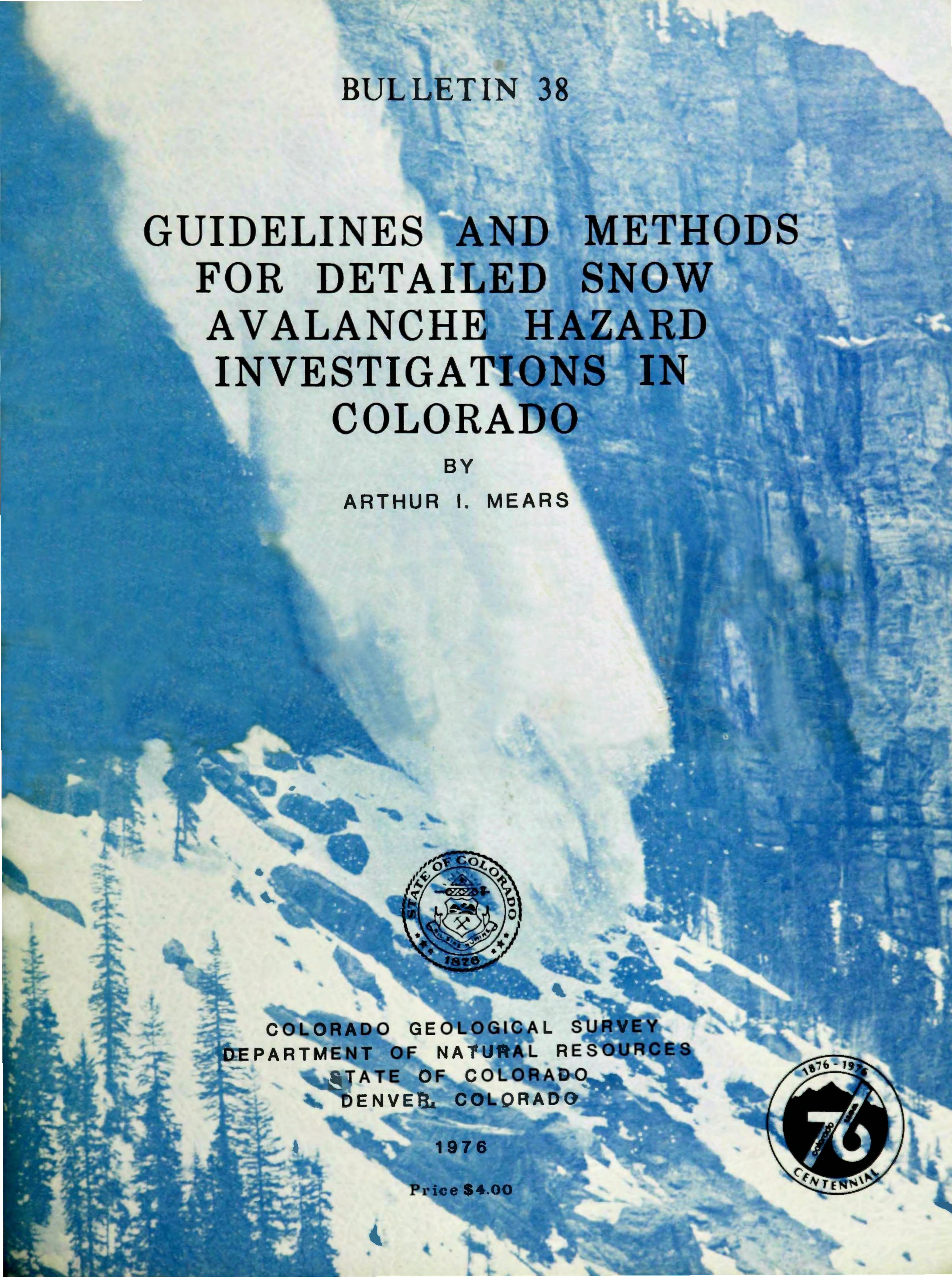

BULLETIN 38

GUIDELINES AND METHODS FOR DETAILED SNOW AVALANCHE HAZARD INVESTIGATIONS IN COLORADO

BY

ARTHUR I. MEARS

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
STATE OF COLORADO
DENVER, COLORADO

1976

Price $4.00

STATE OF COLORADO
Richard D. Lamm, Governor

DEPARTMENT OF NATURAL RESOURCES
Harris D. Sherman,
Executive Director

COLORADO GEOLOGICAL SURVEY
John W. Rold, Director
and State Geologist

MISSION OF THE COLORADO GEOLOGICAL SURVEY

The Colorado Geological Survey was legislatively re-established in February 1969 to meet the geologic needs of the citizens, governmental agencies, and mineral industries of Colorado. This modern legislation is aimed at applying geologic knowledge toward the solution of today's and tomorrow's problems of an expanding population, mounting environmental concern, and the growing demand for mineral resources.

SPECIFIC LEGISLATIVE CHARGES ARE:

"Assist, consult with and advise state and local governmental agencies on geologic problems."

"Promote economic development of mineral resources."

"Evaluate the physical features of Colorado with reference to present and potential human and animal use."

"Conduct studies to develop geological information."

"Inventory the State's mineral resources."

"Collect, preserve and distribute geologic information."

"Determine areas of geologic hazard that could affect the safety of or economic loss to the citizens of Colorado."

"Prepare, publish and distribute geologic reports, maps and bulletins."

"Evaluate the geologic factors affecting all new subdivisions in unincorporated areas of the State."

"Promulgate model geologic hazard area control regulation."

"Provide technical assistance to local governments concerning designation of and guidelines for matters of State interest in geologic hazard areas and the identification of mineral resource areas."

"To provide other governmental agencies with technical assistance regarding geothermal resources."

Cover photographs by Stacy Standley.
Front cover is an avalanche falling in San Miguel County. Back cover is the same avalanche moments later in the runout zone.

BULLETIN 38

GUIDELINES AND METHODS FOR DETAILED SNOW AVALANCHE HAZARD INVESTIGATIONS IN COLORADO

BY

ARTHUR I. MEARS

DOI: https://doi.org/10.58783/cgs.b38.okrg9801

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
STATE OF COLORADO
DENVER, COLORADO

1976

STATE OF COLORADO

RICHARD D. LAMM
GOVERNOR

JOHN W. ROLD
Director

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
254 COLUMBINE BUILDING — 1845 SHERMAN STREET
DENVER, COLORADO 80203 PHONE 892-2611

May 1, 1976

The Honorable Richard D. Lamm
Governor of Colorado

Dear Governor Lamm:

We are pleased to present to you Colorado Geological Survey Bulletin No. 38, "Guidelines and Methods for Detailed Snow Avalanche Hazard Investigations in Colorado."

The Colorado Geological Survey has for some time recognized the existence of locally severe avalanche hazards and their impact on man and his activities in Colorado. Our initial involvement with and growing concern for avalanches resulted from our reviewing subdivision activities under S.B. 35 and other land-use proposals. It is well known that avalanches were a serious hazard to life and property during the early history of the State when mining activities led to extensive development of high mountain areas. During the first half of this century, however, decreased mining activity and related decreasing occupancy of land susceptible to avalanches served to minimize public awareness of this hazard.

Since World War II, rapid growth of the winter recreation industry and mountain residential development have forced the growing mountain populations to consider avalanche hazards in their growth and development planning. Specific recognition of avalanche hazards as geologic hazards and as matters of state concern is contained in H.B. 1041, which was enacted on July 1, 1974. Under that law the Colorado Geological Survey is named as the lead agency for identifying geologic hazards and furnishing related advice and counsel to local governments.

As part of our responsibility under H.B. 1041, we retained a consultant, Mr. Arthur I. Mears, to study and identify avalanche hazards in selected areas of the State. These reports were made available as a series of open-file reports. The present study is an extension of the earlier work and consists of a manual of procedures for detailed evaluation of identified avalanche hazard areas and methods for quantifying risks, design parameters, and mitigation procedures for various kinds of avalanche hazards.

We hope that the attached publication will be useful to land use planners, consultants and others in the evaluation and administration of avalanche hazard areas and will contribute toward safer development in the State's mountainous areas.

Respectfully,

John W. Rold

John W. Rold
Director and State Geologist

William P. Rogers

William P. Rogers, Chief
Engineering and Environmental
Geology Section

JWR/WPR/ls

ACKNOWLEDGEMENTS

This study was one of the objectives of a contract to the author provided through Colorado House Bill 1041, and administered by the Colorado Geological Survey. Administrative liaison and technical assistance by William P. Rogers of the Colorado Geological Survey was invaluable. I would also like to thank John Rold and David Shelton of the Colorado Geological Survey for their assistance.

The U.S. Forest Service, Forest and Range Experiment Station, gave me much helpful advice and assistance throughout the project. Frequent communication with Arthur Judson during the winter and spring of 1974/75 enabled collection of data on avalanches shortly after they occurred. Pete Martinelli reviewed a draft of the manuscript and made many helpful suggestions, particularly in the chapters on avalanche terrain and dynamic equations.

The author benefited greatly from experience gained while working as a consultant to the University of Colorado, Institute of Arctic and Alpine Research (INSTAAR), on a contract designed to delineate and study natural hazards in mountainous regions of Colorado. The contribution of INSTAAR to the field of natural hazard research is a continuing one, and the preparation of this manuscript has benefited from the review of Jack D. Ives, director of INSTAAR.

Edward R. LaChapelle, University of Washington, provided an early review of chapter 4, and a complete review of the entire paper at a later date. His suggestions on chapters 3, 4, 5, and 6, in particular, have been incorporated into the final draft and have been very helpful.

Hans Frutiger of the Swiss Institute for Snow and Avalanche Research provided stimulating and valuable discussion on avalanche dynamics and on the methods of avalanche analysis presently used in Switzerland.

Figure 2-1 was drawn by G. Ladwig, all other figures by S. Zicus, photos taken by A. Mears.

CONTENTS

Chapter 1: Introduction and Scope of Study 1

Chapter 2: Terminology and the Necessary Elements of Avalanche Hazard Analysis

1. Terminology 7
2. General remarks and limitations 10
3. Areal extent of the avalanche path 14
4. Distribution of impact pressures 17
5. Types of avalanches 20
6. Avalanche frequency 20

Chapter 3: The Effect of Terrain on Large Avalanches

1. General remarks 24
2. Topographic conditions conducive to large avalanches 24

Chapter 4: The Areal Extent of the Avalanche Path: Methods of Determination

1. Introduction 38
2. Air photo interpretation of avalanche terrain 38
3. Statistical prediction of avalanche runout distance as related to terrain variables 49
4. Use of dynamic equations of avalanche flow 52
   a. unconfined flowing avalanches 53
   b. use of broken tree data 60
   c. confined avalanches 68
   d. powder avalanches 74
   e. runout zone dynamics 82

Chapter 5: Avalanche Impact

1. Introduction 89
2. Powder avalanche impact 91
3. Powder avalanche air blast 92
4. Impact of dense, flowing avalanches 94
5. Impact pressure variation with depth 95

Chapter 6: Avalanche Frequency

1. Introduction 100
2. Prediction of avalanche size from initial snowpack and weather conditions 103
3. Frequency prediction from past history of avalanching 105
4. Frequency prediction through tree ring analysis 107

Chapter 7: Avalanche Defenses

1. Introduction 113
2. Avalanche defense in the starting zone 113
3. Controlled release of avalanches 114
4. Avalanche control in the runout zone 115
5. Design criteria for runout zone defenses 116
6. Other direct protection defense structures 119

References 123

ILLUSTRATIONS

			Page
Figure	1-1.	Photograph of the Battleship avalanche path near Silverton, Colorado	3
	1-2.	Photograph of runout zone of Battleship avalanche path	4
	1-3.	Photograph of stump of large tree broken in the runout zone of a powder avalanche	5
	1-4.	Photograph of avalanche paths entirely below timberline at Vail, Colorado	6
	2-1.	Drawing showing various elements of a typical Colorado avalanche path	15
	2-2.	Schematic drawing showing general distribution of hazard intensity within a runout zone ..	19
	2-3.	Graph showing impact pressures with various combinations of density and velocity	21
	2-4.	Drawing showing differing chacteristics of dense and powder avalanches	22
	3-1.	Photograph of a wide unconfined avalanche path	25
	3-2.	Photograph of a large, complex avalanche path	25
	3-3.	Photograph of an avalanche path with complex starting zone below timberline	26
	3-4.	Photograph of a long, narrow starting zone below timberline	26
	3-5.	Photograph of avalanche paths starting in timber and flowing over cliffs	27
	3-6.	Schematic drawing of unconfined and confined avalanche paths	32
	3-7.	Schematic drawing showing how cliffs can affect a dry flowing avalanche	33
	3-8.	Map showing how different parts of a runout zone can be affected by wet snow vs. powder avalanches	36

Page

Figure 4-1. Vertical aerial photograph of a large confined avalanche path 40

4-2. Ground photograph of the large avalanche path shown in Figure 4-1 42

4-3. Schematic drawing showing elements of a confined avalanche path and the dimensions used in dynamic calculations 50

4-4. Photograph of unconfined slope avalanche paths in the vicinity of Vail, Colorado 61

4-5. Photograph of a typical broken aspen tree found in avalanche paths of Figure 4-4 61

4-6. Graph of relationship between frequency and diameter of broken trees on paths of Figure 4-4 62

4-7. Graph of avalanche impact pressure wedge, showing location of an equivalent concentrated load 65

4-8. Schematic cross section of an avalanche track showing different depth and configuration for a flowing avalanche and a powder avalanche .. 79

4-9. Photographs of typical damage to trees found in large Colorado avalanches 80

4-10. Graph of relationship of density to velocity at constant pressure for powder avalanches 83

4-11. Graph of runout distance vs. commonly used values for kinetic friction 86

5-1. Graph of powder avalanche stagnation pressures at typical velocities and densities 97

5-2. Graph of dense flowing avalanche impact pressures on wide, rigid obstacles 98

5-3. Theoretical stagnation pressure profile for powder avalanches and flowing avalanches of low density 99

			Page
Figure	7-1.	Schematic drawing of a deflecting structure showing design parameters	121
	7-2.	Diagram of various design forces acting on a deflecting wall	122

CHAPTER 1: INTRODUCTION AND SCOPE OF STUDY

Thousands of snow avalanches occur throughout the Colorado mountains each year, and the potential exists wherever the combination of steep slopes and adequate snowfall occurs. The majority of these avalanches occur in remote mountain areas and do not affect man. This statement will serve to emphasize that the avalanche phenomenon does not become a hazard until man or his effects are involved. However, the degree of hazard depends both on the frequency of occurrence of the avalanche and man's length of exposure to it. Winter recreational use of the backcountry by cross-country skiers and snowmobilers is becoming increasingly popular. These people often travel through areas of avalanche activity, but because of their short time of exposure, accidents are relatively rare. However, as the number of winter backcountry users increases, the number of deaths due to avalanches will also increase. The increase in deaths is due not only to the fact that an increased number of people are exposing themselves to avalanches, but also because a larger number of them are unfamiliar with the hazards and safety precautions necessary for safe use of the mountains in winter. The problem of public awareness is being worked on through a research and education program organized by the U.S. Forest Service. They maintain a network of meteorological and avalanche observation stations throughout the U.S. and issue avalanche warnings when conditions become critical. A selected bibliography of publications relating to this subject is included at the end of this publication.

A second type of problem is encountered on steep slopes at commercial ski areas and on highways or railroads traversing avalanche areas. In this case the total time of exposure may be quite long. However, it is possible for these ski slopes and transportation arteries to be closed while avalanche control operations, such as artificial avalanche release, take place. Consequently, the danger to man from this type of situation can be significantly reduced.

A third problem is caused by the construction of dwellings in the lower parts of avalanche paths that are reached by avalanches only rarely. In this case the time of exposure is very long especially during winter months when people spend a great deal of time indoors. The difficulty in such cases is determining how far this rare avalanche will go and what its destructive force will be. Since avalanches reach their potential limits at infrequent, irregular intervals, and man's direct observational record in most areas is short, it is unlikely that the extreme event will have been observed. Observing and recording the events of a few winters is useless in the delineation of potential hazard unless the extreme event happens to occur during this time.

The objective of this publication is to provide guidelines for evaluating quantitatively the potential size and destructive force of avalanches in Colorado through indirect methods of analysis. Because avalanche dynamics are imperfectly understood, no clear-cut solutions to problems can be offered. Instead, it is continually emphasized that several different, completely independent methods of analysis should be employed simultaneously, thereby reducing the uncertainty inherent in a single method. It is hoped that this publication will not only provide useful guidelines for avalanche analysis, but will also stimulate future research.

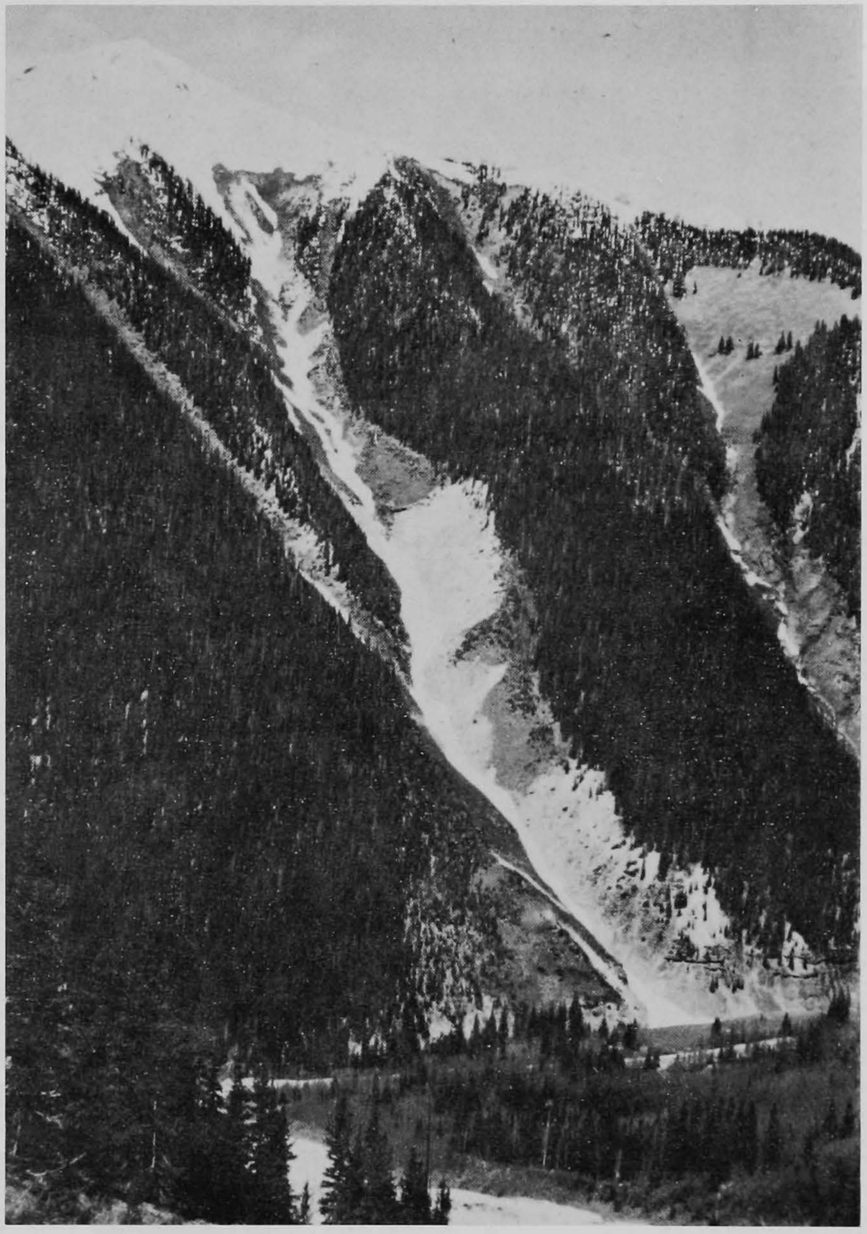

Figure 1-1. Battleship avalanche path, Highway 550, 6 km north of Silverton, Colorado. This is typical of a large Colorado avalanche path, with a starting zone of more than 30 hectares (75 acres) and an incised, well defined track.

Figure 1-2. At the bottom of the track the Battleship has sufficient energy to cross the stream, climb more than 80 meters (250 feet) vertically, cross the highway, and break trees 60 to 90 cm (2 to 3 feet) in diameter near the highway edge.

Figure 1-3. The destructive force of this avalanche after climbing 80 meters (250 feet) above the stream is illustrated by the size of the trees broken. The tree in this photograph has a trunk diameter of about 70 cm (30 inches), and was probably broken by a low-density, high-velocity powder avalanche. The danger to motorists from this particular avalanche must be considered slight, however, because it reaches the road infrequently (indicated return period of about 10-20 years) and highway traffic is light.

Figure 1-4. These avalanche paths at Vail, Colorado, are much smaller than the one shown in Figure 1-1. However, because they can reach residences at return periods of 20 to 50 years, and the residents occupy buildings a large percentage of the time, they are in far greater danger than motorists who occasionally pass below Battleship path (Fig. 1-1).

CHAPTER 2: TERMINOLOGY AND THE NECESSARY ELEMENTS OF AVALANCHE HAZARD ANALYSIS

1. Terminology

An avalanche path (Martinelli, 1974) refers to the specific area in which an avalanche moves. Most paths are made up of three parts: the starting zone(s), the track(s), and the runout zone(s), (Figure 2-1). The role of these terrain features in producing large avalanches is discussed in chapter 3.

Within the starting zone the unstable snow breaks loose and accelerates. This zone typically consists of slopes between 30° (58%) and 45° (100%), although avalanches sometimes start on slopes steeper or more gentle than these. In Colorado, slopes much steeper than 45° are too steep to permit snow to adhere, and small sluffs rather than large avalanches are common.

In the track avalanches reach and maintain maximum or terminal velocity as the snow released from the starting zone is conveyed downslope. Avalanche tracks may be confined by gullies or may be unconfined, open slopes, as wide or wider than the starting zones. Figure 3-6 illustrates both confined and unconfined tracks. Track gradients are usually less than starting zones, averaging 20° to 30° (Frutiger, 1962; Bovis and Mears, 1975).

Avalanches decelerate and stop within the runout zone as the kinetic energy of flow is dissipated through friction. Runout zone slopes are less than about 20° and are sometimes flat. In some cases the runout zone may extend partway up a slope of reversed gradient. It is in the runout zone that the avalanche hazard may not be obvious, and unexpectedly large avalanches sometimes encounter man and his works.

Small to medium-sized avalanches usually do not flow over the entire path. These avalanches, because of lesser mass and velocity, often stop in the starting zone or track and do not reach the runout zone.

Avalanches begin with failure of snow slopes. Two types of failures occur: point failures and slab failures. Point failures result from the failure of cohesionless snow grains on slopes steeper than the angle of repose. They occur often during and after storms and as a result of lubrication of the snowpack by meltwater. Point avalanches, or loose snow avalanches, result from point failures and generally are not very large avalanches and do not constitute a significant hazard to development in the runout zone. They may, however, trigger the more dangerous slab failures, which are brittle releases of a large mass of snow. These may result in large avalanches that flow over the entire path and constitute a significant hazard to man and his works in the runout zone.

Avalanches result from slab failures if the kinetic frictional forces at the base and sides of the slab are exceeded by forces generated by the slab momentum. After the slab has moved a short distance, it breaks into blocks that slide, roll, bound, and collide with one another. This causes the blocks to shatter into smaller chunks of snow that accelerate downslope as an avalanche. The avalanche may entrain additional snow in the starting zone and track and grow in size as it falls. After achieving a velocity of approximately 10 m/s (22mph), flow can be described as turbulent. The chunks of snow are pulverized into still smaller particles, and are suspended in the flow by turbulence. The amount of pulverization that takes place is determined by the strength of the initial slab, and the length, roughness, and steepness of the avalanche path. The different forms of avalanche motion are known as <u>powder avalanches</u>, <u>flowing avalanches</u>, and <u>mixed avalanches</u>.

The powder avalanche is a low density and generally high velocity suspension of small snow and ice particles in air. A necessary condition for its formation is a dry snow slab that permits the disintegration of the snow blocks into progressively smaller particles as the avalanche falls. As velocity and turbulence increase, these small, dry, snow particles become dispersed,and a powder avalanche is formed. A dry snow deposit alone is not a sufficient condition for powder avalanche formation. The terrain must be steep or irregular enough to cause sufficient velocity for fluidization of the avalanche. After reaching velocities of 20 m/s to 30 m/s (45 to 65mph), small snow particles can be suspended. Powder avalanches can also be formed by entrainment of air as a dry flowing avalanche falls over a cliff (Figure 3-7). It is important to recognize the avalanche path characteristics that can lead to powder avalanche formation because these avalanches often travel the longest distance in the run-out zone and must be considered when planning development.

The term flowing avalanche refers to all avalanche types that move close to the ground. The densities and flow depths of these are similar to those of the portion of the snowpack which released and caused the avalanche. Dry flowing avalanches can form from the same snowpack conditions that produce powder avalanches, although their densities are 10 to 100 times greater. In some cases, powder avalanches do not form because entrainment of air into the flowing snow does not take place. Because of much smaller flow depths and greater internal friction, flowing avalanches move more slowly than powder avalanches and, as a result, tend to follow terrain features more faithfully. In spite of lower velocities, they are capable of higher impact pressures than powder avalanches. Their destructive effects are usually restricted to more limited areas in the tracks and runout zones than those of powder avalanches. Wet flowing avalanches are dynamically similar to dry flowing avalanches. They form from heavy, wet snow and have high densities and low velocities. Wet flowing avalanches, because of their low velocities, are easily deflected by terrain irregularities (Figure 3-8).

Mixed avalanches are a combination of dry flowing and powder avalanches, occurring when a portion of the mass of a dry flowing avalanche is whirled into turbulent suspension as a dust cloud.

2. General remarks and limitations

The anticipated avalanche intensity must be determined if informed land-use decisions are to be made within avalanche zones. This quantification should be based on parameters or elements that describe the physical characteristics of the avalanche in question. In this way hazard intensity can be determined and the degree of danger assessed.

On most avalanche paths, hazard varies with position. Many more avalanches occur in the starting zone and upper portion of the track than in the runout zone. Furthermore, when large avalanches occur, impact pressures are generally greatest in the tracks, but diminish toward the outer limits of the runout zones as avalanches decelerate and stop. Therefore, avalanche hazard diminishes toward the outer limits of the runout zone because of reduced frequencies and reduced pressures.

In some mountain valleys it may be difficult to define a completely hazard-free area below avalanche paths. There is always some probability that an avalanche larger than anyone feels is reasonably possible will occur. One objective in an avalanche hazard analysis, therefore, is to define a line of acceptable hazard in which the danger to residents is sufficiently small so that development can proceed. The Swiss (Frutiger 1970), have made the pioneering efforts in land-use planning in avalanche areas.

They have developed avalanche zone maps that generally show three zones of avalanche intensity. Intensity is defined in terms of frequency and possible avalanche pressure on an exposed wall.

a. The red zone (high hazard), which includes terrain exposed to avalanches occurring either frequently or with great destructive potential is defined as

-- a pressure of 1 to 3 t/m^2 (205 to 615 psf) and a return period of 30 years or less,

-- a pressure of more than 3 t/m^2 (615 psf) and a return period of 90 years or less.

b. The blue zone (moderate hazard), which includes terrain exposed to avalanches with either lesser pressures or longer return periods than those in the red zone, and is defined by

-- a pressure of no more than 3 t/m^2 (615 psf) and a return period of more than 90 years,

-- a pressure of 1 to 3 t/m^2 (205 to 615 psf) and a return period of more than 30 years,

-- a pressure of 0.1 to 1.0 t/m^2 (20.5 to 205 psf).

c. The white zone, which is a zone of no hazard.

Swiss avalanche zone maps are generally drawn at scales of 1:10000 or larger with 10-meter contour intervals. These maps are more detailed than those generally available in the United States. The information contained on the Swiss maps comes from centuries of historical records and from detailed dynamical calculations.

Buildings are generally excluded from the red zone and are permitted in the white zone without any restrictions. Buildings are also permitted in the blue zone provided certain techniques are employed in their construction so that they will safely resist design avalanches.

The Colorado Geological Survey (Mears, 1975) has developed similar maps for about 20 critical areas in Colorado. These maps subdivide avalanche paths into "high" and "moderate" zones based on expected frequency and impact pressures. Avalanches in the moderate hazard zone will occur at return periods estimated at 25 years to "one or two centuries" and will produce impact pressures of 1000 psf or less. More detailed specification of hazard intensity is not possible because of the small scale (1:24000) of the available maps and the short period of avalanche records in Colorado.

Recommendations accompanying the Colorado Geological Survey maps suggest that buildings might be permitted in moderate hazard zones if more detailed studies are done providing the necessary design criteria for building. Guidelines for these studies are given in subsequent chapters of this publication.

It is suggested that the intensity of an avalanche event is adequately described when the following is known:

a. the areal extent of the avalanche, with particular emphasis on the runout zone;

b. distribution of impact pressures and forces likely to be exerted upon obstacles within the area of interest;

c. the types of avalanches likely to reach various locations; and

d. the frequency (in terms of return period or annual probability) of avalanche occurrence within the area of interest.

The derivation of these four parameters necessitates the specification of flow depth, density and velocity, as discussed later.

It must be emphasized, however, that <u>it is not possible to specify any of these four parameters precisely</u>. Avalanches are one of many imperfectly understood natural phenomena. The large, infrequent avalanches of interest for planning purposes have seldom been observed and have almost never been instrumented to determine velocities, densities, and impact pressures. Data about the frequency, periodicity, or return period of the extreme event are almost completely lacking in the United States. Empirical and theoretical methods for calculating the frequency of events of a given size, such as those developed over the past few decades in river flood discharge-frequency analyses have not been developed for avalanches. Consequently, although the methods described in subsequent chapters yield numbers upon which planning and engineering design can be based, the attained results will be best approximations only.

The normal engineering safety factors, developed over decades from a wealth of empirical data, are not conservative enough for design within avalanche areas. In view of the uncertainties inherent in avalanche analysis and in the obvious consequences of underdesign of structures, it is strongly recommended that an especially conservative approach be taken to design and planning within or adjacent to these areas.

The four parameters adequately describe avalanches for most purposes, but they are probably not all necessary for all purposes. A general land-use map for state or county planning purposes may be drawn on a scale of 1:24000 or smaller to illustrate zones of potential avalanche activity so that property owners and developers can be alerted to problems before there is land-use change. It is sometimes possible to zone these areas for a land use that will not conflict with the hazard, such as agriculture, open space, or summer use, thus avoiding complications.

On the other hand, if dwellings are to be built within areas of potential avalanche activity, then the degree of hazard must be defined much more precisely. This information should be presented on a detailed map (scale about 1:2000 or larger) showing the topographic details of the avalanche track and especially the runout zone. These maps cannot be made by enlarging 1:24000 U.S.G.S. topographic maps. A new, detailed survey and map must be made providing topographic details of the area to be developed.

The reasons for specifying these parameters are given below, while methods used and recommended for their calculation are discussed in subsequent chapters. The following discussion refers to all parts of an avalanche path, including the starting zone, track, and runout zone. However, permanent dwellings are seldom placed within starting zones and tracks[1] because steepness of terrain, resulting slope instability, other geologic hazards and access problems generally make building unfeasible or undesirable. The active areas within avalanche starting zones and tracks are relatively easily avoided because the greatly increased frequency makes the hazard obvious. The most serious problem usually exists within the runout zone, and especially that part of the runout which is seldom reached by avalanches.

3. Areal extent of the avalanche path

The runout zone is of great practical importance in land use vs. hazard considerations because upon casual examination, such land appears most suitable for development. Figure 2-1 is a drawing of an avalanche path. In this path, avalanches occur frequently enough to prohibit growth of a mature conifer forest in the runout zone. Since this time, large aspen have established themselves in the area

[1]Mountain highways frequently cross avalanche tracks. However, the resulting hazard to motorists is proportionately lower than it would be for permanent residents of such an area because of a greatly reduced time of exposure and active avalanche control programs.

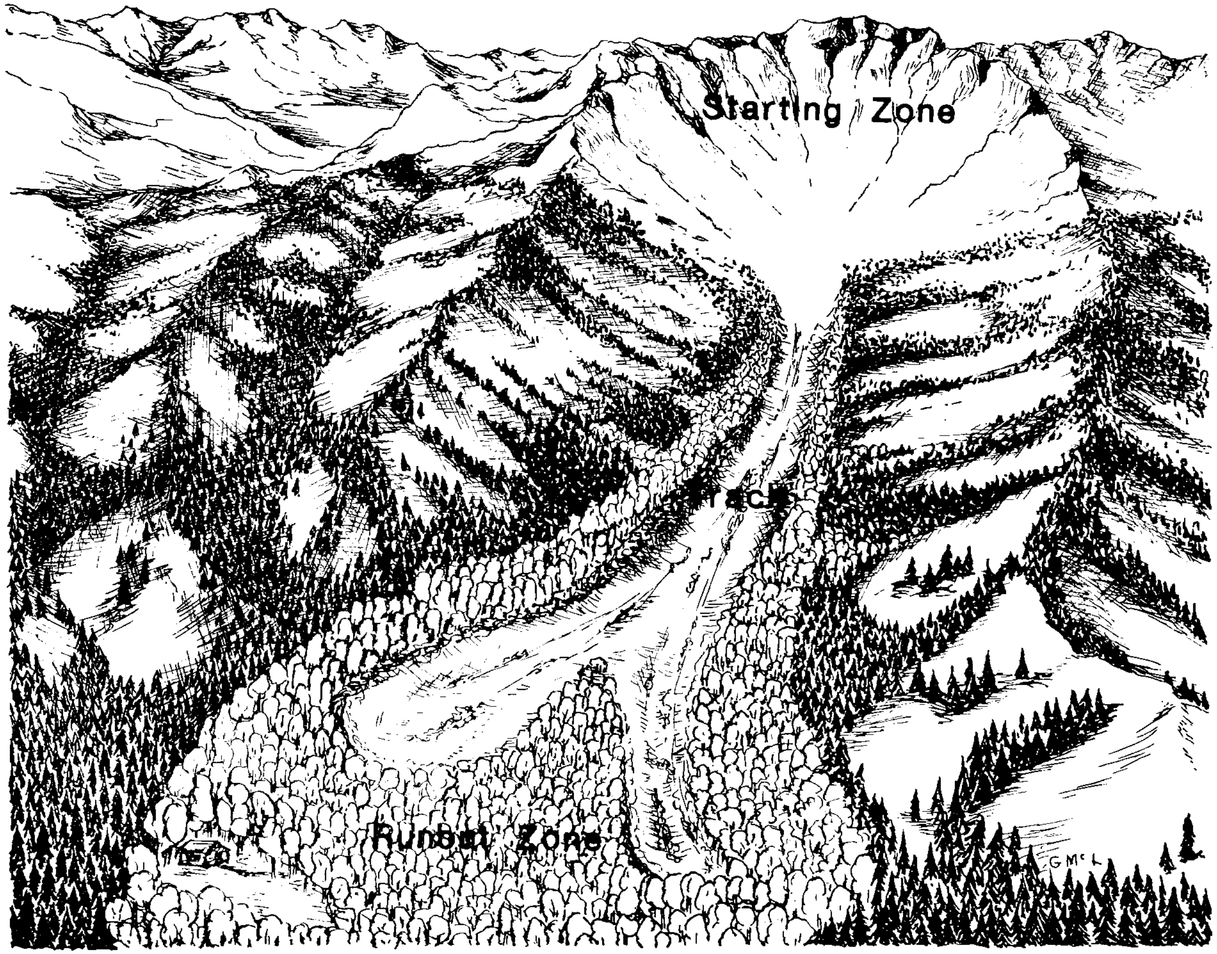

Figure 2-1. Drawing of a large avalanche path, showing the starting zone, track, and runout zone. The runout zone is clearly delineated through events of two magnitudes. The smaller zone, reached more frequently, is cut through the aspen forest, and is obvious. The larger zone is reached much less frequently, is revegetated by aspen, and must be considered when planning development.

creating a sunny, especially desirable-looking building location. Building has already begun in the left foreground--more may be planned in the future. Cuts through the aspen forest closer to the avalanche track are the result of much more recent, and more frequent avalanches. Because of their frequency, these smaller avalanches are often well known to local residents and misinterpreted by proponents of land-use change as representing the maximum extent of avalanches that need be considered in planning.

Avalanches have extended downhill past the location of the building in the past, and there is obviously some finite probability that they will recur in the future. When[2] this avalanche "runs big" in the future, it will encounter man and his works, destroy his property and perhaps even cause death. The future event may then be misinterpreted as an unusual or "freak" natural occurrence, insurance will be collected, buildings repaired and resold and normal activity will resume. This unfortunate sequence of events has occurred in many mountain areas and will recur unless the hazard is understood, its boundaries delineated, and the hazard avoided or controlled.

Although the avalanche hazard boundary shown in Figure 2-1 appears clearly delineated by a vegetation trimline between aspen and conifer forest, there are similar locations in the state of Colorado being developed or for which development is proposed at this time. Unfortunately, many runout zones are not nearly as well defined as the one depicted. The indirect evidence that is easily seen in this case does not exist in locations devoid of forest, where avalanche debris is swept away by floods, or removed by man. As a result,

---

[2] It is important to recognize that the question is not "if" the avalanche will run big again, but "when" it will happen.

other indirect methods must be used to predict the areal extent of the runout zone. These are discussed in chapter 4.

4. Distribution of impact pressures in the avalanche path

Building within an avalanche runout zone may be unavoidable in some cases. When such construction is planned, it is obviously desirable to have it designed and built so that future impacts will not destroy, damage or relocate it. Certain defense measures in the runout zone can be used to deflect, guide, arrest, or dissipate avalanche energy, and these must also be built to withstand impact, although such design is usually not a problem with massive earthen structures.

It is logical to expect that impact pressures would be higher near the bottom of the avalanche track where velocity is near maximum and would decrease toward the lateral margins of the runout zone as the flow widens and decelerates. When a very large avalanche occurs and sweeps through the aspen forest, in the path shown in Figure 2-1, very high impact pressures would be exerted in the unforested region which is also affected by more frequent avalanches. These pressures would progressively diminish toward the edges.

It is within the capabilities of engineering science to design structures, including personal residences, that will withstand the maximum pressure any avalanche can produce. Some very large avalanches in Europe were instrumented, and impact pressures of about 100 metric tons per square meter (t/m^2) (20500 pounds per square foot),[3] were measured. More commonly, large dry snow and powder avalanches capable of running the longest distance in Colorado might produce

[3] 1 t/m^2 = 205 psf.

impact pressures of less than 20 t/m^2 (4100 psf). Large avalanches of dense, wet snow, although more limited in areal extent, may produce pressures in excess of 20 t/m^2 (4100 psf). For contrast, buildings in the United States are usually designed for side loading by wind, which enables them to resist pressures of less than 0.25 t/m^2 (50 psf).

It seems reasonable that some criteria should be set that restrict buildings to a zone in which impact pressures are not expected to exceed a given amount. Swiss law, for example, prohibits building in a region subject to pressures greater than 3.0 t/m^2 (615 psf). This corresponds to the "red zone " discussed earlier. If such a procedure were to be instigated in this country, then it would be necessary to subdivide the runout zone into subzones of impact pressure, taking into account the various avalanche types that might occur. Acquisition of data required to justify such subzonation requires acceptance of a model of avalanche flow, as discussed later in chapter 4. A typical avalanche runout zone is shown in Figure 2-2; the intermediate hazard area is subdivided into zones of pressure intensity, also corresponding to zones of frequency. The frequency or probability of avalanche occurrence decreases with distance from the track. The detailed, high-quality historical data necessary to draw such maps is not available in this country. However, methods by which these zones may be approximated are presented in chapters 4 and 5.

The derivation of pressure zones through assumption of a dynamic model is an inexact procedure. For this reason, it is worth re-emphasizing that extreme conservatism should be used in building design based on derived pressure data.

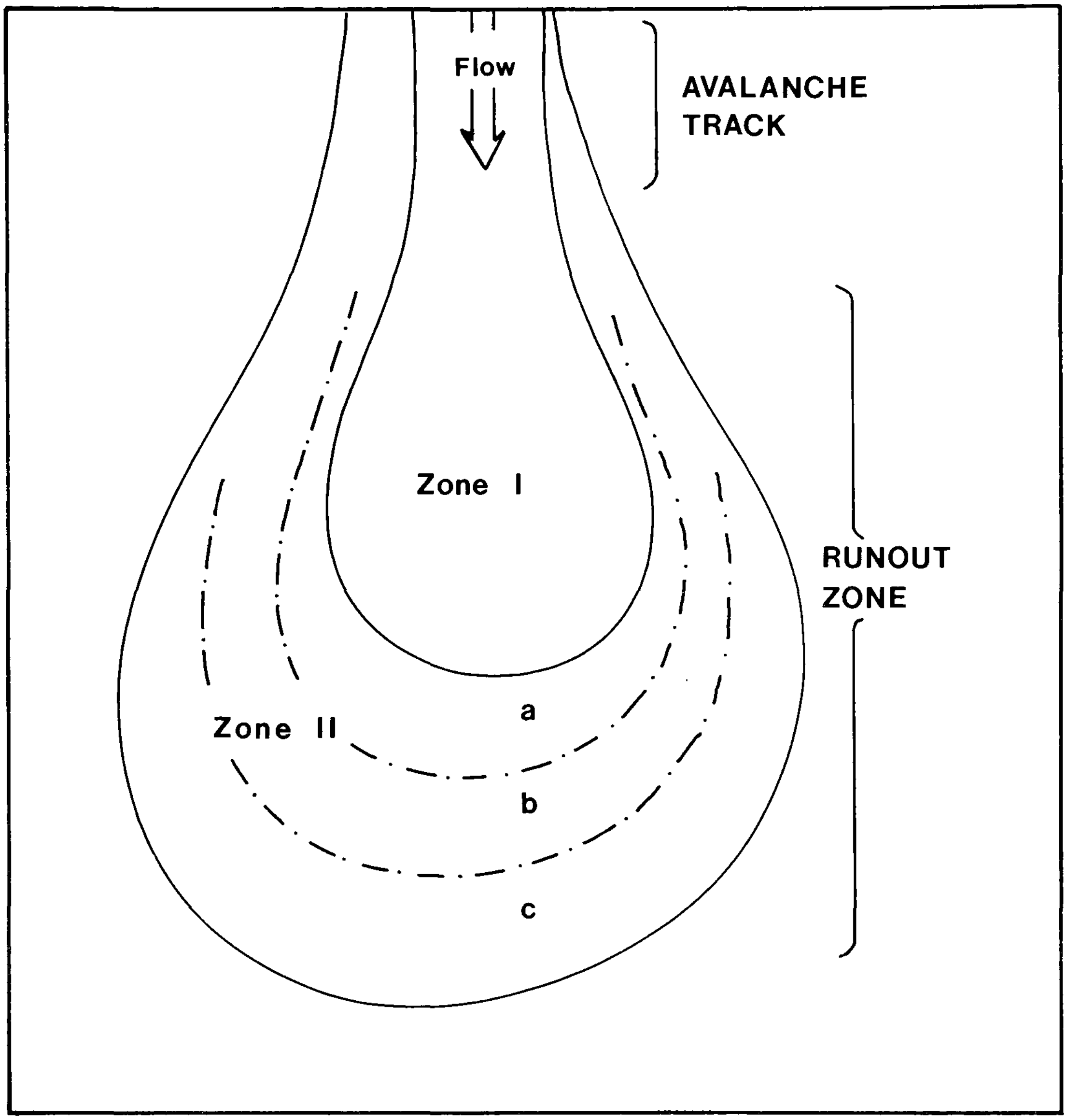

Figure 2-2. Hazard intensity within the runout zone. Zone I is high hazard affected by avalanches with either short return periods or large impact pressures. Zone II is affected by both longer return periods and lesser impact pressures than Zone I. This zone may be subdivided, as shown, because hazard level does decrease toward the outer margin of the runout zone.

5. Types of avalanches occurring

It is important to know whether powder avalanches, or wet or dry flowing avalanches will occur because the various types differ greatly in velocity, mechanics of impact and suitability for control. Important differences in loading will occur on an obstacle, depending on the avalanche type even though the calculated impact pressure can be the same in two cases. The pressure, P, is proportional to the avalanche specific weight, γ, and the square of the velocity, U This is written

$$P = k \frac{\gamma}{g} U^2 \quad , \qquad (2\text{-}1)$$

where g is the gravitational acceleration, and k is a variable that depends on the shape and size of the object and the type of flow, usually ranging between 0.1 and 1.0. Equation (2-1) is satisfied, for a given P, by many combinations of γ and U. For instance, if a pressure, P, of 3.0 t/m^2 is considered acceptable for a given structure, then the various combinations of γ and U producing this pressure are shown in Figure 2-3. The same pressure may be produced by a slow moving dense avalanche or a high-velocity powder avalanche. Since protective measures depend not only on the pressure, but also on other dynamic characteristics of the avalanche, they too should be specified. Figure 2-4 illustrates a building subject to two avalanche types capable of the same pressure.

6. Avalanche frequency, or return period

This remaining factor in avalanche hazard evaluation is also difficult to estimate. The term return period is redefined here to eliminate misunderstanding.

The return period is a measure of the average length of time between avalanches of a given size over a long period of time. The reciprocal of return period is equal to the annual probability. Thus

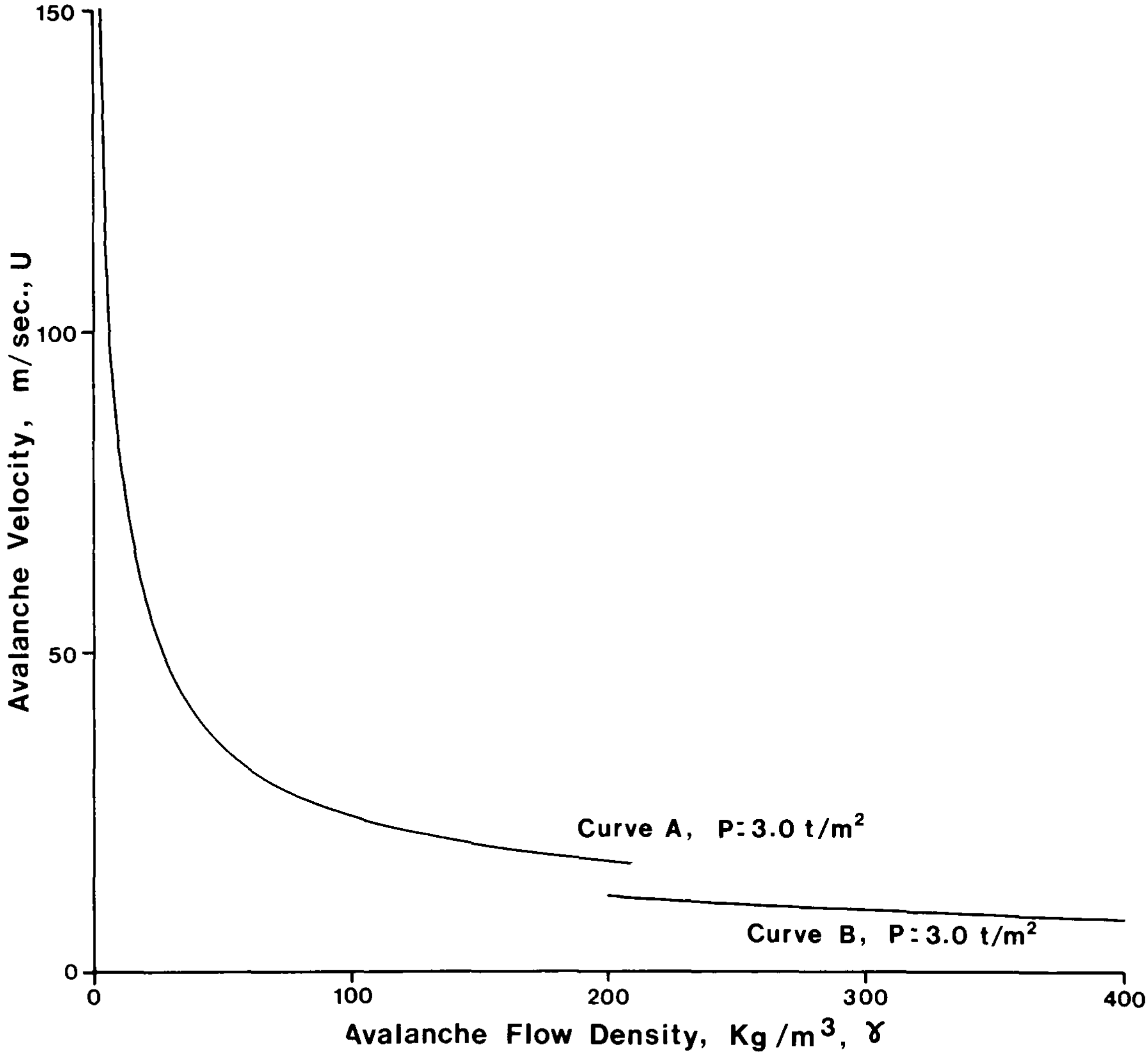

Figure 2-3. Impact pressure can be caused by an undefined number of combinations of density and velocity. Consequently, it is necessary to establish reasonable upper and lower limits for density and velocity through specification of avalanche type. Curve A indicates powder or dry flowing avalanches; curve B indicates wet flowing avalanches.

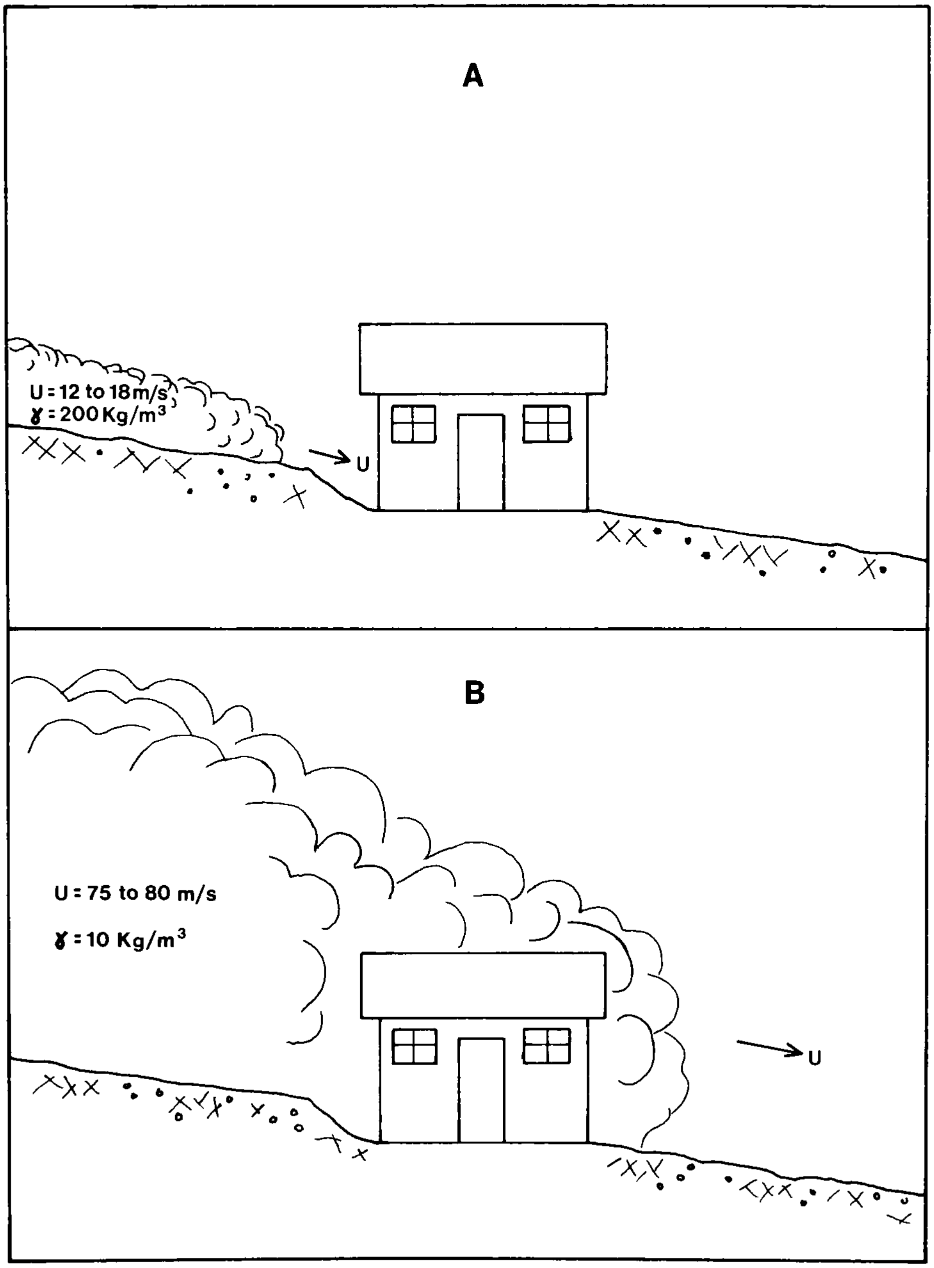

Figure 2-4. Different types of avalanches can produce the same impact pressures but represent very different hazards. The slower moving, higher density avalanches in "A" can probably be deflected or controlled in the runout zone, while "B" although capable of the same pressure, completely engulfs the house, causing both drag and uplift forces. Because of its high velocity, "B" is difficult to control. See Figure 3-8 for more comparisons on the hazard from different types of avalanches.

a return period of 50 years corresponds to an annual probability of 2%. The actual timing of avalanche events is assumed to occur randomly through time so that the 50-year avalanche may occur on successive years without changing the probability of occurrence in succeeding years. It is a statement of probability rather than a prediction of when an avalanche will occur.

The probability of an avalanche reaching some point must be determined because the degree of hazard depends on the probability of avalanching, as well as the destructive force. Just as the impact pressures from avalanches decrease with distance from the track (Figure 2-2), the probability of avalanching also decreases (or the return period lengthens) with distance. Long-term records (at least 2 or 3 centuries) are required for reliable determination of return periods of a century or more. Records of this length are lacking in the United States. Indirect methods for estimating frequencies are presented in Chapter 6.

CHAPTER 3: THE EFFECT OF TERRAIN ON LARGE AVALANCHES

1. General remarks

Snow avalanches in Colorado may occur whenever the proper combination of steep slopes and deep snowfall occur. Generally, unstable conditions may prevail whenever the snowpack depth exceeds the height of ground surface irregularities, such as boulders and transverse ridges. Steep slopes, with average gradients of 100% (45°) or more usually avalanche first, during or after storms. In general, these are small avalanches that involve little mass and travel short distances at relatively low velocities. They are a significant hazard, however, to those who use the mountains for recreational purposes, because they occur frequently during and after storm cycles. A correlation may exist between the steepness of slope and the frequency of avalanching (Mellor, 1968). It also appears that an inverse correlation exists between the sizes of single avalanche releases and the steepness of slope (Bovis and Mears, 1976).

The mechanism of avalanche release is affected by the general terrain. On a convex slope, longitudinal stresses will be tensile, favoring fracture of the snowpack and subsequent release of a slab avalanche. This type of failure requires, of course, that the snowpack has developed into a slab capable of transmitting stresses over a wide area and capable of failing as a rigid unit.

Given optimum avalanche-producing weather conditions, potential avalanche size is determined largely by the topographic setting of the path. These topographic factors are discussed below.

2. Topographic conditions conducive to large avalanches

The topography of many avalanche paths can be divided into 3 parts

Figure 3-1. A wide, unconfined slope avalanche path.

Figure 3-2. A large, complex avalanche path. Large areas on this mountain face may simultaneously release, although the flow will not be concentrated into a single gully.

Figure 3-3. A path with a complex starting zone below timberline. Releases may be limited to one zone or, under certain conditions, all parts can release at once, causing a simultaneous discharge of greater mass.

Figure 3-4. A long, narrow starting zone not shaped so that the flow is concentrated into a narrow channel. Flow depth in this example would not be increased by channelization as much as in examples shown in Figure 3-3.

Figure 3-5. These avalanches start in the trees and flow over cliffs. Although thick timber is usually an inhibiting factor in avalanche formation, it is not always complete protection. (See Figure 3-6).

as briefly described in chapter 2: 1) the starting zone; 2) the track; and 3) the runout zone. In some avalanche paths, these parts are well defined and easily separated, whereas in others, they are not so easy to distinguish.

a. starting zone

Avalanches are initiated in the starting zone either artificially (through control measures such as explosives) or naturally. Natural releases occur and rapid downslope movement begins when the strength of the snowpack is exceeded by stresses exerted on it by its own weight. Failure and release are initiated through, 1) snowpack weakening at constant stress, 2) increased stress through snow accumulation at constant strength, or 3) some combination of strength change and stress change. The ability of an avalanche to simultaneously discharge a large snow mass depends on its ability to fail as a large, rigid unit. Given optimum avalanche-producing weather and snowpack conditions, the upper size limit of this unit is determined by the dimensions and topography of the avalanche path, and in particular, the starting zone. In complex avalanche paths, such as in Figure 3-2, small avalanches may trigger larger ones in other parts of the starting zone, causing an avalanche of large volume. However, it is unlikely that much of the flowing mass will become concentrated at the same point in the track at the same time to produce a large discharge (volume per unit time). In simple avalanche paths (Figure 1-1) it is more likely that the discharge from the starting zones will meet in mid-track, and result in a larger discharge and velocity.

Some examples of avalanche starting zones are shown in Figure 3-1 through 3-5. The example in Figure 3-1 is a wide unconfined slope. It is possible for a fracture to propagate over a long distance around this bowl-shaped depression and a large mass of snow to release at one time. Figure 3-2 is a complex starting zone above timberline. In this path, however, the flow of snow is not concentrated into a single gully which serves as the avalanche track. Figure 3-3 illustrates a complex starting zone below timberline. The starting zone of Figure 3-4 is long and narrow, and the flow cannot be as effectively concentrated toward the bottom of the avalanche path as those shown in Figures 3-2 and 3-3. Figure 3-5 illustrates a much smaller starting zone that begins in the trees. Although avalanches from this slope do not become channeled, they do fall over cliffs. This can cause some dry snow avalanches to develop into powder avalanches. Although these starting zones all differ greatly in the potential mass of snow that can be released, the danger in the lower part of the avalanche path is highly dependent on the configuration of the avalanche track, as discussed below.

Most avalanches in Colorado release from starting zones with inclinations of 55% to 100% (29° to 45°), although avalanches may start from slopes steeper or more gentle than these. If starting zones include large areas in the 55% to 70% (29° to 35°) range, thick deposits of snow may accumulate before release. Consequently, the potential for large avalanches may actually be greater from these lower gradient starting zones. Most of the volume of snow released from the starting zones of the giant Twin Lakes avalanche that claimed seven lives in 1962 was from slopes of 55% to 70% (pers. comm., H. Frutiger, 1975). Some large Colorado avalanches have starting zones of more than 40ha (100 acres) in the 55% to 70% range. The general smoothness of the starting zone topography is also important when considering the potential size of avalanche releases. A smooth surface with no gullies, ridges or other irregularities higher than the snowpack depth will permit fracture and release over a large area. In contrast, a starting zone broken up by large surface protuberances may limit any single release to a fraction of the total starting zone area. Although the total mass released from such complex starting zones may be large, the maximum discharge through some cross section may be limited to that of one of the isolated starting zones.

Many starting zones occur below timberline and are at least partly tree covered. However, slab avalanches can occur in forested starting zones, particularly if the timber growth is young or sparse. These timbered areas can be the starting zones for large soft slab releases, which, due to the weaker mechanical strength of the slab, can more easily develop into fast moving powder avalanches as the slab fractures into small particles and becomes fluidized. Partially timbered starting zones are illustrated in Figures 3-3 and 3-5. Large soft slab releases as well as hard slab releases often occur in starting zones above timberline.

Other factors contributing to potential avalanche size include starting zone elevation and orientation relative to sun and wind. In Colorado, snow accumulation generally increases with elevation. High elevation starting zones will accumulate and maintain a deep winter snowpack more readily than those at lower elevations, providing large volumes of snow for avalanches during certain winters. If a starting zone is oriented so that it accumulates snow by wind deposition from storms approaching from the most common direction, avalanches will be more frequent. Prolonged wind loading of a starting zone may produce hard slabs more readily than soft slabs. Soft slabs, however, disintegrate and form powder avalanches more easily than hard slabs. Because a powder avalanche is capable of traveling the longest distance in the runout zone, the potential for soft slab development may be more critical than wind-loading orientation when considering the maximum runout potential of avalanches in a given path. This maximum runout distance must be considered for land-use planning near avalanche paths.

During an average winter, slopes with sunny south-facing exposures experience more snow melt and consequently have a shallower snowpack than north-facing slopes. However, sufficient snow does accumulate on south-facing slopes to produce large avalanches, particularly at elevations exceeding roughly 3000 m (10,000 ft). Large wet snow avalanches are probably more likely on south-facing paths as direct rays of the sun warm and weaken the snowpack quickly in late winter and spring. However, because observations of destruction in Colorado indicate that powder avalanches cover the largest areas in the runout zones of both north- and south-facing paths, powder avalanche potential should also be considered. The development of powder avalanches may be related more to individual storm characteristics than to orientation with respect to either sun or wind. However, it is extremely rare for lower elevation (less than about 3000m) south-facing slopes in Colorado to maintain a winter snowpack much deeper than the surface irregularities. Even infrequent, maximum-sized events from these lower-elevation slopes are not likely to be very large.

The type of snow in the starting zone and track can be as important in determining the extent and area covered by the avalanche as the volume of snow released because it helps to determine the type of avalanche which will develop (see chapter 2, section 1).

b. avalanche track

The development of the various types of avalanches is strongly influenced by the type of terrain traversed in the track. The tracks are of two basic types: unconfined and confined (Figure 3-6).

The volumes that may be released from the starting zones in Figure 3-6 A and B are approximately equal, as are the discharges through each section "a". However, in path B the discharge is forced

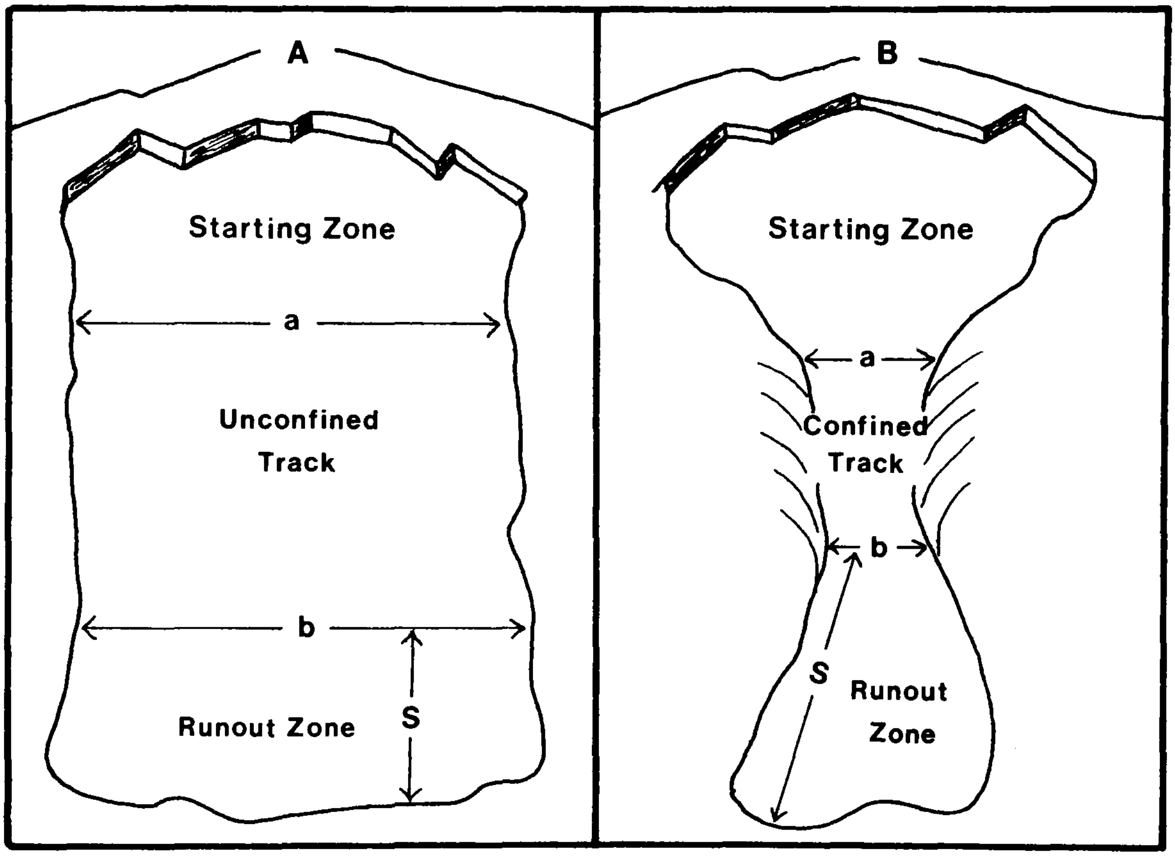

Figure 3-6. An unconfined avalanche path, (A), and a confined path, (B). In path (A), the runout distance, S, is not affected by the width of the starting zone because concentration of discharge does not occur at (a) and (b). In path (B) all the released snow is conveyed through the confined track at (a) and (b). Therefore, the runout distance, S, in path (B) depends on the size of the starting zone. (After Salm, 1975).

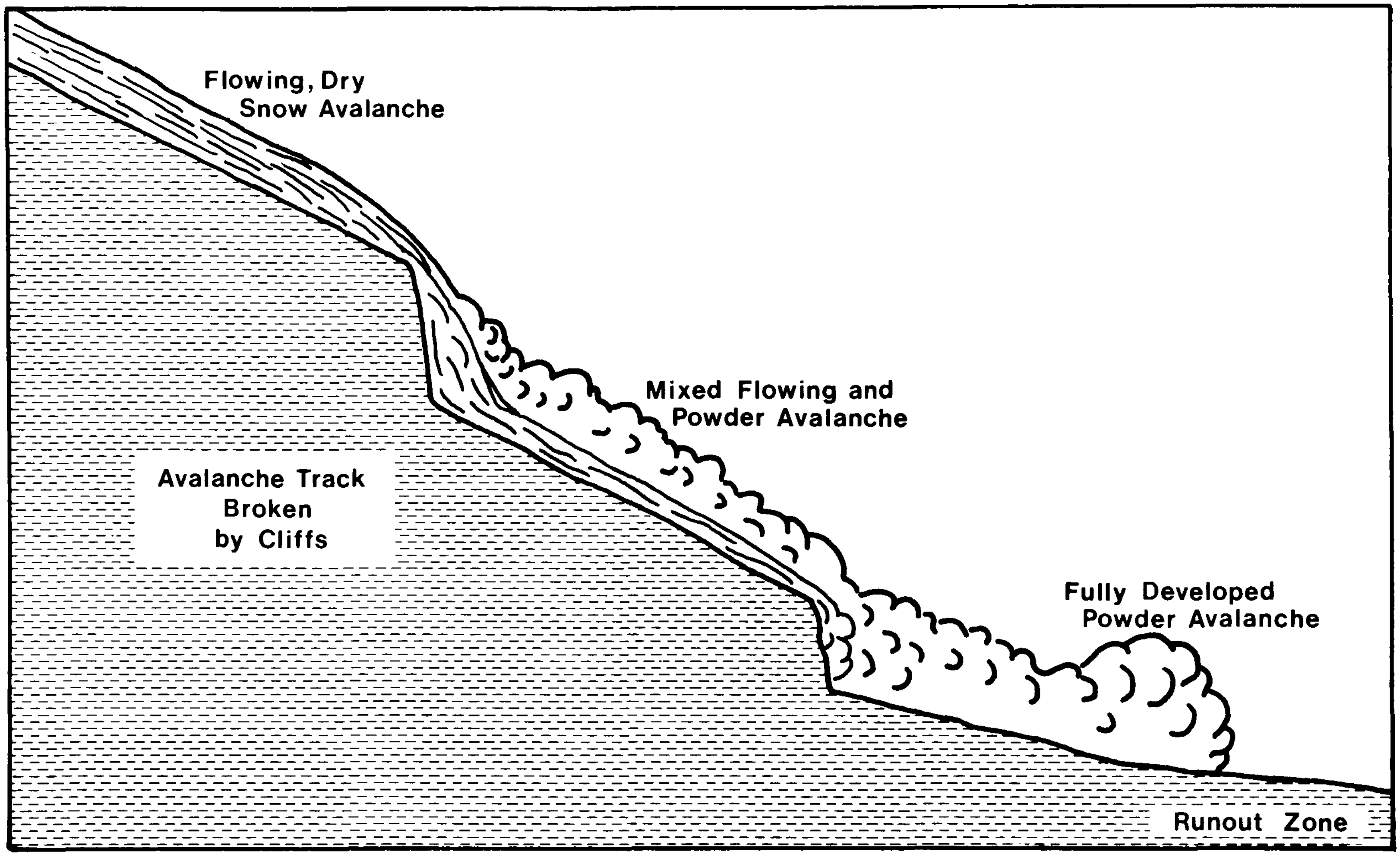

Figure 3-7. A dry flowing avalanche which falls over cliffs can develop into a deeper higher velocity powder avalanche capable of destruction for long distances in the runout zone.

through a narrow, confined track. This causes increased flow depth and velocity. The volume of snow released from the starting zone of path B helps determine the velocity and runout distance, S. In path A, although a very large avalanche can release, the discharge is not concentrated into a narrow track because the flow is unconfined. Therefore, the runout distance, S, in path A, is independent of the width of the starting zone. This is the major difference between confined and unconfined avalanches and it must be considered in calculations, as discussed in chapter 4. Examples of confined avalanches are figures 1-1, 1-4, and 3-3. Unconfined avalanches are shown in Figures 3-1, 3-4, and 3-5.

In many locations, avalanche tracks are "stepped" or broken up by cliff bands. Low gradient shelves above cliffs may stop small avalanches but can cause higher velocity dry snow avalanches to develop into powder avalanches (Figures 3-5 and 3-7).

The majority of Colorado avalanche tracks have inclinations of 30% to 60% (17° to 31°) (Frutiger, 1964; Bovis and Mears, 1975). The larger tracks tend to have the lesser gradients. In exceptional cases of large avalanches flowing in confined tracks, avalanches may travel 2000 meters or more on gradients as low as 20% to 25% (11° to 14°). Although track gradient may not be an important factor in the velocities of deep powder avalanches, it is important as a controlling factor in the velocities of less deep flowing avalanches.

Smooth, straight tracks dissipate less energy than curved tracks. When tracks are curved, it is possible that some of the avalanche mass will be deposited on the outsides of the curves. This can reduce the flow depth, discharge, velocity, and energy farther down the track.

c. runout zone

The portion of the path where avalanches decelerate, deposit, and stop is the runout zone. A deposit is formed within this zone by loss of flow energy. In many Colorado avalanche paths the runout zone gradients are less than 30% (Bovis and Mears, 1975). In some cases, runout zones will extend across entire valley floors and part way up the opposite valley sides. For example, one large Colorado avalanche ran 800 meters (2500 ft) on an 18% (10°) gradient before stopping against the opposite valley wall. At that point, it still maintained energy sufficient to break trees with trunks two feet in diameter (Ives and others, in press). Alluvial cones that are deposited at the base of many steep stream channels can also serve as the runout zones of confined avalanches. It is convenient to define the runout zone in such cases as that part of the path in which the flow is no longer confined laterally by gully walls, and is free to spread.

Different types of avalanches may reach entirely different parts of the same runout zone. As illustrated in Figure 3-8, the runout zone of wet snow avalanches is greatly influenced by the irregularities on the runout zone surface. Gullies 3 to 6 meters (10 to 20 ft) deep can contain the flow of these slower moving avalanches although such channelization causes long runout distances by maintaining an adequate flow depth. Because they are so easily influenced by terrain irregularities, slow-moving dry or wet snow avalanches can often be deflected from their course in the runout zone by avalanche defense structures. Sometimes their flow can be contained by guidance walls designed to be higher than the expected flow depth. This is discussed in chapter 7.

Powder avalanches, in contrast to the wet snow avalanches, are not deflected by ridges and gullies on the alluvial fan surface shown in Figure 3-8. They will be traveling at such high velocities at the top of the fan that they will advance in the direction of discharge attained in the gully that serves as the avalanche track. Because of their great depth, a certain amount of widening of flow

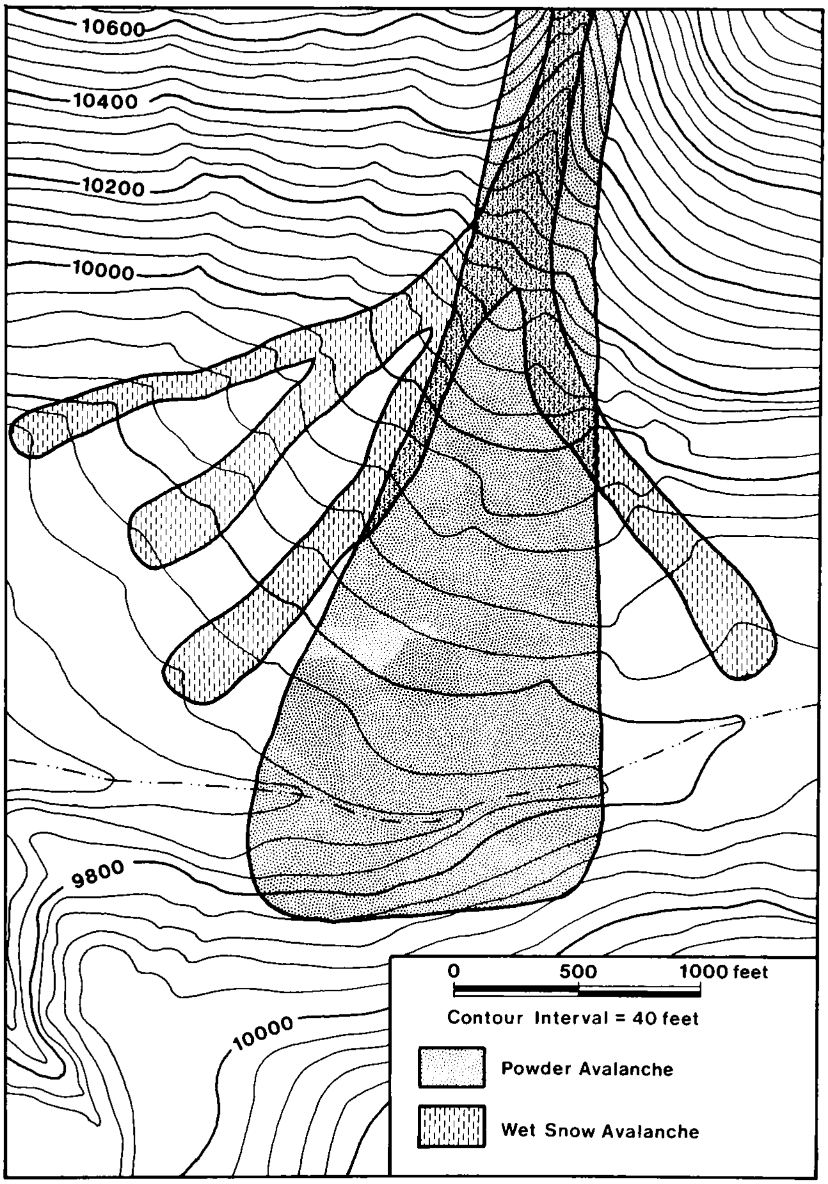

Figure 3-8. Different types of avalanches can affect different parts of the runout zone on this alluvial fan. Slow-moving wet snow avalanches follow gullies quite closely. They may sometimes be deflected by obstacles that are about as high as their flow depths. Powder avalanche direction is determined primarily by the direction attained in the lower portion of the avalanche track. Terrain surface irregularities on the alluvial fan, all of which are small when compared with powder avalanche flow depth, cannot change the direction of flow. Powder avalanches will generally widen as they advance onto an unconfined runout fan, progressively diminishing flow depth and velocity, but still possessing great energy well into the runout zone.

will take place on the fan. Note that the runout zone in Figure 3-8 extends more than 150 feet up the opposite valley wall. This is an area of powder avalanche impact. The complete runout zone of this avalanche path obviously consists of the runout potentials of both wet snow and powder avalanches. A great deal of uncertainty may exist in specifying exactly where the runout limits should be drawn. In locations like that illustrated in Figure 3-8, it might be best to designate the entire alluvial fan as potential hazard.

CHAPTER 4: THE AREAL EXTENT OF THE AVALANCHE PATH: METHODS OF DETERMINATION

1. Introduction

The necessity for determining the extent of the avalanche path and especially the runout zone is discussed in chapter 2, section 3. It is worth reemphasizing that it is the extent of the infrequent, or extreme event that is of special interest for planning purposes. The more frequent events in a path, which may occur every year or every few years are not useful in mapping for planning purposes because they do not approach the outer boundaries of the long-term hazard. Unfortunately, most direct observational data are on the small event. These observations can be extremely misleading when trying to calculate the infrequent event. The dynamics of flow and type of avalanche-snow associated with very large avalanches may be quite different from that of more common slides, and extrapolation from small to large events is difficult.

Consequently, we must turn to indirect methods to estimate the size of the extreme event. These methods require data collection, interpretation, and analysis which are subject to some error. Nevertheless, some analysis must be done in order for planning and design to proceed. Because all indirect methods of avalanche analysis are subject to an undefinable degree of uncertainty it is important to employ as many independent methods as possible. If these independent methods indicate similar results, the results may be used with greater confidence.

2. Air photo interpretation of avalanche terrain

Air photo interpretation is an indispensable part of any avalanche hazard analysis. Photos provide the user with the inestimable advantage of perspective in which he can see in a single photo the whole mountainside over which an avalanche starts, flows, and runs out. Obvious differences between the sizes of various slide paths as related to terrain, and the resulting differences in runout potentials often become apparent through the study of photos. Such perspective is never gained from the valley floor. From the valley floor the observer may overemphasize the importance of relatively small features such as irregularities in the lower track because they seem big to him even though they are insignificant with respect to the flow of major avalanches. Details of terrain analysis are discussed more fully in section 3 of this chapter.

At this writing, the best widely available air photos for avalanche terrain analysis of mountain regions of Colorado are the low-altitude black and white photos of the U.S. Forest Service. These are available for all mountain regions of the state, and are printed on a 9" x 9" format at scales of 1:15000 to 1:20000. These low-altitude photos have good resolution (individual trees may easily be perceived) but because of the low altitude are not scale consistent from ridge top to valley bottom. Most of this photography was taken during the last 10 to 20 years. Through the U.S. Forest Service, new, low-altitude color photos are also now available for many mountain areas of Colorado.

Another excellent source of air photos is the National Aeronautics and Space Administration (NASA). These photos were usually taken from a higher altitude than the USFS photos and they are generally newer. They are available in both color infrared and true color. The higher elevation reduces the problems of scale distortion of the USFS photos. Although at a smaller scale (usually 1:30000 to 1:100000) the high resolution permits good image enlargement. They are not presently available for all Colorado mountain regions.

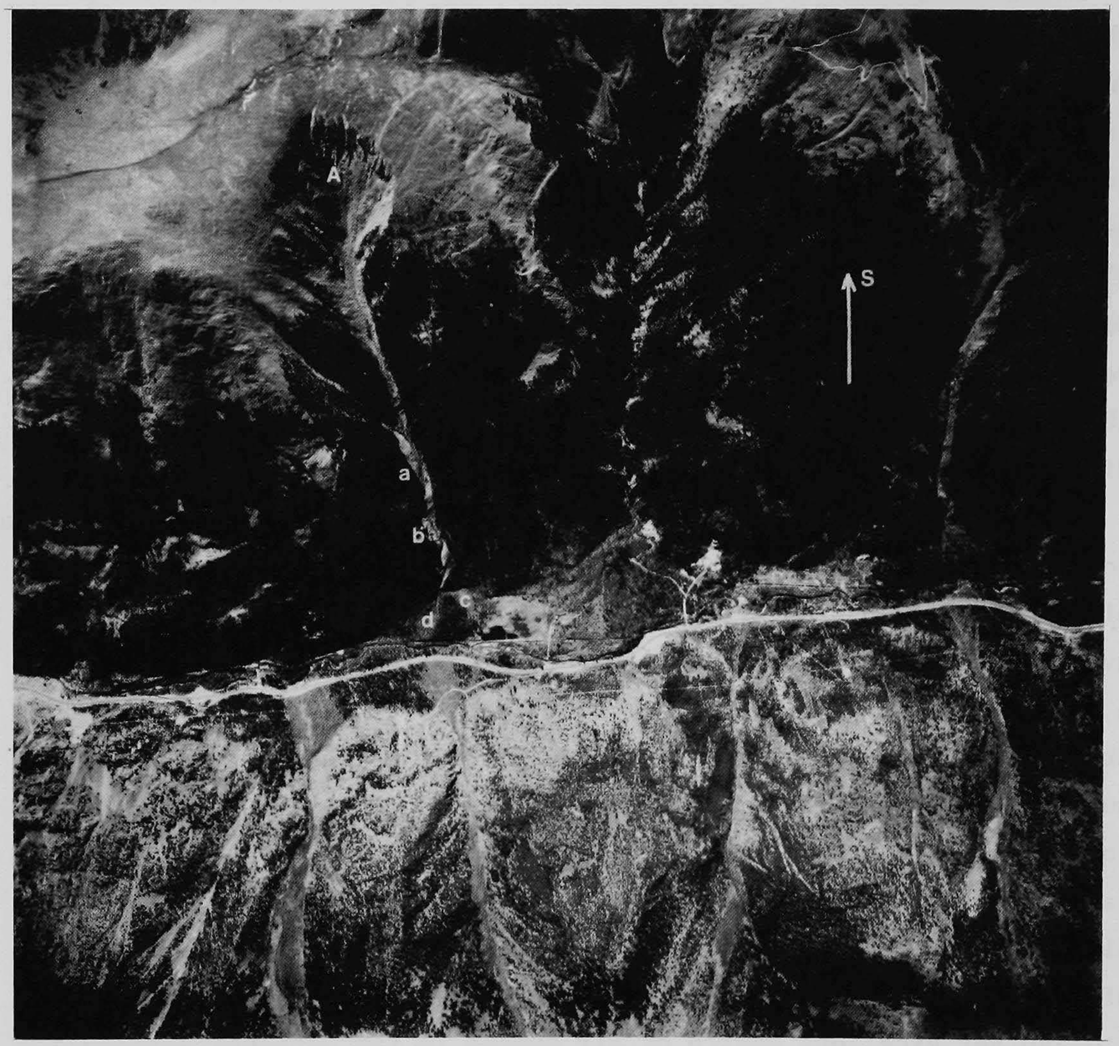

Figure 4-1. Vertical air photo of a large, confined avalanche path; scale about 1:20000. The starting zone is a bowl-shaped hollow above timberline and the track is an incised stream gully. Potential size is determined mostly by the starting zone area. Avalanches have overrun curves in the track in the past at points "a" and "b", attesting to high velocities and flow depths. High velocity avalanches have jumped the ridge at the bottom of the track and run out into area "c". Smaller, or slower moving avalanches are deflected by this same ridge and run out into "d".

Both USFS and NASA photos are available in stereoscopic pairs, so that topographic relationships may be viewed in three dimensions. This enhances the interpreter's ability to assess the importance of path steepness, roughness, and gully effect.

Although air photo interpretation is a great aid to avalanche hazard mapping, it should never be relied on to provide all of the information for a given area. Field work and dynamic analysis remains an indispensable part of any avalanche hazard study. This is discussed more fully in subsequent sections of this chapter and in later chapters.

Virtually all development or proposed development in Colorado exists or is planned well below timberline, i.e., below 3400m to 3600m (11,200 ft. to 11,800 ft.). Developable mountain valleys such as Vail, Aspen, Crested Butte, Telluride, Silverton, and Breckenridge are situated at elevations of 2500m to 3000m (8000 ft. to 10,000 ft.). Therefore, air photo interpretation of Colorado avalanche areas is usually enhanced by the fact that avalanches must cut through forests on the way to valley bottoms or other potential development sites. There are some exceptions to this rule, such as very high elevation mines or mining settlements or low elevation sites devoid of forest. Nevertheless, important information may be gained about most avalanches in a region from a study of paths that pass through the forest. This information may often be transferred to physiographically similar regions in which there are no forests and the available information is not so clear.

A typical group of Colorado avalanche paths is shown in Figure 4-1. Avalanche "A" starts in the bowl-shaped depression (starting zone) at and above timberline, becomes confined to the gully (a confined track) in which the flow accelerates and achieves terminal velocity, and stops somewhere on the gently sloping valley floor

Figure 4-2. Photograph taken in mid-April, 1975 of the avalanche path shown in Figure 4-1. Avalanches have tended to widen and straighten the track. The ridge at the top of the runout zone appears much larger in this photo, but has been overtopped by avalanches. During the winter preceding this photo, little snow accumulated in the starting zone. Observations over a short time period could tend to underestimate the total mass which could avalanche. During some winters, the entire basin could fill with snow and avalanche.

(runout zone). Other smaller slides are evident as downslope lineations in the forest to the left of path A. Photos like this are useful because they show the combined effects of many years of avalanches at one location. The record of their sizes is available through detailed study and interpretation of forest damage, since all types and sizes, from slow moving wet slides to high velocity powder avalanches, have occurred in the past.

Path "A" is typical of many moderate to large sized slide paths in Colorado.[1] The snow accumulation basin serves also as the starting zone for most avalanches. The basin in path "A" is partly above timberline and therefore is exposed to heavy concentrations of snow from precipitation and especially from wind-loading. As discussed in the terrain analysis section (section 3, chapter 4), the amount of snow that can be simultaneously released from this basin is the most important single factor in determining the discharge, velocity, and runout distance of avalanches in this path. Therefore, an essential diagnostic feature in analysis of confined avalanche paths is the determination of the size of the potential starting zone, or accumulation basin. Air photo interpretation allows us to link this basin with the channelled track and runout zone below it, thereby clearly distinguishing the potential size of path "A" from the small slides to the west of it.

The roughness and steepness of the basin strongly control the volume of snow that may be released simultaneously. Steep sections, broken up by sharp gullies and ridges will not contribute much volume because snow will not adhere to such steep slopes. More moderate gradients, in the 55% to 70% (29° to 35°) range are most

[1]The designation "small," "moderate," and "large" is based on the potential mass available to avalanche; this is correlated roughly with starting zone area.

dangerous because a much thicker snowpack can build up before the downslope components of stress exceeds the general strength of the snowpack and failure occurs. However, in assessing the potential for large avalanches in Colorado, all slopes between 55% and 100% (29° to 45°), should be considered as potential starting zones.[2] Steeper slopes contribute mostly to harmless sluffing but can trigger massive releases on lesser slopes even though they do not contribute much volume to the avalanches.

The basin in Path "A" is relatively smooth so it is easy to see how a single fracture could propagate across the whole basin and cause a single large release. In contrast, many avalanche paths have several unlinked starting zones, all funneling into the same track. Avalanche paths with unlinked starting zones may also be a source of large avalanches because releases from the various isolated starting zones may undercut and release one another. However, it is unlikely that the discharges from such unlinked starting zones will combine at the same point at the same time in the track. Consequently, very high velocities caused by channelization effects and the resulting long runout distances are more probable from large, smooth starting zones above confined tracks, such as illustrated in Figures 1-1, 4-1, and 4-2.

The avalanche track for a channelized avalanche is located where the convergence of snow from the starting zone ends and the flow becomes confined laterally. In path "A" the gully serves as the avalanche track. It concentrates the mass of snow released from the bowl-shaped starting zone into a track whose lateral boundaries are rigidly determined by the topography. Under such confinement, the

---

[2] In maritime climates, such as the Pacific Northwest and the Alaskan coast near Juneau, wet snow commonly accumulates on slopes steeper than 100% (45°).

flow cannot spread out, so it must become deep, which causes an acceleration of the flowing mass of snow. Thus, another very important diagnostic feature is easily determinable through air photo interpretation -- the identification of a large starting zone above a laterally constrained avalanche track which increases both velocity and runout potential by increasing flow depth. The concentration of mass in the channel (track) concentrates the flow energy and makes the avalanche more dangerous and far reaching in the runout zone.

The size of the flow cross section of past avalanches in path "A" may also be estimated from inspection of vegetation trimlines at the lateral boundaries of the track. Wet slides, because of their lesser velocities, are confined to the inner portion of the gully which serves as the avalanche track. They follow the bends and curves of the gully faithfully. Consequently, the steepness, roughness, and degree of curvature in the gully is an important factor in determining the velocity of wet snowslides. However, the gully of path "A" has also been affected by much wider, and, as a consequence of the gully shape, deeper avalanches. Field inspection of the avalanche track usually reveals that this wider damage at the lateral track limits was caused by powder avalanche impact. Dynamic analysis, discussed in section 4 of this chapter, reveals that it is physically unrealistic to assume that dense flowing avalanches caused the damage at the upper trimline boundaries. Hence, the lateral limits of the avalanche in path "A" can be safely assumed to have been caused by powder avalanches. The steepness and roughness of the gully has little influence on powder avalanche velocity; however, the increased flow depth caused by lateral constraint does increase the velocity. When an avalanche track is confined to a gully as deep as in path "A", even powder avalanches will be totally confined. However, because of their great flow depths and velocities, which cause a tendency to run straight downhill, they override minor terrain obstacles. The effect of this deep, high-velocity flow can be seen near bends in the channel where the flow has climbed high on the outside of the curves. Air photo analysis of the track provides rough fluid-dynamic boundaries of the large avalanche events of the past.

It is not possible to determine the age of the apparently undisturbed trees beyond the avalanche boundaries by photo interpretation. However, if these trees are cored and determined to be 100 years old, for instance, then it is realistic to assume that slides capable of high impact pressures have not occurred wider than these boundaries during the last century. There is some probability that larger avalanches will occur in the future, and widen the track even more. Even if this does happen, we may deduce from the orientation of the starting zone and track that this larger event will also be symmetrically centered over the main gully, and will not jump out of the track in mid-slope.

The top of the runout zone of path "A" is easily defined as that portion of the path in which the flow is no longer laterally confined. This is coincident with the lower gradient portion of the path and is clearly identifiable in the photo.

By field inspection, the ridge at the top of the runout zone is found to be about 10 m high (Figure 4-2). This is sufficient to deflect the wet slides to the northeast. In other words, the flow energy of these avalanches is insufficient to permit them to climb the ridge in the direction of flow attained in the upper track.

However, this same ridge is not sufficient to deflect the flow of deeper, faster moving avalanches and powder avalanches overtop it to continue in a northerly direction. The damaged forest clearly visible in the photo on the north side of the ridge indicates that this has happened in the past. The runout zone from powder avalanches is in an entirely different location from that of wet slides.

The outer limit of the runout zone is of great importance in planning development. In some cases, this limit can be delineated quite clearly through air photo analysis. It may show up as a clear demarcation between mature and immature forests, or as a boundary between deciduous and coniferous forests. In path "A" the runout zone apparently extends into the meadow north of the track. Differences in vegetation show up most clearly on color infrared imagery. On this imagery there is a marked difference between the reflectivities of coniferous forests, deciduous forests, and open meadows and through interpretation, the boundaries between zones of avalanche frequency may be estimated in some cases. For further discussion of avalanche frequency, see chapter 6.

Air photo analysis has definite limitations in delineation of avalanche runout zones. It can be used best where avalanches run out into forests, for the reasons discussed above. However, differences in the type, age and areal distribution of forests have other causes, including fire, human activity, beaver cutting, bedrock and soil or moisture differences, or effects from intense wind storms. In many cases, runout zones are on open meadows, devoid of forests, or on flood plains. In all cases, the runout zone extent as determined through air photo interpretation, must be checked by completely independent methods, including field investigation and dynamic analyses, both of which are discussed in subsequent sections of this chapter.

Several smaller avalanche paths are visible to the east and west of path "A" in Figure 4-1. These paths are evident as open cuts through the timber aligned in the downslope direction. It is apparent from the air photos that they do not extend as far into the runout zone as path "A", even though they have tracks which are just as steep, or steeper. The difference in these runout potentials is due primarily to the differences in the sizes of the starting zone areas. Path "A" has a bowl-shaped starting zone of over 15 ha, (40 acres), most of which can release at one time, forming a single large avalanche. However, the smaller slides west of path "A" run mostly in the tracks, never involve as much snow and, consequently, stop quickly in the runout zone.

Air photo interpretation can be combined effectively with analysis of topographic maps on which the slope inclinations can be easily measured. Typical inclinations of the large avalanches of interest are 55% to 100% (29° to 45°) in the starting zone, 30% to 60% (17° to 29°) in the track, and less than 30% (17°) in the runout zone. Some avalanches which reach the bottoms of narrow valleys do not have runout zones. If the slope gradients of various parts of suspected avalanche paths are determined during the early part of the analysis, many slopes and gullies may be eliminated from consideration when it is found that gradients are too gentle for large avalanche releases. The areas of starting zones or accumulation basins may also be estimated by planimetry from topographic maps. This cannot be done as accurately on photos because of the problems of scale inconsistency from point to point associated with low altitude photography.

Air photo interpretation is best suited to the reconnaissance mapping of the potential extent of avalanche activity. A general "feel" for the size of a path, along with its runout extent is made possible through recognition of the relationship between starting zone size, track configuration and runout zone size. However, important additional information, essential in structural design in the track and runout zone, must be obtained through other methods. This information includes avalanche velocity and impact pressure.

3. Statistical prediction of avalanche runout distance as related to terrain variables

This section presents the results of a study (Bovis and Mears, 1976) that relates avalanche runout distance to certain terrain variables easily measurable on topographic maps and air photos.

Avalanche paths measured in this study were large and had confined tracks. Hence, the results cannot be applied to small avalanche paths, or paths with unconfined tracks.

A least-squares regression equation to predict avalanche runout distance was derived from a sample of 67 avalanche paths in several mountain ranges in Colorado. The paths sampled have known runout distances, as determined from field checking and air photo interpretation of the limits of avalanche debris and timber damage in the runout zone. The length of the runout zone extends from the lower boundary of the avalanche track to the outer limit of impact from avalanches. This length was taken as the dependent variable. The independent variables used in the regression equation were track slope, runout zone slope, and area of the avalanche starting zone.

The results of the regression equation indicated that 65 percent of the variation in runout distance could be accounted for by variation in starting zone area alone, while track slope and runout slope accounted for less than 2% of this variation. Because of this, the regression equation was reduced to simple linear form:

$$S = 214 + 11.4A \qquad (4\text{-}1)$$

where S is the runout length, in meters, A is the starting zone area in hectares, [1] and the S-intercept is in meters. The 95 percent

[1] 1 hectare = $10^4 m^2$ = 2.47 acres

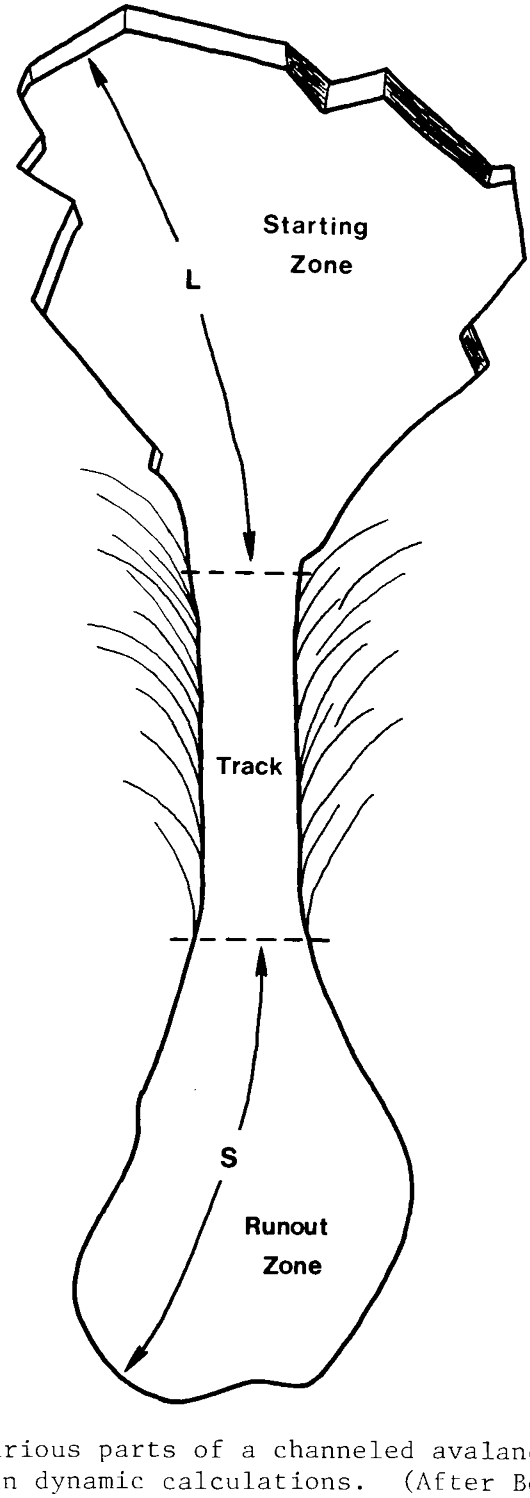

Figure 4-3. The various parts of a channeled avalanche path showing dimensions used in dynamic calculations. (After Bovis and Mears, 1976).

confidence intervals for the intercept and slope are respectively $174 < B_o < 254$ and $9.3 < B_1 < 13.5$.

Equation (4-1) indicates that, for the sample included in the analysis, the runout distance may be predicted by measuring the area of the starting zone alone. This area can be determined by measurement on 1:24000 scale topographic maps. In Figure 4-3 the starting zone lies within the catchment basin, and in exceptional cases may encompass the entire basin. Often parts of the catchment basin are too steep or irregular to permit the accumulation of a deep snow layer. For this reason, slopes steeper than about 100% (45°) should be be excluded. The lower boundary of the starting zone is drawn at the point beyond which a flowing snowmass becomes laterally confined in the track. A further constraint can be imposed on the dimensions of the starting zone from field observations on slab geometry reported by Brown and others (1972). They note that snow slabs involved in slab avalanches are usually wider than they are long. For this reason, a conservative upper limit of unity should be used for the ratio L/W of starting zone length to width. The value is conservative because it probably encompasses the dimensions of slabs and entrained snow associated with the very large, rare avalanches which must be considered when runout distance calculations are applied to the land-use zoning of mountain terrain.

The general relationship given in equation (4-1) is the same as that discussed previously in chapter 3, and section 2 of this chapter--a large starting zone above a laterally constrained avalanche track increases both velocity and runout potential through increasing flow depth.

The use of equation (4-1) in the prediction of avalanche runout distance has certain important limitations. There probably exist regional differences in avalanche potential when terrain factors are held constant. Some mountain ranges not only receive more snow than others, but may also receive more snowstorms conducive to widespread, destructive avalanches. For example, the San Juan Mountains of southwestern Colorado may constitute a separate population from the Front Range, at the eastern margin of the Colorado Rockies.

Detailed information on the geometry and roughness of avalanche tracks was not included in the regression equation. Although these factors are important in controlling the velocity of wet or dry flowing avalanches, they are probably not very important in controlling powder avalanche velocity.

This method which is subject to the limitations described, provides an additional means of estimating the runout distance of large channeled avalanches, and it can be used for approximations of runout distances in areas where debris or damaged timber is not present.

4. Use of dynamic equations of avalanche flow

Additional information about runout extents, velocities and impact pressures may be derived by employing certain equations of avalanche flow. Wherever possible these methods should be used in conjunction with the air photo interpretation and terrain analysis methods discussed in the preceding two sections. Dynamic equations can provide completely independent estimates of avalanche size as well as additional information about important design parameters such as velocity and impact pressure. However, because results derived from the use of these dynamic equations are highly dependent on assumptions about important flow parameters, they should not be used alone.

The results obtained by applying dynamic equations provide numerical values for velocity, flow depth, discharge, impact pressure, and runout distance. It is common practice to formulate engineering design and proceed with planning after these numerical values are derived. A building, for example, may be located just beyond what has been calculated to be the runout limit of an avalanche. The safety of residents of that building depends on the assumptions used in the analysis which provides design parameters. Therefore, it is very important to recognize that the results of the analysis are dependent upon these assumptions. The flow parameters that affect avalanche velocity, impact pressure and runout distance include avalanche volume, flow depth, density, discharge rate, turbulent friction, kinetic friction, and geometry of the released snow mass. Since none of these values are known, they must be estimated. The estimated values usually lie somewhere between "commonly acceptable" limits which, unfortunately vary widely (see Schaerer, in press; Sommerhalder, 1964). The equations of motion, and their applications and limitations are discussed below.

a. dynamic analysis of unconfined, flowing avalanches

As discussed in chapter 3, it is important to distinguish between two different topographic conditions over which avalanches flow. The first case is the "unconfined slope" case discussed here; the second is the "channeled" case, discussed in the next section (Figure 3-6).

In the idealized situation, an unconfined avalanche track is simply an inclined plane unmodified by gullies and ridges. An avalanche on such a slope is not concentrated by gullies into a narrower, deeper, and faster moving snow mass within the track. The unconfined case exists, for practical purposes, when gully depths are smaller than expected avalanche flow depths, or when these gullies are filled in by the winter snowpack.

Although channelization effects are not present in unconfined avalanches, some avalanches may grow considerably in size as more snow is entrained into the flow. In this way it is possible for avalanche volume, discharge rate, flow depth and velocity to increase as an avalanche flows down an unconfined slope. However, this possibility is not considered in the equations discussed below because no measurements or estimates on the amount of entrainment are available. It should be pointed out, however, that the type of snow in broad avalanche tracks can change the dynamics of flow considerably. For example, a dry snow avalanche encountering wet snow in the lower track can develop into a wet snow avalanche.

Inspection of topographic maps will reveal many mountain locations that seem suitable for unconfined avalanches. However, most U.S. Geological Survey topographic maps for mountain areas have contour intervals of 40 feet and are not detailed enough to show small gullies that can modify the flow of snow. Low altitude air photos will often reveal the locations of small gullies whose existence can then be confirmed, and their importance further evaluated through field checking.

Occasionally avalanche tracks (both unconfined and channeled) are cut by steep rock outcrops (Figures 3-5, 3-7). These cliff bands must be considered wherever dry snow avalanches are expected. As dry snow avalanches fall over cliffs, they can entrain air and develop into airborne powder avalanches capable of higher velocities and longer runout distances than flowing surface avalanches. The flow of powder avalanches can not be analyzed by the dynamic equations discussed in this section, but is discussed separately in section 4d of this chapter.

Equations (4-2 and 4-5) were derived by Voellmy (1964, in translation) and are applicable strictly to flowing avalanches. Such avalanches may consist of either dry, damp, or wet snow, but they are all similar because their flow densities are not much different from the densities of the snowpack prior to avalanche release. Voellmy derived these equations assuming that avalanches behave as fluids, and he used previously developed relationships of hydraulics. The hydraulic analogies are probably justified in fully developed avalanches flowing at or near terminal velocity, but are less accurate during the final stages of flow in the runout zone. Here avalanches of dense snow may behave like compressible solids, and large blocks may slide rigidly. The flow of fully developed avalanches may be described as a turbulent cascade of solid particles and blocks of snow which, because of their high water content (as in the case of wet snow avalanches) or large particle sizes (as in avalanches released from hard slabs) do not become dispersed in air to become powder avalanches. Typical flow densities have not been measured but probably lie somewhere between 50 kg/m^3 and 300 kg/m^3 for dry snow avalanches and between 300 kg/m^3 and 400 kg/m^3 for wet snow avalanches (de Quervain, 1975).

Voellmy's equation for calculating terminal, or maximum velocity of a flowing avalanche on an unconfined slope is

$$U^2 = \xi h' (\sin\alpha - f \cos\alpha) \qquad (4\text{-}2)$$

in which U is terminal avalanche velocity averaged over the flow depth, ξ is the coefficient of turbulent friction, h' is the depth of flow, α is the angle of slope inclination, and f is the coefficient of kinetic friction at the interface between the avalanche and the snow or ground beneath it.

Equation (4-2) is applicable only after terminal velocity is attained, that is, after the driving and resisting forces are equal and acceleration is zero. According to Salm (1975), 90% of terminal velocity is attained in a distance of 40 h'. The difficulty of choosing parameters of avalanche flow can be illustrated by inspection of equation (4-2). The turbulent friction coefficient ξ must depend on terrain roughness in the same way that roughness coefficients vary in river hydraulics. Several different opinions have been offered regarding values of ξ. Voellmy (1964) first suggested $400 \leq \xi \leq 600$ m/s^2. These values have been reaffirmed by experience in Switzerland as suggested by Salm (1975). The theoretical studies of Shen and Roper (1970) give values of ξ up to 750 m/s^2 for fast moving avalanches of dry snow. The most recent attempt to measure the parameters of avalanche flow was by Schaerer (in press). He found $400 \leq \xi \leq 800$ m/s^2 for slides in rough terrain but suggested values up to 1800 m/s^2 for avalanches flowing on hydrodynamically smooth surfaces, such as compact, old snow. The value is probably dependent in some complicated way on velocity and contact surface with the ground, and also contains other terms such as frontal drag at high velocity which are not explicitly considered.

A variety of opinions have been offered as well on values of f. Voellmy (1964) first suggested $0 \leq f \leq 0.3$, with lower values applying to powder avalanches, or avalanches of very wet snow in which there is a great deal of lubrication by interstitial water or air. The Swiss workers (Salm, 1975) presently suggest $0.15 \leq f \leq 0.3$. However, Schaerer (in press) feels that f should be inversely proportional to velocity and suggests the relationship $f = 5/U$. This would decrease the importance of f at high velocity (Schaerer suggests f is negligible at $U > 50$ m/s) but it would become increasingly important at low velocities. Schaerer's suggestion seems reasonable because at low velocity the mean free distance between snow particles should decrease as turbulence is suppressed, and viscous forces become more important (Mears, 1975). If Schaerer's suggestion is adopted, then equation (4-2) becomes

$$U^2 = \xi h' (\sin\alpha - 5/U \cos\alpha) \quad (4\text{-}3)$$

which is a cubic equation in U and is therefore more difficult to use. However, it does reduce the subjectivity inherent in the selection of f.

The depth of avalanche flow, h', is also difficult to estimate because we must be concerned with maximum h' which might be expected over a long time period. For flowing avalanches, h' is approximately equal to the thickness, h_o, of the released snowpack. The problem, therefore, is changed to one of estimating h_o, through meteorological statistics, for example. Statistical approaches to the estimation of values is discussed in chapter 6. For dry snow avalanches at higher velocities (> 30 m/s) the approximation $h_o \cong h'$ become questionable because avalanche flow attains a greater degree of fluidization. At locations in which powder avalanches can occur, especially where dry snow avalanches fall over cliffs at high velocities, the approximation $h_o \cong h'$ is not valid. For example, if a fresh snow deposit of unit weight γ_o, of 100 kg/m^3 is entirely converted to a powder avalanche of unit weight γ_p of 10 kg/m^3, then the resulting flow depth,

$$h' = \frac{\gamma_o}{\gamma_p} h_o \tag{4-4}$$

If h_o = 1 meter, then h' = 10 meters, and increased velocities would result. For this reason powder avalanches should not be analyzed by the flowing snow equations (eqs. 4-2 or 4-3) but should be treated separately as discussed in section 4d.

Unfortunately, the foregoing discussion provides very little guidance for choosing values of the avalanche flow parameters. The divergence of opinions offered is summarized in Table 4-1.

TABLE 4-1: Values of avalanche parameters used in the equation 4-3.

Parameter	Source			
	Schaerer (1974)	Shen and Roper (1970)	Voellmy (1964)	Salm (1975)
$\xi (m/s^2)$	400 to 1800	up to 750	400 to 600	400 to 600
f(dimensionless)	$f = 5/U$; $f \leq 0.5$ (U in m/s)	---	0 to 0.3	0.15 to 0.3
h'(m)	must be estimated for the particular location			

With such a wide divergence in results and opinions, it is suggested that the following conservative approach be taken in the analysis of unconfined, flowing avalanches in Colorado:

1) Let $f = 5/U$ (Schaerer, in press), thereby eliminating the necessity of guessing at this value. The precise relationship of f to U may change as more data is collected, but the decrease of f with increasing U should be considered in analyses.

2) Assume the following values for ξ:

a) $400 < \xi < 800$ for rough terrain covered with boulders and trees. The lower value ($\xi = 400$) should be used when many boulders and large trees split avalanche flow; $\xi = 800$ should be used for sparsely wooded, but otherwise smooth slopes.

b) $800 < \xi < 1200$ for avalanches running on smooth slopes essentially free of trees and rock projections or for avalanches running on old compact snow. Since different types of avalanche running surfaces may be found in the starting zone, track, and runout zone, different values of ξ may be used for various parts of the path.

3) The approximation $h' \cong h_o$ should be used only for flowing avalanches.

A second equation (Voellmy, 1964) enables calculation of the run-out distance, S, an avalanche will travel in a zone of reduced gradient, in which steady flow cannot be maintained:

$$S = \frac{U^2}{2g(f\ \cos\beta\ -\ \tan\beta\ +\frac{U^2}{2\xi h})} \qquad (4\text{-}5)$$

where g is the gravitational acceleration, β is the slope of the runout zone (usually less than 20°), h is equal to h', and other terms are as defined above.

Since U^2 appears in equation (4-4), and U depends on ξ, f, and h as already discussed, the runout distance is also highly dependent on assumptions. Furthermore, Sommerhalder (1965), suggests that $h' \leq h \leq h' + U^2/4g$. However, for unrestricted runout zones the assumption $h \cong h'$ is adequate because excessive damming of snow does not take place.

Sample calculations using equations 4-4 and 4-5. Assume for a Colorado avalanche path the following conditions: α = 35°, β = 10°. Values used in the equations are:

Case 1: h' = 1.5m, ξ = 800 m/s^2, f = 5/U = 0.23

Case 2: h' = 2.0m, ξ = 1000 m/s^2, f = 5/U = 0.17

The values derived using equations 4-4 and 4-5 are:

Case 1: U = 21 m/s, S = 90m (assuming f = 0.25)

Case 2: U = 29 m/s, S = 186m (assuming f = 0.2)

Note that the derived values for runout distance, S, using equations 4-4 and 4-5, and two pairs of assumed values for flow depth, h' and turbulent friction, ξ, differ by more than a factor of two. An investigator could probably not estimate h' and ξ any more closely than this. The values of f used in calculating runout distance were somewhat in excess of those calculated for flowing snow at terminal velocity in the track. Details of runout zone dynamics are discussed in section e of this chapter. With these difficulties in mind, an independent method was developed (Mears, 1975) by which estimates of avalanche pressures and velocities can be made through interpretation of damage to trees in avalanche paths.

b. Calculation of avalanche velocities, impact pressures, and runout distances through interpretation of broken tree data.

In an attempt to calculate dynamic properties of dense flowing avalanches on unconfined slopes, an area that is known to be affected by avalanches was studied. This slope (Figure 4-4) is subject primarily to wet or damp snow avalanches, generally occuring in the spring. Small dry snow avalanches also occur at this location during mid-winter, but generally do not impact trees with forces sufficient to uproot or break them. Therefore, if building takes place below these slopes, the design must allow for wet snow avalanche impact.

Aspen, by far the most common tree on these slopes, are occasionally subjected to snow avalanche impact in the lower meter or so. The avalanches may also carry debris. This adds to their destructive potential and scars the trees.

Three types of damage occurred to trees on these slopes. Tree trunks were either uprooted, bent until the main trunk snapped, or scarred by pieces of wood in the flow. Uprooting was ignored as a means of estimating impact pressure because the strength of the root-soil system could not be evaluated for each tree. Those trees which clearly failed in bending (Fig. 4-5) could be used to determine the bending stress exceeded at time of failure. Young trees of diameters less than 5 cm generally did not fail, probably because they were quite flexible. Observed bending failure was quite common at diameters of 10 to 15 cm, the frequency decreasing quickly at larger diameters, (Fig. 4-6). Broken aspen trunks with diameters up to 25 cm were observed but were uncommon. These diameter failures may have occurred because of impact of debris in the flow, or

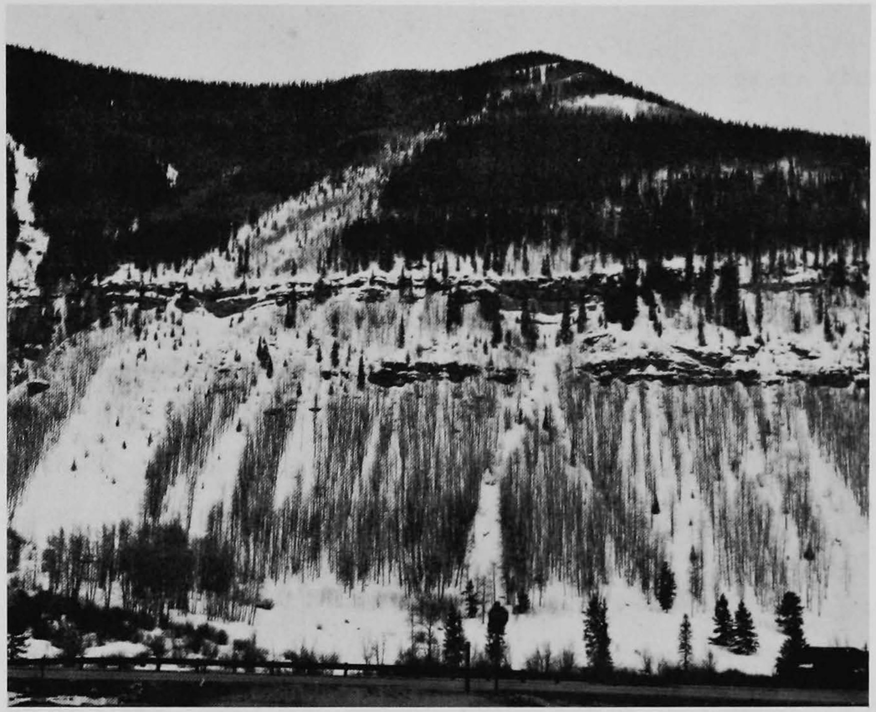

Figure 4-4. Unconfined slope avalanche of the type used in the collection of broken tree data discussed in section 4a. (After Mears, 1975)

Figure 4-5. Typical broken aspen found on slope in Figure 4-4. (After Mears, 1975)

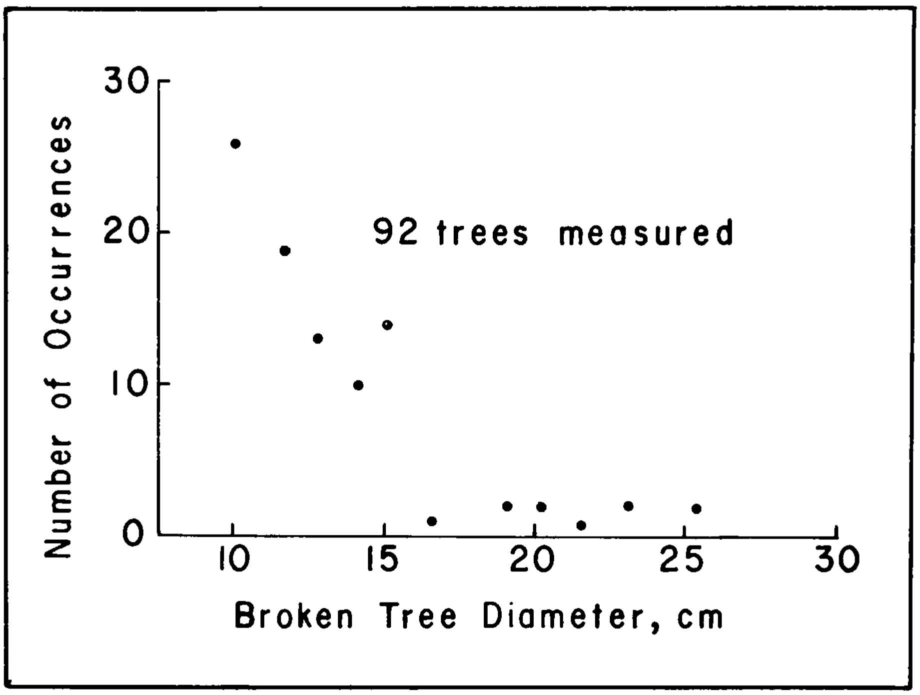

Figure 4-6. Relationship of tree diameter to frequency, found on slope depicted in Figure 4-4. Trees with trunk diameters larger than 15 cm commonly withstood impact. (After Mears, 1975)

because, due to previous impact or stress concentrations in the trunk, trees were actually weaker than would normally be expected for these diameters. Trunks with diameters greater than 15 cm withstood impact much more often than they were broken. Scars on these larger trees were often used to estimate the depth of flow, as discussed later. On the basis of the data of Figure (4-6) it is suggested that a good "representative maximum" aspen diameter commonly observed broken is 14 cm.

The depth of avalanche flow, h' was determined from the height of impact scars on trees growing in avalanche tracks. Only well-defined scars on the uphill side of trees were used. A total of 145 trees exhibiting impact scars were measured. This sample showed a mean of 110 cm for the height of scarring with a standard error of the mean of 2.4 cm. Thus the sample indicates a 95% probability that the mean value of the maximum flow depth, h', is 110 cm $\pm$ 5 cm. Observed scars of apparently equal age usually were visible to the base of the trees, indicating that the avalanche flowed to ground level. Full depth avalanches of this type are common in the spring. This procedure provides data which greatly reduces the uncertainty of subjectively estimating h' for use in equation (4-3).

Avalanche impact pressure was calculated by using field date on flow depth and tree trunks that failed due to avalanche induced bending stress. The resistance to bending at rupture, M_r, can be written in terms of the modulus of rupture, σ, and diameter, d, for a circular cross section as

$$M_r = \frac{\sigma \pi d^3}{32} \tag{4-6}$$

The induced bending moment, M_i, caused by avalanche pressure can be written in terms of the average force, F, on the tree trunk normal to the flow, and the length of the moment arm from the base of the flow to the center of pressure on the trunk. Snow avalanche impact is discussed in detail in chapter 5.

The impact pressure, P, is related to avalanche velocity, U, by

$$P = \frac{1}{2}\rho U^2 \; * \qquad (4\text{-}7)$$

(Schaerer, 1973), where ρ is the flow density, and U = U(z), a function of height above the ground. Voellmy (1964) suggests

$$U(z) = \bar{U}\left[\frac{4}{3} - \left(\frac{z'}{h'}\right)^2\right]. \qquad (4\text{-}8)$$

where $\bar{U}$ is the average velocity, occurring at 0.58h' below the top of the flow, and z' is the vertical distance below the top of the flow. Combining equations (4-7) and (4-8) it can be seen that the pressure is also a function of distance above the ground, written as

$$P(z) = \frac{1}{2}\rho\left[U(z)\right]^2 = \frac{1}{2}\rho\left\{\bar{U}\left[\frac{4}{3} - \left(\frac{z'}{h'}\right)^2\right]\right\}^2 . \qquad (4\text{-}9)$$

The maximum induced bending moment, M_i, occurs at the base of the tree trunk and can be computed by integrating the pressure profile, P(z), over the height of impact h', and multiplying the integration by the tree trunk width, d, and a coefficient of drag, C_D. This integration is written

$$M_i = \frac{C_D d\rho}{2}\int_{z=o}^{z=h'} \bar{U}\left[\frac{4}{3} - \left(\frac{h'-z}{h'}\right)^2\right]^2 z\,dz \qquad (4\text{-}10)$$

with the limits of integration taken as ground level and height of impact scarring.

---

*ρ = γ/g where γ is the unit weight and g is the gravitational acceleration.

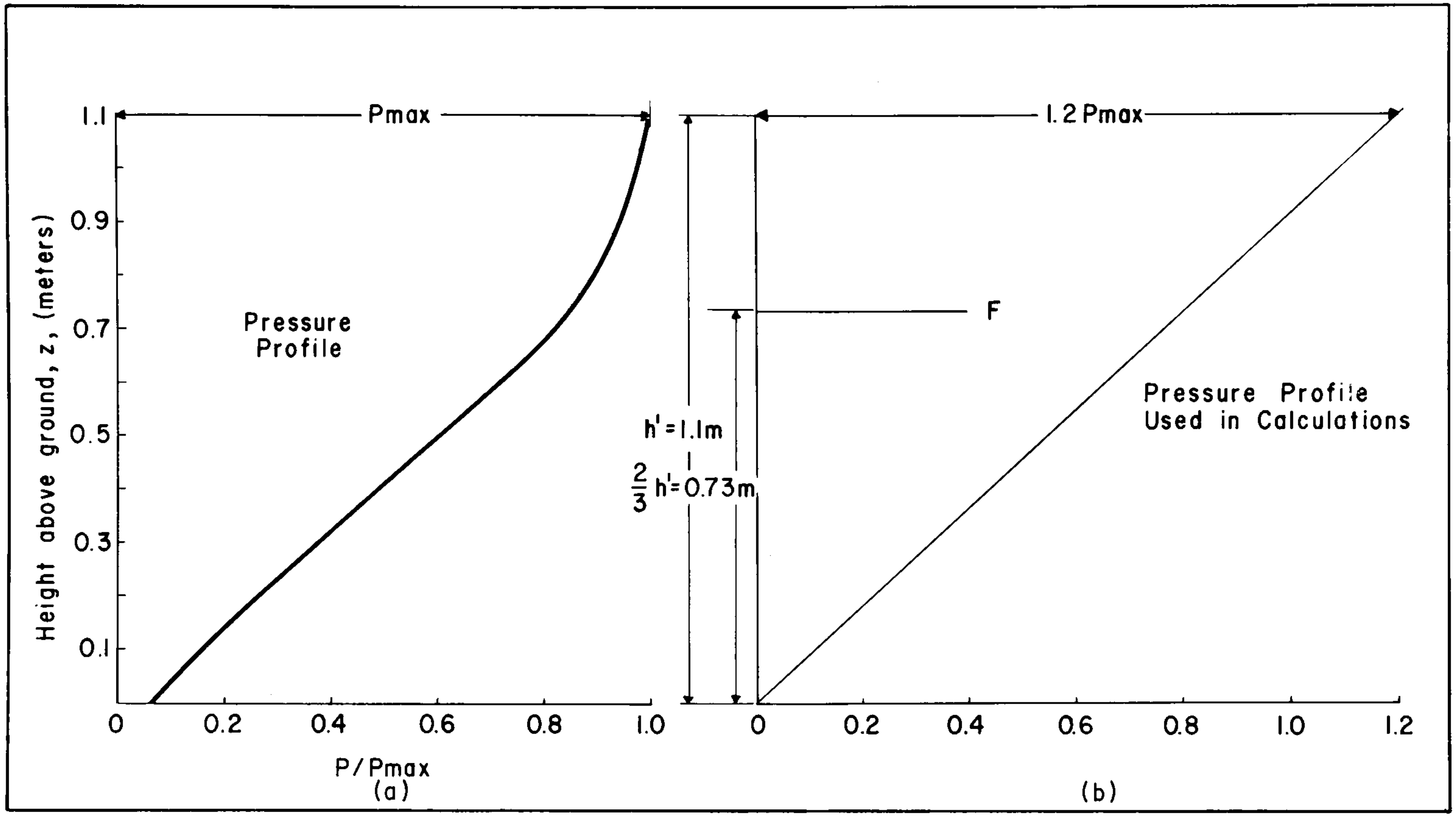

Figure 4-7. Pressure wedge assumed in calculations of avalanche impact pressure, showing the location of an equivalent concentrated load (center of pressure). Theoretical curve is shown in Figure 5-3. (After Mears, 1975)

An accurate graphical representation for the integration of equation (4-10) is achieved by assuming a triangular pressure wedge as in Figure (4-7). This may be resolved into a single concentrated load, F, where $\overline{P}$ is the average pressure over the height of impact, by

$$F = \overline{P}(dh') = 0.6\, P_{max}(dh') \quad , \tag{4-11}$$

and the induced moment, M_i is

$$M_i = F(\tfrac{2}{3}\, h') = 0.4\, P_{max}(dh'^2) \quad . \tag{4-12}$$

Equating (4-6) and (4-12) enables the pressure at the top of the flow, P_{max}, to be written in terms of measurable parameters of flow and size of tree trunk as

$$P_{max} = \frac{\sigma \pi d^2}{12.8\, h'^2} \quad . \tag{4-13}$$

The pressure computed in equation (4-13) actually refers to the static pressure equivalent of the avalanche impact pressure. However, a tree impacted by a wet avalanche must respond to avalanche impact almost instantaneously, differing appreciably from loading of a powder avalanche. The actual impact pressure, P'_{max} necessary to produce the observed damage need by only about $\frac{1}{2}P_{max}$ (Norris, 1959). Therefore, avalanche impact pressure,

$$P'_{max} = \frac{\sigma \pi d^2}{25.6\, h'^2} \quad . \tag{4-14}$$

For a tree of diameter 14 cm assuming $2.7 \times 10^7 < \sigma < 3.5 \times 10^7$ NT/m^2 ($4000 < \sigma < 5000$psi) for green aspen (Betts, 1919), the impact pressure is 8.0 to 10.0 t/m^2.*

---

* 1 t/m^2 = 1000 kg/m^2. Pressure is defined to be dimensionally consistent with $\frac{1}{2}\rho u^2$.

Impact pressure may be translated to avalanche velocity through equation (4-7). If it is assumed that $\rho = 300\ kg/m^3$, as is consistent with the observations of Schaerer (in press). Then U_{max}, at the top of the flow is 22.9 to 25.6 m/s. This corresponds to average velocities, $\overline{U}$, of 17.2 to 19.2 m/s through equation (4-8).

If values of h' and U obtained in this study are inserted into equation (4-3) and equation (4-3) is solved for ξ assuming a slope angle α of 37° it is found that $700\ m/s^2 < \xi < 825\ m/s^2$. This places it within the range of ξ suggested by Schaerer and the two independent methods agree quite well for a flow density of $300\ kg/m^3$ and depth of 1.1 m.

This method, when used alone in the analysis of an unconfined avalanche, is subject to certain difficulties which must be recognized. First, the exact nature of loading on trees upon impact is not known, so a simple dynamic loading is assumed. Second, the bending strength and stress configuration leading to failure within the tree trunk are not known; a simple linear stress distribution and modulus of rupture are assumed in calculations. Third, it is not known if impact loading by debris carried in the avalanche contributed to tree failure, and if it did, how this would affect the equations. Finally, the application of this method must be restricted to timbered slopes. Fortunately, this is a fairly common situation in Colorado. These uncertainties suggest that the method might be as dependent on various assumptions as are the dynamic equations discussed in the previous section (equations 4-3 and 4-4).

Therefore, it is recommended that this method be used in addition to equations (4-3 and 4-4) in avalanche analysis. If the two methods, using a field determination of h', yield comparable results, a much greater confidence may be placed in the overall analysis. If the results are greatly divergent, and calculated velocities differ by more than 50%, then the investigator is at least no worse off than if he had employed only one method. He may decide to choose the more conservative result.

Both methods yield an avalanche velocity, U, at the bottom of the track and the top of the runout zone which can be used in equation (4-5) to determine a runout distance.

c. Dynamic analysis of confined, channeled avalanches

Channeled avalanches require a different method of analysis. This type of avalanche includes many of the moderate to large avalanche paths in Colorado, as already discussed under statistical analysis of avalanche terrain variables in section 2 of this chapter.

In Figures 4-2 and 4-3 avalanche paths of this type are illustrated. The starting zones are wide when compared to the widths of the tracks. A large-scale release of snow of volume K in the starting zone will therefore produce a large discharge rate Q in the track at cross-section a-a', for example. The value of Q is dependent on K and on the ability of the starting zone to convey the released snow quickly to the cross-section a-a'. In this sense a broad starting zone with most of the area located relatively close to a-a' can be considered more "efficient" than a long, narrow starting zone in conveying the released snow. If avalanche flow within the track is confined by gully walls and K is large, the resulting flow depth, h', and hydraulic radius, R, within the track will both be large. The hydraulic radius, R, is defined as A_t/P, where A_t is the cross-sectional area of avalanche within the channel, and P is the length of the wetted perimeter. For the channeled avalanche case the flow depth, h', in equation 4-4 should be replaced by the hydraulic radius R, so that the terminal velocity

$$U^2 = \xi R(\sin\alpha - \frac{5}{U}\cos\alpha) \tag{4-15}$$

Equation (4-15) indicates that the terminal flow velocity is proportional to the square root of the hydraulic radius. The term $(\cos\alpha)^{\frac{1}{2}}$ varies by only a small amount across the range of slopes on which large avalanches occur (Bovis and Mears, 1976), and the term $(f \cos\alpha)^{\frac{1}{2}}$ is insignificant at high velocities (Schaerer, in press).

The physical dependence of R on starting zone area is best illustrated by combining equation (4-15) with the continuity principle of hydraulics. For a given starting zone of area A and thickness of released snow slab h_o, the volume of snow released, K, is:

$$K = Ah_o \quad . \qquad (4\text{-}16)$$

As discussed by Salm (1975), the volume K is completely discharged through a-a' when the upslope margin of the detached slab has traversed the distance L (Figure 4-3). The time required to discharge the snow slab is therefore:

$$\Delta t = L/\overline{U} \qquad (4\text{-}17)$$

in which $\overline{U}$ is the mean flow velocity over distance L. $\overline{U}$ can be estimated from equation (4-15) since Voellmy (1964) and Salm (1975) have shown that terminal velocity is approached quickly, so that the accelerating phase may be disregarded, and the approximation $U = \overline{U}$ suffices for average velocity. The mean discharge rate from the starting zone is:

$$Q = K/\Delta t \quad . \qquad (4\text{-}18)$$

Continuity requires that this discharge also be conveyed through the channeled portion of the avalanche path so that within the track

$$Q = A_t U_t \qquad (4\text{-}19)$$

where A_t is the track cross-sectional area at a given point and U_t is the average flow velocity through this cross section. Since A_t and R are related through cross-section shape, and U_t is a function of R from equation (4-15), equations (4-15) and (4-19) must be satisfied simultaneously, specifying both cross-sectional area and avalanche velocity through a given cross section.

Clearly, large starting zone areas (large values of K) can produce correspondingly large values of Q and R and thereby result in high flow velocities.

In this way the dynamic analysis of the entire avalanche path can be made. However, it is necessary to assume values of several of the parameters used in the equations, just as it was necessary to make assumptions for unconfined avalanches. These assumptions and the dependence of derived dynamic properties of an avalanche to them are discussed below.

1. The starting zone area, A. This may be estimated by inspection of air photos and topographic maps. As discussed earlier, the critical starting zone inclinations are between 55% and 100% (29° to 45°) because these areas can accumulate a deep snowpack prior to avalanche release and can produce large release volumes. It is also helpful to visit the starting zone in the field during the summer to see if previous avalanches have caused damage in the areas suspected of being starting zones. Winter observations of starting zones can also be helpful, but it is important to remember that a single winter's data might tend to underestimate the amount of starting zone that can slide (see Figure 4-2, for example).

2. The thickness of the sliding snow layer, h_o, within the starting zone. The determination of h_o is very subjective. What is necessary, of course, is to arrive at an estimate of the maximum h_o that could occur during a long time period. The value of h_o used refers to the average thickness of the detatched snow slab throughout the starting zone. In Colorado, h_o is generally assumed to be between 1.0 and 2.5 meters with the larger values assumed for higher elevations. Measurements of large slab avalanches are needed

in order to place constraints on assumed values of h_o. Direct observations of slab avalanches in the area may not provide this maximum h_o unless extreme events are observed. Statistical methods for calculating h_o are sometimes attempted and are discussed in chapter 6.

3. Starting zone volume, K. This is simply equal to the product Ah_o and is obviously dependent on assumptions about these values.

4. Starting zone length, L. This may be measured from the starting zone topography (Figure 4-3) after the dimensions of the starting zone are determined.

5. Starting zone inclination, α. This can be measured in the field or from topographic maps.

6. Turbulent friction, ξ. Suggested values for ξ have been discussed previously in the "unconfined slope" case. These values apply also in broad starting zones. It is suggested that $600 \leq \xi \leq 1200$ m/s^2 be used in starting zone analyses, as this is about midway between the recommendations of Schaerer (in press) and Salm (1975). Larger assumed values of ξ yield larger estimates of avalanche velocity and longer runout distances. Within the channeled track, effective boundary friction may be greater than on an unconfined slope, so that $500 \leq \xi \leq 1000$ m/s^2.

7. Sliding friction, f. Suggested values for f have also been discussed for the open slope case. The approach of Schaerer is once again recommended in which f is a function of velocity and equal to 5/U.

Values of U, Δt, and Q can be calculated in the track through simultaneous solution of equations (4-15 and 4-19) by specifying that Q also be discharged through the channeled portion of the avalanche track.

The dependence of velocity on assumptions about flow parameters is illustrated by the following example in which two sets of assumptions are used in the analysis of a particular avalanche path. In this example it is assumed that the density of the flowing avalanche is the same as the density of the snow released from the starting zone. The physical features of this path, as determined from air photo, map, and field measurements are:

Starting zone area, A	20×10^4 m^2 (50 acres)
Starting zone length, L	540 m
Starting zone inclination, α_1	33°
Gradient of channeled track, α_2	23°

For this example, it is assumed that the channeled part of the avalanche track is smooth, straight, and can be approximated as a triangular cross-section with 40° side slopes. In the analysis of an actual avalanche path, the cross-section would have to be measured by field survey, although the 40° side slopes assumed in this example does approximate the cross-sectional geometry of many avalanche channels. The assumptions used in values calculated through equations (4-15) to (4-18) for avalanche flow within the unconfined starting zone are

Quantity	Case 1	Case 2
Released slab thickness, h_o (m)	1.5	2.0
Turbulent friction, ξ (m/s^2)	700	1000
Kinetic friction, f	5/U = .28	5/U = 0.18
Velocity, U (m/s)	18.1	28.1
Δt (sec)	29.8	19.2
Released volume, K (m^3)	30×10^4	40×10^4
Discharge, Q (m^3/s)	10.1×10^3	20.8×10^3

The derived quantities for flow in the channeled avalanche track are

Quantity	Case 1	Case 2
Flow depth, h' (m)	16.1	19.4
Hydraulic radius, R (m)	6.17	7.43
Track cross section, A, (m^2)	309	449
Average velocity U_t (m/s)	32.4	46.4
Discharge, Q_t, (m^3/s)	10.1×10^3	20.8×10^3
Turbulent friction, ξ (m/s^2)	700	1000
Kinetic friction, f	0.16	0.11

The runout distance was calculated for both cases using equation (4-5), assuming the slope of the runout zone, $\beta = 5°$, $U = U_t$, $f = 0.2$ (which takes into account avalanche deceleration in the runout zone), and $h = h'/2$. The assumption $h = h'/2$ considers that the triangular flow cross section in the track discharges snow onto the runout zone as a rectangular cross section of a width equal to that of the confined avalanche in the channel. The increase of f in the runout zone is discussed more fully in section e-3 of this chapter. These derived quantities are

Quantity	Case 1	Case 2
Runout distance, s (m)	261m	493m

Note that the small differences in assumptions about slab thicknesses and turbulent friction coefficients make big differences in avalanche velocities and runout distances. Because of the difference between the calculated velocities of case 1 and case 2, the size requirements of defense structures in the runout zone also differ.

This example illustrates that when an analysis is done on a large channeled avalanche, the length of the runout zone is dependent on assumed ξ and h_o. The difference of 232m (761 ft) in the two calculated runout distances can be very important when planning development near an avalanche path.

d. dynamics of powder avalanches

Some of the essential differences between the dynamics of flowing avalanches and powder avalanches have been discussed previously. The differences in the sizes, densities, and velocities of these types are so significant that true powder avalanches should not be analyzed by the methods already discussed.

Powder avalanches are a low density, high velocity suspension of snow and ice particles. They attain velocities reported in excess of 100 m/s (Voellmy, 1964) so that in spite of densities less than 15 kg/m^3 (de Quervain, 1975), they are capable of great destruction. They have the highest velocities and greatest flow depths of any of the avalanche types, and consequently are capable of traveling the longest distances in runout zones of low gradient. For this reason it is extremely important that the potential for powder avalanches be recognized in an avalanche hazard analysis of any area. Some topographic conditions that may lead to powder avalanches are discussed in chapter 3.

A necessary but not sufficient condition for the formation of a powder avalanche seems to be the failure of a mass of cold, dry snow. If the particles of snow in the released snow slab are not bonded tightly together, as for example, in many soft slabs of new snow, the downslope motion quickly disintegrates the initial slab, forming a flow of tumbling and bounding snow blocks that quickly fracture further into small particles. As velocity increases, these particles are eventually held in suspension by turbulence and result in an aerosol of low density. The flowing snow mass can become "fluidized" into a powder avalanche when the upward component of turbulent eddies exceeds the free-fall velocity of the particles in the flow. Bagnold (1966) suggests that the upward component of turbulent eddies is roughly 10% of the forward flow velocity. Thus roughly 3 to 5 m/s (depending on the distance from the ground) and snow particles of several millimeters in diameter can be suspended.

Cold, new snow deposits occur often in Colorado mountains, particularly during the months of November through March. Soft slabs are probably more likely to form during storms which have light to moderate winds. Heavy wind loading of starting zones, on the other hand often results in a hard slab deposit that is not as likely to disintegrate into small particles and become a powder avalanche during flow. However, avalanches resulting from the failure of hard slabs falling long distances over rough terrain can also become powder avalanches. In order for a large part of the snow mass to become fluidized as a powder avalanche, certain other terrain conditions probably must be met, regardless of the initial condition of the snow mass before release.

It has been suggested above that velocities of 30 to 50 m/s are probably necessary to cause sufficient turbulence for fluidization of the avalanche. This velocity can be achieved in several ways. Referring to the flowing-snow equation (4-3) and assuming $\xi = 1000\ m/s^2$ and $h_o \cong h' = 2$ meters, it is found that $U > 30$ m/s on a slope of 40°. Further more, 0.9U should be reached in a distance $\ell = 40h' = 80$ meters (Salm, 1975). From this it seems that turbulent suspension should be taking place after a running distance of less than 100 meters on steep slopes, and the approximation $h_o \cong h'$ should no longer apply. The part of the snow mass whirled into suspension would now flow as a higher velocity powder avalanche.

Complete suspension of the flowing snow is probably rarely achieved on smooth, unbroken avalanche paths. Turbulent flow theory predicts lower velocities near the base of the flow due to frictional drag at the avalanche-ground interface. Within this lower zone, the velocity necessary for turbulent suspension may not be achieved.

In addition, the mechanical strength of stronger slabs does not permit fracturing of particles into sizes small enough to be suspended. In these cases, a mixed flowing and powder avalanche could be formed with an indistinct boundary between the upper and lower portions. If the powder avalanche is formed in the upper layers of the avalanche, and high velocities are attained, then this part will gradually separate from the dense lower portion and accelerate downslope, possibly reaching the runout zone several seconds before the main mass of the avalanche.

A second topographic situation conducive to powder avalanche formation is a track broken by steep cliff bands (Figs. 3-5, 3-7). As a dry snow avalanche falls over a cliff, entrainment of air and acceleration of flow can quickly create a powder avalanche. Both large and small dry flowing avalanches can develop into powder avalanches.

Practical difficulties arise when attempts are made to calculate the velocities and runout distances of powder avalanches from assumed initial snowpack conditions. Voellmy (1964) suggested the following equation for powder avalanche velocity:

$$U^2 = 2gh_o \frac{\gamma_o}{\gamma_L} \tag{4-20}$$

where γ_o is the initial snowpack unit weight, γ_L is air unit weight, h_o is the snowpack depth which is completely converted to a powder avalanche and g is the gravitational acceleration. For typical Colorado conditions which can produce powder avalanches, γ_L = 1 kg/m^3 and 50 kg/m^3 < γ_o < 150 kg/m^3. The snowpack depth, h_o must be estimated for the particular analysis, as is necessary in equations (4-2 and 4-3). The velocity calculated through equation

(4-20) is independent of slope angle provided it is sufficiently steep or irregular to permit complete fluidization of the avalanche. Equation (4-20) assumes fluidization so complete that the flow density of the powder avalanche approaches that of air. This results in a very great depth of flow.

For h_o = 1.5m and γ_o = 100 kg/m^3, U = 54 m/s and the powder avalanche is 150 meters deep. If these values are used to calculate runout distance from equation (4-5), and it is assumed that f = 0, as Voellmy suggests for powder avalanches, then the avalanche will not stop in a runout zone steeper than 5.6° and will travel 15300 meters on a flat runout zone. These results, although calculated from seemingly reasonable initial conditions, yield runout distances that are much longer than those observed in Colorado and deduced from timber damage. Difficulties in obtaining reasonable results from these equations has led to neglect in considering and calculating the powder avalanche case in Colorado. Previous calculations have almost always assumed flowing avalanches as discussed in sections 4a and 4b, even in locations in which powder avalanches can occur, and in some cases have probably underestimated the extent of the hazard. Powder avalanches probably diffuse over wide areas in the runout zone causing much shorter runout distances than those in the above example.

Difficulties in the use of the powder avalanche equation are estimating the amount of the snowpack actually fluidized and estimating powder avalanche density, γ_p. As suggested earlier, most avalanches are mixtures of various types so that only a fraction of the total volume released may become a powder avalanche. Equation (4-20) also assumes $\gamma_p = 2\gamma_L$ = 2kg/m^3 at typical Colorado altitudes, although it has been suggested by Sommerhalder (1965) and de Quervain (1975), that γ_p may be in excess of 10 kg/m^3. Lesser values of h_o and greater values of γ_p would invalidate equation (4-20).

Because it is essential that the possible effects of powder avalanches be evaluated, the following alternative method is suggested that follows the same basic approach described in section 4b.

This method has been applied to the special case of an avalanche that flows down a gully through a forest. In this case the flow is confined laterally and remains within the gully. The total depth of flow may be estimated by measuring the height of the avalanche cross section (Figures 4-8, 4-9) for cases in which the flow boundaries can be interpreted by timber damage. A straight section of the avalanche track must be chosen for these measurements because flow around a bend in the track results in an unsymmetrical cross section (see Figures 4-1 and 4-2 for example).

Three types of damage to trees are commonly observed in these avalanche tracks. Trees are uprooted, have trunks broken by bending stress, or remain standing but have limbs broken off to some height above the ground. The last two types of damage are used to calculate the "boundary conditions" at the time of avalanche passage.

It is important to understand that the damage inflicted on these trees could not have been caused by flowing avalanche impact for several reasons. First, the damage is often located well above the level of flowing avalanches, sometimes occurring 50 meters or more above the channel bottom. Second, limbs are often broken 10 or more meters above ground level although the tree trunks are not broken. It is unlikely that a tree could withstand such deep impact from the more dense flowing avalanche without the trunk breaking. Furthermore, it is extremely unlikely that a flowing avalanche could be that deep because it would require an unreasonably large discharge of snow. The calculated flow depths of the channeled avalanche example in the previous section were only 16.1 to 19.4 meters, considerably less than the height of boundary destruction (Figure 4-8) sometimes

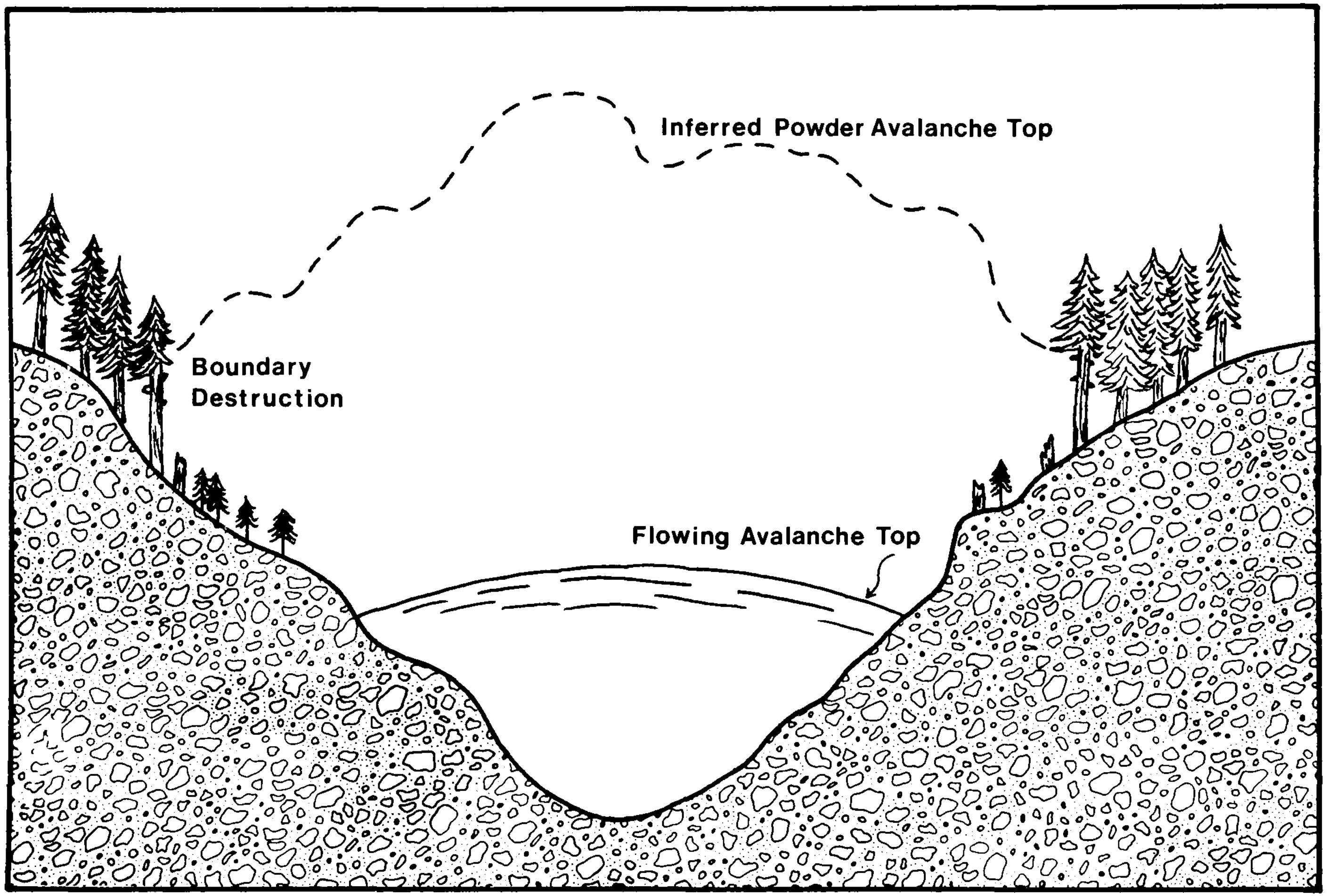

Figure 4-8. Cross section of channeled, powder avalanche, showing the location of the zone of boundary destruction of the lateral trimline. This zone is sometimes also the location of valuable data on the frequency of large avalanches, obtained through dendrochronology (Chapter 6). Symmetry of destruction indicates this is a straight section of the track.

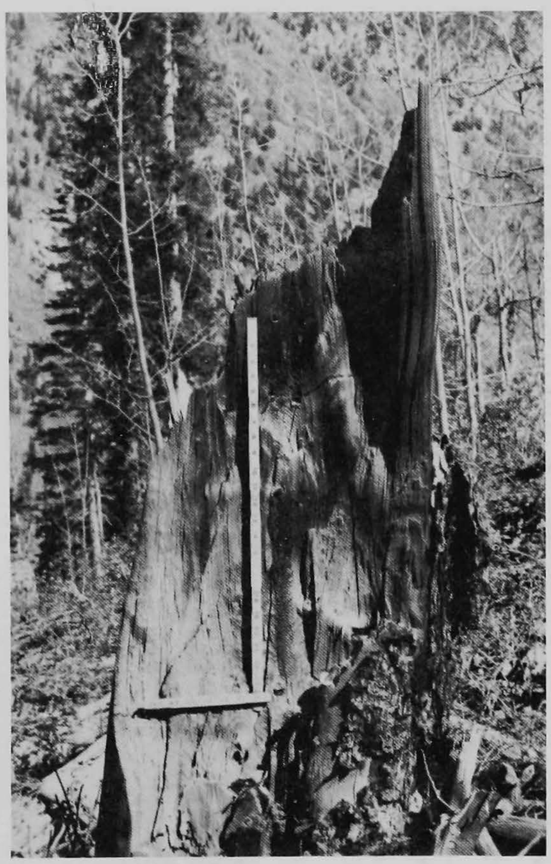

Figure 4-9. Photos of typical damage found in large Colorado avalanches at the zone of boundary destruction (Figure 4-8). Damage includes broken tree trunks and trees with branches stripped off. Damage is assumed to have been caused by powder avalanches.

observed.

Farther from the center of the avalanche track, beyond the boundary of destruction, the undisturbed forest will be found (Figure 4-8). It is reasonable to conclude that no avalanche that was deep enough or wide enough to cause destruction beyond this boundary has occurred during the lifetime of these undamaged trees. Tree corings obtained by Glenn (1974) in the Vail area of Colorado indicate boundary zone trees that may be well over a century old. Hence, determining the track boundaries in this way also provides the boundaries of all large avalanches throughout a long time period. This is discussed in chapter 6.

Observations and photographs of powder avalanches indicate that the flow depths might be as much as twice that indicated by measuring to the height of tree damage because flow is deeper near the center of the track than at the lateral boundaries.

The avalanche impact pressure may be calculated through data on the tree trunk diameter and height of impact upon trees at these boundaries. The method has previously been derived (Equations 4-6 to 4-14). Equation (4-14), however, should be adjusted to account for powder avalanche loading, which, due to the finite time required for pressure rise, probably lies between flowing avalanche loading and wind loading. For powder avalanches, equation (4-14) should be written

$$P'_{max} = \frac{\sigma \pi d^2}{C_D 15 h'^2} \qquad (4\text{-}21)$$

where P'_{max} is the pressure at the top of impact trimming on the trees at the avalanche boundary (Figure 4-8). The modulus of rupture, σ, can be found from tables on wood properties, and d and h' are measured in the field. C_D is the coefficient of drag of the impacted tree. Values of C_D may be obtained from tables in most textbooks on fluid mechanics and aerodynamics (Daugherty and Franzini, 1965, p. 427). When using such tables, remember that powder avalanches are fully turbulent with Reynolds numbers of more than 10^6, and C_D should not vary with avalanche velocity for a particular object. Maximum pressures near the center of large avalanches with flow depths of 25 meters or more may be as much as 50% higher than those calculated by equation (4-21).

Powder avalanche impact pressure, P, is related to velocity, U, through equation (4-7). Figure 4-10 gives the relationship between γ and U for fixed values of P corresponding to those calculated by equation (4-21). If it is assumed that $U < 100$ m/s and $5\ kg/m^3 < \gamma_p < 15\ kg/m^3$, then a range of possible velocities can be calculated.

This method enables independent estimates of avalanche flow depth and velocity that can be used with equation (4-5) to calculate run-out distance. The use of this method is not necessarily restricted to channeled powder avalanches that flow through gullies bounded by forests, a setting quite common in Colorado. It can also be used for powder avalanches on unconfined slopes if estimation of the flow depth can be made at these locations through observations of timber damage.

e. runout zone dynamics

The equation for calculating the avalanche runout distances was given previously in section 4a of this chapter:

$$S = \frac{U^2}{2g(f\cos\beta - \tan\beta + \frac{U^2}{2\xi h})} \qquad (4\text{-}5)$$

in which U is avalanche velocity at the beginning of the runout zone, g is the gravitational acceleration, β is the slope angle, ξ is the turbulent friction coefficient, and h is the flow depth in the runout

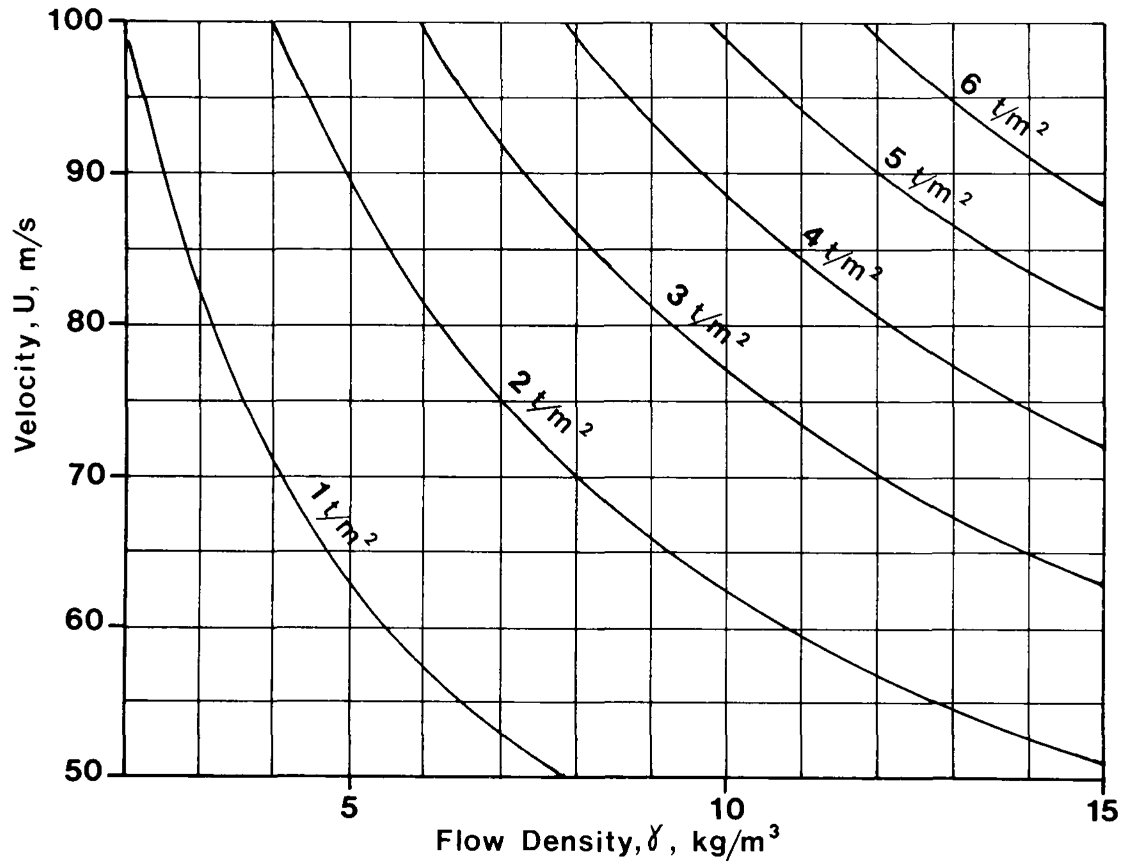

Figure 4-10. Relationship of density to velocity, U, at constant pressure, for powder avalanches.

zone, usually assumed equal to h'. The strong dependence of S on calculated and assumed flow parameters such as U, h, ξ, and f was discussed previously.

Additional difficulties arise when equation (4-5) is used to calculate and map an avalanche hazard area. Equation (4-5) gives the length of the runout zone only, but does not give its width, area, or any estimate of the impact pressures that might be expected in the runout zone. These topics are discussed in the next sections.

1. Topographic influences on runout zone shape. The shape of the runout zone for flowing avalanches that move close to the ground at relatively low velocities is highly dependent on the topography. Deep, high-velocity powder avalanches will not be so strongly affected by topography. As shown on Figure 3-8, slower moving wet snow avalanches tend to be deflected to either side of the alluvial fan, while powder avalanches tend to advance directly down the center of the fan. For this reason, the hazardous area in a runout zone consists of a composite of the hazards from different types of avalanches.

2. Lateral spreading in the runout zone. As a confined, channeled avalanche flows from the mouth of a gully on to an unconfined runout zone, lateral spreading of the flow takes place. It has been suggested (Schaerer, pers. comm., 1975) that an avalanche probably does not spread to a width of more than about twice that of the channeled track. The velocity and amount of spreading probably depends in some complicated way on flow depth, velocity, and on the type of avalanche.

Lateral spreading was measured on deposits of a few Colorado avalanches during the winter of 1974-1975. The spreading angle was found to vary from roughly 10° to 20° in the top one-half of the runout zone. Spreading angles within this range were also measured on vegetation trimlines caused by large avalanches in the past if it could be determined with confidence that the trimlines were caused by a single large event.

These suggested values of lateral spreading angles apply only to runout zones in which flow is not strongly controlled by topography.

3. Velocity and pressure in the runout zone. Regardless of the type of avalanche reaching the runout zone, its velocity must decrease from some initial value at the top to zero at the distance S which marks the bottom of the runout zone. The avalanche impact pressure must also decrease with decreasing velocity. Since all avalanche flows are turbulent throughout most of the runout zones, and the rate of kinetic energy dissipation is probably dependent on the velocity, then velocity and pressure may decrease in some predictable manner over the runout zone.

If D is some distance within the runout zone measured from its beginning, and $D \leq S$, then as suggested by Sommerhalder (1965), the velocity U, at a distance D can be calculated by

$$U_1^2 = (1 - D/S)\ U_0^2 \qquad (4\text{-}22)$$

where U_0 is the velocity at the top of the runout zone, and, because pressure is proportional to U^2,

$$P_1 = (1 - D/S)\ P_0 \qquad (4\text{-}23)$$

where P_0 is the pressure at the beginning of the runout zone, and P_1 is the pressure at some distance D.

These assumptions are very important in drawing zones of impact pressure within the runout zone. Through equation (4-23) a distance, D, at which the pressure falls below some acceptable level can be found.

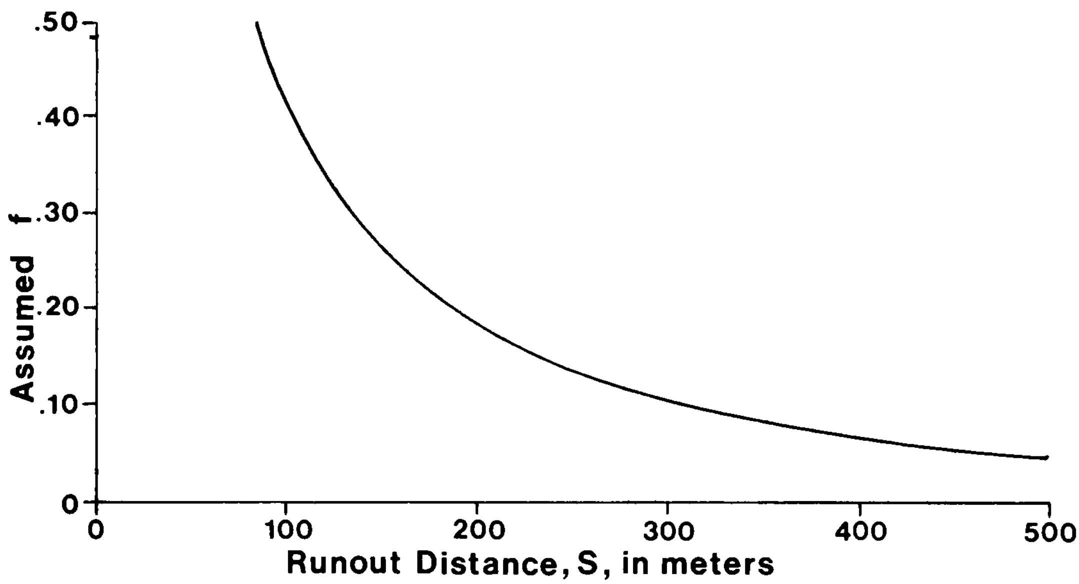

Figure 4-11. Runout distance, S, is dependent on values assumed for kinetic friction, f. In this example, the runout distance varies by a factor of 2.4 between the commonly used limits of $0.1 \leq f \leq 0.3$. An alternate method for using the friction term is given in the text.

4. Use of a variable friction coefficient in runout calculations. The runout distance can be calculated by equation (4-5). Selection of values for U, β, ξ, and h is determined by methods described previously in this chapter. However, the runout distance, S, is dependent of values assumed for the friction coefficient, f. Figure 4-11 plots S vs. f for avalanche case 2, described in section 4a of this chapter. The calculated runout distance varies by a factor of 2.4 between the commonly used limits of $0.1 \leq f \leq 0.3$. No matter how carefully the analysis of the avalanche starting zone and track is done, the calculated runout distance is quite subjective because of this strong dependence on f. The following method suggests a modification of the use of equation (4-5) in which the value of f is continually increased with distance travelled in the runout zone.

Equation (4-22) indicates that velocity progressively diminishes with distance, x, and becomes zero at x = S. It was suggested by Schaerer (in press) that f depends on velocity, and is related by

$$f = 5/U. \qquad (4\text{-}24)$$

Although Schaerer's measurements were made on avalanches flowing in the track, a similar relationship may also apply within the runout zone as the avalanche decelerates, turbulence is suppressed, and "viscous" forces are increased as snow particle collisions become more frequent. Therefore the value of f used in equation (4-5) should also depend on U, which, according to equation (4-22), also depends on distance run, x.

Equation (4-5) may be solved assuming f = f(x) in the following way. First, the runout distance, S, is calculated using values of f, U, and h that were used in calculating velocity in the track. The velocity, $U(x_1)$ at some distance x_1 is then calculated by equation (4-22). It is recommended that $0.2 \leq x/S \leq 0.5$. Within this range of x/S ratios, the runout distance calculated by this method varies by less than 10% for initial velocities of 20 to 50 m/s. The velocity at point x_1 and a recalculated value of $f = 5/U(x_1)$ are now used in equation (4-5) to calculate a new runout distance S_2. A new velocity and friction term is now calculated at the point $x_1 + x_2$; equation (4-5) is re-used, and the entire procedure is repeated until $f \geq 0.5$. Friction factors in excess of 0.5 have rarely been measured (Sommerhalder, 1975). After $f \geq 0.5$, the sum of $x_1 + x_2 + \ldots + x_n$ equals the runout distance, S. This method is time consuming and is greatly facilitated through use of a computer.

The method outlined above eliminates the need of assuming a value of f and, consequently, reduces the subjectivity inherent in calculating runout distances. Using this method on case 2, section 4a, with $x/S = 0.3$, results in a runout distance of 209 meters.

CHAPTER 5: AVALANCHE IMPACT

1. Introduction

Knowledge of probable avalanche impact pressure is important in the total evaluation of avalanche hazard because it aids in design of structures. The equations presented in this chapter are borrowed from fluid mechanics and, for this reason, are most applicable to avalanches flowing rapidly enough to assume fluid properties. Fluid properties are probably maintained at velocities in excess of about 10m/s. However, in the final stages of movement, dry and wet flowing avalanches may slide as large blocks and produce distinct shear planes between moving blocks. At this point avalanches should probably be regarded as deformable solids rather than as fluids.

Impact pressure or "thrust pressure" can be calculated by the equation

$$P = K \frac{\gamma}{g} U^2 \quad , \qquad (5\text{-}1)$$

(Voellmy, 1964; Mellor, 1968), in which P is the pressure in Kg/m^2*, γ is the avalanche flow density in Kg/m^3, g is the gravitational acceleration in m/s^2, and U is avalanche velocity in m/s. Equation (5-1) was shown to be reliable by Schaerer (1973) for avalanches with velocities up to 53 m/s (119 mph) in field measurements taken near Rogers Pass, British Columbia. The factor K is dimensionless and varies between the approximate limits of 0.1 and 1.0, depending on the type, density and velocity of the avalanche, and the size and shape of the obstacle subjected to impact. Values of K close to unity are applicable to flowing snow avalanche impact against a

---

*1 Kg = 1 kilogram force; 9.81 Kg = 1 Newton. Pressure is commonly given in metric tons per square meter (t/m^2) = 1000 Kg/m^2 = 205 pounds per square foot (205 psf).

wide, rigid obstacle such as a flat wall. In such cases it may be reasonable to assume that the flow is completely stopped behind the object, and all of the kinetic energy of flow is dissipated. The smaller values of K correspond to aerodynamic forces created when a low-density powder avalanche completely engulfs an object. These two cases are diagrammed in Figure 2-4.

Calculation of P obviously depends on γ and U as well as K. Methods by which velocity, U, can be calculated are discussed in chapter 4. Velocity depends on avalanche size, type, terrain configuration and surface roughness, all of which affect the friction coefficients assumed in calculations.

Flow density, γ, varies widely, depending on the type of avalanche. For fully developed powder avalanches, $2 kg/m^3 < \gamma < 15 kg/m^3$, (de Quervain, 1975). Flowing avalanches of dry snow have densities in the range $50 kg/m^3 < \gamma < 300 kg/m^3$, while the highest densities probably occur in damp or wet snow slides and range up to $400 kg/m^3$. These density figures are estimates only. Direct measurements of the density in moving avalanches have never been reported. It is likely that many dry snow avalanches have density gradients with higher density snow flowing near the ground and a much lower density powder or "dust" cloud accompanying the flow. Laboratory experimentation (Tochon-Danguy and Hopfinger, in press) suggests, however, that the density near the front or head of fully developed powder avalanches may be quite uniform. This is also suggested by Shen and Roper (1970). It is probably also reasonable to assume a uniform density throughout the depth of dense flows and slides of wet snow, because the larger, denser blocks of snow comprising this type of avalanche are not likely to be whirled into suspension by turbulence.

Knowledge of the type or types of avalanches likely to reach the point of interest is necessary not only because of their great differences in density, but also because of their greatly differing mechanics of impact.

2. Powder avalanche impact

The dynamics of powder avalanches are discussed in chapter 4, section 4d. The relationship of terrain to powder avalanche formation is discussed in chapter 3. It may be assumed, for pressure calculations, that powder avalanches are a fully turbulent, low-density suspension of snow and ice particles in which as much as 90% of the mass is concentrated into little more than 1% of the total volume. According to Mellor (1968) impact may therefore be calculated as in aerodynamics, and the stagnation pressure near the center of an object submerged within the flow is

$$P = \frac{1}{2} \frac{\gamma}{g} U^2 \quad . \qquad (5\text{-}2)$$

Although aerodynamic impact is assumed, it is not permissible to assume a flow density equal to that of clear air. As the foregoing discussion suggests, powder avalanche density is estimated as 2 to 15 times that of air. Since pressure, P, is directly proportional to density, the pressure may be up to 15 times that of air flowing at avalanche velocity. Thus powder avalanche "air blast" must be considered separately and may occur beyond the limits of powder avalanches.

The total drag force, F_D, on an object is calculated by multiplying the pressure, P (Equation 5-2), by the cross sectional area of the object normal to the flow, A, and by a coefficient of drag, C_D. The complete expression for drag force, F_D becomes

$$F_L = AC_D P = AC_D \left(\frac{1}{2} \frac{\gamma}{g} U^2\right) \qquad (5\text{-}3)$$

Values of P for typical powder avalanche velocities and densities are given in (Figure 5-1).

When an object in the path of a powder avalanche is submerged in the flow (Figure 2-4) it is also subjected to aerodynamic lift forces. The total lift force F_L can be calculated

$$F_L = AC_L P = AC_L \left(\frac{1}{2}\frac{\gamma}{g}U^2\right) \quad , \qquad (5\text{-}4)$$

in which A is the area parallel to flow, such as the roof of a building, and C_L is a coefficient of lift. Once again, the term in parenthesis in equation (5-4) can be taken from (Figure 5-1).

Coefficients of drag and lift are not readily available, and must be obtained by an aerodynamic analysis of structural parts exposed to the flow. Values of C_D usually range from about 0.5 to 1.5 depending on the object's shape, with recommended values of C_L equal to about 75% of C_D.

The important point is that objects reached by deep powder avalanches experience both drag and lift forces and must be designed accordingly.

Equations for powder avalanche impact do not consider impact from much denser layers of flowing and sliding snow, which often accompany powder avalanches. It must be determined prior to design which type of avalanche will reach the point in question. Methods by which this may be estimated are discussed in chapter 4.

3. Powder avalanche air blast

The avalanche wind, or air blast, is the subject of much controversy. It is generally agreed that such a parcel of high-velocity air is associated only with high-velocity avalanches. As discussed by Mellor (1968), much of the damage attributed to air blast may have actually been caused by low-density powder avalanches, as evidenced by a fine coating of powder on objects in the damage region. This region should be included in the hazard zone of the powder avalanche, while the air blast zone would be that affected by clear air alone.

According to Mellor (1968) the maximum velocity attained by the air blast should not exceed that of the avalanche. This should limit air velocity to approximately 100 m/s, which is near the maximum known velocity of powder avalanches. At the typical elevations of Colorado avalanches, air density is about 70% to 80% of sea level density, or equal to about 1 kg/m^3. Therefore, according to equation (5-2), assuming U = 100 m/s, pressure should not exceed 0.5 t/m^2 (100 psf). This is probably a reasonable upper limit for the stagnation pressures caused by the clear air blast of high-velocity powder avalanches. Pressures of this magnitude are certainly not high enough to cause some of the damage traditionally attributed to air blast, such as snapped off telephone poles. However, they are high enough to cause serious structural damage to ordinary buildings. Hence the potential range, or "runout distance" of the air blast becomes a matter of practical interest.

Mellor (1968) derived a relationship by which the deceleration of an idealized parcel of high velocity air is calculated, assuming no change in the air parcel shape, and using values of boundary friction taken from studies of blowing snow. The time, Δt, needed for an air parcel of height H to decelerate from a velocity U_1 to a velocity U_2 is given by

$$\Delta t = \frac{H}{5 \times 10^{-3}} \left(\frac{1}{U_2} - \frac{1}{U_1}\right) \quad . \qquad (5\text{-}5)$$

Assuming H = 20 m, U_1 = 100 m/s, and U_2 = 60 m/s, Δt is 27 sec.

During this time it would travel roughly 2200 meters and be capable of a pressure of 0.25 $t/m^2 \cong 50$ psf, which is still potentially destructive. This would extend the potential damage zone completely across most Colorado valleys.

In fact a given air parcel would probably diffuse, dissipate energy over a wider front, and decelerate more quickly than indicated by equation (5-5). However, this potential for destruction must be considered when planning buildings directly below areas which could be affected by powder avalanches, even if buildings lie somewhat beyond calculated runout zones.

4. Impact of dense, flowing avalanches

The impact of flowing avalanches differs significantly from that of powder avalanches because of their greater densities and lesser velocities. When a dense flow of snow strikes a wide, rigid object, such as a wall perpendicular to the flow, it probably cannot separate and flow to either side of the object. Instead the mass of snow is brought to rest on the side of the object from which the avalanche approached and all of the kinetic energy of flow is lost. The resulting pressure can be calculated as

$$P = \frac{\gamma}{g} U^2 \quad . \tag{5-6}$$

The total force on the object is equal to the pressure calculated through equation (5-6) times the cross-sectional area normal to flow. Values of impact pressure, P, for typical dense, flowing avalanche velocities and densities are shown in (Figure 5-2). Comparison of (Figures 5-1 and 5-2) reveals that pressures from dense snow avalanches can be much greater than those caused by powder avalanches in spite of much lower velocities.

Mellor (1968) suggests that even higher pressures than those calculated by equation (5-6) and (Figure 5-2) may be caused by densification of the snow mass upon impact. This causes shock propagation in the deformed snow mass and equation (5-6) could be written

$$P = \frac{\gamma_1}{g} U^2 \left(1 + \frac{\gamma_1}{\gamma_2 - \gamma_2}\right) \quad , \tag{5-7}$$

in which γ_1 is the density of the avalanche prior to impact and γ_2 the density after impact. The additional terms become very important if γ_1 and γ_2 have close to the same values. Such shock effects may become important in the final stages of flow when some avalanches behave more like sliding solids than as fluids. Although it is not known if shock propagation does occur to increase pressure, it may be wise to consider this possibility and use conservative safety factors in design.

For dense flowing avalanches the hydrostatic pressure can increase the total pressure, particularly in the runout zone where flow depths and densities are greatest. The additional pressure term, P_s, is a linear function of distance z below the top of the flow and is written

$$P_s = \gamma z \quad . \tag{5-8}$$

For a flow 5 meters deep with a density of 300 kg/m^3 this results in an increased pressure of 1.5 t/m^2 at the base of flow.

5. Impact pressure variation with depth

Voellmy (1964) suggests that avalanche velocity increases with distance above the ground. A vertical velocity profile is known to occur in river flow and in wind blowing across the ground surface, so it probably also occurs within a turbulent flow of snow. A velocity profile was also reported by Tochon-Danguy and Hopfinger (in press) in laboratory simulations of powder avalanches. Voellmy (1964) recommends a parabolic velocity distribution U(z), of

$$U(z) = \bar{U} \left[\frac{4}{3} - \left(\frac{z}{h'}\right)^2\right], \qquad (5\text{-}9)$$

where $\bar{U}$ is the mean flow velocity throughout the depth, h' is the depth of flow, and z is the distance below the top of the flow. A velocity profile of this type allows for a sliding velocity at the avalanche base, an assumption that seems consistent with equations (4-2, 4-3, and 4-15) in which a dynamic or sliding friction coefficient is assumed. It is also possible that the velocity distribution is logarithmic, as in turbulent shear flow, however, specification of a logarithmic profile necessitates also specifying a boundary roughness length, which probably varies considerably in different avalanches and is difficult to estimate. The vertical pressure profile, P(z), can be derived by combining equations (5-2 and 5-9) so that

$$P(z) = \frac{1}{2}\frac{\gamma}{g}\; U(z)^{\;2} = \frac{1}{2}\frac{\gamma}{g}\left\{\bar{U}\left[\frac{4}{3} - \left(\frac{z}{h'}\right)^2\right]\right\}^2 \qquad (5\text{-}10)$$

This assumes a constant density, γ, throughout the depth of flow, an assumption discussed earlier.

Tochon-Danguy and Hopfinger (in press) suggest that the velocity profile reverses itself in the upper half of powder avalanches, which, if true, permits the assumption that the center of pressure is at one-half the flow depth thereby simplifying force calculations. For dense flowing avalanches such a velocity reversal would not take place, however, and the resulting center of pressure on an object would occur near the upper surface of the flow (Figure 5-3).

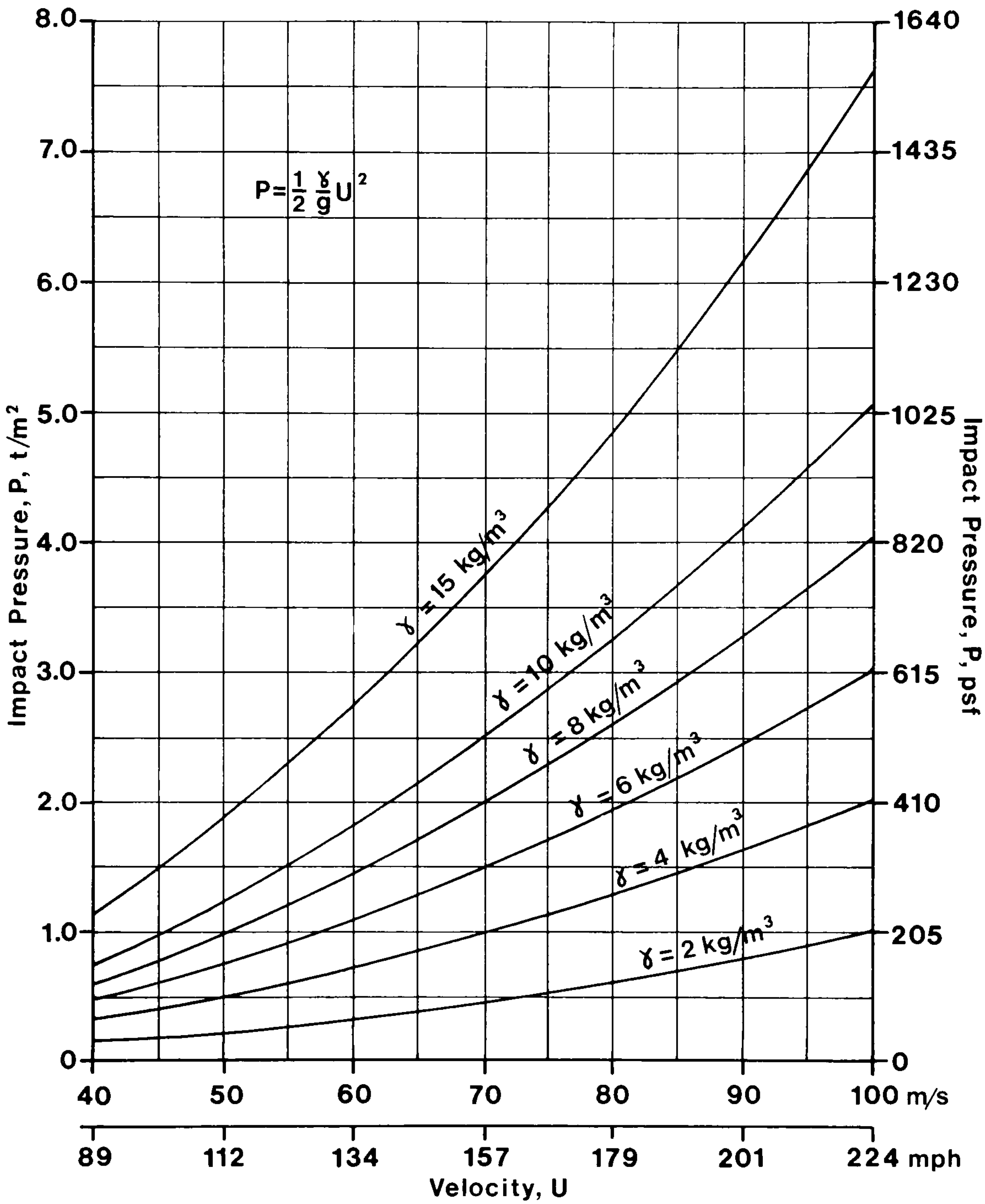

Figure 5-1. Powder avalanche stagnation pressures at typical velocities and densities (after Mellor, 1968).

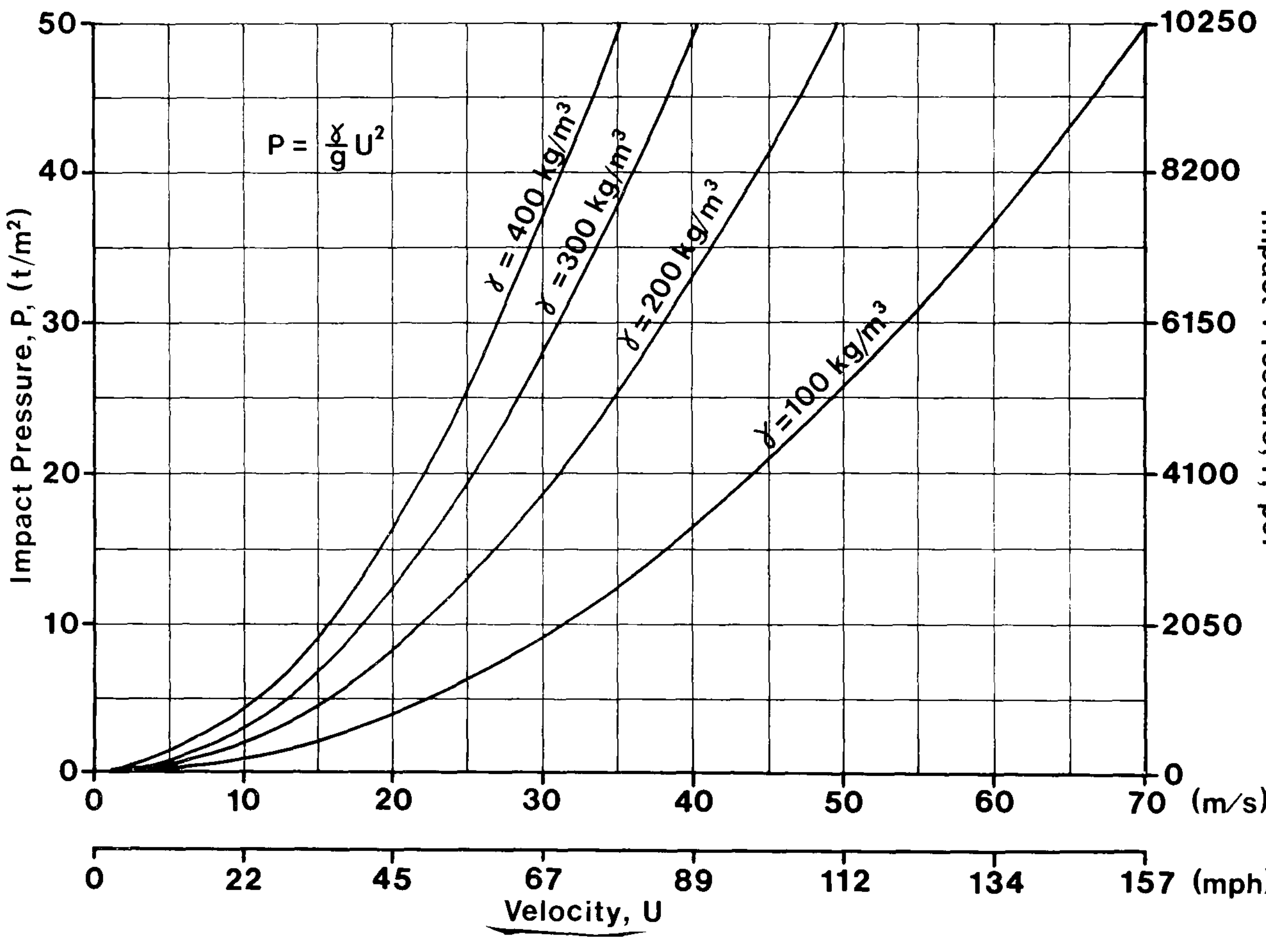

Figure 5-2. Dense flowing avalanche impact pressures on wide, rigid obstacles. It is assumed that all flow energy is lost behind obstacle, or that flow is deflected through 90°.

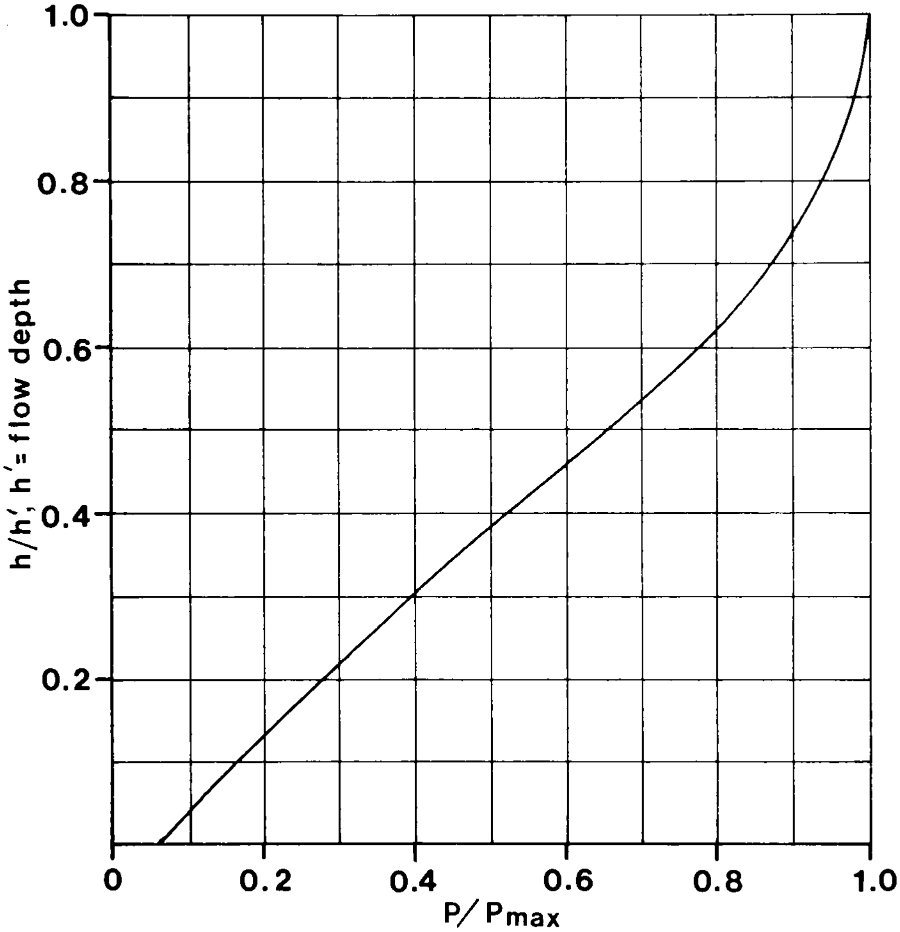

Figure 5-3. Theoretical stagnation pressure profile for powder avalanches and flowing avalanches of low densities.

CHAPTER 6: AVALANCHE FREQUENCY

1. Introduction

Avalanche frequency is commonly expressed in terms of return period, T, in years, or as an annual probability, P. These two quantities are reciprocally related so that

$$T = 1/P \quad . \tag{6-1}$$

Thus an avalanche with a return period, T, of 100 years, also has an annual probability of occurrence, P of 0.01, or 1%. The concept of return period is a statistical one, and is not related to the timing of avalanche events. The avalanche conditions of each year are considered to be independent of conditions in all previous years, so that the "100-year avalanche" may occur on successive years. Naturally, the probability of an avalanche varies considerably within any given year through changes in weather and snowpack conditions. However, the prediction of immediate hazard becomes a matter of avalanche forecasting, which is an important and widely studied problem. The U.S. Forest Service has conducted research in avalanche forecasting for many years, and the University of Colorado, Institute of Arctic and Alpine Research has studied avalanches as related to weather and snowpack conditions in the San Juan Mountains since 1971. Avalanche forecasting will not be considered here.

Within a given avalanche path, T and P vary considerably with location. The starting zone generally consists of the steepest slopes in the avalanche path. Loose snowslides and small slab avalanches may occur here several times a winter. The probability, P, of an occurrence within the starting zone in any given year may be close to 100%, and the hazard should be obvious. The probability that an avalanche will extend the length of the track is less, although many paths do generate slides of sufficient mass to traverse the entire track on an annual basis. Once again the hazard should be obvious. The real difficulty in assessing T is in the runout zone (Figure 2-2). Although the upper portion of this zone (the high hazard zone) may be reached by avalanches every few years and these avalanches may be well documented by local residents, the annual probability, P, that an avalanche will reach far into the moderate hazard zone becomes progressively smaller with distance from the lower end of the track.

If permanent residences and other construction is planned within the runout zone it generally occurs where the hazard is not so obvious, and the return period is longer. Quite often avalanches have never been observed or documented within the "moderate hazard" zone. With no historical record of avalanches the analyst must turn to indirect methods to determine the frequency.

On the time scale of centuries or tens of centuries, the frequency of an avalanche of a given size on a particular path probably fluctuates considerably in response to climate change. However, it is not known for certain how the climate is changing, or how any change might affect avalanche frequency. In view of these uncertainties, it may be assumed that P and T are not changing with time. Therefore, the past record, if available, is generally assumed to be representative of future probability. For example, if avalanches are known to have reached subzone "a" of the moderate hazard zone (Zone II of Figure 2-2) four times in the last 120 years, then it is usually assumed that T = 120/4, or 30 years at this location. The validity of this assumption is examined in more detail later in this chapter.

The determination of T is of practical importance in the economics of planning. It may be necessary to calculate the "encounter probability," E, that an object at some location will be reached once during its lifetime, L. If lives are not at stake, it may be acceptable to risk complete destruction of some object if E is low, rather than build expensive structures to protect the object. The alternatives of protecting and not protecting may be compared through appropriate economic analyses (Taylor, 1959) if T, L, and E are known. These quantities are related through

$$E = (1 - \frac{1}{T})^L \quad . \tag{6-2}$$

The useful life of the object, L, can be determined through past experience, so that, given knowledge of T, E may be easily calculated. LaChapelle (1966) has produced tables of encounter probability for values of L and T.

Similarly, it is a planning decision whether or not to allow the building of residences in a zone of some avalanche frequency. The analogy to the concept of the 100-year flood is apparent. In many areas current practice excludes new development within the limits of the 100-year flood. A similar practice might also be adopted for areas endangered by avalanches, although it must be recognized that enfringement on the limits of the 100-year avalanche might have far more serious consequences than enfringement on floodplain limits. It would appear that development within the limits of the 100-year or 200-year avalanche should be allowed only if certain conditions are met, such as special design to resist some level of impact pressure, or some avalanche defense construction. Swiss efforts at land planning in areas subject to avalanche activity are discussed by Frutiger (1970). The Swiss permit building within the boundaries of the 30-to 90-year avalanche providing special building design is undertaken to resist impact pressures of some specified level.

It is apparent from the preceding discussion that some means of calculating T is essential. In Colorado, direct observational records are few, and human experience in mountain regions is short. Furthermore, the indirect methods suggested below are subject to serious difficulties and uncertainties, as is the entire field of avalanche analysis. It is suggested that safety factors be employed when calculated results are used.

2. Prediction of avalanche size from initial snowpack and weather conditions

As discussed in chapter 4, section 4b, the volume of snow discharged as an avalanche is limited to the amount of unstable snow released and set into motion in the avalanche path. The conditions in the snowpack leading to avalanche release are obviously determined by antecedent weather conditions which affect the snowpack. If the probability of the primary causative factors in avalanche formation could be evaluated, then the size of the design avalanche might be related to the size of the design storm. The design storm must be coupled to the physical properties of the snowpack prior to the storm. Many variables would have to be evaluated. It should be reemphasized that the avalanches of largest volumes may not always be responsible for the longest runout distances or the largest areas of destruction. Powder avalanches, because of high velocities, can cause more widespread damage than flowing avalanches even though powder avalanches may not involve nearly as much mass.

de Quervain (1975) emphasized the importance of new snow accumulation during a 3-to 5-day period in the formation of unusually large avalanches in Switzerland. Swiss conditions are different from Colorado conditions, so the same factors may not prove as important here. de Quervain presents data which suggest that snow accumulations of 120cm or more over a 3-day period are related to destructive avalanche cycles. At air temperatures below -8°C, the storm series is not interrupted by a single day during the storm with little new snow because settlement and strengthening of the snowpack is minimal. However, a pause in the storm at high temperatures may result in consolidation and stabilization of the snowpack. The danger is increased on the lee slopes if new snow accumulations reach 100cm in 3 days. If similar weather relationships are related to large avalanches in Colorado, then approaches may be made to estimate the probability of large avalanches through the probability of a design storm, such as is done in flood studies.

The influences of snowpack history and wind loading will complicate the design storm approach. The snow involved in an avalanche may involve some or all of the old snow, as well as snow deposited in the design storm. The amount involved depends on the distribution of stresses in the snowpack and the locations of regions of strong and weak layers. These vary both with location and through time, and are difficult to evaluate quantitatively.

In addition it is difficult to determine the amount of snow deposited in a starting zone by making measurements at other locations. Snow depths in starting zones are sometimes strongly modified by wind and topography, resulting in uneven snowpack distribution and stress concentrations.

Occasionally the weather and snow conditions preceding large avalanches are known. Examples are presented in LaChapelle (1961) and Williams (1975). Examination of such data should prove useful in developing a design storm approach.

In some cases attempts have been made to relate the depth of the released slab of the design avalanche to nearby snowpack records. This usually involves an analysis of snowcourse records to estimate the amount of snow which could be expected at the snowcourse site over some time period (usually 50 to 100 years). Usually snowcourse records are relatively short (10 to 30 years), and some statistical technique must be applied to estimate the depth occurring over a long time period. Such an approach cannot be recommended for the following reasons. First the extrapolation of a short record to a long-term record is not justifiable unless it can be proven that the magnitude-frequency distribution observed over the short time period is also applicable over a long time period. Statistical studies by Dalyrmple (1960) suggest that 25 years of record are necessary to predict the 25-year event to within ±25%. Second, winters with excessive snow accumulations may not correspond to winters with big avalanches because large avalanches are probably more closely related to snowpack instabilities resulting from factors which may occur independent of total snowpack depth. Third, snowcourse records are not taken from starting zones and may not reflect the amount of snow in starting zones.

Because of the difficulties in predicting avalanche size-frequency relationships from initial conditions, the approaches outlined in the following sections are recommended.

3. Frequency prediction from past history of avalanching

The prediction of avalanche frequency from the past history of avalanche events is a more direct and more reliable method than that discussed in section 2. It is not necessary to make assumptions about all the contributory factors of avalanche formation such as snowpack depth released, type of snow in the starting zone and track, and antecedent weather conditions. The frequency and dimensions of avalanches that have occurred are the things of interest.

With a long period of avalanche records, assumptions about avalanche frequency can be made with some confidence if it is assumed that the past conditions were similar to those that will occur in the future. The level of confidence increases greatly with the length of record. For example, one might feel quite confident about predicting the 100-year avalanche if several centuries of data were available. In general the length of a period of observation need be at least as long as the return period of interest (Dalyrmple, 1960).

Unfortunately, in Colorado the direct observational record of avalanche events is generally very short. The mining boom of the last century brought many encounters with avalanches, both near mines and settlements and along railroad access routes. Newspaper accounts of avalanche accidents understandably were more concerned with the personal circumstances of the accidents than with the distance a particular avalanche traveled. However, it is precisely the latter information that is needed for planning. A careful study of old local newspapers is necessary in order to uncover as much data as possible.* At certain locations which are few in number, very good data are available, sometimes because great personal tragedy made the event memorable. Such an example is the Gordon Gulch Avalanche, at Twin Lakes, Colorado. An avalanche occurred there in January, 1962, destroying several buildings and claiming seven lives. Historical records show that an avalanche of about the same size also occurred in 1882. The indicated return period is 80 years, although the actual return period may be more or less than 80 years.

Lacking additional data, we can assume this is the "80-year" avalanche, however, in making such an assumption, it must be recognized that the true 80-year avalanche may be either larger or smaller than those observed. The conservative approach is to plan as if the observed events are actually representative of a somewhat shorter

---

*Such an historical study is presently being conducted by the University of Colorado, Institute of Arctic and Alpine Research, in Silverton, Colorado. The results are not yet available.

return period, say 50 years. If only one large event is known, there is no indicated return period, and indirect methods such as tree ring analysis must be applied.

4. Frequency prediction through tree ring analysis

Tree ring analysis or dendrochronology can sometimes be used to determine past dates of avalanche occurrence when historical records are not available or are nonexistent. This is a highly promising method in Colorado because mature trees within and adjacent to avalanche paths are commonly more than a century old. It has also been used in Wyoming (Potter, 1969) and in the North Cascades of Washington (Smith, 1973). In some cases individual trees have been found which are more than 300 years old and have withstood avalanche impact several times. If these trees are located so that they have experienced, but resisted, avalanche impact in the past, and this impact is revealed through study of the tree rings, long, reliable chronologies may be established. An obvious requirement for a successful study of this type is an abundance of datable trees growing in avalanche paths.

It is most useful if trees which have been impacted within the runout zone can be studied. This data becomes more valuable if return periods can be related to position within the runout zone. The runout zone illustrated in Figure 2-2 should be reached less often by avalanches in subzone "c" than in subzones "a" or "b". In the most desirable cases an empirical curve of runout distance versus return period might be constructed. Such ideal conditions are seldom found. In many locations the runout zone is devoid of trees, and attention must be turned to the avalanche track.

Large channeled avalanches (Figure 4-8) are commonly swept clear of trees in the lower portion where dense flowing avalanches occur. Deep, diffuse powder avalanches may impact but not destroy trees at the zone of boundary destruction (Figure 4-8). It is these old, strong trees that have withstood repeated impacts over a long time period that may provide valuable data on return periods. These trees also establish the lateral limits of the flow cross sections, as discussed in chapter 4, section 4d. Thus the magnitude and frequency may be estimated by study of the avalanche boundary. Large avalanches on unconfined slopes may also damage but not remove trees. Impact will sometimes strip branches to some height. These trees can sometimes be reliable indicators of avalanche frequency.

Smaller avalanches can flow through forests, selectively removing weaker trees but leaving the stronger ones. The stronger remaining trees are often damaged by impact. This may occur several times during the lifetimes of trees exposed to these smaller avalanches, and an average return period may be established.

If the return period of avalanches of given sizes can be established in the track, then through application of the dynamic equations of chapter 4, estimates may be made of return periods at various locations in the runout zones.

A discussion of the detailed techniques of dendrochronology is beyond the scope of this paper, and only a brief outline can be given here. A chronology must be established for each species sample within the avalanche path. This chronology must be taken from trees within a control area unaffected by avalanches so that the variations in tree ring growth in response to annual variations in climate can be seen without the complicating influence of impact induced growth stress. This chronology will show the annual variation common to all trees, including those in avalanche paths. The effect of impact damage can then be determined by comparing tree rings sampled within the avalanche path with control trees.

In studies of Colorado avalanche paths, Glenn (1974) utilized four species of trees to determine past periods of avalanching: aspen (Populus tremuloides), Engelmann spruce (Picea engelmanni), Douglas fir (Pseudotsuga menziesii), and lodgepole pine (Pinus contorta). The results of this study were submitted to the Town of Vail in a series of unpublished reports by the University of Colorado, Institute of Arctic and Alpine Research, in 1973.

Smith (1973) determined avalanche frequencies through tree ring analysis and vegetation patterns in the North Cascades of Washington. Dendrochronological criteria used in this study are similar to those used by Glenn (1974) and are summarized below.

a) time of appearance of reaction wood

Reaction wood appears when a tree is tilted from the vertical (as through avalanche impact). Reaction wood refers to the specialized type of wood produced on the wide side of eccentric trunk cross sections (Smith, 1973). It will appear during the growing season following avalanche impact, and if a chronology has been developed for the particular species, the avalanche can be dated. If a chronology has not been developed and reaction wood appears more than once in a single tree, then the approximate length of time between events causing the reaction wood may be determined by counting the number of tree rings between appearances of reaction wood. In species used in studies of avalanche paths in the Vail area, the ratio of tree rings to years probably does not vary by more than $\pm$ 0.2 (Glenn, personal communication, 1974).

b) datable scars on trees

Trees in avalanche paths are sometimes scarred by avalanche impact as the snow removes branches and carries pieces of rock or wood against trees. If the scar is visible, a slice may be cut so that it includes the scar and the wood produced since scarring. The number of rings produced since scarring can then be counted and will approximate the number of years since the avalanche.

c) datable breakage

Avalanches often break tree trunks. The number of growth rings in the broken tree or stump provides a rough estimate of the number of years since an avalanche producing a force sufficient to break a tree of this size occurred. This approach should be treated with caution because large avalanches may have occurred when the tree was small and flexible, or may have occurred an undeterminable length of time before the tree was growing in the avalanche path. On conifers a lateral branch sometimes will grow vertically and become a new leader. Smith (1973) found that the number of rings in the new leader occurring above the height of the break gave a rough indication of the number of years since the break occurred.

d) age of debris

In many cases dead trees are deposited in the avalanche track and runout zone, and are clearly associated with avalanche activity. Tree trunks are often aligned parallel with the avalanche flow direction. In some dead trees, the growth ring pattern will correspond to those of live trees in the avalanche path. In such cases the number of additional rings in live trees give an estimate of the number of years since the avalanche.

e) abrupt changes in growth pattern

An abrupt change in growth rate may indicate a change in a tree's growing condition. An increase in growth rate may be caused when competitors are removed by an avalanche. This would be obvious from inspection of the area near the tree. A decreased growth rate may be caused by mechanical damage to a tree or by removal of adjacent trees which had previously provided protection. In either case the length of time since the change in environment can be estimated by ring counts.

Changes in growth rates can be caused by many other factors, such as climate change, soil and moisture changes, and disease. Trees in avalanche paths should be compared with control trees sampled in areas free from avalanches so that factors affecting all trees in an area can be separated from those caused by avalanches alone.

Smith (1973) points out that reaction wood and datable scars proved to be the two most reliable methods of dating past avalanches in the North Cascades. Glenn (1974) found the same to be true in his studies of Colorado avalanche paths.

Trees on steep mountain slopes can be disturbed by many natural processes other than snow avalanches. Some of these include landslides, rockfalls, soil creep, fires, mudflows, and debris flows. Some of these processes also produce the types of disturbances to trees described above. Therefore, it is important to determine that the trees sampled were damaged by avalanches. In some locations avalanche occurrence determinations made through tree ring studies will correspond to historical data obtained from newspapers and interviews. Similar results from independent sources tend to reinforce one another and an effort should be made to obtain as many different sources of information as possible.

Much more confidence will result through use of these methods as the amount of data collected from a path increase. One should be aware of certain observable relationships within the path. If dating what appears to be a large event, then the same date for damage should appear on opposite sides of the track. Single dates are much less reliable indicators than several dates collected throughout the entire path.

Dendrochronology may also have applications in establishing broad regional avalanche frequency relationships. Certain selected paths of a region that are representative of various avalanche sizes, elevations, and orientations may be studied in detail to establish these general relationships. It is important to recognize how the sampled paths compare in terms of avalanche frequency to those not sampled.

CHAPTER 7: AVALANCHE DEFENSES

1. Introduction

At locations in which avalanche hazards cannot be avoided, and permanent residences and buildings already exist or are planned, some type or types of avalanche defenses must be employed. Defenses in the starting zone are discussed in detail by Frutiger (1962), Frutiger and Martinelli (1966), and Mellor (1968). These publications should be consulted for engineering design details of avalanche starting zone defenses.

2. Avalanche defense in the starting zone

These defenses are of two types and are designed to either a) alter snow deposition in the starting zone or b) anchor the snowpack to the mountain. The former are devices designed to disturb the natural wind flow in and above avalanche starting zones. Various forms are discussed by Mellor (1968). Although they may prove effective in reducing the frequency of common avalanches that form as a result of wind loading of the starting zone, it is not likely that they will prove effective against avalanches that form as a result of prolonged, heavy snow loading by relatively windless storms. It is this type of storm that may lead to large scale soft slab avalanches which may develop into powder avalanches and run long distances in the runout zones (see chapters 3 and 4).

Supporting structures in the starting zone are built to alter the stress configuration within the snowslab, and prevent large scale slab avalanche releases. They must withstand impact loading of small slides which may occur between structures, and must also withstand very high creep pressures of the snowpack, especially during the spring. The Swiss are world leaders in design and use of supporting structures. Their federal government pays for up to 80% of the cost of these defense systems if they follow certain rigid construction guidelines (Frutiger, 1962) and are accompanied by an afforestation project. This large government subsidy is very important to local governments because structural defense in the starting zone is very expensive. Costs for supporting structures exceed $100,000/acre of structures in Switzerland (Frutiger, pers. comm., 1975). It is difficult to translate these costs to equivalents in the United States in the mid 1970's. There is almost no practical experience with these structures in this country and first attempts would be especially expensive as experience is gained. Initial costs could exceed $200,000/acre although it would vary considerably, depending on location, terrain, and accessibility. Such costs can rarely be afforded by local government or developers and, because of this, supporting structures are probably not a viable form of defense at this time in the United States.

If in the future, if it becomes possible or necessary to employ this type of defense, it is recommended that we adopt some form of guidelines similar to those used by the Swiss as discussed by Frutiger (1962).

3. Controlled release of avalanches

This has been effective in areas such as ski areas or highways that can tolerate many small slides without damage. The effectiveness depends on knowledge of current and past avalanche and snowpack conditions. This method is unacceptable in areas where avalanche paths cannot be completely evacuated or where valuable objects cannot be removed. Avalanches released in this way are sometimes much larger than expected.

4. Avalanche control in the runout zone

Avalanche control in the runout zone includes arrestor dams, breakers, deflecting dikes, and direct protection structures. Control in the runout zone is probably the most viable form of structural control in the United States at this time because it is relatively inexpensive and can be used on private land.

It is a matter of practical concern to design and build defense structures so that they will not be overtopped or broken by avalanches. The parameters which are needed to determine the necessary sizes and strengths of defense structures are

a) velocity, U,

b) flow depth, h',

c) impact pressure, P,

d) density, γ,

e) undisturbed snow depth, h_o,

Parameters a through d can be estimated by the use of the dynamic equations, (chapter 4 and 5), while the undisturbed snowpack depth must be determined through meteorological records of the area of interest.

Arrestor dams are designed to stop the flowing snow by forcing it upwards until the kinetic energy is dissipated. They are usually massive structures formed by pushing unconsolidated surface material into a ridge with a crest perpendicular to the avalanche flow direction. The design height, H, of arrestor dams must be calculated by taking the dynamics of the design avalanche into consideration. In this way it can be built high enough so that the design avalanche will not flow over the top. Design for impact is not a problem with massive earthen structures.

Deflecting dams are designed to change the direction of an avalanche, thereby protecting an area. Because they are usually placed to deflect the avalanche through much less than 90°, they may not need to be as high as arrestor dams. Structural deflecting dams, in contrast to massive earthen structures, must be designed to withstand the forces which result from changing the avalanche direction.

Avalanche breakers or retarding structures may be either earthen mounds or tripods designed to resist avalanche forces. Breakers are placed in the avalanche path in order to dissipate energy by breaking the flow into several smaller sections. Because of greatly increased friction and cross currents generated within the flow, runout distance can be shortened. Earthen mounds used for this purpose will be most effective if they are designed so that they will not be overtopped by the flow.

Direct protection structures are built immediately adjacent to the object to be protected and are sometimes incorporated into the design of the object. Such structures are most useful for protecting isolated objects such as buildings. Buildings can sometimes be protected by placing a wedge which splits the flow on the side from which the avalanche approaches. Such construction is often of reinforced concrete, occasionally backfilled with rubble, and must be designed for pressures and climbing heights.

5. Design criteria for runout zone defenses

The relationship between initial avalanche flow direction and the location and orientation of a deflecting wall or dam is shown in Figure 7-1. The design avalanche velocity, U_x, is calculated at the location of the defense structure by equation (4-22). The deflection angle, ϕ, is the angle through which the avalanche flow is changed or deflected by the defense structure. In the limiting case of an arrestor dam built at right angles to the flow, $\phi = 90°$, and impact forces and climbing heights are a maximum. Whenever an avalanche reaches an obstacle in its path, such as an arresting or deflecting dam, an earth mound, or a building wall, its flow depth is increased as the avalanche is stopped, slowed, or deflected. This new flow depth is the design height, H, and equals the sum of the snowpack depth, h_o, the flow depth, h', and the climbing height, h

$$H = h_o + h' + h \quad . \tag{7-1}$$

When dense flowing avalanches constitute the design case, the avalanche may not flow on top of the snowpack and the value used for h_o may be reduced. The climbing height,

$$h = (U_x \sin\phi)^2/2g \quad , \tag{7-2}$$

so that the design height (equation 7-1) becomes

$$H = h_o + h' + (U_x \sin\phi)^2/2g \quad . \tag{7-3}$$

Inspection of equation (7-3) shows that design height decreases quickly with decreasing deflection angle. For example, stopping an avalanche with U_x = 25m/s, h_o = 1m, and h' = 2m would require a wall 35 m (114 ft) high, whereas deflecting the flow through an angle of 25° would require a wall only 8.7 m (28.5 ft) high. The second alternative, however, would require a wall 2.4 times as long in order to protect the same area.

Figure 1-2 illustrates the futility of attempting to arrest or deflect a high-velocity dry snow or powder avalanche. In this case the avalanche climbed 80 m (250 ft) up the natural obstacle at the bottom of the avalanche track which was the opposite valley wall. At this point it still maintained considerable destructive energy (Figure 1-3).

In addition to this increased flow depth, forces are exerted on the object as the avalanche velocity and momentum are changed by it. These forces are F_n, normal to the wall, F_s, parallel to it, and

F_v, in the vertical direction. They are strongly influenced by variation in U_x and ϕ. In the following discussion these forces are converted to specific forces per unit area (pressure and shear) and are written P_n, P_s, and P_v, respectively. The forces, shown in Figure 7-2, act over the entire wall lengths and over the height H.

The normal pressure

$$P_n = \frac{\gamma}{g} (U_x \sin\phi)^2 \quad , \qquad (7\text{-}4)$$

and $P_s = P_v = 0.5P_n$ (Sommerhalder, 1965). In the previous example, for $\phi = 200 kg/m^3$, and $\phi = 90°$, $P_n = 6.4\ t/m^2$ (1300psf), but for $\phi = 25°$, $P_n = 1.1\ t/m^2$ (230psf).

The effectiveness of runout zone defenses is influenced by the design parameters and by the terrain on which they are placed. Two adverse effects are recognized: overtopping and damming.

Overtopping is an effect already discussed, but it should be related to terrain. It is recommended by Salm (1975) and Sommerhalder (1975) that retarding and breaking structures are less effective on slopes steeper than 30%. They prove most effective if placed where average sized avalanches stop naturally. This corresponds to the runout zones of the design avalanches. Within this zone velocity decreases with distance, and a location may be chosen where the design velocity, U_x, is small enough for the defense structure size to be practical.

Damming of snow can occur at a defense structure if avalanche velocity is diminished and internal frictional forces are activated. Equation (4-3) suggests that internal friction is velocity dependent and becomes large at low velocities where avalanches behave less like a fluid and more like a solid. If deflecting dams or splitting wedges are located so that avalanches are forced past them on slopes much less than 30%, low velocities and damming of snow may occur.

In this case the dam would act like an arrestor, snow would be deposited against the wall, and the structure would prove less effective against future avalanches.

The area of the runout zone of a channeled avalanche can sometimes be reduced by building a deflecting dike near the point where the avalanche discharges from the gully. In this case the deflecting angle may be kept small and a large area of the runout zone made safe from flowing avalanches. However, this procedure may actually lengthen the runout distance in the direction to which the avalanche is deflected. Structural control of this type probably would not be effective against high velocity powder avalanches.

6. Other direct protection defense structures

Avalanche galleries or "snowsheds" have provided direct protection for highways and railroads in this country for many years and may also be practical for some buildings. Design criteria for gallery defenses are discussed in Mellor (1968). Such defenses are probably most suited to steep slopes where the avalanches will pass over the protected object and not dam up on top of it. Such damming could bury a building under a large avalanche even though it would be designed to withstand the forces caused by avalanche passage. However, if such defenses are located on steep slopes, avalanches may occur much more often than is desirable from the standpoint of zoning criteria (chapter 2). It is unlikely, for these reasons, that gallery defenses would prove suitable for buildings occupied during winter.

If it is known that buildings will be located within range of powder avalanches, then it becomes necessary to design them for forces generated by powder avalanche passage. Powder avalanches are often too deep and fast moving to be stopped or deflected. Buildings in powder avalanche paths must be designed for stagnation pressures (Figure 5-1) which, when multiplied by appropriate shape factors and exposed surface areas, yield design forces. Shape factors for drag and lift are not readily available and must be obtained through an aerodynamic analysis of the building or structure.

7. Safety factors used in design of runout zone defenses

Design sizes and strengths of runout zone defenses are readily obtainable in terms of velocity, flow depth, impact pressure, and density, through use of the equations presented in this chapter. As stressed in earlier chapters these avalanche parameters are subject to a certain range of uncertainty and are always subjective to a degree. Failure of a structure through mechanical damage or overtopping can have serious consequences for occupants of the protected area. Building codes have not been developed for avalanche defenses; so, until more experience is gained, it is not possible to specify rigid safety factors. In the meantime it is suggested that the size of safety factors used in design be similar to those used in other designs such as dams, in which failure may result in loss of life.

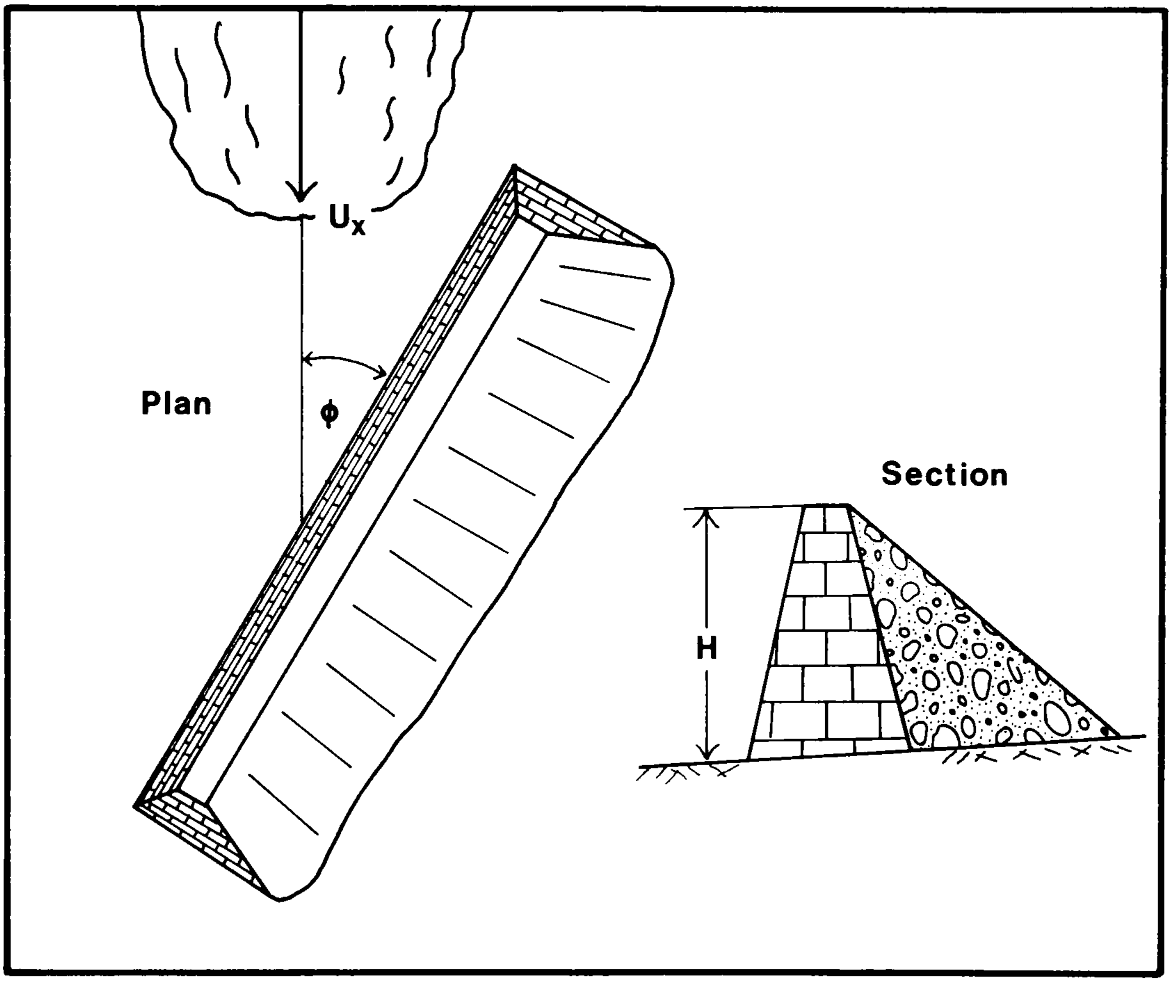

Figure 7-1. A dam (or dike) placed to deflect a flowing avalanche. Design quantities are:

U_x = Initial avalanche velocity and direction
ϕ = Deflection angle
H = Design height = $h_i + h' + (U_x \sin\phi)^2/2g$

The design quantities also apply to splitting wedges or arrestor dams with steep faces.

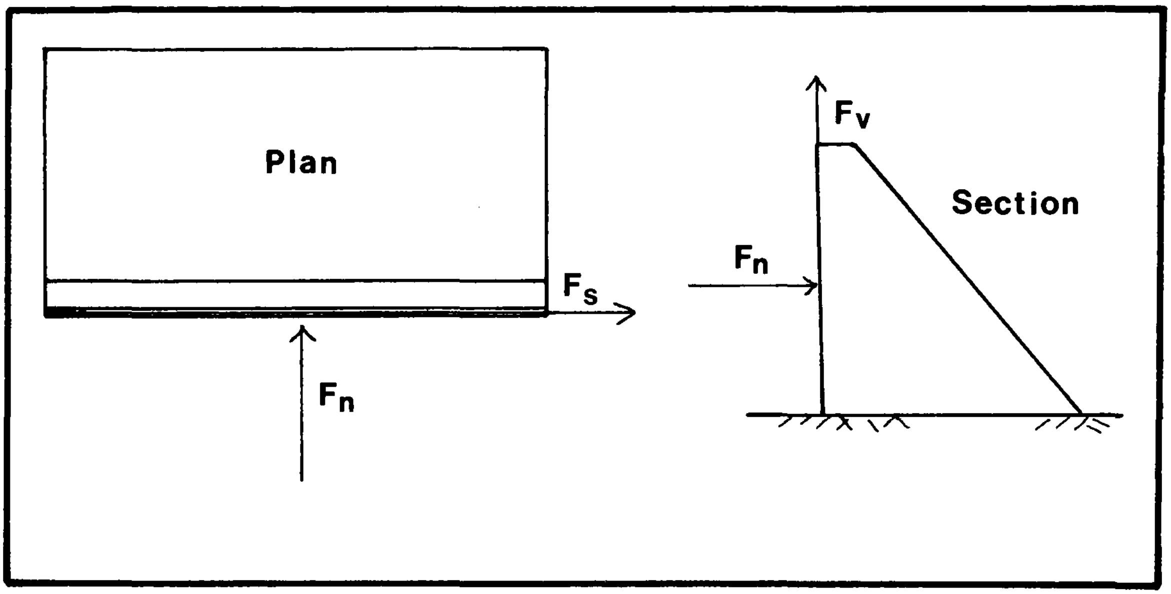

Figure 7-2. Directions of design forces on deflecting wall, dike, or splitting wedge with vertical face of area A.

$$F_n = AP_n = \frac{\gamma}{g} (U_x \sin\phi)^2 \text{ (normal)}$$

$$F_s = 0.5\ F_n \text{ (shear)}$$

$$F_v = 0.5\ F_n \text{ (vertical)}$$

REFERENCES

Part I. Avalanche Dynamics and Land Use

Bagnold, R. A., 1966, An approach to the sediment transport problem from general physics: U.S. Geol. Survey Prof. Paper 422-I, 37 p.

Betts, H. S., 1919, Timber, its strength, seasoning and grading: New York, McGraw-Hill Book Co., 234 p.

Bovis M. J., and Mears, A. I., 1976, Statistical prediction of snow avalanche runout from terrain variables: Arctic and Alpine Research, v. 8, no. 1, p. 115-120.

Brown, C. B., Evans, R. J., and LaChapelle, E. R., 1972, Slab avalanching and the state of stress in fallen snow: Jour. Geophys. Research, v. 77, no. 24, p. 4570-80.

Dalrymple, Tate, 1960, Flood-frequency analyses: U.S. Geol. Survey Water-Supply Paper 1543-A, 80 p.

Daugherty, R., and Franzini, J., 1965, Fluid mechanics with engineering applications: New York, McGraw-Hill Book Co., 574 p.

de Quervain, M., 1975, Avalanche formation, in Avalanche protection in Switzerland: U.S. Forest Service Gen. Tech. Rept. RM-9.

Frutiger, Hans, 1962, Avalanche control in the starting zone: U.S. Forest Service Sta. Paper 71, 60 p.

__________1964, Avalanches along Colorado mountain highways: U.S Forest Service Research Paper RM-7. 86 p.

__________1970, The avalanche zoning plan: U.S. Forest Service Translation 11, 24 p.

Frutiger, H., and Martinelli, M., 1966, A manual for planning structural control of avalanches: U.S. Forest Service Research Paper RM-19.

Glenn, M., 1974, Tree-ring dating of snow avalanches [abs.]: Colorado-Wyoming Acad. Sci. Jour., F(5): v. 5, p. 46.

Ives, J., Mears, A. I., Carrara, P., and Bovis, M., Natural hazards in montane Colorado: (in press).

LaChapelle, E. R., and Atwater, M., 1961, The climax avalanche—a study of case histories: U.S. Forest Service, 34 p.

LaChapelle, E. R., 1966, Encounter probabilities for avalanche damage: U.S. Forest Service Misc. Rept. 10, 10 p.

Martinelli, M., 1974, Avalanche sites, their identification and evaluation: U.S. Forest Service Agriculture In. Bull. 360, 26 p.

Mears, A. I., 1975, Dynamics of dense-snow avalanches interpreted from broken trees: Geology, v. 3, no. 9, p. 521-523.

__________1976, Snow avalanche hazard zones of selected areas in Colorado: Colorado Geol. Survey Spec. Pub. 7 (in press).

Mellor, M., 1968, Avalanches, Cold regions Science and Engineering Part III: Engineering, Section A3: Snow technology, 213 p.

Norris, C. H., 1959, Structural design for dynamic loads: New York, McGraw-Hill Book Co., 453 p.

Potter, N., 1969, Tree-ring dating of snow avalanche tracks and the geomorphic activity of avalanches, northern Absaroka Mountains, Wyoming: Geol. Soc. America Spec. Paper 123, p. 141-165.

Salm, B., 1975, Principles of structural control of avalanches, in Avalanche protection in Switzerland: U.S. Forest Service Gen. Tech. Rept. RM-9, 168 p.

Schaerer, P. A., 1973, Observations of avalanche impact pressures, in Perla, R. I., ed., Advances in North American avalanche technology—A symposium, 1972: U.S. Forest Service Gen. Tech. Rept. RM-3, 54 p.

__________(in press), Friction coefficients and the speed of flowing avalanches, (paper presented at the International symposium on snow mechanics, Grindelwald, Switzerland, 1974)

Shen, H., and Roper, A., 1970, Dynamics of snow avalanche (with estimation for force on a bridge): Internat. Assoc. Sci. Hydrology Bull. v. 15, no. 1.

Smith, L., 1973, Indication of snow avalanche periodicity through interpretation of vegetation patterns in the North Cascades, Washington, in Avalanche studies: Washington State Highway Dept. Research Program Rept. 8.4.

Sommerhalder, E., 1965, Avalanche forces and the protection of objects: U.S. Forest Service Translation 6, 14 p.

__________1975, Deflecting structures, in Avalanche protection in Switzerland: U.S. Forest Service Gen. Tech. Rept. RM-9, 168 p.

Taylor, G., 1964, Managerial and engineering economy: New Jersey, Van Nostrand Co., 487 p.

Tochon-Danguy and Hopfinger, E., (in press): Simulation of the dynamics of powder avalanches, (paper presented at the International symposium on snow mechanics, Grindelwald).

Voellmy, A., 1964, On the destructive force of avalanches: U.S. Forest Service Translation 2, 64 p.

Williams, K., 1975, The snowy torrents: U.S. Forest Service Gen. Tech. Rept. RM-8, 190 p.

Part II. Avalanche Safety, Travel and Rescue

LaChapelle, E. R., 1970, The ABC of avalanche safety: Denver, Colorado. Outdoor Sports Co., 56 p.

Perla, R. I., 1968, Modern avalanche rescue: U.S. Forest Service Snow Safety Guide 1.

SELECTED COLORADO GEOLOGICAL SURVEY PUBLICATIONS RELATING TO GEOLOGY AND LAND USE

ENVIRONMENTAL GEOLOGY SERIES

1 Geologic Aspects, Soils, and Related Foundation Problems, Denver Metropolitan Area, J. L. Hamilton and W. G. Owens, 1972. 1.00

2 Engineering Geology Report for Planning District 1, State of Colorado, F. M. Fox & Associates, 1974. 1.00

3 Engineering Geology Report for Planning Districts 7 and 13, State of Colorado, F. M. Fox & Associates, 1974. 1.00

4 Engineering Geology Report for Planning District 9, State of Colorado, F. M. Fox & Associates, 1974. 1.00

6 Environmental and Engineering Geology of the Windsor Study Area, Larimer and Weld Counties, Colo., D. C. Shelton and W. P. Rogers. (in preparation)

7 Potentially Swelling Soil and Rock in the Front Range Urban Corridor, Colo., S. S. Hart, 1974. 3.00

8 Roaring Fork and Crystal Valleys Environmental and Engineering Geology Study, F. M. Fox & Associates, 1974. 6.00

9 Ground Subsidence and Land-Use Considerations Over Coal Mines in the Boulder-Weld Coal Field, Colorado, Amuedo and Ivey, Geological Consultants, 1975. (in press)

SPECIAL PUBLICATION SERIES

1 Proceedings of the 1st Governor's Conference on Environmental Geology, 1970. 1.00

2 Geothermal Resources of Colorado, R. H. Pearl, 1972. 1.00

4 Geology of Ground Water Resources in Colorado, R. H. Pearl, 1974. 1.50

5-A Sand, Gravel, and Quarry Aggregate Resources, Colorado Front Range Counties, S. D. Schwochow, R. R. Shroba, and P. C. Wicklein, 1974. 3.00

5-B Atlas of Sand, Gravel, and Quarry Aggregate Resources, Colorado Front Range Counties, S. D. Schwochow, R. R. Shroba, and P. C. Wicklein, 1974. (revised and reprinted 1975). 10.00

6 Guidelines and Criteria for Identification and Land-Use Controls of Geologic Hazard and Mineral Resource Areas, W. P. Rogers and others, 1975. 3.00

7 Avalanche Hazards in Colorado, Special Studies of Selected Development Areas, A. I. Mears, 1975. (in press)

MAP SERIES

1 Geologic, Energy and Mineral Resources Maps of Routt County, Colo., A. E. Miller, 1975, scale 1:126,720. 5.00

2 Hydrogeology of the St. Charles Mesa Area, Pueblo County, Colo., J. M. Dumeyer, 1975, scale 1:24,000. 2.00

MISCELLANEOUS

Geologic Map of Colorado, U.S. Geological Survey, 1935. Reprinted by the Colorado Geological Survey, 1975, scale 1:500,000. 5.00; 6.50 mailed.