Furukawa (1957), Matviyenko (1968), Gongadze (1954), and Shoda (1966).

Schaerer (1973) has probably made the most field observations of impact pressures, using load cells mounted in the avalanche track. His observed peak specific pressures produced by dense flowing snow agree with pressures calculated by the equation:

$$p_{max} = \frac{V^2}{2g} \gamma_u$$

where

$V$ = the speed of the avalanche front, and

$\gamma_u$ = the specific weight of the deposited snow in the runout zone.

Schaerer found that average pressures were approximately 30 percent of the peak due to variations in particle size and specific weight, which caused extreme fluctuations in measured pressures. Observed pressures varied from 2,447 to 44,346 kg/m² for eight events from 1970 to 1972. Dense blocks of snow produced the series of peaks for the avalanche in figure 7 (Schaerer 1973), whereas airborne snow caused the lower pressures.

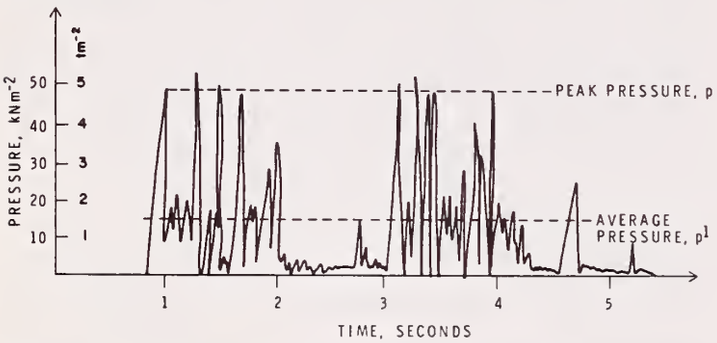



**Figure 7.—Variation of avalanche impact pressure (Schaerer 1973).**

If the avalanche impinges upon a surface inclined at an angle $\beta$ to the flow, then:

$$p_\beta = \gamma_u \frac{V^2}{2g} \sin \beta \qquad [26]$$

Voellmy points out that eq. [26] applies to the specific resistance of an inclined surface (referred to the projection in the flow direction), since this equation agrees with observations more favorably than "with the complicated results of the flow theory." From eq. [15] and eq. [25], the following more general expression for the total energy head results:

$$H = h' + (V^2/2g)\,[1 - (V_u/V)^2 (1 - \sin \beta)] \qquad [27]$$

which can be substituted into eqs. [23] and [24] for computing the specific thrust pressure.

The total force per unit length on a circular cylinder of radius r is:

$$P = (\pi/2)(r\gamma\, V^2/2g) \qquad [28]$$

An obstacle of width b, in the path of an avalanche of width B, causes a loss of energy given by:

$$P = bh\gamma \frac{V^2}{2g} = Bh(\gamma/g)(\Delta V)V \qquad [29]$$

where $\Delta V = Vb/2B$

### Suction Effects

Voellmy points out that suction effects resulting from powder avalanches are explainable as eddy effects. Although avalanches entrain some air, the velocity of incoming air seldom reaches 5 percent of the avalanche velocity. Suction pressures are possible behind small obstacles completely overrun by powder avalanches moving at high velocity. The maximum negative pressure is given by:

$$p_{(-)} = \gamma_a V^2/2g \qquad [30]$$

where

$p_{(-)} < 1/10$ atmosphere.

### Thrust and Uplift

Uplift and thrust are associated with damming, and can load a structure in any direction. The snow is deflected immediately on impact with a minimal effect on velocity and friction. Wide avalanches colliding with large obstacles are dammed up in accordance with eq. [22] to the damming height $H \cdot \gamma_m/\gamma_{max}$. The vertical velocity at the height h* is given by:

$$u = [2g(H - h^*)]^{1/2} \qquad [31]$$

The specific upward pressure on projecting surfaces is:

$$p_v = \gamma_{max} u^2/2g \qquad [32]$$

where $\gamma_{max}$ is determined from eq [18]. The unit uplift force on vertical wall surfaces is given by the equation:

$$R_v = p\mu \qquad [33]$$

where

$R_v$ = the uplift per square meter of wall surface, and

$\mu$ = $\gamma_{max}/1000$ to $\gamma_{max}/2000$, according to Voellmy.

Voellmy points out that eqs. [32] and [33] are important in that "the vertical forces cause much of the severe destruction since most structures in avalanche-prone areas are not designed to withstand uplift."

In terrain that descends in the direction of flow, a downward component of thrust and friction forces can occur. Voellmy suggests that total dynamic thrust per meter of width on a horizontal roof overrun by an avalanche is:

$$P_H = \gamma h' \, (h'/2 + V^2/g) \tan \psi/2 \qquad [34]$$

The pressure distribution on the roof is such that neither the specific damming pressure (eq. 26 ) nor the static damming pressure at the level being considered is exceeded. In addition, when a structure is overrun, the weight of the snow ($\gamma h'_u$) as well as the frictional forces caused by the moving snow ($\mu\gamma h'_u$) should also be considered.

### Debris Entrained in Avalanches

In addition to impact loadings from the snow itself, the dynamic effects of debris such as rocks, trees, and ice fragments entrained in avalanches should also be considered. Avalanches will pick up debris as soon as the thrust force, including uplift, renders this material unstable. Modes of transport can include saltation or sliding. The work expended by the avalanche in entrainment of debris is negligible for all practical purposes.

## PART II. FIELD VERIFICATION

The equations summarized in Part I are based on technically sound engineering principles. With careful judgment, they can be used to provide a logical basis for evaluating avalanche hazards.

Even though more field data are needed to improve the equations, enough information has been collected to provide examples that can be used to show how to apply several of the equations in Part I. Data were obtained from Frutiger (1964), Gallagher (1967, Williams (1975), and field observations.

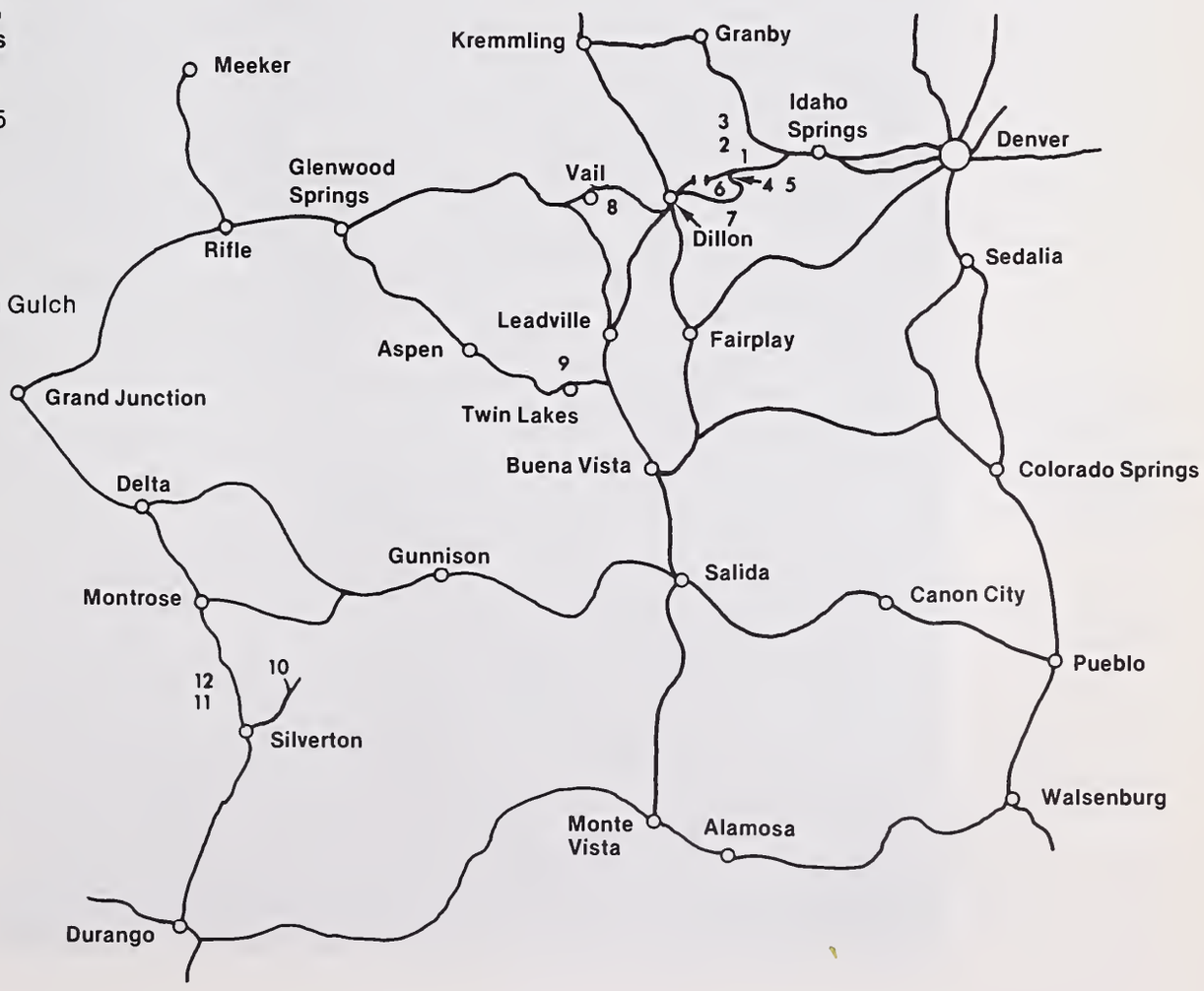
Twelve avalanche paths in Colorado were selected for study. Although the data are limited, they constitute a representative sample of avalanche problems pertinent to land use. We did not attempt to completely analyze the avalanches, nor to evaluate them according to a detailed frequency classification.

Our objective in this part of the report was to utilize as much field data as possible to test the suitability of the primary equations summarized in Part I. It should be emphasized that a more comprehensive engineering study, including a careful frequency analysis of avalanche hazards, should be made prior to any final determination of runout distances, impact forces, and other pertinent engineering data.

The 12 avalanche paths analyzed in Part II are discussed in terms of the avalanche classification system used by Frutiger (1964), which designates size as *small* (starting zone less than 7 acres), *medium* (starting zone 7 to 30 acres), or *large* (starting zone more than 30 acres). It also designates the frequency with which the avalanche runs to the highway as *frequent* (into the road one or more times per winter), *occasional* (into road once each 3 to 6 years), or *erratic* (into the road no more than once each 7 to 10 years). The frequency classifications used in the following sections are based on short periods of record, and may be modified as more information accumulates.

**Avalanches in Colorado included in case studies**

1 Dam
2 Jones Brothers No. 5
3 Stanley
4 Seven Sisters No. 3
5 Seven Sisters No. 7
6 Little Professor
7 Pallavicini
8 Timber Falls
9 Parry Peak—Gordon Gulch
10 Hematite Gulch
11 Battleship
12 Ironton Park



## Case Study No. 1—Dam Avalanche

### U.S. Highway 40, south of Berthoud Pass, Colorado

**Location**

Front Range; northeast slope of the east shoulder of Engelmann Peak.

**Catchment Basin**

A V-shaped depression in the slope; above and below timberline; 11,800-10,800 ft (3597-3292 m) m.s.l.; 50 acres (20 ha).

**Track**

Gully; vertical drop, 2,120 ft (646 m); length, 3,600 ft (1097 m); average slope, 59 percent.

**Runout Zone**

Lower section of gully, Clear Creek valley bottom, and opposite slope where highway lies. Highway is 40 ft (12 m) above Clear Creek and 200 ft (61 m) away from it. Runout zone in lower section of gully; approximate length, 1,500 ft (457 m). Usually avalanches stop on this gentle section or in bed of Clear Creek. Large avalanches, however, reach highway and beyond.

**Avalanches**

Avalanche, shot down April 8, 1957, crossed the highway; killed two men. Most avalanches stop before reaching the creek.

**Classification**

Large-erratic. This avalanche has not reached the highway since 1957.

## CALCULATIONS

*Assumptions:*

$\xi = 1200\ m/s^2$
$\gamma_a = 1.25\ kg/m^3$
$\gamma = 150\ kg/m^3$
$\gamma_o = 150\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 2.5\ m$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Main track | $31° \psi_1$ |
| 2 | Runout | $21° \psi_2$ |
| 3 | Runout | $-20° \psi_3$ |

*Flow Height [Eq. 13]:*

| Reach | h′ | Calculations |
|---|---|---|
| | *(m)* | |
| 1 | 2.5 | Assumed |
| 2 | 2.8 | $\frac{h_2'}{2.5} = \left[\frac{\sin 31}{\sin 21}\right]^{1/3}$ |

*Terminal Velocity [Eqs. 1b and 13]:*

| Reach | $V_{max}$ | Calculations |
|---|---|---|
| | *(m/s)* | |
| 1 | 34.0 | $V_1^2 = 1200 \times 2.5 \left(1 - \frac{1.25}{150}\right) \left[\sin 31° - \frac{5}{V_1} \cos 31°\right]$ |
| 2 | 30.1 | $\frac{V_2}{34.0} = \left(\frac{\sin 21°}{\sin 31°}\right)^{1/3}$; $V_2 = (34)(.8861)$ |

*Head [Eq. 23a, with $V_u = 0$]:*

$$H \cong 2.8 + 30.1^2/2(10)\left[1 - \left(\frac{0}{V}\right)^2\right]$$

$$\boxed{H = 48.1\ m}$$

*Specific Thrust Pressure [Eq. 24]:*

$$p \cong 800\left\{\left[(q/2)^2 + \frac{48.1 \times 10{,}000}{800}\right]^{1/2} - q/2\right\}$$

where

$$q = \frac{10{,}000}{150} - \left[\frac{48.1}{2}\right]\left[1 + \frac{150}{800}\right] = 38.1$$

$$p \cong 800\left\{\left[\left(\frac{38.1}{2}\right)^2 + 601.2\right]^{1/2} - \left(\frac{38.1}{2}\right)\right\} \cong 800 \times 12$$

$$\boxed{p \cong 9{,}600\ kg/m^2}$$

*Maximum Specific Weight [Eq. 18]:*

$$\gamma_{max} \cong \left[150 + 800\left(\frac{9{,}600}{10{,}000}\right)\right] \Big/ \left(1 + \frac{9{,}600}{10{,}000}\right)$$

$$\boxed{\gamma_{max} \cong 468\ kg/m^3}$$

*Runout Distance [Eq. 21a]:*

$$s \cong \frac{(30.1)^2}{20\left[\frac{5}{30.1} \times \cos 20° + \tan 20°\right] + \frac{(30.1)^2 \times 10}{1200\, h_m}}$$

where

$$h_m \cong h' + \frac{V^2}{4g}$$

$$h_m \cong 2.8 + \frac{(30.1)^2}{40} \cong 25.45$$

$$\boxed{s \cong 85\ m}$$

**Discussion**

The Dam slide was shot down April 8, 1957. It overran the highway without depositing snow in Clear Creek. Approximately 9.2 m of snow was dammed up against the cutbank, located some 90 m upslope from the valley bottom.

## Case Study No. 2—Jones Brothers No. 5 Avalanche

**West of U.S. Highway 40, near Jones Pass, Colorado**

**Location**
Front Range; southern flank of Stanley Mountain; 0.65 mi (1.1 km) west of U.S. Highway 40 along County Road up West Fork of Clear Creek toward Jones Pass.

**Catchment Basin**
Small depression about timberline; 11,800-11,200 ft (3597-3414 m) m.s.l.; 6 acres (2.5 ha).

**Track**
Narrow crooked slot down timbered slope; vertical drop 1,100 ft (335 m); length 1,800 ft (550 m).

**Runout Zone**
Lower slope and flat valley of West Fork Clear Creek.

**Classification**
Medium-frequent.

## CALCULATIONS

*Assumptions:*

$\xi = 1400\ m/s^2$
$\gamma = 200\ kg/m^3$
$\gamma_o = 200\ kg/m^3$
$\gamma_f = 800\ kg/m^3$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Main track | 24° |
| 2 | Track | 20° |
| 3 | Runout | 13° |
| 4 | Runout | 3° |

*Flow Height [Eq. 13]:*

| Reach | h′ |
|---|---|
| | *(m)* |
| 1 | 2.0 |
| 2 | 2.1 |
| 3 | 2.4 |

*Terminal Velocity [Eq. 1b and 13]:*

| Reach | $V_{max}$ |
|---|---|
| | *(m/s)* |
| 1 | 24.9 |
| 2 | 23.5 |
| 3 | 20.5 |

*Head [Eq. 23a, with $V_u = 0$]:*
$H = 23.4\ m$

*Specific Thrust Pressure [Eq. 24]:*
$p = 5536\ kg/m^2$

*Maximum Specific Weight [Eq. 18]:*
$\gamma_{max} = 414\ kg/m^3$

*Runout Distance [Eq. 21]:*
$s = 103\ m$

**Discussion**

The avalanche of January 28, 1975 filled the road cut and put light debris to the stream 200 ft (60 m) beyond.

## Case Study No. 3—Stanley Avalanche

**U.S. Highway 40, south of Berthoud Pass, Colorado**

**Location**

Front Range; southeast slope of the east shoulder of Stanley Mountain.

**Catchment Basin**

A bowl-shaped depression on the slope; above timberline; 12,400-11,600 ft (3780-3536 m) m.s.l.; 20 acres (8 ha).

**Track**

Not confined; three slots in timber; vertical drop, 2,400 ft (732 m); length, 4,400 ft (1341 m).

**Runout Zone**

Lower section of the track with a more gentle slope and valley bottom of Clear Creek; length, 900 ft (274 m). Width of track and runout zone, 2,000 ft (610 m).

**Avalanches**

Stanley frequently blocks the upper highway. Most avalanches do not reach the valley bottom; however, the larger ones have been known to overrun the lower highway and come to rest at the foot of the opposite slope.

**Classification**

Medium-frequent. Stanley can be expected to run after each medium to large snowstorm. It has also "run big" (15 ft (4.6 m) or more snow on upper road) five times in the past 25 years.

## CALCULATIONS

*Assumptions:*
$\xi = 800\ m/s^2$
$\gamma_a = 1.25\ kg/m^3$
$\gamma = 150\ kg/m^3$
$\gamma_o = 150\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 1.5\ m$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Main track | 29° |
| 2 | Runout | 12° |

*Terminal Velocity [Eq. 1b]:*
$V_{max} = 15.60\ m/s$

*Head [Eq. 23a, with $V_u = 0$]:*
$H = 13.7\ m$

*Specific Thrust Pressure [Eq. 24]:*
$p = 2228\ kg/m^2$

*Maximum Specific Weight [Eq. 18]:*
$\gamma_{max} = 268\ kg/m^3$

*Runout Distance [Eq. 21]:*
$s = 100\ m$

**Discussion**

The Stanley Avalanche crosses U.S. 40 twice. The upper crossing is about 1100 m (map distance) below the main starting zone; the lower is another 400 m down the slope. Stanley has frequently come to rest in that portion of the runout between the highways. The calculations above would place debris approximately to the edge of the lower highway. A slide in January 1975, placed debris on the lower highway. It resulted from windblown snow that fractured in a lower starting zone to the lee of the uppermost narrow strip of timber (see photo).

## Case Study No. 4—Seven Sisters No. 3 Avalanche

## Case Study No. 5—Seven Sisters No. 7 Avalanche

U.S. Highway 6, north of Loveland Pass, Colorado

**Location**
Front Range; north slope near Loveland Basin ski area.

**Catchment Basins**
At and below timberline; north slope 11,800-11,400 ft (3597-3475 m) m.s.l. There are seven small, bowl-shaped starting zones that are separated by timbered ridges. The starting area of all seven avalanches is about 20 acres (8 ha).

**Tracks**
One of seven gullylike tracks on a timbered slope; vertical drop, 900 ft (274 m); length, 1,400 ft (427 m).

**Runout Zone**
Transition zone at the highway. The avalanche, after filling the road cut with snow, can travel across the road toward Clear Creek. Approximate length of runout, 500 ft (152 m).

**Avalanches**
Very frequent; usually released four to six times a winter by artillery fire. Avalanche cycles are recorded as early as mid-November and as late as the end of April.

**Classification**
Small-frequent.

**Track**
Easternmost of seven gullylike tracks; vertical drop, 900 ft (274 m); length, 1,800 ft (550 m).

**Runout Zone**
Transition zone at the highway. The avalanche, after filling the road cut with snow, can travel another 500 to 600 ft (150-180 m) toward Clear Creek.

**Classification**
Small-frequent.

## Case Study No. 4—Seven Sisters No. 3 Avalanche

### CALCULATIONS

*Assumptions:*
$\xi = 800\ m/s^2$
$\gamma_a = 1.25\ kg/m^3$
$\gamma = 200\ kg/m^3$
$\gamma_o = 200\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 1.0\ m$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 35° |
| 2 | Track | 28° |
| 3 | Runout | 10° |

*Flow Height [Eq. 13]:*

| Reach | h′ |
|---|---|
| | *(m)* |
| 1 | 1.0 Assumed |
| 2 | 1.1 |

*Terminal Velocity [Eqs. 1b, 13]:*

| Reach | $V_{max}$ |
|---|---|
| | *(m/s)* |
| 1 | 15.8 |
| 2 | 14.8 |

*Head [Eq. 23a, with $V_u = 0$]:*
$H = 12.0\ m$

*Specific Thrust Pressure [Eq. 24]:*
$p = 2634\ kg/m^2$

*Maximum Specific Weight [Eq. 18]:*
$\gamma_{max} = 325\ kg/m^3$

*Runout Distance [Eq. 21]:*
$s = 62\ m$

**Discussion**

This is one of the more frequent of this group of seven small frequent avalanches. It has crossed the road an average of eight times per winter for the eight winters preceding 1970-71. These are both natural and artillery released avalanches.

## Case Study No. 5—Seven Sisters No. 7 Avalanche

### CALCULATIONS

*Assumptions:*
$\xi = 500\ m/s^2$
$\gamma = 150\ kg/m^3$
$\gamma_o = 150\ kg/m^3$
$\gamma_f = 800\ kg/m^3$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 38° |
| 2 | Track | 32° |
| 3 | Track | 29° |

*Flow Height [Eq. 13]:*

| Reach | h′ |
|---|---|
| | *(m)* |
| 1 | 1.0 Measured fracture height |
| 2 | 1.0 |

*Terminal Velocity [Eqs. 1b and 13]:*

| Reach | $V_{max}$ |
|---|---|
| | *(m/s)* |
| 1 | 12.0 |
| 2 | 11.4 |

*Head [Eq. 23a, with $V_u = 0$]:*
$H = 7.5\ m$

*Specific Thrust Pressure [Eq. 24]:*
$p = 1177\ kg/m^2$

*Maximum Specific Weight [Eq. 18]:*
$\gamma_{max} = 218\ kg/m^3$

*Runout Distance [Eq. 21]:*
s = No stop in Reach 3

**Discussion**

The avalanche of February 18, 1975 had a fracture line about 110 ft (34 m) long and 3 ft (0.9 m) deep. Most of the debris stopped in the road. Just above the road the debris was 185 ft (56 m) wide with a maximum depth of 6 ft (1.8 m) in the center and a uniform taper to zero at the edges. Density of snow in the debris cone was measured as 350 $kg/m^3$. Accordingly, estimates of $\gamma$ and $\gamma_o$ are too low (more like 200 $kg/m^3$). Equations indicate that this avalanche would have run to the valley had the road not been plowed.

## Case Study No. 6—Little Professor Avalanche

### U.S. Highway 6, south of Loveland Pass, Colorado

**Location**

Front Range; southeast slope of summit point 12,293, northwest of Arapaho Basin ski area.

**Catchment Basin**

Uniform southeast slope; above timberline; 12,100-11,600 ft (3688-3536 m) m.s.l.; 7 acres (3 ha).

**Track**

Wide opening in the timber of the slightly bowl-shaped slope; vertical drop, 1,260 ft (384 m); length, 2,700 ft (823 m). This avalanche has a tendency to spread out in the lower part; the width of the track is 800 ft (244 m) near the highway.

**Runout Zone**

No transition zone above the highway; avalanches reach the parking lot of Arapaho Basin ski area.

**Avalanches**

February 2, 1965, covered the highway 20 ft (6 m) deep. Has run to the road 10 times in past 25 yr.

**Classification**

Small-frequent.

## CALCULATIONS

*Assumptions:*

$\xi = 800\ m/s^2$
$\gamma_a = 1.25\ kg/m^3$
$\gamma = 200\ kg/m^3$
$\gamma_o = 200\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 2.0\ m$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 28° |
| 2 | Track | 29° |
| 3 | Runout | 9° |
| 4 | Runout | -4° |

*Flow Height [Eq. 13]:*

| Reach | h′ | |
|---|---|---|
| | *(m)* | |
| 1 | 2.0 | Assumed |
| 2 | 1.98 | |
| 3 | 2.88 | |

*Terminal Velocity [Eqs. 1b and 13]*

| Reach | $V_{max}$ |
|---|---|
| | *(m/s)* |
| 1 | 19.8 |
| 2 | 20.0 |
| 3 | 13.7 |

*Head [Eq. 23a, with $V_u = 0$]:*
$H = 12.3\ m$

*Specific Thrust Pressure [Eq. 24]:*
$p = 2684\ kg/m^2$

*Maximum Specific Weight [Eq. 18]:*
$\gamma_{max} = 327\ kg/m^3$

*Runout Distance [Eq. 21a]:*
$s = 21\ m$

**Discussion**

On February 2, 1965, Little Professor deposited approximately 20 ft (6 m) of debris on the center line of the road. This avalanche also reached the Arapaho Basin parking lot (reach 4). Equation [21a] places the runout at 21 m upslope in reach 4, which is in general agreement with field observations.

## Case Study No. 7—Pallavicini Avalanche

### U.S. Highway 6, south of Loveland Pass, Colorado

**Location**

Front Range; north slope of summit point 12,144, southwest of Arapaho Basin ski area.

**Catchment Basin**

Bowl-shaped depression in the north-facing slope; above and below timberline; 12,000-11,200 ft (3658-3414 m) m.s.l.; 15 acres (6 ha).

**Track**

Wide opening in the heavily timbered slope; vertical drop, 1,280 ft (390 m); length, 2,700 ft (823 m).

**Runout Zone**

Flat bottom of the Snake River Valley; under severe conditions the avalanche may run across the 500-ft-wide (152 m) valley bottom and reach the highway on the opposite slope.

**Avalanches**

The starting zone is controlled intensively by explosives and protective skiing because it lies within the Arapaho Basin ski area.

**Classification**

Medium-erratic. Intensive skiing stabilizes the snowpack in the starting zone. Therefore, it is very unlikely that big snow masses will start. During prolonged and severe storms, however, when no skiing is possible, snow masses become big enough to form avalanches that reach the highway.

## CALCULATIONS

*Assumptions:*

$\xi = 800\ m/s^2$
$\gamma_a = 1.25\ kg/m^3$
$\gamma = 200\ kg/m^3$
$\gamma_o = 200\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 1.5\ m$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 31° |
| 2 | Track | 24° |
| 3 | Track | 17° |
| 4 | Runout | 9° |

*Flow Height [Eq. 13]:*

| Reach | h′ |
|---|---|
| | *(m)* |
| 1 | 1.50 Assumed |
| 2 | 1.62 |
| 3 | 1.81 |

*Terminal Velocity [Eqs. 1b and 13]:*

| Reach | $V_{max}$ |
|---|---|
| | *(m/s)* |
| 1 | 18.3 |
| 2 | 16.9 |
| 3 | 15.1 |

*Head [Eq. 23a, with $V_u = 0$]:*
$H = 13.2\ m$

*Specific Thrust Pressure [Eq. 24]:*
$p = 2911\ kg/m^2$

*Maximum Specific Weight [Eq. 18]:*
$\gamma_{max} = 335\ kg/m^3$

*Runout Distance [Eq. 21]:*
$s = 61\ m$

**Discussion**

This calculation shows debris stopping about 60 to 70 m short of the creek. On two occasions in the last 25 yr, this avalanche crossed the creek and ran 75 to 80 m up a 16° slope to cross the highway.

## Case Study No. 8—Timber Falls Avalanche

### Highway I-70, east of Vail, Colorado

**Location**
Vail, Colorado.

**Catchment Basin**
Approximately 47 acres (19 ha).

**Track(s)**

T1 East Ridge—Poorly defined slide path with minor drainageway; vertical drop, approximately 2,000 ft (610 m); length, approximately 3,500 ft (1067 m).

T2 Aspen Slide—Poorly defined; vertical drop, approximately 2,200 ft (610 m); length approximately 4,000 ft (1219 m). Both T1 and T2 have a shelf near the bottom of the slope which has prevented smaller avalanches from reaching the valley below.

T3 East Slide—Poorly defined; spills snow into main track. Vertical drop, approximately 1,500 ft (457 m); length approximately 3,500 ft (1067 m). Shelf near bottom also stops smaller slides.

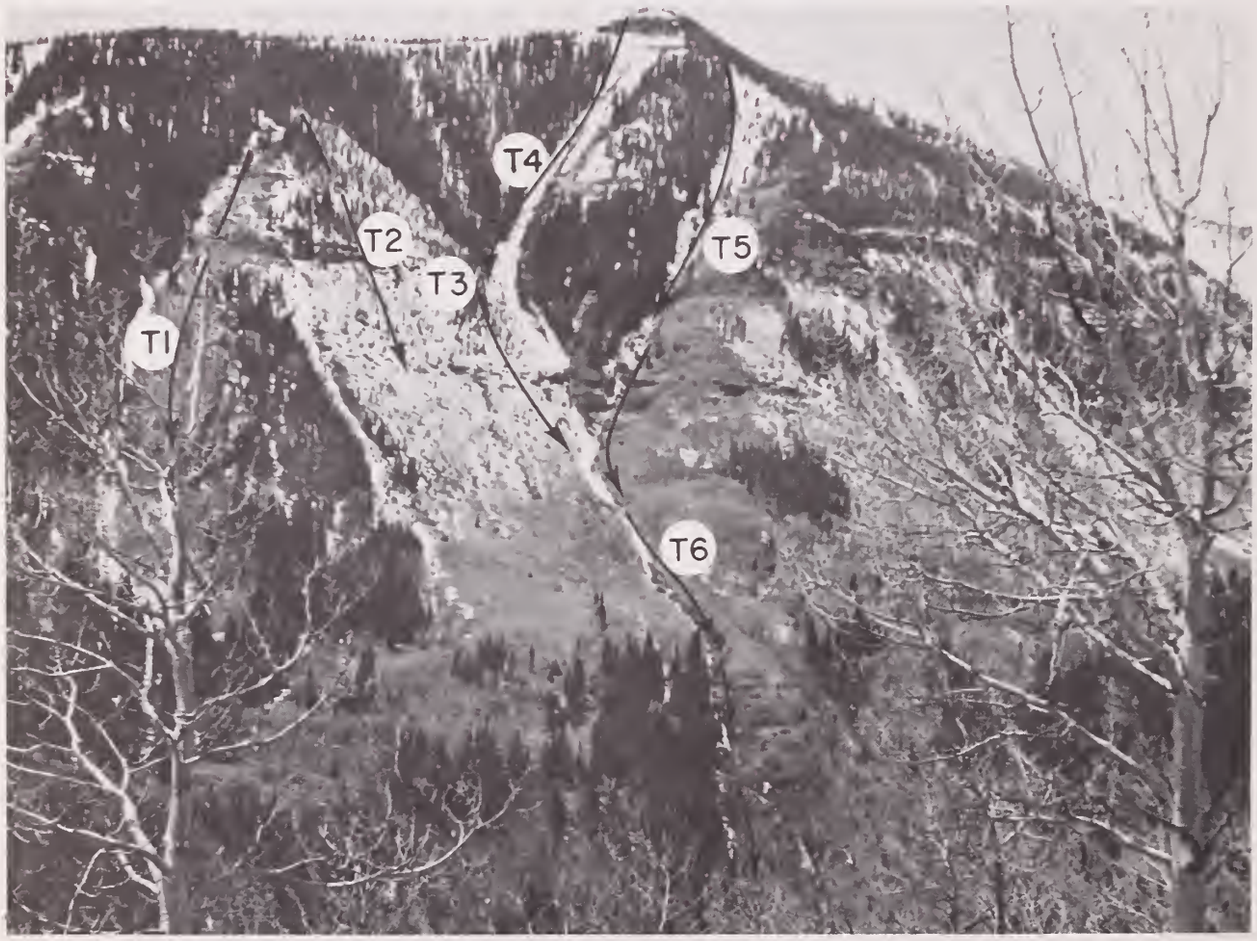
T4 West Upper Fork—Below large cliff-like rock; vertical drop, approximately 2,300 ft (701 m); length, approximately 4,200 ft (1280 m) with bend at intersection of T3.

T5 West Lower Fork—Originates from large rock at head of T4. Well-defined track which drops approximately 1,250 ft (381 m); length, approximately 2,700 ft (823 m).

T6 Main Track—Extends from just above the junction of T4 and T5 at a cliff-like rock outcrop. Well-defined track with three bends in the alinement which are associated with rock outcrops. A shelf near the bottom of the track retains much of the flowing snow. Vertical drop to valley (including T4 or T5) approximately 2,300 ft (701 m); length, approximately 4,200 ft (1280 m).

**Runout Zone**
Broad valley of Gore Creek.

**Classification**
Medium-erratic. During the avalanche season of 1967-68, T6 ran and deposited snow high on the alluvial fan. In 1950-51, slides in the area ran to the valley floor as far as Gore Creek (Borland 1973).



## CALCULATIONS

*Assumptions:*

| | (T1) | (T2) | (T3-6) |
|---|---|---|---|
| $\xi$ = | 500 m/s² | 500 m/s² | 800 m/s² |
| $\gamma$ = | 150 kg/m³ | 150 kg/m³ | 150 kg/m³ |
| $\gamma_o$ = | 150 kg/m³ | 150 kg/m³ | 150 kg/m³ |
| $\gamma_f$ = | 800 kg/m³ | 800 kg/m³ | 800 kg/m³ |

*Longitudinal Profile:*

(T1)

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 32° |
| 2 | Track | 25° |
| 3 | Track | 20° |
| 4 | Track | 31° |
| 5 | Runout | 3.0° |

(T2)

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 36° |
| 2 | Track | 26° |
| 3 | Track | 18° |
| 4 | Track | 28° |
| 5 | Track | 34° |
| 6 | Runout | 5.5° |

(T3-6)

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 32° |
| 2 | Track | 25° |
| 3 | Track | 15° |
| 4 | Track | 10° |
| 5 | Runout | 8.0° |

*Flow Height [Eq. 13]:*

| Reach | (T1) h′ | (T2) h′ | (T3-6) h′ |
|---|---|---|---|
| | *(m)* | *(m)* | *(m)* |
| 1 | 2.5 | 2.5 | 2.5 |
| 2 | 2.7 | 2.8 | 2.7 |
| 3 | 2.9 | 3.1 | 3.2 |
| 4 | 2.5 | 2.7 | 3.6 |
| 5 | | 2.5 | |

*Terminal Velocity [Eqs. 1b and 13]:*

| Reach | (T1) $V_{max}$ | (T2) $V_{max}$ | (T3-6) $V_{max}$ |
|---|---|---|---|
| | *(m/s)* | *(m/s)* | *(m/s)* |
| 1 | 19.8 | 22.5 | 27.2 |
| 2 | 18.3 | 20.4 | 25.3 |
| 3 | 17.1 | 18.1 | 21.5 |
| 4 | 19.6 | 20.0 | 18.8 |
| 5 | | 22.1 | |

*Head [Eq. 23a, with $V_u = 0$]:*

| | | | |
|---|---|---|---|
| H=(in m) | 21.7 | 27.0 | 21.3 |

*Specific Thrust Pressure [Eq. 24]:*

| | | | |
|---|---|---|---|
| p=(in kg/m²) | 3716 | 4754 | 3631 |

*Maximum Specific Weight [Eq. 18]:*

| | | | |
|---|---|---|---|
| $\gamma_{max}$= (in kg/m³) | 326 | 360 | 323 |

*Runout Distance [Eq. 21]:*

| | | | |
|---|---|---|---|
| s=(in m) | 82 | 151 | 125 |

**Discussion**

In a previous study, Borland (1973) determined the following runout distances: Path T1, 67 m; T2, 95 m; and T3-6, 100-106 m. Borland used Voellmy's equations with assumed values of $\xi$ and $\mu$ as suggested by Voellmy. He computed velocities and discharges from careful analyses of each of several channel cross sections. Effects of the previously mentioned bench were accounted for by assuming that approximately 20 percent of the total volume was retained on the slope. Flow height (approximately 2.8 m) was based on a frequency analysis of Soil Conservation Service snow-course data. Assumed recurrence interval was 100 years.

## Case Study No. 9—Parry Peak—Gordon Gulch Avalanches

**Highway 82, west of Twin Lakes, Colorado**

**Location**
Twin Lakes, Colorado.

**Catchment Basin**
Bowl-shaped depression above timberline.

**Track**
Rather broad swale in upper track; adverse slope (91 m in length) located midway in track at confluence with Gordon Gulch; channel constricted somewhat at this point. Vertical drop, approximately 3,000 ft (914 m); length 6,920 ft (2109 m).

**Runout Zone**
Broad valley of Lake Creek.

**Classification**
Large-erratic. Avalanche had not run to highway for approximately 80 years prior to January 21, 1962, when seven people were killed in their homes. Most avalanches are stopped by moraine near midslope which forms a natural barrier (see photo). Climax avalanches in 1962 resulted from near-simultaneous release of the Parry Peak and Gordon Gulch slides which overran adverse slope and reached the valley bottom.

## CALCULATIONS

*Assumptions:*

| | (Parry Peak) | (Gordon Gulch) |
|---|---|---|
| $\xi$ = | 1400 m/s² | 1800 m/s² |
| $\gamma$ = | 200 kg/m³ | 200 kg/m³ |
| $\gamma_o$ = | 200 kg/m³ | 200 kg/m³ |
| $\gamma_f$ = | 800 kg/m³ | 800 kg/m³ |
| h′ = | 2.0 m | 2.5 m |

*Longitudinal Profile:*

(Parry Peak)

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 22.6° |
| 2 | Runout | -18.5° |

(Gordon Gulch)

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 22.3° |
| 2 | Track | 27.5° |
| 3 | Track | 13.5° |
| 4 | Runout | 2.3° |

*Flow Height [Eq. 13]:*

| Reach | (Parry Peak) h′ | (Gordon Gulch) h′ |
|---|---|---|
| | *(m)* | *(m)* |
| 1 | 2.0 | 2.5 |
| 2 | | 2.3 |
| 3 | | 2.9 |

*Terminal Velocity [Eq. 1b and 13]:*

| Reach | (Parry Peak) $V_{max}$ | (Gordon Gulch) $V_{max}$ |
|---|---|---|
| | *(m/s)* | *(m/s)* |
| 1 | 22.1 | 32.6 |
| 2 | | 34.8 |
| 3 | | 27.7 |

*Head [Eq. 23a, with $V_u = 0$]:*

| | | |
|---|---|---|
| H = (in m) | 26.4 | 41.3 |

*Specific Thrust Pressure [Eq. 24]:*

| | | |
|---|---|---|
| p = (in kg/m²) | 6373 | 10,905 |

*Maximum Specific Weight [Eq. 18]:*

| | | |
|---|---|---|
| $\gamma_{max}$ = (in kg/m³) | 433 | 513 |

*Runout Distance [Eq. 21a and Eq. 21]:*

| | | |
|---|---|---|
| s = (in m) | 43 | 257 |

**Discussion**

Available field evidence suggests that Parry Peak slide may have reached the moraine (adverse slope) prior to the Gordon Gulch slide. The smaller Parry Peak slide apparently was not large enough to flow up and over the ridge; however, the debris was sufficient to reduce the adverse gradient. Thus, the snow later released from Gordon Gulch, some 1200 m above the confluence, was able to overrun the debris from the smaller slide, top the ridge, and flow to the valley bottom.

## Case Study No. 10—Hematite Gulch Avalanche

### Highway 110, north of Howardsville, Colorado

**Location**
Northwest of Howardsville, about 5 miles east of Silverton, Colorado.

**Catchment Basin**
Approximately 60 acres (25 ha).

**Track**
Vertical drop, approximately 3,000 ft (914 m); length, approximately 2,200 ft (670 m). Avalanches confined to narrow gully.

**Runout Zone**
Total length on sideslope confined to gully walls approximately 1,300 ft (400 m); thence across broad valley of Animas River.

**Classification**
Medium-erratic.

## CALCULATIONS

*Assumptions:*

$\xi = 800\ m/s^2$
$\gamma = 450\ kg/m^3$
$\gamma_o = 450\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 1.5\ m$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 32° |
| 2 | Track | 24° |
| 3 | Runout | 18° |
| 4 | Runout | 14° |

*Flow Height [Eq. 13]:*

| Reach | h′ |
|---|---|
| | *(m)* |
| 1 | 1.5 Assumed |
| 2 | 1.6 |
| 3 | 1.8 |

*Terminal Velocity [Eqs. 1b and 13]:*

| Reach | $V_{max}$ |
|---|---|
| | *(m/s)* |
| 1 | 19.2 |
| 2 | 17.6 |
| 3 | 16.1 |

*Head [Eq. 23a, with $V_u = 0$]:*
$H = 14.8\ m$

*Specific Thrust Pressure [Eq. 24]:*
$p = 7401\ kg/m^2$

*Maximum Specific Weight [Eq. 23a]:*
$\gamma_{max} = 600\ kg/m^3$

*Runout Distance [Eq. 21]:*
$s = 180$ m in Reach 4

**Discussion**

Field observations agree in general with preliminary calculations for $\gamma_{max}$ and s. Avalanche occurred on May 7, 1975, as a wet slab. Fracture height was 1.5 m, and tapered off to 0.5 m at flanks. Approximately one-fourth of the snow in the starting zone was released. A complete release of snow would produce an avalanche which would overrun the Animas River and be deposited in the valley.

## Case Study No. 11—Battleship Avalanche

### Highway 550, south of Red Mountain Pass, Colorado

**Location**
San Juan Mountains; northeast slope of summit spot elevation, 12,442.

**Catchment Basin**
Three basins on northeast slope; above timberline; 12,200-11,400 ft (3719-3475 m) m.s.l.; 45 acres (18 ha).

**Track**
Narrow gully; vertical drop, 2,500 ft (762 m); length, 5,600 ft (1707 m).

**Runout Zone**
Highway runs 250 ft (76 m) above Mineral Creek on opposite mountain slope. Small, wet snow avalanches stop in Mineral Creek ravine; bad conditions, dry dust avalanches ascend slope and reach highway.

**Classification**
Large-occasional. Seldom reaches highway.

**CALCULATIONS (Nonpowder)**

*Assumptions:*
$\xi = 1800\ m/s^2$
$\gamma_a = 1.25\ kg/m^3$
$\gamma = 200\ kg/m^3$
$\gamma_o = 150\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 2.5\ m$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Starting zone | 30° |
| 2 | Upper track | 26° |
| 3 | Lower track | 18° |
| 4 | Runout zone | -25° |

*Flow Height [Eq. 13]:*

| Reach | h′ | Calculations |
|---|---|---|
| | *(m)* | |
| 1 | 2.5 | Assumed |
| 2 | 2.6 | $\frac{2.5}{h_2'} \cong \left[\frac{\sin 26°}{\sin 30°}\right]^{1/3}$ |
| 3 | 2.9 | $\frac{2.6}{h_3'} \cong \left[\frac{\sin 18°}{\sin 26°}\right]^{1/3}$ |

*Terminal Velocity [Eqs. 1b and 13]:*

| Reach | $V_{max}$ | Calculations |
|---|---|---|
| | *(m/s)* | |
| 1 | 42.2 | $V_1^2 \cong \left(1800\right)\left(2.5\right)\left(1 - \frac{1.25}{200}\right)$ |
| | | $[\sin 30° - 5/V_1 \cos 30°]$ |
| 2 | 40.4 | $\frac{V_1}{V_2} = \left(\frac{\sin 30°}{\sin 26°}\right)^{1/3}$ |
| 3 | 35.9 | $\frac{V_2}{V_3} = \left(\frac{\sin 26°}{\sin 18°}\right)^{1/3}$ |

*Head [Eq. 23a, $V_u = 0$]:*

$$H = h' + V^2/2g \left[1 - \left(\frac{V_u}{V}\right)^2\right]$$

$$= 2.9 + (35.9)^2/2(10)[1\text{-}0]$$

$$H = 2.9 + \frac{1288.81}{20} = 2.9 + 64.44 = 67.34 \text{ m}$$

$$\boxed{H = 67.34 \text{ m}}$$

*Specific Thrust Pressure [Eq. 24]:*

$$p = \gamma_f \left\{[(q/2)^2 + H\, p_o/\gamma_f]^{1/2} - q/2\right\}$$

where

$$q = p_o/\gamma - \left(\frac{H}{2}\right)\left(1 + \frac{\gamma}{\gamma_f}\right)$$

$$= \frac{10{,}000}{200} - \left(\frac{67.34}{2}\right)\left(1 + \frac{200}{800}\right)$$

$$\boxed{q = 7.9}$$

$$p = 800 \left\{\left[\left(\frac{7.9}{2}\right)^2 + \frac{(67.34)(10{,}000)}{800}\right]^{1/2} - \frac{7.9}{2}\right\}$$

$$\boxed{p = 20{,}260 \text{ kg/m}^2}$$

*Maximum Specific Weight [Eq. 18]:*

$$\gamma_{max} = \left[\gamma + \gamma_f \left(\frac{p}{p_o}\right)\right] \Big/ (1 + p/p_o)$$

$$= \left[200 + 800 \left(\frac{20{,}265}{10{,}000}\right)\right] \Big/ \left(1 + \frac{20{,}265}{10{,}000}\right)$$

$$\boxed{\gamma_{max} = 602 \text{ kg/m}^3}$$

*Runout Distance [Eq. 21a]:*

$$s \cong V_3^2 \Big/ \left[2g\left(\frac{5}{V_3}\cos 25° + \tan 25°\right) + V^2 g/\xi h_m\right]$$

where

$$h_m = h_3' + V_3^2\, 4g = 2.9 + \frac{(35.9)^2}{4(10)} = 35.1$$

$$s \cong \frac{(35.9)^2}{2(10)\left(\frac{5}{35.9}.9063 + .4663\right) + \frac{(35.9)^2(10)}{1800(35.1)}}$$

$$\boxed{s \cong 109 \text{ m}}$$

**Discussion**

In February 1958, this avalanche ascended the adverse slope and deposited 5 ft (1.5 m) of snow on the highway. The highway is approximately 600 ft (200 m) up the 25° slope from Mineral Creek. Even a large avalanche (2.5 m crown surface) with a high coefficient of turbulent friction ($\xi = 1800$) will place the avalanche only half way to the highway.

## CALCULATIONS (Powder)

*Assumptions:*

$\xi = 1200 \text{ m/s}^2$
$h = 1.0 \text{ m}$
$h_a = 0.5 \text{ m}$
$\gamma_a = 1.25 \text{ kg/m}^3$
$\gamma_o = 150 \text{ kg/m}^3$
$\gamma_f = 800 \text{ kg/m}^3$
$P_o = 10{,}000 \text{ kg/m}^3$

*Longitudinal Profile:*

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Starting zone | 30° |
| 2 | Upper track | 26° |
| 3 | Lower track | 18° |
| 4 | Runout zone | −25° |

*Specific Weight of Flowing Snow [Eq. 10]:*

| Reach | $\psi$ | $\gamma$ | Calculations |
|---|---|---|---|
| | | *(kg/m³)* | |
| 1 | 30° | 37.5 | $\left[\frac{(1.25)(1200)}{2(10)}\right] \sin 30°$ |
| 2 | 26° | 32.9 | $\left[\frac{(1.25)(1200)}{20}\right] \sin 26°$ |
| 3 | 18° | 23.2 | $\left[\frac{(1.25)(1200)}{20}\right] \sin 18°$ |
| 4 | -25° | | |

*Flow Height [Eq. 9]:*

| Reach | h′ | Calculations |
|---|---|---|
| | *(m)* | |
| 1 | 6.00 | $\frac{150}{37.5}(1.0 + 0.5)$ |
| 2 | 6.84 | $\frac{150}{32.9}(1.0 + 0.5)$ |
| 3 | 9.70 | $\frac{150}{23.2}(1.0 + 0.5)$ |

*Terminal Velocity [Eqs. 11 and 13]:*

| Reach | $V_{max}$ | Calculations |
|---|---|---|
| | *(m/s)* | |
| 1 | 60.0 | $2(10)(1 + 0.5)\left(\frac{150}{1.25}\right)$ |
| 2 | 57.4 | $60/V_2 = \left(\frac{\sin 30}{\sin 26}\right)^{1/3}$ |
| 3 | 51.1 | $57.4/V_3 = \left(\frac{\sin 26}{\sin 18}\right)^{1/3}$ |

*Head [Eq. 23a, with $V_u = 0$]:*

$$H = 9.7 + \frac{(51.1)^2}{2(10)}$$

$$\boxed{H = 140.26 \text{ m}}$$

*Specific Thrust Pressure [Eq. 24]:*

$$p = \gamma_f \left\{ [(q/2)^2 + H\, p_o/\gamma_f]^{1/2} - q/2 \right\}$$

where

$$q = p_o/\gamma - \frac{H}{2}\left(1 + \gamma/\gamma_f\right)$$

$$q = \frac{10{,}000}{23.2} - \frac{140.26}{2}\left(1 + \frac{23.2}{800}\right)$$

$$\boxed{q = 358.87}$$

$$p = 800 \left\{ \left[\left(\frac{358.87}{2}\right)^2 + (140.26)\,\frac{10{,}000}{800}\right]^{1/2} - \frac{358.87}{2} \right\}$$

$$\boxed{p = 3857 \text{ kg/m}^2}$$

*Maximum Specific Weight [Eq. 18]:*

$$\gamma_{max} = \frac{\left[\gamma_o + \gamma_f\left(\frac{p}{p_o}\right)\right]}{1 + \frac{p}{p_o}}$$

$$= \frac{150 + 800\left(\frac{3857}{10{,}000}\right)}{1 + \frac{3857}{10{,}000}}$$

$$\boxed{\gamma_{max} = 331 \text{ kg/m}^3}$$

*Runout Distance [Eq. 21a]:*

$$s \cong \frac{V^2}{2g(\mu \cos \psi_u + \tan \psi_u) + \frac{V^2 g}{\xi h_m}}$$

(For a powder avalanche, let $\mu \to 0$)

where

$$h_m = h' + \frac{V^2}{4g}$$

$$h_m = 9.7 + \frac{(51.1)^2}{4(10)}$$

$$h_m = 74.98 \text{ or } 75 \text{ m}$$

$$s = \frac{(51.1)^2}{2(10)(\tan 25) + \frac{(51.1)^2(10)}{(1200)(75)}}$$

$$= \frac{2611.21}{9.62}$$

$$\boxed{s = 271 \text{ m}}$$

**Discussion**

This is more than enough runout distance to reach the road, even though a crown face of only 1 m and a turbulent friction coefficient ($\xi$) of 1200 m/s² were used.

## Case Study No. 12—Ironton Park Avalanche

### Highway 550, north of Red Mountain Pass, Colorado

**Location**
San Juan Mountains; southeast slope of Hayden Mountain.

**Starting Zone**
Wide, uniform slope below Half Moon Basin; below timberline; 11,300-10,600 ft (3444-3231 m) m.s.l.; 60 acres (25 ha); starting zone is indefinite.

**Track**
The entire slope; vertical drop, 1,640 ft (500 m); length, 2,800 ft (853 m).

**Runout Zone**
Level bottom of Ironton Park; large avalanches have traveled over the flat ground to the highway—a distance of 1,050 ft (320 m).

**Avalanches**
Avalanches of 1958 reached the road and crossed it.

**Classification**
Large-erratic.

### CALCULATIONS

***Assumptions:***

$\xi = 1400\ m/s^2$
$\gamma_a = 1.25\ kg/m^3$
$\gamma = 200\ kg/m^3$
$\gamma_o = 200\ kg/m^3$
$\gamma_f = 800\ kg/m^3$
$h' = 2.0\ m$

***Longitudinal Profile:***

| Reach | Description | Slope angle |
|---|---|---|
| 1 | Track | 31° |
| 2 | Runout | 0° |

***Terminal Velocity [Eq. 1b]:***
$V_{max} = 32.7\ m/s$

***Head [Eq. 23a, with $V_u = 0$]:***
$H = 55.5\ m$

***Specific Thrust Pressure [Eq. 24]:***
$p = 15{,}806\ kg/m^2$

***Maximum Specific Weight [Eq. 18]:***
$\gamma_{max} = 567\ kg/m^3$

***Runout Distance [Eq. 21]:***
$s = 321\ m$

**Discussion**
On one occasion, debris was deposited to a depth of 5 ft (1.5 m) on the road, some 1,050 ft (320 m) from the slope. With the assumptions made above, the computed runout distance is 1,054 ft (321 m).

## CONCLUSIONS

Although the calculations in Part II are by no means a comprehensive analysis of specific avalanche hazards, they do illustrate application of the more important equations in Part I. If carefully applied, they will provide a realistic quantitative assessment of avalanche hazards in terms of runout distance and the impact forces upon obstacles in the runout.

It is again emphasized that several of the avalanches in Part II are capable of running much larger than the calculations in this report show. For example, while the Stanley avalanche (Case Study No. 3) is classified as "medium-frequent," it is capable of running to the slope on the opposite side of the valley and generating specific thrust pressures in excess of 21,000 kg/m$^2$.

The assumptions in Part II should be considered preliminary and subject to refinement. A complete engineering study should include: (1) careful frequency analyses; (2) calculation of snow volumes in the starting zone and track; (3) detailed cross-section and profile measurements, with velocities computed in terms of R and D rather than h′; and (4) the lateral extent of debris in the runout. Given the limited field data, more detailed calculations were not justified in the case studies presented in this report.

A word on the selection of an appropriate coefficient of turbulent friction, $\xi$, may be in order at this point. In Part II, $\xi$ was varied from a maximum of 1800 m/s$^2$ for Battleship (Case Study No. 11) to a low of 500 m/s$^2$ for Timber Falls T1, T2 (Case Study No. 8). Schaerer (1975b) suggests the following values of $\xi$ based on track and roughness:

| | |
|---|---|
| Smooth snow cover, no trees | 1200-1800 m/s$^2$ |
| Average, open mountain slope | 500-750 m/s$^2$ |
| Average gully | 400-600 m/s$^2$ |
| Boulders, trees, forest | 150-300 m/s$^2$ |

Data are still insufficient to provide an objective basis for selecting this important parameter. However, enough field observations have been generated to indicate that for some purposes—such as zoning—calculations should be based on relatively high values of $\xi$ to simulate major events. On the other hand, a lower estimate of $\xi$ may be justified in cases where more "average" conditions are needed. For example, $\xi$ = 800 m/s$^2$ may be a reasonable assumption for many of the avalanches on the Stanley path (Case Study No. 3). However, this particular avalanche is capable of running very large under certain conditions. For these occurrences, an estimate of $\xi$ = 1400 to 1800 m/s$^2$ is justified.

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## APPENDIX A

### Measurement Systems

The calculations in this paper are based on an engineering or *gravitational* system of measurements. Because of the recent adoption in the United States of the *Systems International d'Units* (SI), which is an absolute system of measurement (ASTM 1972), a short discussion of measurement systems might be helpful.

### Types of Measurement Systems

There are two basic types of measurement systems, gravitational and absolute. Gravitational systems are based on the fundamental quantities of length, *weight*, and time. Absolute systems are based on the fundamental quantities of length, *mass*, and time. In both types, additional quantities such as acceleration, force, pressure, and density are derived from the fundamental quantities. The primary difference between gravitational and absolute systems is the change from weight to mass as one of the fundamental quantities.

The following are several reasons for the confusion that exists about measurement systems:

1. The rather hazy distinction between mass and weight that many people have.
2. The complication that arises from the use of two units of measurement—metric and British in addition to the two basic types of systems—gravitational and absolute.
3. The use of the same word (gram in cgs version of metric, and pound in the British units) to mean a unit of *mass* when used in the absolute system and a unit of force (*weight*) when used in the gravitational system.
4. The generally overlooked fact that there is only a slight variation in gravity from place to place on earth which has led to the calibration of most metric scales and balances to give *mass* rather than weight in spite of the common use of the term weight to describe the value.

### Mass and Weight

The *mass* of a body is a measure of the amount of material in it as evidenced by the body's inertia—or resistance to change of motion. It is constant unless matter is added or removed from the body. It is also independent of location but not completely independent of velocity. The fundamental unit of mass is the kilogram which is represented by the kilogram prototype—a platinum alloy block kept in France.

The *weight* of a body is the *force* with which that body is attracted toward the center of the earth. A free falling body is acted on only by the force of its own weight which is the product of the mass of the body times the acceleration of gravity (g) at that place. Hence the weight of a body will change from place to place but at any location weight/g = mass. Although somewhat redundant some authors use the expressions pound-force (lbf), gram-force (gf), and kilogram-force (kgf) to emphasize the fact they are working with units of weight in a gravitational or engineering system of measurements.

### Force, Density, Specific Weight, and Pressure

From Newton's second law,

$$F = k\,ma \qquad [A1]$$

where force (F), mass (m), and acceleration (a) can be in any units, provided the proper value is assigned to k. More commonly equation [A1] is shortened to

$$F = ma \qquad [A2]$$

and sets of units are used in which one of the units is defined to make k=1. Three examples of this follow:

1. A *newton* is defined as the force that will give a 1-kilogram mass an acceleration of 1 meter per second$^2$ (m/s$^2$) (SI—one of the metric absolute systems).
2. A *dyne* is defined as the force that will give a 1-gram mass an acceleration of 1 centimeter per second$^2$ (cm/s$^2$) (cgs—another metric absolute system).
3. The *slug* is defined as the mass to which a force of 1 pound will give an acceleration of 1 foot per second$^2$ (ft/s$^2$) (the British gravitational system).

The equation,

$$F = Wa/g \qquad [A3]$$

is valid for any units so long as the force, F, and weight, W, are expressed in the same units of force, and a and g are in the same units of acceleration.

Some of these points are illustrated in the following tabulation:

| Name of system | Unit of mass | Unit of force | Unit of acceleration |
|---|---|---|---|
| SI (mks) absolute | kilogram | newton | $m/s^2$ |
| cgs absolute | gram | dyne | $cm/s^2$ |
| cgs gravitational | weight/g (no name) | gram | $cm/s^2$ |
| British absolute | pound | poundal | $ft/s^2$ |
| British gravitational | slug | pound | $ft/s^2$ |
| Any system | weight/g | same units as used for weight | same units as used for g |

In the tabulation above, g is acceleration due to gravity ($9.8\ m/s^2 = 980\ cm/s^2 = 32\ ft/s^2$. The mks system uses meters, kilograms, and seconds as units of measurement, whereas the cgs system uses centimeters, grams, and seconds as units of measurement.

These are some of the basic concepts in measurement systems. It is important to understand, however, that the variation is gravity from place to place on earth is so small (about 0.5 percent from equator to the poles and less than that from sea level to the top of Mt. Everest) that special instruments are needed to measure it. Although these small differences are important for certain types of geophysical exploration, they are of no practical concern for most engineering and avalanche problems. Hence the acceleration due to gravity for all locations on earth can be considered constant. An additional and *very important* thing that is not commonly understood is that metric spring scales and balances are calibrated to give mass rather than weight. This is not true, however, for the British measurement units. **Metric spring scales have been calibrated so they give W/g directly.** The effect of gravity cancels out when an object is weighed on a balance because both sides of the balance are subjected to the same gravitational force. As a result, the units read from a balance are mass and not weight since most sets of "weights" are manufactured to be equivalent to laboratory standards of mass.

*Density*, $\rho$, is defined as mass per unit volume and *specific weight*, $\gamma$, as weight per unit volume. In this paper we have followed the lead of Voellmy and used specific weight. This means that *pressures* which are merely force per unit area, will be in $kgf/m^2$. In the British gravitational system, pressure is usually expressed as pounds-force/$ft^2$ abbreviated as psf. In the SI, pressure would be expressed as newtons/$m^2$.

$$1\ kgf = 1\ kg \times 9.8\ m/s^2 = 9.8\ \text{newtons}$$

The following examples illustrate some of the above points:

If a cube of snow $0.01\ m^3$ ($\cong 0.22$ m on a side) is found to weigh 2.7 kg, what is its specific weight, $\gamma$, and its density, $\rho$?

$$\gamma = 2.7\ kgf \times 100 = 270\ kgf/m^3$$

To get to density, first multiply by 9.8 newtons/kgf to get newtons.

$$270\ kgf \times 9.8\ \text{newtons/kgf} = 2646\ \text{newtons}$$

Now, since F = ma or F = mg,

$$2646\ \text{newtons} = m \times 9.8\ m/s^2$$

$$m = 2646/9.8 = 270\ kg$$

from the definition of a newton.

Thus the specific weight expressed in kgf is numerically equivalent to density expressed as $kg/m^3$.

If a block of the above snow, 1.6 m on a side ($\cong 4.0\ m^3$ volume), slides down a slope with an acceleration of $4.9\ m/s^2$ and hits a long, tall wall at right angles to the flow, what is the force, F, on the wall? What is the pressure, p, on the wall?

$$F = (W/g)a$$

where

$$W = 270\ kfg/m^3 \times 4\ m^3$$

$$F = \frac{(270)(4)(4.9)}{9.8} = 540\ kgf$$

$$p = 540/1.6 \times 1.6 = 211\ kgf/m^2$$

$$\underline{\times 9.8}\ \text{newtons/kgf}$$

$$2067\ \text{newtons}/m^2$$

or in the SI,

$$F = ma$$

where

$$m = 270\ kg/m^3 \times 4\ m^3$$

$$F = (270)(4)(4.9) = 5292\ \text{newtons}$$

$$p = \frac{5295}{(1.6)(1.6)} = 2067\ \text{newtons}/m^2$$

## APPENDIX B

### Hand Calculator Programs for Several Avalanche Dynamics Equations

The following programs for the H-P 65 have been found useful for solving the equations listed below:

**Avalanche velocity V [Eq. 1b]:**

$$V = \sqrt{\xi h' (\sin\psi - \frac{5}{V}\cos\psi)}$$

The term $(1 - \gamma_a/\gamma)$ in the more complete equation is considered negligible.

**Avalanche runout distance, s [Eq. 21]:**

$$s \cong V_{LT}^2/[2g(\mu\cos\psi_u - \tan\psi_u) + V_{LT}^2 g/\xi h_m]$$

where
$h_m = h' + V^2/4g$
$\mu = 5/V_{LT}$
$V_{LT}$ = velocity in lower track

**Avalanche runout distance, s′:**
A modification of Eq. [21] to allow for a slowing of velocity and an increase in $\mu$ to a maximum of 0.5 in the runout zone.

**Head, H [Eq. 23a]:**

$$H = h'_{LT} + (V_{LT}^2/2g)[1 - (V_u/V_{LT})^2]$$

where
$V_u$ = 0 = final velocity
$h'_{LT}$ & $V_{LT}$ = flow height and velocity in lower track

**Specific thrust pressure, p [Eq. 24]:**

$$p = \gamma_f \left\{ [(q/2)^2 + H p_o/\gamma_f]^{1/2} - q/2 \right\}$$

where

$$q = p_o/\gamma - (H/2)(1 + \gamma/\gamma_f)$$

**Maximum specific weight, $\gamma_{max}$ [Eq. 18]:**

$$\gamma_{max} = [\gamma_o + \gamma_f(p_d/p_o)]/(1 + p_d/p_o)$$

where
$p_d$ = p from eq. [24]

**Test Cases** (HP-65 Program Form 3)

| | A | B |
|---|---|---|
| In register 8 | 0 | 0 |
| In register 3 ($h'_{LT}$) | 2.8 m | 2.8 m |
| In register 4 ($\xi$) | 1200 m/s² | 1200 m/s² |
| In register 6 ($\psi_u$) | -20° | -20° |
| In register 7 (max $\mu$) | 0.5 | 0.3 |
| Key in ($V_{LT}$) | 30.1 m/s | 30.1 m/s |
| Avalanche runout distance, s′ | **= 68.19 m** | **= 58.51 m** |
| Running time | ≅ 45 s | ≅ 25 s |

Program modified from one developed by A. Mears.

**Test Case** (HP-65 Program Form 4)

In register 1 $\gamma_o = 150$ kg/m³
In register 2 $V_{LT} = 30.1$ m/s
In register 3 $h_{LT} = 2.8$ m
In register 4 $\gamma_f = 800$ kg/m³

**Head, H = 48.10 m**
Running time ≅ 3 s

**Specific thrust pressure, p = 9599.64 kg/m²**
Running time ≅ 5 s

**Maximum specific weight, $\gamma_{max}$ = 468.36 kg/m³**
Running time ≅ 2 sec

## 1 HP-65 Program Form

Title AVALANCHE VELOCITY: $V = \sqrt{E h' (\sin\psi - \mu \cos\psi)}$ where: $\mu = 5/V$ Page 1 of 1

SWITCH TO W/PRGM PRESS f PRGM TO CLEAR MEMORY

| KEY ENTRY | CODE SHOWN | COMMENTS |
|---|---|---|
| | 00 00 | |
| 1 | 01 | |
| 0 | 00 | |
| 0 | 00 | |
| 0 | 00 | |
| 0 | 00 | |
| STO 6 | 33 06 | |
| . | 83 | .05 initial μ |
| 0 | 00 | |
| 5 | 05 | |
| STO 2 | 33 02 | |
| LBL | 23 | |
| A | 11 | |
| RCL 1 | 34 01 | |
| ENT | 41 | |
| f | 31 | |
| SIN | 04 | sin ψ |
| g x⇄y | 35 07 | |
| f | 31 | |
| COS | 05 | cos ψ |
| RCL 2 | 34 02 | |
| X | 71 | |
| − | 51 | |
| RCL 3 | 34 03 | |
| X | 71 | |
| . | 83 | |
| 5 | 05 | |
| g | 35 | |
| $y^x$ | 05 | |
| STO 4 | 33 04 | 1st estimate of Velocity |
| 5 | 05 | |
| g x⇄y | 35 07 | |
| ÷ | 81 | |
| STO 5 | 33 05 | new μ Value |
| RCL 4 | 34 04 | |
| 1 | 01 | |
| 0 | 00 | |
| 0 | 00 | |
| X | 71 | |
| f | 31 | Integer of 100 (velocity) |
| 83 | 83 | |
| RCL 6 | 34 06 | |
| g x≤y | 35 22 | |
| GTO | 22 | |
| B | 12 | |
| g x⇄y | 35 07 | |
| STO 6 | 33 06 | new Velocity |
| RCL 5 | 34 05 | |
| STO 2 | 33 02 | Replacing old μ with new |
| GTO | 22 | |

| KEY ENTRY | CODE SHOWN | COMMENTS |
|---|---|---|
| A | 11 | |
| LBL | 23 | |
| B | 12 | |
| RCL 4 | 34 04 | |
| R/S | 84 | |
| RTN | 24 | |
| NOP | 3501 | |
| NOP | 3501 | |

μ = 0.05 is programmed into R2. This will work for velocities up to 100 m/s

For velocities < 45 m/s a manual entry of 0.1 in register 2 will speed calculations of velocity.

To Run Program.

Store slope angle ψ in R1

Store h'E in R3

Hit RTN & R/S

Test Case:

ψ = 31°

h' = 2.5 m

E = 1200 m/s

(h'E = 3000)

$\boxed{\text{Velocity} = 34.19 \text{ m/s}}$

Running Time ≈ 25 sec.

Program modified from one developed by A. Miars.

| REGISTERS | |
|---|---|
| R1 | ψ |
| R2 | μ = .05 |
| R3 | h'E |
| R4 | |
| R5 | |
| R6 | |
| R7 | |
| R8 | |
| R9 | |
| LABELS | |
| A | |
| B | |
| C | |
| D | |
| E | |
| 0 | |
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| 6 | |
| 7 | |
| 8 | |
| 9 | |
| FLAGS | |
| 1 | |
| 2 | |

9320-0616

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## 2 HP-65 Program Form

Title AVALANCHE RUNOUT DISTANCE (s) in meters Page 1 of 1

SWITCH TO W/PRGM PRESS f PRGM TO CLEAR MEMORY

| KEY ENTRY | CODE SHOWN | COMMENTS |
|---|---|---|
| | 00 00 | |
| LBL | 23 | |
| A | 11 | |
| RCL 1 | 34 01 | $V_{LT}^2$ |
| ENT | 41 | |
| ENT | 41 | |
| 4 | 04 | |
| 0 | 00 | |
| + | 81 | $V_{LT}^2/4g$ |
| RCL 4 | 34 04 | |
| + | 61 | $h'_{LT} + V^2/4g$ |
| RCL 3 | 34 03 | E |
| X | 71 | |
| ÷ | 81 | |
| 1 | 01 | |
| 0 | 00 | |
| X | 71 | |
| STO 5 | 33 05 | $V_{LT}^2 g / E(h'_{LT} + \frac{V_{LT}^2}{4g})$ |
| RCL 2 | 34 02 | |
| f | 31 | |
| COS | 05 | |
| 5 | 05 | |
| X | 71 | |
| RCL 1 | 34 01 | |
| f | 31 | |
| √x | 09 | |
| ÷ | 81 | |
| RCL 2 | 3402 | |
| f | 31 | |
| tan | 06 | |
| − | 51 | |
| 2 | 02 | |
| 0 | 00 | |
| X | 71 | |
| RCL 5 | 34 05 | |
| + | 61 | |
| RCL 1 | 34 01 | |
| g x⇄y | 35 07 | |
| ÷ | 81 | |
| R/S | 84 | |
| RTN | 24 | |
| NOP | 3501 | |
| NOP | 3501 | |

$$s = \frac{V_{LT}^2}{2g[\mu \cos\psi_u - \tan\psi_u] + \frac{V_{LT}^2 g}{E(h'_{LT} + \frac{V_{LT}^2}{4g})}}$$

Let: g = 10 m/s² & μ = 5/$V_{LT}$

To Run Program:

STORE: Vel.² in down track in 1, slope of runout in 2, E in 3, flow ht. in lower track in 4

Hit RTN & R/S

REMEMBER!

when $\psi_u$ is negative (adverse grade in runout zone) hit the CHS key after the slope angle and before the STO 02.

Test Case:

$V_{LT}^2 = (30.1 \text{ m/s})^2 = 906.01$

$\psi_u = -20°$

E = 1200 m/s²

$h'_{LT}$ = 2.8 m

$\boxed{s = 84.69 \text{ m}}$

Running time ≈ 5 sec.

| REGISTERS | |
|---|---|
| R1 | $V_{LT}^2$ |
| R2 | $\psi_u$ |
| R3 | E |
| R4 | $h'_{LT}$ |
| R5 | |
| R6 | |
| R7 | |
| R8 | |
| R9 | |
| LABELS | |
| A | |
| B | |
| C | |
| D | |
| E | |
| 0 | |
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| 6 | |
| 7 | |
| 8 | |
| 9 | |
| FLAGS | |
| 1 | |
| 2 | |

9320-0616

TO RECORD PROGRAM INSERT MAGNETIC CARD WITH SWITCH SET AT W/PRGM

## 3 HP-65 Program Form

Title: AVALANCHE RUNOUT DISTANCE -- Allowing Velocity to slow down and $\mu$ to increase to 0.5 in runout zone  Page 1 of 2

SWITCH TO W/PRGM PRESS [f] [PRGM] TO CLEAR MEMORY

| KEY ENTRY | CODE SHOWN | COMMENTS |
|---|---|---|
| | 00 00 | |
| LBL | 23 | |
| 3 | 03 | |
| STO 1 | 33 01 | Velocity in lower track |
| ENT | 41 | |
| X | 71 | |
| STO 2 | 33 02 | $V_{L.T.}^2$ |
| 4 | 04 | |
| 0 | 00 | |
| ÷ | 81 | |
| RCL 3 | 34 03 | |
| + | 61 | |
| RCL 4 | 34 04 | |
| X | 71 | $E(h'_{L.T.} + V^2/4g)$ |
| RCL 2 | 34 02 | $V^2$ |
| x⇄y | 35 07 | |
| ÷ | 81 | |
| 1 | 01 | |
| 0 | 00 | |
| X | 71 | |
| STO 5 | 33 05 | |
| 5 | 05 | |
| RCL 1 | 34 01 | |
| ÷ | 81 | |
| RCL 7 | 34 07 | |
| x⇄y | 35 07 | |
| x>y | 35 24 | |
| GTO | 22 | |
| 4 | 04 | |
| RCL 6 | 34 06 | |
| f | 31 | |
| cos | 05 | Cos |
| X | 71 | |
| RCL 6 | 34 06 | |
| f | 31 | |
| tan | 06 | |
| − | 51 | |
| 2 | 02 | |
| 0 | 00 | |
| X | 71 | |

| KEY ENTRY | CODE SHOWN | COMMENTS |
|---|---|---|
| RCL 5 | 34 05 | |
| + | 61 | |
| RCL 2 | 34 02 | |
| x⇄y | 35 07 | |
| ÷ | 81 | $s = 84.69$ |
| . | 83 | } .2 may use other decimal values |
| 2 | 02 | |
| X | 71 | |
| STO | 33 | |
| + | 61 | |
| 8 | 08 | |
| . | 83 | } if .2 is changed above this must change so the two add to 1.0 |
| 8 | 08 | |
| RCL 2 | 34 02 | |
| X | 71 | |
| f | 31 | |
| √x | 09 | |
| GTO | 22 | |
| 3 | 03 | |
| LBL | 23 | |
| 4 | 04 | |
| RCL 8 | 34 08 | |
| R/S | 84 | |

TO RUN PROGRAM:

STORE: $h'_{L.T.}$ in 3
$E$ in 4
$\psi_u$ in 6
max $\mu$ in 7
0 in 8

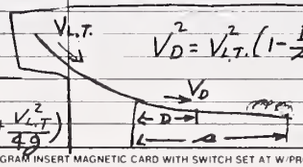
Key in: Velocity (in lower track)

Hit: RTN & R/S

REMEMBER:

Key 0 into R8 each run
Hit CHS when $\psi$ is −

$$s' = \frac{V_{L.T.}^2}{2g[\mu \cos\psi_u - \tan\psi_u] + \frac{V_{L.T.}^2 g}{E(h'_{L.T.} + \frac{V_{L.T.}^2}{4g})}}$$




$$V_D^2 = V_{L.T.}^2\left(1 - \frac{D}{s}\right)$$

REGISTERS: R1 $V_{L.T.}$; R2 $V_{L.T.}^2$; R3 $h'_{L.T.}$; R4 $E$; R5 $\frac{V_{L.T.}^2 g}{E(h'_{L.T.} + \frac{V^2}{4g})}$; R6 $\psi_u$; R7 max $\mu$ (.5); R8 $s$ set to 0 for each Run; R9

LABELS: A B C D E 0 1 2 3 4 5 6 7 8 9

FLAGS: 1 2

9320-0616  TO RECORD PROGRAM INSERT MAGNETIC CARD WITH SWITCH SET AT W/PRGM

## 4 HP-65 Program Form

Title: AVALANCHE HEAD (H); SPECIFIC PRESSURE (P) and MAXIMUM SPECIFIC WEIGHT ($\gamma_{max}$)  Page 1 of 2

SWITCH TO W/PRGM PRESS [f] [PRGM] TO CLEAR MEMORY

| KEY ENTRY | CODE SHOWN | COMMENTS |
|---|---|---|
| | 00 00 | |
| 1 | 01 | } 10,000 = $\rho_0$ |
| 0 | 00 | |
| 0 | 00 | |
| 0 | 00 | |
| 0 | 00 | |
| STO 7 | 33 07 | |
| RCL 2 | 34 02 | |
| ENT | 41 | |
| X | 71 | |
| 2 | 02 | |
| 0 | 00 | |
| ÷ | 81 | |
| RCL 3 | 34 03 | |
| + | 61 | |
| R/S | 84 | HEAD in meters |
| STO 5 | 33 05 | |
| RCL 1 | 34 01 | |
| RCL 4 | 34 04 | |
| ÷ | 81 | |
| 1 | 01 | |
| + | 61 | |
| x⇄y | 35 07 | |
| 2 | 02 | |
| ÷ | 81 | |
| X | 71 | |
| RCL 7 | 34 07 | |
| RCL 1 | 34 01 | |
| + | 81 | |
| x⇄y | 35 07 | |
| CHS | 42 | |
| + | 61 | |
| STO 6 | 33 06 | } value |
| 2 | 02 | |
| ÷ | 81 | |
| ENT | 41 | |
| X | 71 | |
| RCL 5 | 34 05 | |
| RCL 7 | 34 07 | |
| X | 71 | |
| RCL 4 | 34 04 | |
| ÷ | 81 | |
| + | 61 | |
| . | 83 | |
| 5 | 05 | |
| 9 | 35 | |
| $y^x$ | 05 | |
| RCL 6 | 34 06 | |
| 2 | 02 | |
| ÷ | 81 | |

| KEY ENTRY | CODE SHOWN | COMMENTS |
|---|---|---|
| CHS | 42 | |
| + | 61 | |
| RCL 4 | 34 04 | |
| X | 71 | |
| R/S | 84 | Specific Pressure Kg/m² |
| STO 8 | 33 08 | |
| RCL 7 | 34 07 | |
| ÷ | 81 | |
| RCL 4 | 34 04 | |
| X | 71 | |
| RCL 1 | 34 01 | |
| + | 61 | |
| RCL 8 | 34 08 | |
| RCL 7 | 34 07 | |
| ÷ | 81 | |
| 1 | 01 | |
| + | 61 | |
| ÷ | 81 | |
| R/S | 84 | MAX. SP. Weight in Kg/m³ |
| RTN | 24 | |

TO RUN PROGRAM:

STORE: $\gamma_0$ in R1
$V_{L.T.}$ in R2
$h'_{L.T.}$ in R3
$\gamma_f = 800$ in R4

HIT: RTN & R/S

First Number is H in m

HIT: R/S
NEXT Number is SP. Pres in Kg/m²

HIT: R/S
NEXT Number is $\gamma_{max}$ in Kg/m³

DO NOT USE THIS PROGRAM FOR SPECIFIC PRESSURE OR MAXIMUM SPECIFIC WEIGHT FOR POWDER AVALANCHES!

REGISTERS: R1 $\gamma_0$ Initial S.P. wt. (dens); R2 $V_{L.T.}$; R3 $h'_{L.T.}$; R4 $\gamma_f = 800$; R5; R6; R7; R8; R9

LABELS: A B C D E 0 1 2 3 4 5 6 7 8 9

FLAGS: 1 2

9320-0616  TO RECORD PROGRAM INSERT MAGNETIC CARD WITH SWITCH SET AT W/PRGM

(SEE TEST CASES ON PAGE 47)

## APPENDIX C

### List of Symbols

$A$ = cross-sectional area (of avalanche track) in $m^2$

$B$ = width of avalanche path eq. [29]

$b$ = width of an obstacle in an avalanche path of width B eq. [29]

$C$ = Chezy resistance coefficient

$C_D$ = dimensionless drag coefficient

$C_L$ = dimensionless lift coefficient

$c_p$ = specific heat of air for constant pressure

$c_v$ = specific heat of air for constant volume

$D$ = hydraulic depth (A/T*) in meters

$F_D$ = drag force on an obstacle in kg

$F_L$ = lift force on an obstacle in kg

$g$ = acceleration due to gravity (9.8 or $\cong$ 10 $m/s^2$)

$H$ = total energy head, in meters

$H'$ = damming height

$H^*$ = mean height of air parcel in meters

$h$ = vertically measured crown surface (fracture face) in the starting zone, in meters

$h'$ = vertically measured height of flowing snow, in meters. $h' \cong R$ for wide channels

$h'_n$ and $h'_{n-1}$ = flow height of moving snow on the upper slope (n) and on the lower slope (n−1)

$h'_u$ = flow height in runout zone

$h^*$ = height on an obstacle where upthrust is to be computed, in meters

$h_D$ = depth of avalanche debris, in meters

$h_a$ = height (depth) of natural snow lying in front and below an avalanche that is entrained in the avalanche, in meters

$h_m$ $\cong$ mean flow height in the runout zone and is equal to $h' + V^2/4g$ when the debris is piled into a short, high cone

$h_o$ = flow height in section of the track just uphill from runout zone

$h_{max}$ = maximum height of dammed snow in runout zone $h_{max} = h_o + \Delta h$

kgf = kilogram weight or force

$m$ = mass. In engineering system of units m = weight/g

$n$ = Manning's roughness coefficient

$P$ = total force on an object, in kg

$P^*$ = "wetted" perimeter (of avalanche track), in meters

$P_H$ = total dynamic thrust per meter of width on a horizontal roof overrun by an avalanche

$p$ = specific thrust pressure in $kg/m^2$

$p^*$ = specific pressure at a depth z below surface of the avalanche

$p_d$ = dynamic overpressure due to compression as the avalanche stops (greater than $p_o$ = 1 atmosphere)

$p_o$ = reference pressure head in Bernoulli's equation—elsewhere atmosphere pressure (approx. 10,000 $kg/m^3$)

$p_v$ = specific upthrust pressure on projecting surfaces $kg/m^2$

$p_{max}$ = maximum possible thrust pressure

$\Delta Q$ = amount of heat transferred

$q$ = an accumulated term in runout distance equation

$$(q = \frac{P_o}{\gamma} - H/2\,(1 + \gamma/\gamma_f)$$

$R$ = hydraulic radius (A/P*), in meters

$R_v$ = uplift on a wall surface $kg/m^2$

$r$ = radius of a circular cylinder

$S$ = slope of avalanche path

$s$ = runout distance of an avalanche from the top of the runout zone, in meters

$s_t$ = distance of travel in meters required for an avalanche to reach 80% of terminal velocity

$s_u$ = transition distance for uniform flow to become reestablished when an avalanche flows over less steep terrain but does not stop

$T$ and $T_o$ = temperature in degrees kelvin

$T^*$ = top width (of avalanche track), in meters

$t$ = time, in seconds

$t^*$ = temperature, in degrees Celsius

$u$ = vertical component of avalanche velocity at height h* when an avalanche hits an obstacle $m/s^2$ (when used as a subscript it refers to the runout zone)

$u_a$ = air velocity (after Mellor 1968)

$u_f$ = velocity of avalanche front in m/s (after Mellor 1968)

$u_w$ = wind velocity toward center of a parcel of moving air in m/s (after Mellor 1968)

$u_1$ = avalanche velocity in m/s (after Mellor 1968)

$V$ = velocity in m/s

$V'$ = velocity at a depth, z, below the surface of all but powder avalanches

$V_n$ and $V_{n-1}$ = velocity along segment n and n-1 of the avalanche path. Same notation applies to h′ and $\psi$.

$V_o$ = velocity in a part of the track that is above a more gently sloping part, m/s

$V_u$ = velocity in the more gently sloping part of the track or runout zone

$V_{max}$ = maximum velocity in m/s

W = heat from friction and compression in kcal/m³ (in appendix A = weight)

Z′ = height in meters above a reference datum

z = depth below surface of all but powder avalanches

$\beta$ = angle between avalanche flow and the surface of an obstacle hit by an avalanche

$\gamma$ = specific weight of flowing snow in kg/m³

$\gamma_a$ = specific weight of air (~ 1.25 kg/m³)

$\gamma_d$ = specific weight of snow as the result of the dynamic compression of pressure, $p_d$, over atmospheric pressure, $p_o$

$\gamma_e$ = effective specific weight of an air-snow mixture kg/m³

$\gamma_f$ = maximum attainable specific weight of snow due to compression in the runout zone in kg/m³

$\gamma_i$ = specific weight of ice (approx. 917 kg/m³)

$\gamma_m$ = average specific weight during compression

$\gamma_o$ = average specific weight of the natural snow cover in starting zone, in kg/m³

$\gamma_s$ = specific weight of snow

$\gamma_u$ = specific weight of deposited snow in runout zone

$\gamma_{max}$ = maximum specific weight after compression by overpressure $p_d$ above $p_o$

$\gamma_1$ = specific weight of flowing snow (from Mellor 1968) equivalent to $\gamma$ in kg/m

$\gamma_2$ = specific weight of snow after impacting the object in kg/m³ (after Mellor 1968)

$\Delta h$ = $V^2/2g$

$\Delta p$ = impact pressure imparted to an obstacle (from Mellor 1968)

$\mu$ = coefficient of kinetic friction, often considered 5/V with maximum value of 0.5 for slow moving avalanches

$\xi$ = coefficient of turbulent friction in m/s²

$\rho$ = density or mass per unit volume (kg/m³)

$\psi$ = slope of avalanche path in degrees

$\psi_n$ and $\psi_{n-1}$ = angle of upper (n) and lower slope (n-1)

$\psi_u$ = slope angle in runout zone



Agriculture—CSU, Fort Collins

Leaf, Charles F., and M. Martinelli, Jr.
1977. Avalanche dynamics: Engineering applications for land use planning. USDA For. Serv. Res. Pap. RM-183, 51 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Voellmy's (1955) avalanche dynamics equations are reviewed and combined with more recent findings of other workers. Equations are used to estimate flow heights, velocities, specific thrust pressure, maximum specific weight of avalanche debris, and runout distance for 12 avalanche case studies from the Colorado Rocky Mountains. Suggestions are made for using this engineering approach for avalanche zoning and land use planning.

**Keywords:** Avalanche dynamics, avalanche zoning, land use planning.

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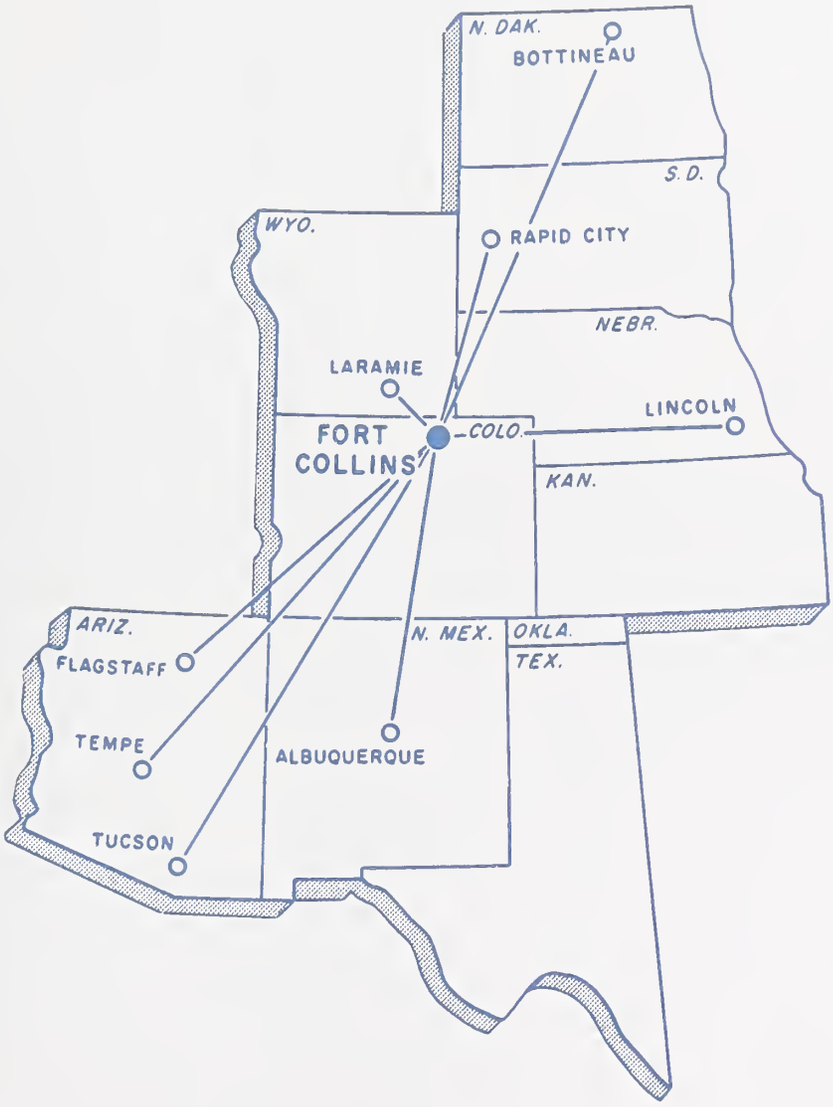
N. DAK.
BOTTINEAU
S. D.
WYO.
RAPID CITY
NEBR.
LARAMIE
LINCOLN
FORT COLLINS
COLO.
KAN.
ARIZ.
N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
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