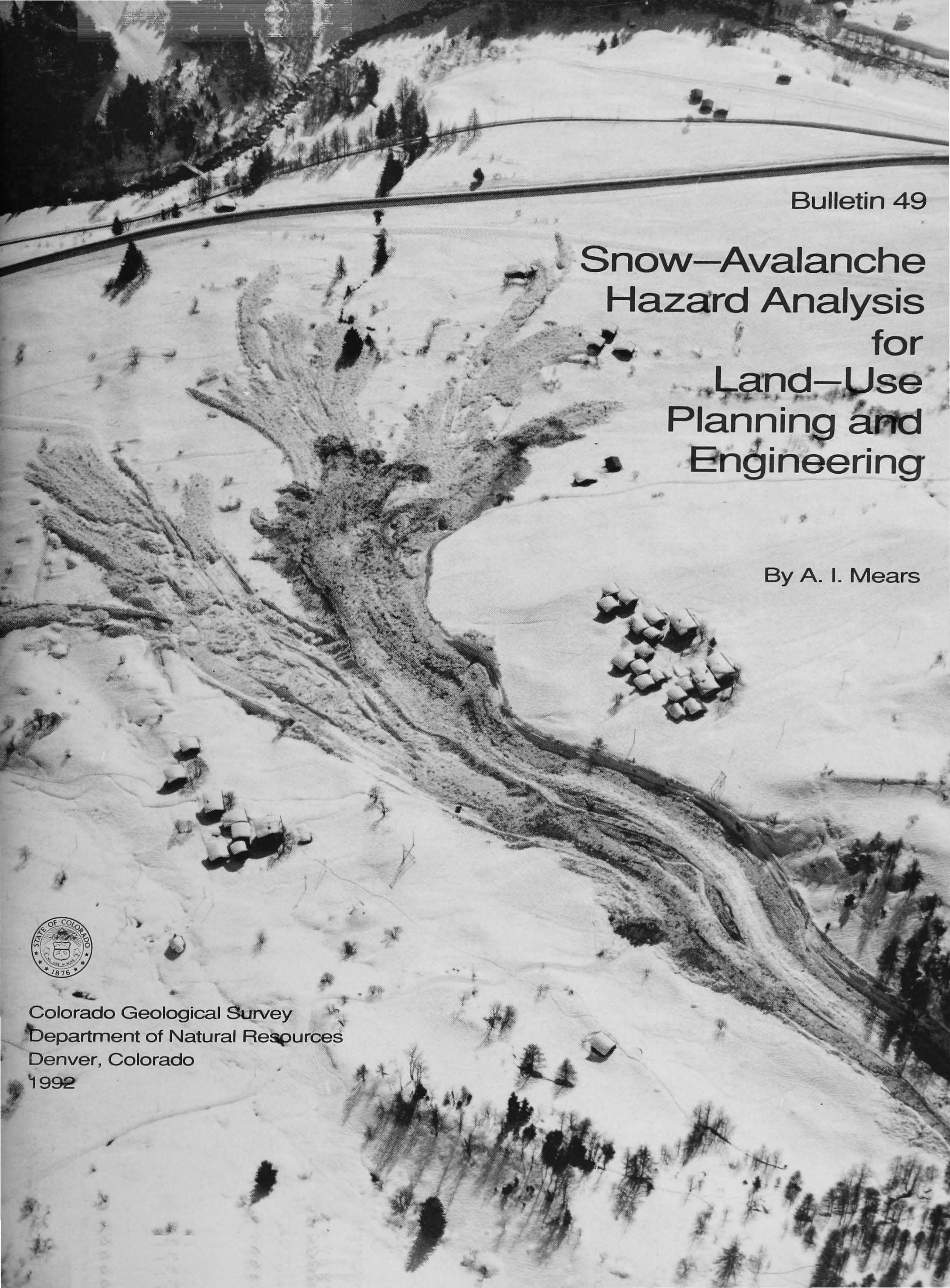

Bulletin 49

Snow–Avalanche Hazard Analysis for Land–Use Planning and Engineering

By A. I. Mears

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
1992

Cover photograph: Runout of a large wet-snow avalanche onto a populated alluvial fan in Switzerland, 1980. Photograph by the Swiss Army, and supplied by the Swiss Federal Institute for Snow and Avalanche Research.

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Chapter 1

Objectives and Limitations

Snow Avalanche Hazard—an Overview

Hundreds of thousands of snow avalanches fall throughout the world's mountains each year. Most occur in remote mountain areas and pose no threat to man, his structures, or activities. In recent decades, however, man's activities in North America have increasingly expanded into mountainous terrain. The resulting increase in winter recreation, recreational facilities, mountain homes, transportation and communi- cation lines, utilities, and mining have increased the hazard in proportion to the length of time man's activity and structures are exposed in avalanche terrain.

The various types of avalanche hazard can be subdivided into several categories which depend on land use:

a. **Residential construction**—Exposure of buildings and other fixed facilities and the hazard to persons using these facilities within mountain residential areas;
b. **Highways and railroads**—Exposure of structures on highways and railroads;
c. **Mountain travelers**—Hazard to people using highways and railroads;
d. **Utilities**—Exposure of structures associated with mountain communications and utilities systems;
e. **Commercial/Industrial Use**—Hazard associated with mining and other industrial activities;
f. **Ski Areas**—Hazard associated with avalanches at ski areas and similar recreational areas (not buildings or structures); and
g. **Recreational Use**—Hazard to those who use the mountains for recreational activity and are exposed to or trigger avalanches.

The various hazards described in c, f, and g, are best reduced through *education, rescue training, closure,* and *avalanche warnings*. Numerous organizations throughout the United States and Canada provide education and training in the avalanche phenomena, rescue, and safe use of the backcountry. In addition, avalanche-forecast centers exist in Colorado, Utah, and Washington. These centers, which are staffed with meteorologists and professionals trained in snow-stability evaluation, provide regional daily forecasts on weather and snow stability and issue avalanche hazard advisories and warnings when necessary. Numerous local avalanche-forecast centers also exist throughout the western states and Canada that provide similar services. These important private and public supported services have certainly reduced the avalanche hazard through education and avoidance. Ski areas with significant avalanche hazards usually employ snow-safety specialists who are responsible for avalanche forecasting and mitigation, and who are equipped for rescue within ski-area boundaries.

The hazards described in a, b, d, and e usually involve structures exposed for years or decades within avalanche paths. These facilities are usually located outside the steep terrain and obvious, frequent avalanche areas but sometimes are located where unusual, rare avalanches can reach. The problem of quantifying the exposure to valuable structures and the persons using them is therefore similar to that associated with defining the "100-year" flood, the "design" earthquake or other long-return period natural processes.

An example of the design-magnitude "100-year" avalanche is shown in Figures 1 and 2, which illustrate the effects of a major "design-magnitude" avalanche in Colorado. Large avalanches in the Deadman Gulch avalanche path had not occurred for many decades prior to a major dry-snow event in 1984 that extended the obvious avalanche-path limits and destroyed a lodgepole pine forest approximately 100 years old that had colonized the runout zone. Development of the area at the foot of Deadman Gulch clearly requires planning for the rare event.

This publication focuses on the methods and limitations of avalanche analysis for land-use planning and engineering purposes, (categories a, b, d, and e). Snow stability evaluation and avalanche forecasting

Figure 1. Deadman Gulch avalanche path, Colorado Front Range. This photograph was taken in 1976 and shows the results of multiple small avalanches over a period of several decades which have cleaned the central gully of trees and large vegetation. Avalanches have usually been deflected to the left, but larger avalanches have overtopped the channel boundary and run out onto the top of the alluvial fan to the right.

Figure 2. Deadman Gulch in 1984. Shortly before this photograph was taken, a major dry-snow/powder avalanche released from the upper right half of the starting zone, widened the avalanche boundaries in the channel, and enlarged the runout zone, destroying a forest 100 years old. This event, which far exceeded the size of avalanches during the past several decades, is the design-magnitude event for land-use planning purposes.

(important in c, f, and g) are beyond the scope of this publication.

Limitations

Quantification procedures that can be used to describe the design-magnitude, long-return-period avalanche have many analogies in the geological and geotechnical engineering fields, particularly in the hydrological and meteorological sciences. However, hydrology and meteorology procedures are applied throughout the world, thus many scientists and engineers have devoted entire careers to study of methods used to quantify flood and weather processes. A large body of knowledge about these processes exists and analytical procedures are well established. Although the "state of the art" continues to evolve as more is learned, it tends to be fairly well defined at any one time, therefore large numbers of scientists and engineers use the same or similar established procedures. Consequently, corrections and modifications to the methods used are based on the research and results of large numbers of professionals.

In contrast to other hydrological and geological processes, relatively few scientists have studied avalanches with the intent of quantifying their physical characteristics. Few procedures exist that can be used to calculate velocities, impact-pressure potentials, or runout distances, even though these are important elements in land-use planning and engineering. Although the state-of-the-art has advanced considerably since the pioneering Swiss work of the 1950s, it certainly has not stabilized. Substantial research and changes to our knowledge and procedures have taken place during the 15 years since publication of Colorado Geological Survey Bulletin 38 (Mears, 1976). These changes have prompted the re-writing, rather than revision of this publication.

The snow-avalanche process is highly variable in terms of size, material properties, and behavior. Therefore, regardless of the supposed reliability and appropriateness of various analytical procedures, a high level of precision about avalanche design parameters (velocity, impact potential, runout distance, etc.), cannot yet be attained. We therefore recommend, as was done in Bulletin 38, that multiple approaches be used whenever possible in defining the avalanche hazard. This should reduce the uncertainty resulting from application of one method by itself and will increase the confidence of avalanche analysis for land-use planning and engineering. This multiple-techniques approach is emphasized in Chapter 3.

Finally, several physical and statistical procedures and equations are presented in this publication. These are intended to aid in the identification and quantification of avalanche characteristics. The procedures outlined here are thought to be reasonably reliable engineering and planning tools, however, they may not apply in certain specific or unusual cases. It remains the responsibility of the user to determine the appropriateness of the various methods given in this publication.

Chapter 2

The Avalanche Phenomena

Introduction

This chapter describes avalanche terrain, release, motion, and impact with an emphasis on the physical characteristics that are important in land-use planning, engineering, and quantification of the snow-avalanche process. Similar to other mass-wasting phenomena, snow avalanches vary considerably in mass, velocity, and internal properties. Consequently, they have widely varying effects on man-made and natural objects. The various analytical methods of avalanche analysis discussed in following chapters are only best approximations to this complex natural process. We feel the investigator must be aware of the limitations of the methods used to estimate and calculate avalanche properties for engineering purposes. These limitations are best appreciated with a basic understanding of the avalanche phenomena.

Avalanche Terrain

The term ***avalanche path*** is used to describe terrain boundaries of known or potential avalanches. Avalanche paths extend from steep upper terrain where snow releases, accelerates, and avalanches grow in mass, to gentle terrain where avalanche deceleration and debris deposition occur. The gentle terrain, or ***runout zones*** are often locations where facilities are exposed and land-use planning and engineering design is necessary for hazard reduction and the protection of objects. Avalanche paths vary in length over at least two orders of magnitude, from less than 100 m to greater than 10,000 m, and avalanches range in mass over seven orders of magnitude, from 10^3 kg to 10^{10} kg.

The world's largest avalanches consist of rock, soil, and glacial ice, not seasonal snow, and may contain 100 to 1000 times the mass of the largest snow avalanches. These massive events are well documented in the geologic literature (e.g., Voight 1978), and will not be discussed in this publication. The largest snow-avalanche paths near populated areas in North America are as much as 4,000 m long and have vertical drops of up to 1,800 m. Typical paths of interest in land-use planning and engineering range from 300 to 3,000 m in length. However, much smaller avalanche paths (lengths of less than 100 m, vertical drops of 50 m or less) have caught, buried, and killed people and have damaged structures or vehicles.

The avalanche path can usually be divided into *(1)* starting zone(s), *(2)* track(s), and *(3)* runout zone(s) (Figure 3). The following refers to those features of the avalanche path most important in estimating potential avalanche size, a characteristic which is related to velocity, destructive force, and runout distance.

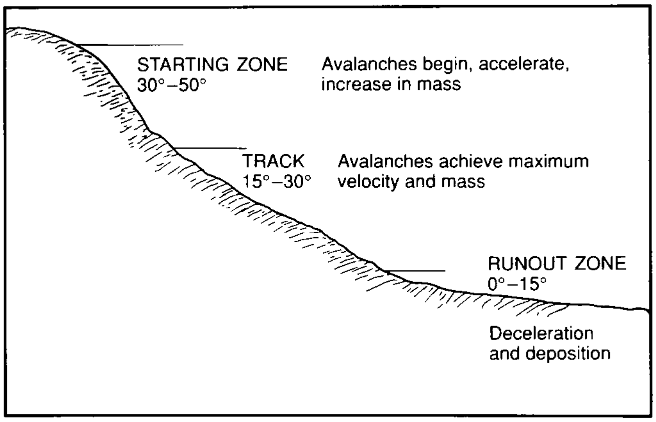


Figure 3. Profile overview of an avalanche path, showing typical slopes of the starting zone, track, and runout zone.

The ***starting-zone*** features discussed below are important in planning and design but the discussion may not apply to route-finding, avalanche forecasting, or rescue. The following factors should be considered in identification of starting zones and estimation of released snow volumes.

a. Average vertical angles over entire starting zones typically range from 25° to 50° However, most large, long return period avalanches begin within the narrow steepness range of 30° to 40°. When snow release depth is estimated (see page 8) and starting-zone boundaries are known through terrain analysis, released snow volume can be computed.

b. Ground surface roughness strongly affects bonding strength between snow and ground. Dense, closely-spaced forests, steep ridges, or very rough, broken or benched terrain may tend to anchor the snow to the ground even within generally steep, starting zones. In some cases this may limit the starting zone to a fraction of the total steep terrain. The areas that will *not* release, even during conditions of widespread snow instability, must be recognized so that unrealistically large estimates of avalanche size are avoided. Open, widely-spaced forests (generally skiable terrain), however, will not anchor the snowpack and will not inhibit avalanche release. In general, avalanches are able to release from starting zones when the ground surface roughness elements (e.g., rocks, low vegetation), are covered with snow. Smooth slopes, therefore, do not require a deep snowcover to serve as starting zones. In contrast, rough slopes may require a deep snowcover to form a smooth sliding surface and thus may not avalanche on typical years.
c. Transverse shape can be planar slopes, well-formed bowls or may even be convex. During conditions of deep, continuous snowcovers, starting zones can extend around and over ridges.
d. During the extremely unstable snowpack conditions leading to the major avalanches of primary interest in engineering and planning, large masses of unstable snow will behave as a single rigid *slab* which will be bounded by distinct fracture surfaces (see page 7). The fractures can propagate long distances over open slopes, through forests and over terrain irregularities. These long fractures may connect several adjacent areas that usually release independently, triggering several paths simultaneously.

Starting zones are best identified by careful analysis of topographic maps, study of stereo air photos, and field inspection. The most detailed topographic maps widely available in the United States are U.S. Geological Survey quadrangle maps with 1:24000 scale and 40-foot contour intervals. National map accuracy standards ensures that such maps will maintain vertical accuracy to within ±50 percent of one contour interval and horizontal accuracy of "well-defined points" to within ±50 feet at least 90 percent of the time. Therefore these maps can be useful in determining inclinations and areas when starting zones are sufficiently large to minimize the importance of map accuracy (>50,000 m^2; 5 hectares; about 12 acres). Topographic map study is not as useful for identification of small starting zones unless detailed maps are used because the margin of error becomes more important.

The U. S. Forest Service maintains comprehensive, stereo photo coverage, usually at approximate scales of 1:10,000 to 1:20,000 throughout the National Forests, areas that include most of the mountains and almost all of the avalanche terrain in the western states. Study of these photos is essential for determination of forest cover and ground-surface conditions. In addition to the topographic map and photo study, field checking within the starting zones is always required to confirm the accuracy of the topographic mapping and to determine if any changes have taken place since the most recent aerial photography.

A combination of aerial-photo study and topographic-map analysis is necessary for understanding the relationships and connections between the starting zone and track. Such reconnaissance study may reveal the presence of several starting zones that feed a single track, thus showing important relationships not apparent from valley-bottom inspection. Study of oblique aerial photographs and view from an aircraft or from the opposite side of a valley may also provide important perspective.

Within the ***avalanche track*** maximum avalanche velocity is usually attained. Track slopes are usually within the 15° to 30° range. Within the track, entrainment of snow may be balanced by deposition (see page 9), therefore mass probably does not systematically increase or decrease during large events unless snow is saturated throughout with water and easily entrained. Small avalanches will often stop in the track or starting zone. The cross-sectional shape of avalanche tracks vary considerably from one path to another.

1. ***Channelized*** or ***confined*** avalanche tracks follow the same small drainages as debris flows or small mountain streams. Channels direct and concentrate the flow of small, particularly wet-snow avalanches and tend to increase flow depth and perhaps impact-pressure potential and runout distances within the runout zones. Large, deep avalanches sometimes overtop the lateral boundaries of channels. Channelized tracks often discharge onto alluvial fans, therefore the transition (vertical-angle difference) from channel to fan is usually smooth. This reduces energy losses in snow avalanches and enables long runout distances on the alluvial fans.
2. Many paths follow ***unconfined*** or ***planar*** slopes to the valley bottom. The transition at the bottom of the unconfined slopes generally will be fairly abrupt because alluvial fans do not develop at these locations. This abrupt slope change causes energy losses and may shorten avalanche travel distances.

Some avalanche tracks show both confined and unconfined characteristics. Small avalanches may follow obvious central channels while the larger avalanches in the same path, which are usually of most interest in planning, often consist of deep, diffuse snow and entrained air. These large-volume events overtop channel boundaries and spread into adjacent terrain.

The avalanche ***runout zone*** is the lower part of the path where final deceleration occurs and a dense, hard deposit of snow and other debris is formed. From a land-use planning perspective, the runout zone is usually the most important part of the path because here slopes are gentle, private property is located, and roads, buildings, and other facilities are built and exposed to avalanches. As with starting zones and tracks, a wide variety of runout-zone forms occur.

a. Runout zone gradients are usually less than approximately 15°, may be flat, or can even extend up an adverse slope. When large avalanches impact narrow valley bottoms at right angles, evidence of avalanche impact sometimes extends 100 m or more vertically up the opposite side of the valley.
b. If avalanches run down small drainage basins, the runout zones will generally be on alluvial fans. Wet-snow avalanches in particular (see page 12) may transport snow and solid debris long distances on fans. Fans may tend to spread the flow of certain types of fast-moving avalanches while deflecting slow-moving avalanches sharply on the fan surfaces.
c. Unconfined avalanches may fall directly onto low-gradient or flat valleys, going through an abrupt transition from steep to gentle slopes. The abrupt transition will decrease avalanche runout distance and produce a deep deposit at the base of the steep slope.
d. Runout distances of large, high-velocity, dry-snow avalanches will sometimes extend 500–1000 m on slopes of 5°–10°. Exceptional avalanches have produced even longer runout. In some cases, small paths have produced avalanches with runout distances longer than the vertical fall height above the runout zone.
e. Although some runout zones are unforested and clearly are overrun by avalanches fairly often, others may support mature forests because they are seldom reached by avalanches. Forest cover is no assurance that a given area is not a potential runout zone.

The overall average slope angle of an avalanche path, measured from the top of the starting zone to the lower tip of the runout zone, (the "Alpha" angle), ranges from 15° to 30° in almost all long-return-period avalanches studied in North America. In 300 major avalanches studied in Colorado, Wyoming, Utah, and California (Mears, unpublished), roughly 50 percent of all these events have Alpha angles of 18° to 25°. The alpha-angle is an important and well studied measure of potential avalanche runout (page 23).

Avalanche Release

Understanding fundamental principles of snow-avalanche release and snow mechanics forms the bases for snow stability evaluation, avalanche forecasting, and explosive control. These topics are beyond the scope of this publication but are discussed in many other sources (e.g., Perla and Martinelli, 1976). A brief discussion is provided here so the investigator of avalanche potential for design and land-use planning will have some understanding of avalanche development during the initial stages of motion in the starting zone.

Avalanches begin with the failure of snow slopes, a failure occurring as either a *cohesionless* or *cohesive* material (Figure 4). Cohesionless failure occurs in snow when the internal cohesive strength in the upper snowpack is small compared to the bonding strength of the snow to some deeper layer. Such failures are generally referred to as *point* or *loose-snow* avalanches. They are common within new dry snow layers particularly on slopes exceeding roughly 40°, or in wet, water-saturated snow, occasionally on slopes as gentle as 20° or even less.

Loose-snow avalanches are usually smaller than slab avalanches, do not involve large masses of snow, and do not reach dangerous proportions, except to skiers or mountaineers who may be exposed on or below steep terrain. They often serve to gradually redistribute freshly-fallen snow to more gentle gradients. Occasionally, however, loose-snow avalanches are large enough to reach and damage facilities located in the runout zone. The larger cohesionless-snow avalanches almost always consist of wet snow and reach large sizes when snow in the avalanche path is water-saturated from the starting zone through the runout zone. Loose-snow avalanches may also trigger the larger and potentially more dangerous slab avalanche.

Slab avalanches are fractures of cohesive, well-bonded snow in which an entire starting zone may be involved in a single, massive release of large volume. On smooth, continuous terrain, slab fractures of more than 3,000 m length have been observed. Slab avalanches will occur in all starting zones, given a long enough time period. They will invariably produce the larger, more energetic avalanches that must be considered in planning and design of fixed facilities.

Snow slabs can form whenever the internal cohesive strength within the upper slab layer or layers is greater than the bonding strength at the basal and lateral slab boundaries. This general definition of a slab layer allows for a wide variety in strengths, material properties, densities, and water content. Slab densities have been measured within the wide range of 60 kg/m^3 to 700 kg/m^3, strength variations of at least a factor of 100 have been measured, and slabs are known to form when the snow is cold and dry or fully saturated with water. Dense, thick slabs can accumulate on steep slopes when snow is strong and may produce large destructive avalanches. Smaller avalanches will be released when slab boundaries are weak and cannot support a heavy new snow load.

Most measurements of dry slab avalanches have found average densities within the range of 150 kg/m^3 to 300 kg/m^3. Larger densities (up to approximately 500 kg/m^3) are commonly measured in slabs formed by vigorous wind redistribution of snow, although such high densities are usually found primarily within thick wind drifts near the tops of starting zones. Wet-slab densities usually exceed 400 kg/m^3 and may reach 700 kg/m^3 in water-saturated slabs.

At the instant of fracture, five surfaces (including the two flanks), bound the released slab (Figure 4). Avalanches obviously will not accelerate downslope unless all boundary surfaces fracture and separate.

a. **The Bed Surface**—This large surface is parallel to the ground or snow surface and fails in shear. The vertical distance between the bed and the snow surface, *H*, is the height of the slab. Slab thickness, $d = H \cos \theta$, where θ is slab inclination.
b. **The Crown Surface**—The upslope boundary of the slab (the "fracture line"), is perpendicular to the bed and fails in tension. The fracture thickness (sometimes referred to as the "fracture height"), will generally be larger than the average slab thickness, *d*.
c. **The Flank Surfaces**—The lateral boundaries of the slab fail in shear and tension. The average distance between the flanks is the width, *W*, of the initial slab failure.
d. **The Stauchwall**—This lower boundary of the slab is subject to compressive stresses. The average slope distance between the crown surface and stauchwall is the length, *L*, of the slab.

The slab volume, which is important in some avalanche-dynamics applications (see page 23), can be estimated as

$$\text{Volume} = d \times W \times L. \tag{2.1}$$

The positions of the failure surfaces obviously control the area and volume of the initial slab failure and may strongly influence the potential size of the avalanche, (see page 9). To determine potential slab-release volume, slab area must be estimated by terrain analysis, which will identify potential slab boundaries. Slab thickness, however, must be estimated from storm and snowpack potential in the climatic region. As discussed on page 5, these terrain boundaries can be estimated during snow-free conditions through aerial-photo and topographic-map analysis and field measurements. Winter observations may also be important in assessing wind erosion or deposition patterns in a starting zone. However, a few winters of snow observations may not reveal the potential for deep snow accumulations.

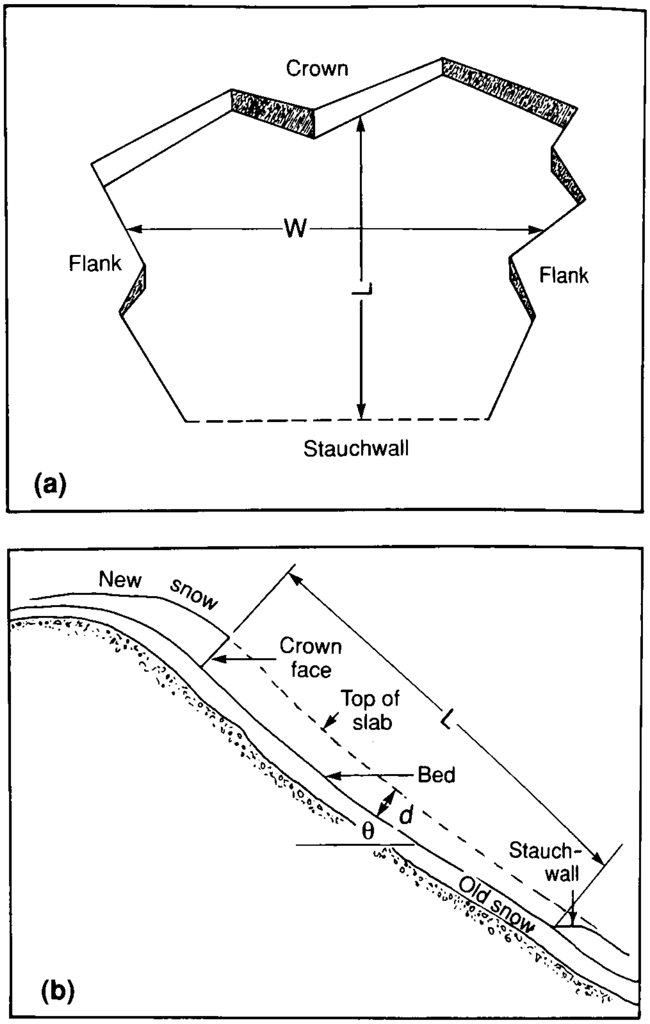


Figure 4. Terminology of a slab avalanche release, (a) plan view, and (b) elevation.

The slab thickness, *d*, measured perpendicular to the bed surface, depends on the storm and snowpack conditions expected in the region of interest over a long time period. Values of *d*, *averaged over the entire starting zone*, probably vary between 0.8 and 2.5 m during conditions producing the largest avalanches. Extreme, widespread avalanches are almost always associated with snowfalls of 1–3 m (sums of 24-hour new snow depths), sustained over a 3–5 day period. Compression of the new snow will typically reduce the depth of the new snow layer to 60–80 percent of the total new snowfall summed over 24-hour increments.

In cool, continental snow climates slab thickness usually exceeds new-snow thickness, because structural weaknesses in the old snow often form bed-surface shear failures well below the new snow/old snow boundary. The weight of new snow serves as the trigger that produces the shear failure, but release of the older snow increases the released slab volume. In warm, maritime snow climates, such as those associated with the Pacific Northwest, the Sierra Nevada, and Switzerland, the slab usually consists primarily of snow from the last big storm. In maritime areas slab thickness can be computed from the statistics of snowfall data (see page 29), given a sufficient data base, because the old snow tends to settle, compress, and strengthen quickly between storms and usually does not release with the avalanche, particularly during dry-slab conditions. Deep-slab releases can occur, however, in all climates when water is introduced into the snow as a result of thaw or rain.

The maximum thickness of a fracture at the crown will often be larger than the average slab thickness because thick deposits of wind-blown snow will accumulate at the crown. Slabs often are "wedge-shaped," tapering from a thick crown to a less thick stauchwall. Data obtained by observers on avalanche fracture thickness, are usually observations from the upper portion of the crown surface and thus are based on the thickest, most spectacular part of the fracture. If these observations are assumed to represent average thickness over an entire slab, potential release volumes will be greatly overestimated.

The released slab changes form immediately after fracture and release because part of the kinetic energy associated with the sliding and accelerating slab causes it to break apart into many blocks which tend to slide, roll, bound, and collide with one another and disaggregate. In this manner, the avalanche rapidly evolves from a sliding slab to a turbulent cascade of "flowing" snow blocks. This disaggregation process, (Figure 5), occurs rapidly when the initial slab consists of dry snow with low strength and density ("soft slabs"). However, within strong, high-density wind slabs, the released snow may break into fairly large blocks with individual members remaining larger than 1 m^3 even after a fall of 500 m or more.

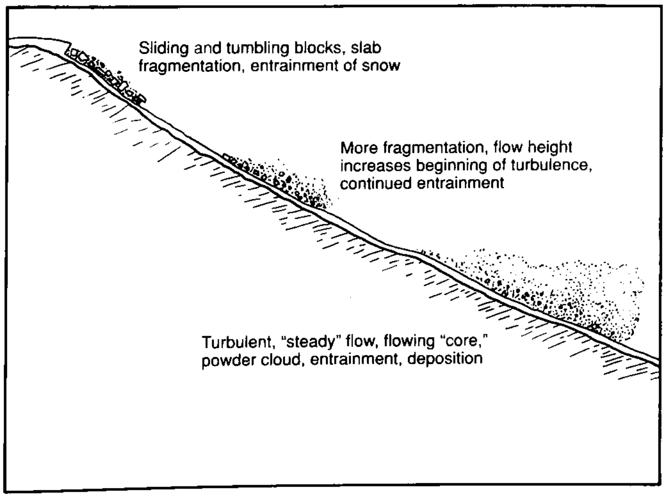


Figure 5. Disaggregation of a sliding slab into a mixed-motion dry-snow/powder avalanche flow.

Wet-slab releases, particularly those with high free-water content, also fracture and become pulverized as described for the dry slabs. However, because of higher densities (commonly >400 kg/m^3), and relatively low strengths due to the free water which reduces cohesive strength, the wet slabs can quickly form a high-density slurry similar to a well-lubricated debris flow.

Avalanche Motion

This section describes characteristics of avalanches in motion. Some understanding of avalanche motion and dynamics is important so that reasonable assumptions can be made about the interaction of avalanches with buildings and other facilities and so avalanche-defense structures can be rationally designed. Quantification of avalanche velocity, impact, and other characteristics important in design are discussed in Chapter 3.

Motion of Dry-Snow Avalanches

Dry-snow avalanches usually will constitute the design case which must be considered in land-use planning and engineering. These avalanches reach the highest velocities, often produce the largest impact pressures, and usually travel the longest distances in the runout zones. The following criteria are usually satisfied when dry avalanches constitute the design case.

1. The released snow is dry, of relatively uniform thickness, and was probably deposited with moderate winds during storms three to five days long.
2. The slabs consist of relatively low-density (< 200 kg/ m^3) snow which can easily be broken into small chunks during the initial stages of motion.
3. The avalanche tracks can be either channelized or unconfined.
4. Avalanche lengths, from the tops of the starting zones to the bottom of the runout zones, are greater than 500 m.

After dry-slab avalanche release (see page 7) and the disaggregation of slabs into a flow of fragments and finely pulverized snow grains, avalanche motion can be described as *sliding, flowing, airborne powder*, or *mixed*. If the avalanche path is extended and the motion continues, the original blocks comprising the slab break apart into progressively smaller particles. The larger blocks slide, roll, tumble, and collide with one another near the ground or on the old-snow surface as a turbulent flow of slab fragments. The smaller particles are suspended by the turbulence of the entrained air to form a powder cloud (Figure 6). This cloud may partially or completely obscure the lower cascade of slab fragments. Inspection of debris deposited by many large, dry-snow avalanches indicates that most of the avalanche mass consists of fragments too large to be suspended by air turbulence. Therefore, it is thought that most of the mass in large, mixed-motion avalanches is transported by granular flow within 5 m of the avalanche running surface in large avalanches and within 2 m in most avalanches. Assumptions about the thickness of the higher-density flow of slab fragments is very important in design of avalanche defenses and is discussed further in Chapter 3. In Switzerland, empirical equations have been developed through which flow height is estimated (see page 30). The vertical density distribution within an avalanche has not been measured, but probably varies, in large, dry-snow avalanches, from roughly 50 kg/m^3 to 200 kg/m^3 near the base to 5 to 10 kg/m^3 near the top of the powder cloud, (Figure 6).

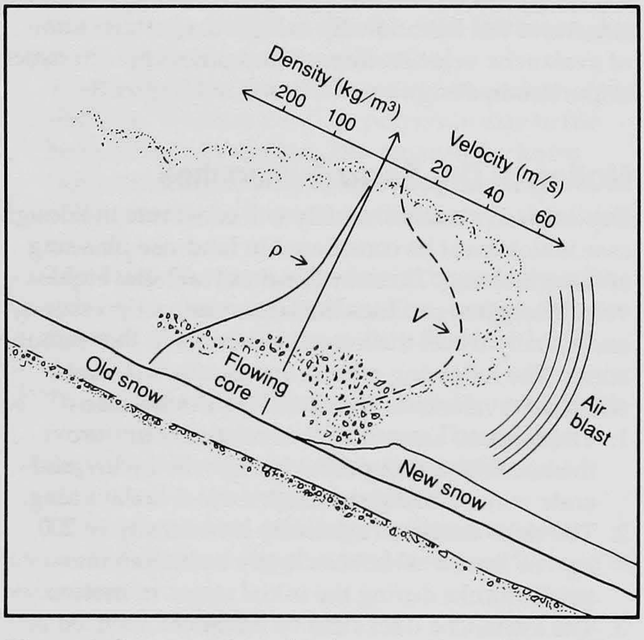


Figure 6. Cross section of a dry-snow/powder avalanche illustrating probable density and velocity distributions (after Perla and Martinelli, 1976).

When new snow has been deposited over much of the path, avalanches can increase in mass as they descend because new snow will be entrained into the avalanche. Although debris drops out continuously at the back, the avalanche will continue to flow down the track, possibly increasing in velocity, as long as new snow is available for entrainment. Based on debris observations in large avalanches, mass can increase (more snow is entrained than drops out) within starting zones on slopes steeper than 30°, mass remains approximately constant in the track between 15° and 30°, and flowing mass decreases in the runout zone on slopes of less than 15°. Small avalanches often stop in the track on much steeper slopes, but these smaller events are usually not important in planning or engineering. Figures 7 through 9 show the development of a large, dry-snow avalanche in Colorado.

Figure 7. Release of the Battleship avalanche. Approximately 150,000 m^2 (40 acres) of snow is released from three adjacent starting zones. (Photo by Tim Lane).

Although measurements of the mass or volume distribution in avalanches do not exist, many observations suggest that the greatest flow heights and probably the greatest concentration of mass occurs toward the front of the flow. The avalanche "hydrograph" at a given point on the path, therefore, probably rises quickly to a steep, initial peak, then decreases gradually as trailing snow follows the front at reduced velocity. The duration of large, dry-snow avalanches at a given point appears to be roughly 10–20 seconds, as suggested by pressure versus time data obtained from

Figure 8. Flow of the Battleship avalanche (upper track). The avalanche entrains new snow as it descends and reaches a maximum velocity of 60 m/s. (Photo by Tim Lane).

sensors mounted in avalanche paths (McClung and Schaerer, 1983; Gubler, 1987; Norem, 1988; Mears, unpublished). Impact pressure measurements obtained in dry-snow avalanches in Colorado (Mears, unpublished) indicate that the powder blast precedes the main mass of flowing snow, perhaps by one second or more.

Velocities of several large, dry-snow avalanches have been measured in Colorado, Canada, Norway, and Switzerland. Maximum velocities measured are approximately 65 m/s for large avalanches after they had descended at least 200–300 m vertically, (Gubler, 1987; Norem, 1988). Velocities did not systematically increase after the initial acceleration, even with continued vertical fall, suggesting a balance between the driving force of gravity and the various frictional resistances within and at the boundaries of the flow. Most of the velocity was attained in the starting zones or upper tracks, over no more than 20–30 percent of the total avalanche path length. Field evidence of buildings and vegetation destroyed in small avalanche paths suggest that relatively high velocity (perhaps >30 m/s) can be attained in dry-snow avalanches after falling only 150 m.

Table 1 provides rough guidelines about the maximum velocities that could be attained in dry-snow avalanches of various sizes. The velocity data presented are only estimates which are based on limited velocity data, destructive effects of avalanches, and avalanche-dynamics calculations.

Figure 9. Flow of the Battleship avalanche (Lower track). The high velocity caused the flow to superelevate on the right side of the channel. (Photo by Tim Lane).

Table 1. Typical dry-snow avalanche maximum velocity estimates.

Vertical Fall (m)	Velocity Range (m/s)
100–200	20–35
200–500	35–55
500–1000	55–70

The velocity estimates given in Table 1 assume dry-slab avalanche releases, a continuous new snow cover over the entire avalanche path, and smooth topography in the avalanche track. These will often be the "design" conditions to be considered in planning and engineering. Many exceptions certainly exist, and site-specific analysis is always required to determine design-avalanche velocity because this can be such an important design parameter.

Within the low-gradient runout zones, the slope-parallel component of gravity is reduced because of the gentle slopes, frictional forces at the avalanche boundaries exceed gravitational forces, and avalanches decelerate. Measurements of avalanche deceleration (Gubler, 1987; Norem, 1988), show that some dry-snow avalanches decelerate quickly toward the distal end of the runout zone. This may be due to an increase in avalanche density and the interlocking of fragments in the avalanche flow as the kinetic energy required for fragment separation is reduced (Mears, 1980; McClung, 1990). Observations of avalanches in motion indicate that the flowing motion of slab fragments does quickly evolve into sliding of reaggregated blocks as velocity decreases during the final seconds of flow. Observations of shear planes within debris near the end of the runout of large dry-snow avalanches often indicates that sliding of slab fragments and interlocked debris dominate the movement toward the end of the avalanche runout (Mears, 1980). Reports of victims caught in avalanches certainly confirms the fact that the flow interlocks even before the motion completely stops. This usually makes escape from avalanche debris impossible.

Because avalanches appear to decelerate quickly and debris sometimes interlocks during the final instants of motion, the flowing form that dominates at higher velocities may no longer be important near the end of the runout zone. These changes in state (from fluid motion to solid-block motion) are usually not explicitly considered in avalanche-dynamics models. McClung (1990), however, does consider the importance of frictional increase as a result of particle interlocking in avalanche-dynamics modeling. Quantification of this effect is discussed further in Chapter 3. Changes in avalanche form and material properties are important limitations in the use of avalanche-dynamics models for engineering design.

Avalanche runout distances of 1000 m or more are sometimes observed on slopes of 5–10° in the runout zone of large avalanche paths. The longest runout distances are usually associated with fast-moving dry flowing and powder avalanches. Well-developed dry avalanches will typically produce a long, wide sheet of avalanche debris which is thickest at the upper runout zone and thins, sometimes to a few centimeters, near the end of the runout zone. However, destructive potential from powder and air blast and light-flowing avalanche debris sometimes extends 100 m or more beyond the end of visible debris deposits and can produce destructive forces. Figures 10 and 11 illustrate the effects of dry-snow and powder avalanche impact in southcentral and southeast Alaska.

Figure 10. Effects of powder-avalanche blast at the "Van Slide," south central Alaska. Powder blast wrapped this unoccupied vehicle, which was parked approximately 10 m upslope, around a cottonwood tree. Flowing-avalanche debris did not reach the tree, however vegetation damage occurred over 100 m downslope.

Motion of Wet-Snow Avalanches

Large wet-snow avalanches may constitute the design case and may be largest and travel the longest distances when the following conditions are satisfied.

1. Thick layers of snow are released simultaneously from the starting zone as a wet slab.
2. The avalanche track offers at least some degree of channelization and contains water-saturated snow that can easily be entrained.
3. The runout zone is located on an alluvial fan with an average gradient of 8–12°.
4. The overall avalanche path length is usually less than 500 m, although important exceptions do exist.

As wet-snow avalanches descend, the energy of avalanche motion reworks the snow into a mixture of

Figure 11. The extensive damage to this subdivision in Juneau, Alaska, was caused by a dry-snow/powder avalanche. The energy of the fast-moving, low-density flow and entrained debris produced the damage. Thick, dense deposits of avalanche debris did not overrun the site.

wet snow, water, wet-slab fragments, and entrained solid debris. Sometimes soil, rock, and other solid debris may be scraped from the ground into the snow and transported downslope. Estimated typical velocities for large wet-snow avalanches are listed in Table 2. These velocities are not based on extensive field data; however the few measurements that do exist indicate velocities substantially less than those associated with dry-snow avalanches.

Table 2. Estimated velocities for wet-snow avalanches.

Vertical Fall (m)	Velocity Range (m/s)
100–200	10–20
200–500	15–30
500–1000	20–35

In spite of lesser velocities, wet-snow avalanches can advance for long distances over slopes of 8–12°, (Figure 12), particularly if the flow is laterally bounded by topographic features that channelize the flow. Long runout distances at small velocities are possible on such slopes because the sliding friction coefficient of wet snow on snow will be similar to the tangent of the runout-zone slope. Reduced frictional resistance probably occurs because wet-snow avalanches lubricate the sliding surface by shearing off the lower portion of the wet-flowing snow to provide a smooth sliding surface or by advancing over wet snow already in the runout zone. Occasionally, wet-snow avalanches have advanced at walking speed for more than 100 m, allowing time for valuable objects to be removed from the path before the avalanche arrived (LaChapelle, pers, comm.; Williams, 1975).

Despite relatively low velocities, wet-snow avalanches can be very destructive. The density of the moving snow will usually be 400–500 kg/m^3 throughout the depth of the flow in large events. When large, wet-snow avalanches develop, the flow thickness may be 5–10 m, particularly where deep avalanches discharge from a channel onto an alluvial fan. Such

Figure 12. Runout of a large, wet-snow avalanche onto a populated alluvial fan in Switzerland. Debris advanced for long distances as sliding, reaggreated blocks of wet snow. Photograph was taken by the Swiss Army, and supplied by the Swiss Federal Institute for Snow and Avalanche Research.

thicknesses and large flow densities tend to crush and entrain debris, including surface vegetation, soil, and rock. Buildings have been removed from their foundations and the frames pushed for long distances over low-gradient terrain. Design for depositional static loads becomes an important consideration when such avalanches are possible.

Although dry, rather than wet-snow avalanches usually travel the longest distances and cover the largest areas in the runout zone, there appear to be some notable exceptions to this rule. For example, a major, warm, mid-winter storm in 1986 produced large amounts of wet snow and even rain below the 2,500 m elevation level in the Sierra Nevada of California and in Utah. Inspection of avalanche deposits and observed damage from these events suggest that extraordinary wet-snow avalanches advanced into forests that had not been reached by any avalanches (dry or wet) for 100–200 years. Runout distances as long as 1,400 m on 5° slopes were observed, substantially exceeding forest destruction from any previous avalanches.

Dry-slab release at higher elevations, producing an initial dry-flowing and powder avalanche, sometimes encounters wet snow at lower elevations. The entrained wet snow tends to increase avalanche density and flow depth while decreasing velocity and potential runout distance. The powder-avalanche component, if well developed, may be unaffected by the entrained wet snow, thus may extend well beyond the limit of thick avalanche deposits at high velocity (Figure 11).

Mathematical modeling of avalanche dynamics, usually assume the frictional resistances, R, to gravitational acceleration can be expressed

$$R = A + BV + CV^2, \qquad (2.2)$$

where A is a constant dynamic friction term, B is a *viscosity* coefficient, C is a *turbulence* coefficient and V is velocity. Because avalanches are complex and tend to change in form from release to deposition, the coefficients A, B, and C are not known and do not apply in all cases; consequently they must be estimated in dynamics-modeling attempts.

Avalanche Impact

As discussed on page 9, avalanches are likely to be highly variable in terms of internal material properties, sizes, and velocities. Avalanches range from wet, dense and slow moving to dry, low-density, high-velocity turbulent flows. Because avalanche impact partly depends on material properties and velocity, the magnitudes and characteristics of impact loading are also highly variable. In general, the magnitude of avalanche impact pressure, P_i, depends on the flow velocity, V, and the mass, m, per unit of volume, k, (m/k = flow density, ρ). The general relationship between these variables is written

$$P_i = 0.5\,(m/k)\,V^2 = 0.5\,(\rho)\,V^2. \qquad (2.3)$$

The *average* impact pressure over a surface, therefore, is equal to the kinetic energy, ($0.5\,mV^2$), per unit of avalanche volume, the "energy density," as expressed in equation (2.3). However, the design impact pressure on a structure will usually be dependent on many other factors not included in equation (2.3) including structure size, shape, orientation, and flexibility as well as avalanche characteristics. Therefore, the actual design pressure may vary by a factor of three or more from the amount calculated in equation (2.3) and must always be carefully considered in site-specific design. A more complete discussion of design for avalanche impact is in Chapter 5.

Even moderate-sized avalanches can produce large impact loads. Assuming a typical velocity of 30 m/s (Table 1), and a flow density of 100 kg/m^3, yields P_i = 45,000 Pa = 45 kPa = 940 lbs/ft^2. This is approximately 10 to 20 times the usual lateral loading capacity of wood frame buildings. Table 3 provides rough estimates of the impact pressure ranges required to produce certain types of damage

Table 3. Impact pressures related to damage

Impact pressure (kPa; lbs/ft²)	Potential Damage
2–4; 40–80	Break windows
3–6; 60–100	Push in doors, damage walls, roofs
10; 200	Severely damage wood frame structures
20–30; 400–600	Destroy wood-frame strutures, break trees
50–100; 1000–2000	Destroy mature forests
>300; >6000	Move large boulders

From the viewpoint of engineering design, avalanche impact almost always represents an extremely large external load. Furthermore, the largest potential loads are usually laterally oriented against flat surfaces of structures normal to the flow direction. This is the most difficult direction to reinforce buildings and other structures. Large vertical shear and fluid-dynamic lift forces may also result when structures are overrun by fast-moving avalanches.

Avalanche impact forces should be separated into two components: *(1)* impact of flowing or sliding debris, and *(2)* turbulent, fluid-dynamic powder blast. Flowing debris impact represents the largest potential loads. These large loads will usually be concentrated within the lower portion of dry-flowing avalanches, where densities may range from 50–200 kg/m³. Density probably decreases quickly with height above the avalanche running surface (Figure 6), but in turbulent, high-velocity flow, a distinct upper surface is difficult to define because fragments of the released slab will be thrown upward above the "mean" surface of flowing debris. Most of the flowing debris will be concentrated within the lower 5 m, even in most large, fast-moving avalanches. Damage to vegetation and direct observations suggest that flow depths for small-to-moderate sized dry avalanches are 1–2 m. Greater depths will occur when the flow is concentrated in well-defined channels. Wet-snow avalanches, because of much lesser velocities, probably maintain a nearly constant density of 400–500 kg/m³ throughout the entire flow depth, which may reach 5–10 m in large avalanches that have discharged from channels. Table 4 provides a summary of avalanche flow heights and densities in unconfined avalanches.

The turbulent powder blast may extend upward to as high as 40 m in large dry-snow avalanches, but

Table 4. Avalanche flow heights and densities.*

Avalanche Type	Size	Typical Flow Ht. (m)	Typical Densities (kg/m²)
Dry Snow	Small	0.5–1.0	50–200
Dry Snow	Medium	1.0–2.0	50–200
Dry Snow	Large	2.0–5.0	50–200
Wet Snow	Small	0.5–1.0	350–450
Wet Snow	Medium	1.0–2.0	350–500
Wet Snow	Large	2.0–10.0	400–500

* Flow heights do not include powder blast, which may extend to 40 m above debris height. Flow heights will be increased in channels.

flow densities will probably be less than 10 kg/m³ within the powder cloud (about 8–10 times air density). Because of their great flow depths, powder avalanches envelop and engulf buildings and other objects like a true fluid, subjecting them to fluid-dynamic drag and uplift forces similar to a tornado-force wind. The average powder-blast drag force, F_D, and lift force F_L, depend on the avalanche energy density (energy per unit of volume) in the powder cloud [equation (2.3)], the cross-sectional area, A, exposed to the avalanche, a coefficient of drag, C_D, or a coefficient of lift, C_L. Drag and lift forces from powder avalanches, therefore are computed

$$F_D = C_i A \,(0.5)\, \rho\, V^2, \text{ and} \tag{2.4}$$

$$F_L = C_L A \,(0.5)\, \rho\, V^2. \tag{2.5}$$

In powder avalanches the drag and lift coefficients must be determined from standard fluid-dynamics tables, assuming a high Reynolds Number in fully-developed turbulent avalanche flow.

The relationships between impact pressure, flow density, and velocity discussed in this section assumes the avalanche behaves as a fluid at the point of impact with a structure. This fluid assumption is probably valid if the following two conditions are true:

1. The avalanche is not composed of solid, sliding blocks, which, as discussed above, often appears to be a characteristic of avalanche movement in the initial and final stages of movement; and
2. The fragments comprising the avalanche flow are small with respect to the impact surface.

If assumption 1 is not valid, impact could be substantially larger than predicted by equation (2.3), because the impact surface may absorb all the momentum of a sliding debris block several meters long. This possibility must be considered for structures located near the end of the runout zone. If assumption 2 is not true, for example, as when an avalanche comprised of large chunks from a hard, wind-deposited slab impacts a small surface, then the magnitude of the impact may also be much larger than the mean value estimated by equation (2.3).

A few measurements of full-scale avalanche impact have been obtained during the past decade. The most complete set of measurements have been taken at the Ryggfonn Avalanche, in Western Norway as reported by Norem et. al. in a series of annual reports (Norem et al. 1985; Norem et al. 1986a; Norem et al. 1986b; Norem et al. 1987; Norem et al. 1988; Norem et al. 1989; Norem et al. 1991). The Ryggfonn avalanche falls nearly 900 m to envelop various types of pressure sensors that record the magnitude and duration of avalanche pressures. At the top of the runout zone, avalanche impact is measured on three rectangular steel plates, each 0.6 m × 1.2 m which are anchored to a massive concrete structure. In addition, the tension strain induced by powder-avalanches is measured on three steel cables that span the avalanche at 8 m, 12 m, and 16 m above the ground surface. The experiment is designed, therefore to measure forces associated with the flowing snow and the powder blast. Velocity measure-ments at the avalanche front are also obtained by remote camera when avalanches can be released artificially.

The largest impact-pressure recorded at the Ryggfonn Avalanche have resulted from large, dry-snow avalanches. These avalanches produced peak pressures of 390–540 kPa (8,150–11,300 lbs/ft^2). Average pressures over 10–20 seconds duration were approximately 30–50 percent of the pressure peaks. Avalanche velocities were in the range of 30–60 m/s. Pressures on the impact plate rose from zero to peak values in less than 0.5 seconds. Tension stresses induced by powder avalanches in the three steel cables decreased quickly with height above the ground. Tensions in the upper cable were typically 10–30 percent of those measured on the lower cable, indicating that powder-avalanche pressures decreased quickly over the range of 8 m to 16 m above the ground, presumably because flow density and possibly velocity also decreased with height. The largest avalanche occurred on April 1, 1990, and consisted of approximately 470,000 m^3 deposit volume, approximately four to five times larger than any observed during the previous 20 years. Electrical power was interrupted therefore data on avalanche duration and pressure distribution was not obtained. Furthermore, many pressure sensors were destroyed. Calculations suggest peak pressures of up to 3,200 kPa (66,900 lbs/ft), however this pressure probably resulted from impact of a large rock carried in the avalanche, not from snow alone.

Similar avalanche-impact results have been obtained from external pressure sensors mounted on an avalanche shed in southwestern Colorado by the Colorado Highway Department. Pressures recorded on 0.093 m^2 (1 ft^2) pressure plates mounted normal to the flow direction have been in the range 95–148 kPa (2000–3100 lbs /ft^2), whereas pressures perpendicular to the avalanche flow and normal to the shed roof have been 4.5–17.0 kPa (90–355 lbs/ft^2). These were dry-snow/powder avalanches but were much smaller than those measured in Norway. The Colorado measurements also indicate that the powder blast reached the pressure sensors approximately 0.5–2.0 seconds before the flowing debris. This indicated that powder blast was moving at greater velocities than the flowing snow over the terrain above the pressure sensors which exceeded 30° inclination.

Characteristics of flowing-snow and avalanche-impact pressures are also reported by McClung and Schaerer (1985). They measured pressures from many avalanches on a circular aluminum plate 0.20 m^2 in area and measured impact frequency on 645 mm^2 pressure cells mounted 0.45 and 0.70 m above the ground. They found that avalanche density, interpreted through frequency of collisions with the cells, decreased with height and that impact pressure was proportional to V^2 [as indicated in equation(2.3)]. Distinct pressure peaks occurred throughout a single event as a result of collisions of snow blocks with the pressure plate. These peaks were approximately two to five times larger than the average pressure.

In summary, the following tentative conclusions can be drawn from the limited data on avalanche loads.

1. Peak pressures on exposed surfaces are reached within one second or less, suggesting avalanche loads must be treated as impact loads in design.
2. Many distinct, short-duration, pressure peaks occur in a single avalanche event, but the average pressure is less than 50 percent of the peaks.
3. Avalanches sometimes produce several waves or groups of pressure peaks within a single avalanche.

Because, as stated above, avalanches tend to be complex phenomena, it is difficult to calculate the loads with a high degree of precision. Therefore, safety factors used in design should be similar to those normally applied to other engineering works which are intended to protect against natural phenomena. When failure is unacceptable because human life is endangered or valuable facilities are exposed safety factors must be chosen accordingly.

Chapter 3

The Design Avalanche— Methods of Determination

Definition and Avalanche Design Periods

The design avalanche is of a *magnitude* (size or destructive potential) that must be considered in land-use planning or design of facilities. Design-avalanche magnitude must be related to some design period, or avalanche return period in order to specify a magnitude-probability relationship for design, planning, and risk analysis. The appropriate design period depends on the proposed land use, exposure of persons, cost of the facility, or risk tolerance.

Table 5 gives some examples of design periods appropriate for various types of land uses.

Table 5. Design periods associated with land uses.

Land-Use Type/Description	Avalanche Design Period (yrs)
Highways and railroads*	< 1
Ski trails*	< 1
Transmission lines	1–10
Telephone lines	1–10
Oil, gas lines	10–50
Parking areas	10–50
Ski-lift terminal areas*	10–50
Highway and railroad structures	50
Residential development, houses	100
Restaurants, schools, hospitals	100–300

* Avalanche control through closure and artificial release is usually used to reduce the risk in these areas.

The range in return periods shown in Table 5 is more than two orders of magnitude. This wide variation in acceptable return periods depends on cost and risk tolerance. Highways, railroads, and ski trails sometimes are built through areas subject to annual (or more frequent than annual) avalanche return periods because the risk is intermittent rather than continuous, valuable structures are not exposed, and areas can be closed during high-risk periods. These factors all reduce the *encounter probability* of persons to avalanches. Public facilities and residential development both lie near the opposite end of the risk-tolerance spectrum. Such land use tends to concentrate human activity, even during the severe conditions likely to produce unusual avalanches, therefore the encounter probability may be high even though avalanche return periods are long. Restaurants, schools, and other buildings and structures cannot be moved, therefore, unlike vehicles or skiers, they will be exposed when avalanches are likely. The acceptable return period for residential development or public facilities, therefore, tends to be long.

Planning and engineering design for avalanches must follow procedures similar to those used in design for similar geophysical processes such as floods, weather events, landslides, earthquakes, etc. Therefore, proper design for avalanches requires defining the "magnitude-probability" relationship, understanding the consequences of improper land use, and understanding the appropriateness and limitations of avalanche mitigation procedures.

Avalanche Magnitude–Probability and Encounter Probability

Design-avalanche magnitude can be defined in several ways which depend upon various definitions of design *failure*. In general terms, a design is said to fail if it does not meet performance standards or expectations. For example, the layout of a residential development can be said to *fail* if a portion of the development is reached by the distal tip of the design 100-year avalanche runout. This could endanger residents, cause property damage, or decrease the value of the investment. In this case, the runout distance or lateral extent of the avalanche is the design standard and is used in avalanche zoning (Chapter 4).

A structure (e.g., bridge, avalanche shed, building, tunnel portal structure, etc.), in an avalanche path fails if avalanche depositional and/or impact loads exceed the design standards and structural collapse occurs. In a given path, the avalanche that produces the longest runout distance is usually a dry-flowing/powder avalanche but this may not produce the largest depositional loads at a given point in the path. Therefore, the magnitude-probability relationship may be different for runout distance than for loading potential because of various possible definitions of magnitude and specific design needs.

Avalanches are often compared to other geophysical processes such as windstorms and floods because probabilities are sometimes associated with events of various magnitudes. The processes are analogous because the avalanches (or floods) of one year are statistically independent of all past events, however, unlike floods, avalanche probability is not necessarily related to the probability of major storms. When a severe rainstorm or snowmelt event occurs in a certain area, then all or most of the streams will experience large discharges and possible flooding. The volume of snowmelt or rain entering the drainage network can be closely correlated to the amount of runoff measured in streams discharging from the same system. Therefore, meteorological predictions of the 100-year storm are often used to predict the size of the 100-year flood.

In contrast, avalanches result from some unique combination of weather *and* snowpack conditions. The joint probability of this combination has never been defined statistically and related to avalanche activity. Major avalanches may result from a major widespread storm of high precipitation intensity or may result from localized wind redistribution of snow into a particular starting zone. The strong wind-loading episodes occur far more often than the 100-year snowstorm, but wind events affect more localized areas and consequently affect only a few isolated starting zones.

Extreme avalanche events with return periods of 100 years or more appear to occur in isolated locations throughout each mountain range at least every few years, probably because of the localized effects discussed above. The fact that these are long-return-period events can be documented by observations of forest damage in the avalanche runout zone. When many trees 50 to 200 years old are destroyed by an avalanche, this damage provides convincing evidence that the avalanche had roughly a 100-year return period. Although heavy snowstorms will certainly produce many large avalanches, only a small percentage of all the paths within the storm boundaries will produce big avalanches. An example of the results of such a major storm occurred during the period February 12–22, 1986 through the Sierra Nevada, Utah, and the central Rocky Mountains of Colorado. During a 8–10 day period, this storm deposited 2.5–4.0m of new snow containing 0.3–0.6m of water equivalent at many mountain locations, and was one of the largest storms of the 20th century. However, even within the mountain areas receiving the full force of this storm, less than 40 percent of the avalanche paths produced avalanches and less than 10 percent produced anything approaching the 100-year avalanche. Wind direction and starting-zone topography strongly controlled the location and magnitude of avalanche activity.

Some paths produce large avalanches every few years whereas others may produce major events at intervals of decades or centuries. At mountain areas that receive frequent, large storms, (e.g., Alta, Utah) the 10-year and the 100-year avalanche in a particular path may be similar in size. In contrast, the 100-year avalanche in some generally low snowfall areas may be many times larger than the 10-year avalanche, (Figures 1 and 2). The historical record or damage to vegetation provides good evidence of avalanche potential in the heavy-snowfall locations, while the low-snowfall locations require extensive applications of indirect techniques to determine the size of the long-return-period event. Fitzharris (1981),in a study of major avalanche magnitude and frequency near Rogers Pass, British Columbia, found that 30-year return-period avalanches contained only approximately 10 percent of the mass of the maximum possible avalanche.

Although avalanche magnitude cannot be correlated with design-storm frequency, return period, and encounter probability concepts can be applied and are useful for planning purposes.

Return period, T, is reciprocally related to annual probability, P as

$$T = 1/P. \tag{3.1}$$

Therefore, a 50-year return-period event has a constant annual probability of 0.02. This probability is constant regardless of previous avalanche activity in a given path. This relationship between T and P can be used to calculate the annual cost of mitigation or to calculate risk. Furthermore, ***encounter probability***, E, quantifies the chance that an avalanche with a return period T years will occur during some time period, L years. The relationship between E, T, and L is expressed

$$E = 1 - (1 - 1/T)^L, \tag{3.2}$$

(LaChapelle, 1966). Table 6 provides solutions for equation (3.2) given various return periods, T, and observations periods, L.

Table 6. Avalanche encounter probabilities.

T (years)	L (years)	E
10	10	0.65
10	30	0.96
10	50	0.99
30	10	0.29
30	30	0.64
30	50	0.82
30	100	0.97
100	30	0.26
100	50	0.39
100	100	0.63
100	200	0.87
100	300	0.95

Table 6 shows, for example, that a 100-year avalanche has a 0.39 chance of occurring in a 50 year period, or a 1– 0.39 = 0.61 chance of not occurring in 50 years. equations (3.1) and (3.2), and Table 6 illustrate why long return period avalanches, which are often the design events for land-use planning and engineering, have not been observed at most North American locations. This is often true simply because the continuous observation periods are short (10–30 years), at many sites. Indirect methods usually must be used to determine the design avalanche size, energy, and destructive effects simply because the relatively short observation periods have not included extreme events of primary interest in planning and design.

Identification of Design-Avalanche Terrain

Direct Observations and History

Observations or photographs of previous avalanches is the most reliable method for determining the area affected by design avalanches. This obviously requires knowledge that the observed event was the design avalanche, not some smaller avalanche. When direct observations are available, they may provide important information about past avalanche boundaries, debris depths, and avalanche destruction, all of which are important in planning and design of facilities. However, as equations (3.1) and (3.2) indicate, the probability of observing extreme avalanches is small unless the observation period is long.

Reports that avalanches have *not* occurred in some avalanche path usually cannot be depended upon to discount the possibility that they *could* occur unless the following criteria are known to be satisfied.

a. The observation period must be at least *twice* as long as the design period, ($L > 2T$). Such a long observation period is necessary in order to be approximately 90 percent confident that the design avalanche will not occur [equation (3.2) and Table 6].

b. The observation period must be continuous and specify for certain that avalanches, including low-density powder avalanches, did not reach a certain area during all the severe weather and snowpack conditions that have occurred during the observation period. Observations within an area, even after a major winter storm, can overlook the effects of powder avalanches because they do not form a conspicuous snow deposit.

Unfortunately, criteria a and b are rarely satisfied in North American locations. Even avalanche paths near developed areas rarely have had good, continuous, long-term observations. These observational limitations therefore require supplementary information to be collected including *(1)* searches of newspapers and other historical information, *(2)* study of vegetation indicators, *(3)* topographic-map analysis, and *(4)* study of aerial photographs.

Written History, Newspapers, Museum Records

Personal accounts of avalanche history can often be extended through study of written documents. Many mountain areas have a fairly long mining or railroad history, sometimes extending back to the 1860s, even in remote mountain locations.

Two good sources for written history in a region are local museums and old newspaper records. Researching and evaluating such documents requires special skills and can be very time consuming because, if an extensive search is done, much information not related to avalanches will have to be sorted through. Occasionally, however, specific information may be obtained about avalanche runout distances and destructive effects. Historical records which are accompanied by photographs are particularly useful because they may show forest or topographic features, roads, or buildings with respect to avalanche boundaries and current features.

Unfortunately, written history usually is not comprehensive over the entire area of interest because it will concentrate on locations where avalanches have reached or damaged facilities or where people have been caught or killed. Major avalanches that may haveoccurred just beyond the limits of past activity are usually unreported, even though such areas may now be of interest in design or planning.

Vegetative Indicators of Avalanche Size and Frequency

Snow avalanches usually produce some changes or damage to forests and other vegetation. This damage is best observed during the snow-free period when any damaged vegetation, including broken trees on the ground surface, is not obscured by the snowpack. However, not all avalanches damage vegetation because some run on top of a deep protective snowpack which prevents disturbance to small trees and shrubs. This protective snow layer is likely to vary in thickness from approximately 1 to 3 m, depending on the time of year, elevation and the snow climate of the region. The larger avalanches will usually break branches at least several meters above the snowpack surface. General vegetative and terrain indicators of avalanche activity are discussed and illustrated in detail by Martinelli, (1974).

Avalanche paths in forested areas usually appear as strips oriented directly down the slope which are characterized by a different type or age of the dominant vegetation or tree type. These vertical swaths through the trees are conspicuous when the change is from coniferous to deciduous forest, or from forested to non-forested slopes (Figure 13), and may still be obvious when the avalanche path contains younger trees of the same species, (Figure 14). The plant species in an avalanche path can be used to infer the size and frequency of avalanching. Avalanche paths with return periods of 1 to 10 years probably have no trees or few large trees and the trees that do exist will be damaged by avalanche impact. Deciduous trees, or small conifers are characteristically present on paths with return periods of 10 to 30 years. If the avalanche has a return period of 30 to 100 years, the path will often support uniformly-aged trees of the same species as those growing in adjacent forests with similar elevation, exposure, and soil conditions. When the avalanche path has a return period of 100 to 300 years, the path boundaries probably will not be discernible by casual inspection of the forest, therefore statistical studies of tree ages may be required to determine avalanche boundaries.

Figure 13. The starting zone and lateral boundaries of this avalanche path are clearly outlined by a bowl shaped snow accumulation area that serves as the starting zone and a track through a mature forest. Lack of trees in the track suggests a return period of less than 10 years for full-width avalanches.

In addition to avalanche width, the flow heights and runout distances of avalanches can sometimes be estimated from vegetation damage. Flow heights can be deduced simply from the heights of tree branch breakage and scars on the uphill sides of trunks, (Figure 14). Flow heights estimated in this way will usually vary considerably (sometimes by a factor of two), over the width of the path, in response to terrain roughness, turbulent fluctuations in the avalanche surface position, and debris impact. The upper limit of vegetation damage may be more than 10 m above the ground surface in large avalanche paths, however, upper damage is often caused by powder blast or impact of solid debris entrained into the flow, not denser flowing snow. Occasionally, very deep, wet snow avalanches have broken tree limbs as much as 10 m above the ground without pushing over trees, but usually large wet avalanches uproot trees and destroy forests. Within the runout zone, where avalanches decelerate and stop, a thick jumble of debris is often deposited, particularly at locations where the ground surface slope flattens abruptly and causes large energy losses and avalanche deposition. Trees in the lower track and runout zone where velocity decreases are usually aligned parallel to the avalanche flow direction. If undisturbed by subsequent activity, this debris will usually be obvious for several decades, depending upon the local climate and the rate of vegetation decomposition.

Table 7. Vegetation as an avalanche-frequency indicator.

Return Period (yrs)	Vegetation Indicators
1–10	Track supports grasses, shrubs, flexible trees up to 2 m high; broken timber on ground and at path boundaries
10–30	Predominantly pioneer species; young trees similar to adjacent forest; broken timber on ground at path boundaries
30–100	Old uniform-aged trees of pioneer species; young trees of local climax species; old and partially decomposed debris
100–300	Mature, uniform-aged trees of local climax species; debris completely decomposed; increment core data required

In some cases, avalanches run down slopes with only scattered trees (Figure 15). Suspected areas should be checked for signs such as broken limbs and trunk scars and debris aligned parallel to flow direction. Low-density, dry-snow or powder avalanches can flow through open, dispersed forests, but may contain energy sufficient to damage structures such as buildings with large, exposed surface areas.

Extracting and analyzing increment bores from trees is an excellent method for estimating avalanche frequency, particularly at locations of long return-period avalanching. Tree ages sampled within suspected boundaries of avalanche paths through use of increment bores can be compared with those outside the boundaries to determine if statistically significant differences in forest ages exist. In this way the return periods for various avalanche widths and runout distances may be quantified. Detailed procedures are described by Burrows and Burrows (1976).

Variations in tree sizes and species distribution, however, may result from soil and groundwater conditions, fires, landslides, or many other factors completely unrelated to avalanches. Therefore, prior to application of these techniques it must be determined that the area investigated is a potential avalanche path, based on the terrain criteria discussed in Chapter 2.

Figure 14. Scars and broken branches on this tree are typical of damage from fast-moving, dry-snow avalanches. The height of broken branches provide one estimate of the avalanche flow height. Powder blast probably exceeds the height of limb damage.

Analysis of Aerial Photographs

Study and interpretation of vertical, stereo photographs is an excellent method to delineate the boundaries of avalanches. This method is particularly useful when the photos are used in conjunction with reliable topographic maps.

Low-altitude aerial photographs taken by the U.S. Forest Service are best for avalanche-path identification.

Figure 15. Small avalanches flow through the trees at this location. Large avalanches will remove some trees and reach beyond the forest boundary with return period of approximately 30 years.

These photos are taken over most mountainous regions of the western states at approximately 10–15 year intervals. In most National Forest districts, aerial photography began in the 1930s or 1940s. Forest Service photography obtained during the past 25 years usually has an approximate scale of 1:15000 to 1:25000 a scale that varies from valley bottom to ridgetop. The more recent photos are usually color; the older photography is black-and-white. Because the photography is often intended for various types of timber surveys, the resolution is very good; individual trees, large rocks, streams, trails, old roads, and small man-made features are visible. When viewed in stereo, the sizes, heights, and consequently the relative ages of trees can be seen on the photos. Boundaries between tree species can be seen. These observations may enable estimates of old avalanche extents which may be delineated by tree sizes and species changes.

Aerial photos, when viewed in stereo, can easily establish relationships between avalanche starting zones, tracks, and runout zones. They usually provide a much better perspective than observations from the valley floor. When combined with U.S. Geological Survey topographic maps, (usually at a scale of 1:24000 with 40-foot contour intervals), avalanche boundaries can be accurately mapped, particularly when the same small-scale features such as stream and road intersections, bedrock outcrops, and forest boundaries appear on both maps and photos.

Because aerial photos a half-century old may be available at some locations, a useful time perspective of avalanche activity can sometimes be obtained. The aerial photographs in Figures 16 and 17 can be compared to estimate the time a large avalanche occurred above what was later to become a portion of the Town of Vail, Colorado. The first photo (Figure 16), was taken in 1950, prior to a large avalanche that fell over a cliff sometime between 1950 and 1962. The second photo (Figure 17) was taken after an avalanche destroyed trees in the runout zone.

Although aerial photos are an invaluable tool for delineating avalanche areas and should always be used when available, several important limitations to their use must be kept in mind. These limitations will always require a careful field inspection of suspected avalanche areas.

a. Available aerial photos can extend the history of an area for several decades at most, a time period which may be less than the design period [equation (3.2), Table 6].
b. Some potential avalanche areas may not have produced a major event for over a century, therefore path boundaries may not appear on photos.
c. Dry-snow and/or powder avalanches may extend into the forest and produce scattered damage that will not appear on photos.
d. Avalanche damage that extends below the lower boundary of forests usually will not appear on aerial photographs unless large tree trunks and other debris have been deposited by avalanches into the lower, non-forested areas.
e. Some distinct forest boundaries may have been caused by fire, logging, other natural or man-made disturbance, soil, bedrock, or exposure changes.

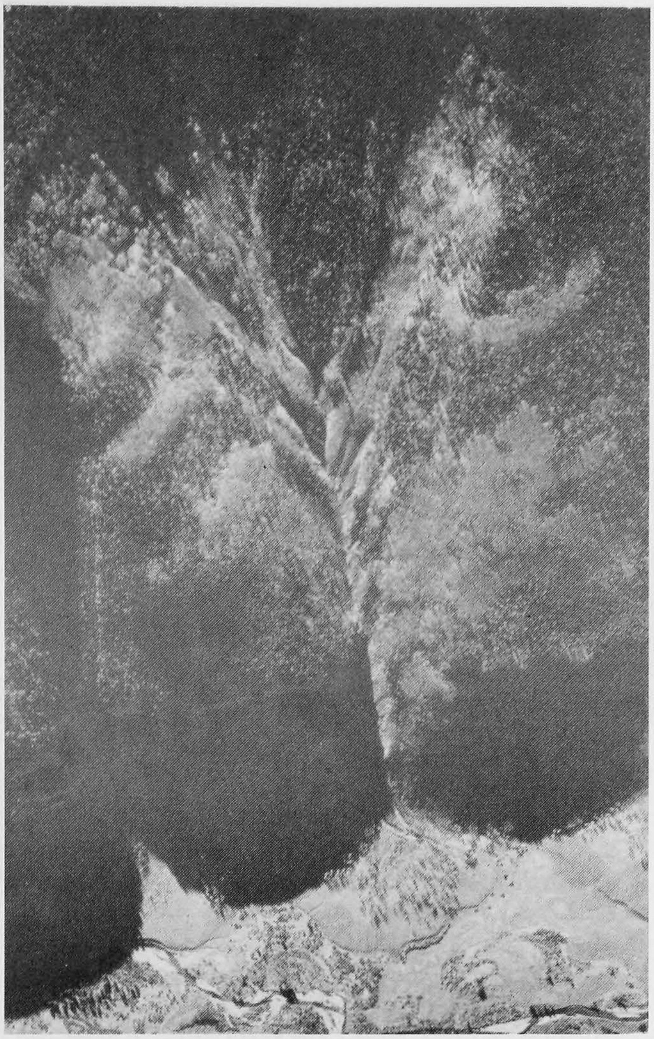


Figure 16. This 1950 aerial photograph of terrain above a part of the future site of a Vail, Colorado subdivision shows an obvious starting zone and track, but no recent activity in the runout zone. Also see Figure 17.

Figure 17. This 1962 aerial photograph indicates a recent avalanche (between 1950 and 1962) reached the runout zone. Also see Figure 16.

Calculation of Avalanche Runout Distance and Velocity

Need for Application of Indirect Methods

Many slopes with potential avalanche terrain lack a long history and show no sign of previous avalanche activity through study of vegetative indicators or aerial photos. Figure 18 is a view of the Warm Springs area of Ketchum, Idaho. This residential area is clearly located directly below potential avalanche terrain. This region does not receive regular heavy winter storms and the developed area has not supported a forest in historic time. The history during the past few decades has proven that large, design avalanches are infrequent, but no forest or geomorphic indicators exist in the runout zone through which past avalanche extents or frequencies can be deduced. Many other mountain areas have clear avalanche starting zones and tracks, but no direct evidence of avalanches in the runout zones. The lack of observational, historic, geomorphic, or vegetative records requires application of indirect methods for computing the runout distance.

Two types of methods for computing avalanche runout distance are available and are used in North America and Europe: *(1)* statistical models, and *(2)* physical (avalanche-dynamics) models.

Statistical Avalanche Runout Models

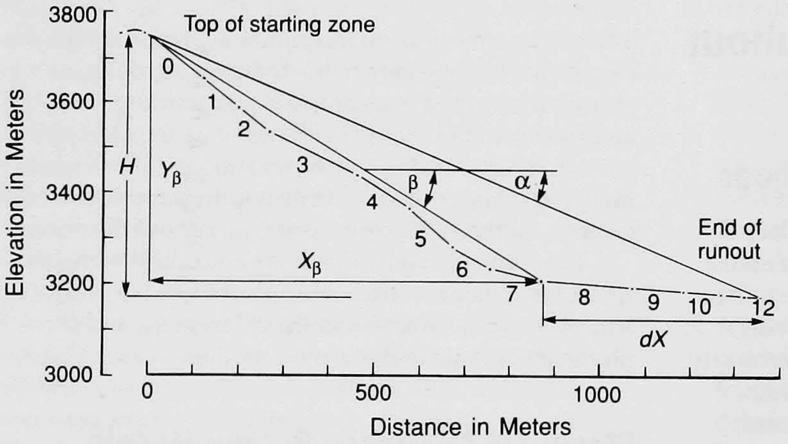
Study of avalanche terrain with known extreme runout distances in western Norway found high correlations between the angles α and β (Figure 19)

Figure 18. Potential avalanche starting zones, (steeper than 30°), steep tracks, and flat runout zones offer no vegetative clues of avalanche activity even though the terrain is highly suggestive of avalanches.

which characterize average steepness in the upper avalanche path and entire path respectively. These high correlations led scientists at the Norwegian Geotechnical Institute (NGI) to derive the "NGI-method" for predicting avalanche runout distance, (Leid and Bakkehoi 1980, Bakkehoi et. al. 1983, Leid and Toppe 1988).

The earlier NGI work studied more than 200 cases of extreme avalanche runout from the Western Fiords region of Norway. Many of the areas studied have settlement histories 100 to 300 years long with accurate historical documentation of extreme avalanche runoutsthat have occurred during that time. The analysis used followed accepted statistical procedures as follows.

a. Avalanche path boundaries, including the extreme runouts, were placed on topographic maps.
b. Path measurements similar to those shown on Figure 19 were made for each path that had historic data on long runout distances.
c. A multiple regression procedure was applied in which α was the dependent variable, and β (and other measurements in the earlier work) were used as independent (predictor) variables.
d. Regression equations were derived that predict α, specify the usefulness of the equations, and provide a confidence-interval estimate for α.



Profile Segments

Seg	L (m)	θ (deg)	Seg	L (m)	θ (deg)
0	150	37.7	7	118	11.9
1	100	37.7	8	200	4.3
2	89	37.7	9	100	4.3
3	218	26.6	10	100	4.3
4	137	32.3	11	50	4.3
5	125	43.0	12	39	4.3
6	98	29.7			

Profile Parameters

α = 22.8°	β = 31.6°	X_B = 872 m
d_X = 488 m	Y_B = 537 m	H = 573 m

Figure 19. Typical avalanche profile showing parameters that can be used in statistical models of avalanche runout distance discussed on page 26. Terrain measurements used in dynamics models are also shown. (Capitol Creek 2 avalanche, central Colorado.)

The runout-distance predictions are derived from a database consisting entirely of a set of 100-year avalanches from Western Norway. Snowpack and dynamics of the avalanches studied are not necessarily known, however they all resulted from some optimum set of conditions that produced maximum runout.

The most recent version of the NGI equation (Lied and Toppe, 1988), used data from 113 avalanches and considered, starting zone size and steepness in addition to β as predictor variables. The regression analysis, however, eliminated all independent variables except β. Other variables were not significant in the regression procedure. The equation derived is:

WESTERN NORWAY—(113 PATHS)

$$\alpha = 0.96\,\beta - 1.7°, \qquad (3.3)$$
$$(r^2 = 0.93;\ s = 1.4°).$$

The regression equation (3.3) indicates a high coefficient of determination ($r^2 = 0.93$) and a relatively small s, (1.4°).

Subsequent work on statistical prediction of avalanche runout distance (Mears, 1988; McClung, Mears, and Schaerer, 1988; Mears, 1989), found that the NGI equations derived for Western Norway produce systematic errors when applied to known avalanche runouts in other mountain regions. In some regions the runout distance is underpredicted (predicted α is too large); in other areas runout distance is overpredicted (predicted α is too small). It would appear that each mountain region supports a unique population of extreme avalanches, perhaps due to regional differences in terrain, weather, and snowpack conditions.

Stepwise multiple regression analyses have also been performed for selected Colorado, Wyoming, and Utah mountain areas, following the four-step procedure outlined above. Equation (3.4) was derived from a database of 112 extreme avalanches in Colorado. The best regression equation uses the parameter X_B in addition to β as a predictor variable. The parameter X_B, was used because of the large range in avalanche lengths analyzed.

COLORADO—(112 Paths)

$$\alpha = -3.0° + 0.79\,\beta + 0.0036\,X_B, \qquad (3.4)$$
$$(r^2 = 0.75;\ s = 1.4°).$$

Equation (3.4) is based on data sets in which a few outliers with large residuals were removed. These outliers were all valid observations, however they may belong to populations different from other cases in the data base. Differences result from dense vegetation that shortened runout distance, channelization, friction and roughness, snow type, event return period, or other extraneous factors which were important in each individual outlier case.

The statistical equations given in this section must be applied with caution. An investigator must know for certain that the avalanche path being studied is not an unusual case in which the potential runout distance would be underpredicted.

Furthermore, the general form of a runout-distance predictor equation must always reduce the predicted α by an error term, e. This will increase the predicted runout distance by a corresponding amount. Values for e could be determined by computing the 95 percent confidence or prediction interval, which, in each application would be proportional to (but not equal to) the values of s which are given in equations (3.3) and (3.4). A general form for a regression equation is therefore

$$\alpha = b_1 + b_2\,\beta + b_3\,X_B + \ldots + b_n\,X_n - e, \qquad (3.5)$$

where the coefficients $b_1 - b_n$ are derived for the particular mountain area which must be considered in the analysis and the confidence interval e is computed as in usual statistical procedures.

In general, the U.S. regression equations are not as reliable as that obtained in Norway. The r^2-values are smaller in the U.S. areas, indicating that the variables used do not predict α as reliably as in Norway.

Although the statistical method appears to be the most reliable and objective method for predicting extreme runout distance, exceptional cases exist in which runout distance is not accurately predicted. The Ruby Peak Avalanche path, Gunnison County, Colorado, (Figure 20), is such an example. The runout distance of this path was accurately determined by destroyed trees and other vegetation damage at the tip of the runout zone. The vegetation damage indicated this was a "100-year" avalanche, approximately. When equation (3.4) is applied to the Ruby Peak path, the predicted angle $\alpha = -3.0 + 0.79(23.8) + 0.0036(1310) = 20.5°$. This is much larger than the real α of 16.7°, and the predicted runout distance is approximately 630 m short of the true runout. Applying a 95 percent *confidence* interval (for the mean of the population of α-values corresponding to $\beta = 23.8°$ and $X_B = 1310$ m) to the prediction of α yields a range of $20.0° <= \alpha <= 21.0°$. The smaller value (20.0°) predicts a runout 580 m short of the true runout. The 95 percent prediction interval (for a population α-value corresponding to $\beta = 23.8°$ and $X_B = 1310$ m) yields the much wider range of $17.3° <= \alpha <= 23.7°$. The smaller value (17.3°) still predicts a stopping position 280 m short of the true runout. Methods used for calculating confidence or prediction intervals can be found in statistics textbooks (e.g., Moore and McCabe, 1989).

The Ruby Peak example illustrates the difficulties in predicting the runout even when a statistical procedure is applied. This may be explained by the fact that

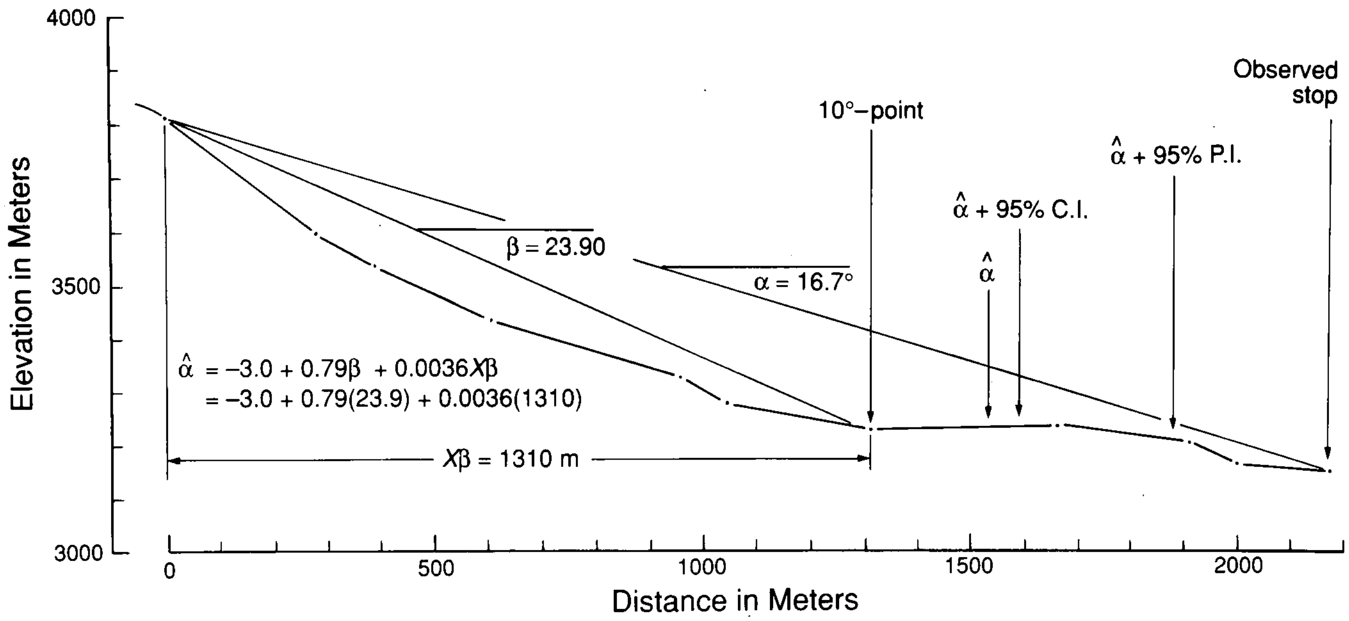


Figure 20. Profile of the Ruby Peak avalanche, central Colorado Rockies. The statistical runout model underpredicts the runout distance in this path even when a 95 percent prediction interval is added to the estimate.

the derivations of equations (3.3) and (3.4) consider only the avalanche profile. Starting zone area, width and other features of the terrain are therefore included with the "extraneous factors" not considered in the regression analyses. These extraneous factors, which consist of 25 percent of the variation in α in the Colorado data, [$1 - r^2$, in equation (3.4)], become very important in certain unusual cases. It remains the responsibility of the investigator to identify if the avalanche path is an unusual case and the equations given here do not predict runout distance accurately.

An alternate method was used to compute extreme runout by McClung and Lied (1986), McClung et al. (1988), and McClung and Mears (1991). They show that the ratio dX/X_B (Figure 19) follows an extreme-value distribution with respect to the reduced variate (*RVar*) expressed as

$$(dX/X_B) = b_1 + b_2\,(\mathrm{RVar}), \qquad (3.6)$$

where $RVar = -\ln(-\ln P)$ and P is the probability of finding a given value of $dX\,/X_B$ in the data set. Significant statistical relationships with $r^2 > 0.95$ and high F values are typically found through when equation 3.6 is applied to the extreme dX/X_B ratios found in each mountain region. The regression coefficients b_1 and b_2 are different within each mountain area. Their work demonstrates that each region constitutes a separate population of extreme runouts and supports the conclusion that each region must be analyzed separately.

Avalanche-Dynamics Models

Several avalanche-dynamics models and procedures are available to compute avalanche velocity, runout distance, and in the more advanced models, avalanche flow depth, deposit depth, and lateral extent. These must sometimes be used in conjunction with the statistical techniques (see page 23) to provide engineering design criteria. A summary of the history of avalanche modeling techniques is provided in Tesche (1986). The dynamics models require input (data or assumptions) on terrain and avalanche material properties, and provide output on avalanche flow and runout-distance characteristics (Table 8).

Terrain measurements are generally available from topographic maps or field measurements in as much detail as necessary. Starting-zone, track, and runout-zone gradients and transverse shapes or cross-sectional shapes are used as input variables to describe the terrain in various models.

Assumptions about material properties within and at avalanche boundaries control friction and turbulence coefficients and velocity. Unlike terrain variables, friction has not been measured and therefore values used in dynamics equations must be subjectively estimated, especially when applied to fully-developed, high-velocity avalanches. Avalanches are known to change form quickly during the accelerating and decelerating phases of movement (Chapter 2), therefore we do not know if the various material-properties assumptions used in avalanche-dynamics models are of the proper magnitude or if they even apply in most cases. There has been no agreement among scientists about which physical models are realistic or where they should be applied.Because the output of avalanche-dynamics models depends on friction assumptions which must be assumed, calculated velocities and runout distances can be subjective, as illustrated later in this section. Statistical analysis (Bakkehoi 1981; Mears, unpublished) has shown that the assumed friction parameters cannot be correlated to measurable terrain variables, such as path size or shape. Therefore, confidence intervals cannot be assigned to friction coefficient estimates as is done with runout predictions based on statistical models. Furthermore, use of complex models requires more assumptions about the values of the controlling parameters, assumptions that are difficult to justify based on available field data.

We present three relatively simple avalanche-dynamics models on pages 27–32. They are used to predict velocity and other flow characteristics along the path profile. Runout distance should be known prior to application of the models and can be determined by methods discussed earlier in this chapter.

Table 8. Input and output features of dynamics models.

INPUT REQUIRED BY MODELS

Avalanche-terrain measurements

a. Starting-zone location, gradient, area, roughness
b. Track gradient, cross section, roughness
c. Runout-zone gradient, shape, roughness

Avalanche material-properties assumptions

a. External boundary friction
b. Flow material properties (viscosity, turbulence)
c. Variations in a and b along path

OUTPUT PRODUCED BY MODEL

a. Acceleration and velocity along path
b. Stopping (runout) position on path profile
c. Flow heights*
d. Lateral spreading*

* Outputs in advanced models

The PCM Avalanche-Dynamics Model

The PCM model (Perla et al. 1980) can be used to compute velocity and acceleration along the avalanche profile. This simple model is an extension of the original Voellmy (Voellmy 1955), model which has been applied in its various versions throughout Central Europe and North America for the past three decades. The model assumes that the important resistive-force terms are proportional to sliding friction and dynamic drag, therefore the force-momentum law for the avalanche center-of-mass is

$$(^1/_2)\,(dV^2/dS) = g(\sin\theta - \mu\cos\theta) - (D/M)V^2, \qquad (3.7)$$

where V is velocity, S is distance, μ is a coefficient of sliding friction, θ is local slope angle, M is mass, D is dynamic drag, and g is gravitational acceleration. Application of the PCM model has shown that increase in path length, vertical drop, and steepness will increase runout distances and velocities. These simple correlations are consistent with observations. Flow height and lateral extent are not computed, but must be determined by field observations of avalanche damage in the area. The PCM model predicts only the center-of-mass position and velocity which, therefore, must be used as approximations to real avalanches which spread in three dimensions from the mass center.

The numerical solutions used in this publication are derived from the PCM model (Perla, et. al., 1980), and consist of three equations that depend on slope, (θ), length, (L), dynamic friction (μ), and a mass-to-drag ratio, (M/D).

Avalanche terrain is represented by a centerline profile (Figure 19) extending from the top of the starting zone to the end of the runout zone. The profile must by subdivided into several segments which are short enough so that θ can be considered constant within each segment of length L. In this way the entire profile will typically be subdivided into 5 to 20 segments, depending on path length and terrain complexity.

If the speed at the beginning of the i th segment is V_i^A and the avalanche does not stop within the segment, then the speed V_i^B at the end of the ith segment is

$$V_i^B = [\alpha_i (M/D)_i (1 - \exp\beta_i) + (V_i^A)^2 \exp\beta_i]^{0.5} \qquad (3.8)$$

where $\alpha_i = g(\sin\theta - \mu_i \cos\theta)$ and $\beta_i = 2L_i/(M/D)_i$. If the avalanche stops before the segment end, the stopping distance S from the beginning of the i th segment is

$$S = [(M/D)_i /2]\, ln\, [1 - (V_i^A)^2/\alpha_i (M/D)_i] \qquad (3.9)$$

Velocity at the bottom of a segment, V_i^B, is used to compute velocity,V_{i+1}^A, at the top of the next segment (Figure 21). This computation is repeated downslope until the center-of-mass stops before the end of a segment. V_i^B cannot always be substituted directly for V_{i+1}^A because it is sometimes necessary to include a correction for momentum change at the slope transition. When $i > i$+1 a correction, based on the conservation of linear momentum used is

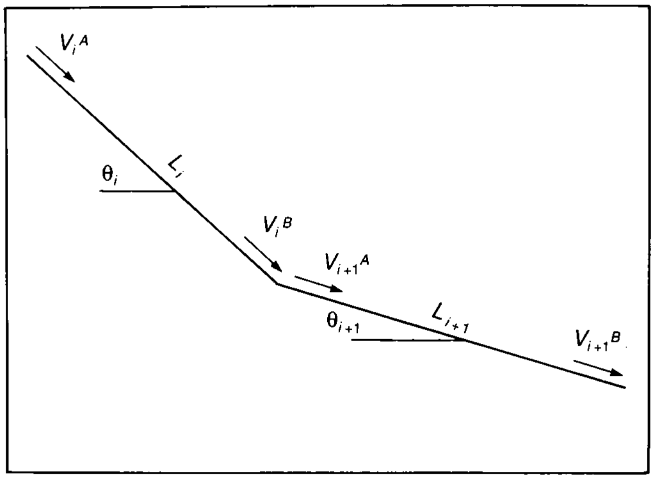


Figure 21. Consecutive profile segments used in the PCM avalanche-dynamics model (after Perla et al. 1980.)

$$V_{i+1}^A = V_i^B \cos(\theta_i - \theta_{i+1}). \qquad (3.10)$$

The PCM model can also be used to model a horizontal curve by applying the momentum correction [equation (3.10)] to lateral deflection at bends in an avalanche channel. Horizontal curves can be modeled by artificial segments of length 1 m with deflection θ that match observed lateral deflection. This correction results in velocity reduction in avalanche channels at sharp curves.

The PCM model was applied to the profile of a "100-year" avalanche that occurred in central Colorado (Figure 19). Velocities computed at the top and bottom of each segment are given in Table 9. A constant value of $\mu = 0.2$ was assumed for each segment in Procedure A, Table 9. The M/D value was chosen by successive iterations, forcing the model to match the observed runout distance. Assumption of a constant μ is the easiest way to apply the model, however use of a variable μ is also discussed below. Larger assumed values of μ will result in larger values of M/D and velocity. Boundary friction, μ, is usually varied from about 0.15 to 0.35. The required M/D, to force the PCM model to achieve known runout distances, typically ranges from 100 m to 10,000 m.

McClung (1990), suggests an alternate method (Procedure B, Table 9) for using the PCM model. His method is based on experimental granular-flow data (which he assumed were similar to dry-flowing avalanches), and velocity data. According to McClung, μ should increase with avalanche velocity and distance traveled along the path. The rate of increase in μ is determined partly by steepness in the upper path as measured by the angle β (Figure 19). His approach uses equations 3.8, 3.9, and 3.10 but μ is increased from a low value of 0.20 at the starting zone to approximately 0.40 or larger at the end of the runout. This requires a larger M/D and computes larger velocities along the path profile than the simple assumption of constant μ = 0.20. To use McClung's method, the avalanche stopping position must also be known in advance, presumably through the empirical or statistical techniques discussed earlier in this chapter.

Table 9. Applications of the PCM avalanche-dynamics model.

	Procedure A		Procedure B		Procedure C	
Seg.	V(top) m/s	V(bot) m/s	V(top) m/s	V(bot) m/s	V(top) m/s	V(bot) m/s
0	0.0	33.8	0.0	35.2	0.0	34.8
1	33.8	41.6	35.2	44.1	34.8	43.6
2	41.6	46.4	44.1	50.2	43.6	49.4
3	45.6	47.3	49.2	53.8	48.5	52.7
4	47.3	50.3	53.8	57.7	52.7	56.8
5	50.3	55.7	57.7	63.8	56.8	62.9
6	54.2	54.3	62.1	63.0	61.2	62.3
7	51.7	45.9	60.0	55.1	59.3	55.2
8	45.5	31.1	54.7	40.8	54.7	39.2
9	31.1	23.7	40.8	32.5	39.2	30.6
10	23.7	15.4	32.5	22.0	30.6	20.3
11	15.4	9.8	22.0	14.4	20.3	13.1
12	9.8	0.0	14.4	0.0	13.1	0.0

Procedure A— μ = 0.20 constant; M/D = 954 m.
Procedure B—Variable μ (McClung, 1990), M/D = 2074 m.
Procedure C— μ = 0.20 above 10°, 0.30 below, M/D = 1548 m.

A third procedure (Procedure C) for applying the PCM model increases friction to a constant value of 0.3 in the runout zone (below the *B* point). This assumption may be justified based on observed interlocking of flow fragments in the runout zone (Chapter 2) which may increase friction locally. Method C produces velocity computations similar to McClung's procedure. As we recommend, all three approaches (A, B, and C) require the user to specify the stopping position in advance.

Stopping position can also be computed directly from the PCM model by assuming both μ and M/D in advance, but this method is very subjective as discussed above and illustrated in Table 10. Using the Capitol Creek 2 profile (Figure 20) as an example, and fixing μ equals 0.20 for the entire path illustrates the variability in runout distance resulting from a relatively small range in M/D. Varying M/D between 500 m and 2000 m, both of which appear to be reasonable estimates for a path of this size, results in a wide range in computed stopping positions, maximum velocity, and velocity at the β point.

The sizes and strengths of avalanche-defense structures are often proportional to V^2, or kinetic energy, (Chapter 5), therefore velocity becomes an important design input. Velocity, Vbeta, ranges from 58.7 to 31.8 m/s at the top of the runout zone where defenses might be considered (Table 10), depending on assumptions about M/D, therefore the V^2 ratio = $(58.7/31.8)^2 = 3.41$, well in excess of engineering safety factors. This illustrates another reason why the PCM model should not be used to compute velocities and stopping positions through arbitrary selection of M/D (or μ).

Table 10. Variations in PCM-model outputs.(μ assumed constant = 0.20)

Profile—Capitol Creek 2 (Figure 20)

M /D	**Runout***	*Vmax*	*Vbeta*
500	−245	44.6	31.8
954	Observed	55.7	45.5
2000	+393	66.0	58.7

* A negative distance is short of true stopping point.

Swiss Avalanche-Dynamics Procedures

In the Swiss Alps, centuries of detailed avalanche runout data are available in many populated areas and a large number of meteorological stations exist through which snowfall amounts and accumulation rates are recorded. This excellent data base and good quality, detailed topographic maps (1:10,000-scale; 10 m contour intervals) enable the Swiss to consider terrain details and expected snow volumes carefully in analysis. They have expanded and refined the original Voellmy (1955) and Sommerhalder (1965) methods to produce guidelines on avalanche dynamics analysis which are used in hazard mapping and design of defense facilities in Switzerland, (Salm et al. 1990). The general form of the Swiss avalanche-dynamics model assumes a force-momentum law identical to the PCM model [equation (3.7)], however the term Mg/D is replaced with ξd, where ξ is a turbulence coefficient and d is flow height. The Swiss recommendations about the use of avalanche-dynamics coefficients discussed below (Salm et al. 1990), are based on observed runout distances of extreme (≥ 30-year) avalanches.

The Swiss avalanche-dynamics analysis subdivides the avalanche path into starting-zone, track, and runout-zone sections of constant slope (Figure 22), which are analyzed separately according to strict rules. In the starting zone, released slab thickness, d_o, is determined from statistical analysis of precipitation data from several Swiss mountain areas. Starting-zone area, A, is determined from 1:10,000-scale topographic map study and terrain analysis, and the volume, K is calculated

$$K = A\, d_o. \tag{3.11}$$

Discharge, Q, (volume/time) of snow flowing through the bottom of the starting zone is computed

$$Q = W_o\, d_o\, v_o, \tag{3.12}$$

for rectangular starting zones where W_o is average width. Velocity, v_o, through the starting zone, is computed

$$v_o = [d_o\, \xi\, (\sin\theta - \mu\cos\theta)]^{1/2}. \tag{3.13}$$

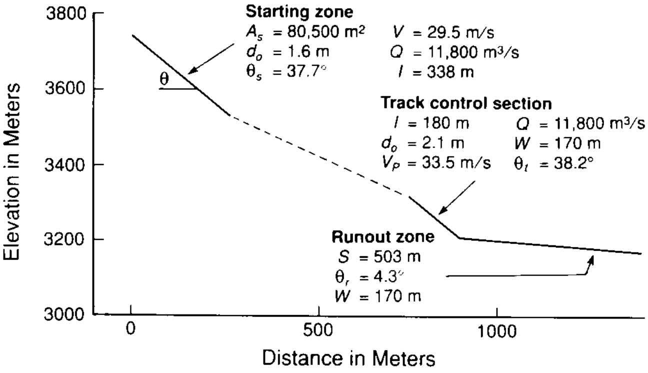


Figure 22. Avalanche-path measurements used in Swiss avalanche-dynamics procedures (Salm et al. 1990), as applied to the Capitol Creek 2 avalanche (see Figure 19 for profile details).

The parameters (μ and ξ) have not been measured but are assumed, based on Swiss experience. The turbulence coefficient, ξ, is varied from 400 to 1067 m/s² in Swiss practice, and the dynamic friction coefficient μ is varied from 0.155 to 0.30. Both ξ and μ are thought to depend on track shape (laterally confined or unconfined) and avalanche volume. In channelized avalanches ξ ranges from 500-600 m/s², whereas unconfined avalanches require larger ξ-values (up to 1067 m/s²). The larger avalanche starting-zone volumes (> 10^5 m³) may require $0.155 < \mu < 0.20$; smaller starting-zone volumes require $0.20 < \mu < 0.30$. Track roughness and snow type also affect the values of μ and ξ. The larger friction values are used with wet-snow avalanches.

Discharge, Q, from an irregular or bowl-shaped starting zone is calculated

$$Q = K/dt, \tag{3.14}$$

where dt is time required to discharge snow from the starting zone. The discharge time, dt is calculated

$$dt = l/v_m, \tag{3.15}$$

where v_m is average velocity over the starting zone length l, a representative distance from the top to the bottom of the starting zone (Figure 22).

The velocity at the bottom of the avalanche *track*, v_P, is computed at the lower end of a "control section," of track, a short reach in which flow is assumed to reach constant velocity. The control section length, x_u, is approximately equal to

$$x_u = 0.7\,(\xi/g)d_p, \tag{3.16}$$

Where

$$d_p = Q/W_pV_p. \tag{3.17}$$

The velocity, v_P at the bottom of the control section of track in unconfined avalanches is computed

$$v_P = [Q/W_P\,\xi\,(\sin\theta - \mu\cos\theta)]^{1/3}, \tag{3.18}$$

where W_P is average avalanche width within the control section, θ is track inclination in the control section, and Q has been determined in the starting zone calculations. Average track width in the control section will be different from starting-zone width or upper track width in many paths; width affects the computed flow depth and velocity. In the track of laterally-confined or channelized avalanches

$$v_P = [R\,\xi(\sin\theta - \cos\theta)]^{1/2}, \tag{3.19}$$

where, the hydraulic radius,

$$R = A/L, \tag{3.20}$$

A is the channel cross-sectional area and L is the channel "wetted perimeter."

If the slope angle changes only gradually at P, then the control section begins above P, at a point where the local angle = $\tan^{-1}\mu + 3.5°$. Although the control section is located above P, runout calculations begin at the original point P, it being assumed that velocity and flow depth will not change significantly between the bottom the control section and P.

The beginning of the *runout zone* is assumed to begin at P. Avalanche motion here is modeled as a flexible, sliding sheet and v^2 decreases linearly with distance in the runout zone. The slope steepness at P is determined by the value of the assumed friction coefficient μ, therefore the angle at P is equal to $\tan^{-1}(\mu)$, and the average angle below this point must be less than $\tan^{-1}(\mu)$, (Figure 22). Therefore, the runout calculations begin on more gentle slopes when larger avalanches are calculated because the assumed μ-values will be smaller.

Runout distance, s, below the P-point is computed

$$s = (d_s\,\xi)/2g\,ln[1 + (v_p{}^2/v^2)], \tag{3.21}$$

where g = gravitational acceleration. Avalanche width in the runout zone may be assumed to be different than the width at the P-point and must be based on local terrain analysis. An increase in width will decrease flow depth and runout distance while a decrease will increase flow depth and runout. Deposit height, d_s, and a velocity parameter, V, used in (3.21) are defined:

$$d_s = d_p + v_p{}^2/10g; \text{ and} \tag{3.22}$$

$$v^2 = d_s\,\xi(\mu\cos\theta - \sin\theta). \tag{3.23}$$

When significant slope changes occur within the runout zone below P, the velocity may be interpolated by the relationship

$$v_{P\,2}{}^2 = v_{P\,1}{}^2(1 - x/s) \tag{3.24}$$

where $v_{P\,1}$ is the calculated velocity at the P point, s is the runout distance given the initial slope, velocity, and flow height at P, and x is the interpolation distance. This interpolation procedure can be repeated as many times as necessary if the runout-zone slope is irregular. In addition to velocity interpolation in the runout zone, the discharge, Q, can also be reduced with distance in the runout zone. Reduction of discharge with distance will also reduce the flow depth and runout distance.

The Swiss avalanche-dynamics calculating procedure requires the user to make several assumptions about the values of input parameters and is strongly dependent upon user experience.

a. The friction coefficients μ and ξ are not known but must be assumed in model applications.
b. The average released slab depth, d_o, must also be assumed. With good meteorological records, such as those available in Switzerland, statistical prediction of d_o is possible but such data are not generally available at North American mountain locations.
c. The avalanche flow is assumed to be of constant density throughout, and flow depth is based on the assumption that discharge does not change from the starting zone through the top of the runout zone.
d. The runout-distance equations (3.21) through (3.23) include empirical relationships which are determined from Swiss experience.

The Swiss procedure was applied to the Capitol Creek 2 avalanche analyzed previously by the PCM model (Figures 19 and 22). Assuming = 0.155, ξ = 1067 m/s^2, and d_o = 1.6 m, the observed runout distance was simulated. However, maximum velocity (at the bottom of the control section and beginning of the runout zone) was computed as only 33.5 m/s. This is substantially less than calculated in the PCM model and is less than expected for such a large, steep dry-snow avalanche during extreme conditions, based on direct observations in Switzerland, Norway, and Colorado.

Although the Swiss method does require the user to make more assumptions about unknown avalanche-flow parameters than the PCM-model, more detail is produced for use in engineering applications. If the user has excellent topographic maps and detailed, long-term weather and snowpack records, the Swiss method can provide estimates of velocity, flow depth, discharge, and runout distance. Furthermore, release volume and track cross-sectional shape can be considered in the Swiss model but not in the PCM model which considers only avalanche path profile. Other factors being equal, runout distance will be substantially longer below a channelized (V-shaped) track than below an unconfined track because discharge, Q, is assumed constant in the starting zone and track and flow depths tend to increase in channels.

Experience with the use of the Swiss method in Switzerland (Gubler, 1989) and in Colorado, indicates the following systematic errors are typical in the computed results:

a. The calculated maximum velocities are often less than expected, based on observations; and
b. Calculated debris heights are greater than observations indicate.

Swiss model does not consider flow density decrease and fluidization of the avalanche during acceleration in the track. Fluidization or partial fluidization of the avalanche may, increase flow depth and velocity, a factor not considered in the model. Measurements also indicate that debris density in the runout zone typically exceeds starting-zone density, probably by a factor of 1.5–2.5. The mass released from the starting zone, therefore, may occupy only half its original volume when the runout zone is reached. Because debris compression in the runout zone is not considered, deposit heights predicted by the Swiss model would tend to be overestimated.

Because climate, snowfall, topography, and prior design-avalanche runout data are rarely available in North America, use of the Swiss method to predict avalanche dynamics using assumed initial slab and friction conditions is probably not justified. The Swiss methodology is useful, however, if the runout distance (or area) can be determined by independent methods, and the Swiss procedure is used to simulate this independently-determined result. The Swiss model can be used as an alternative or supplement to the PCM model in North American locations when the limitations to its use are understood.

Particle Simulation of Avalanche Motion

Perla et al. (1984) describe a particle model in which avalanche movement is simulated as a flow of several hundred particles released from a starting-zone segment. In Figure 19 the starting zone segment is labeled segment "0" on the profile. Each segment below the starting zone is further divided (by computer) into 1 m long sub-segments. The force-momentum equation used in the PCM and Swiss equations of motion were modified in the particle model to include a third term, thus

$$(1/2)\,(dV^2/dS) = g(\sin\theta - \mu\cos\theta) - (D/M)V^2 \pm RV \qquad (3.25)$$

where the new ($\pm RV$) term and the friction and dynamic drag terms act on each of the several hundred particles comprising the avalanche. The model then predicts the velocity and stopping positions of each of the particles comprising the avalanche. This new RV-term, the sign of which is determined by Monte-Carlo simulation, is added or subtracted to the velocity of each particle at the end of each 1 m interval. This produces a range of particle velocities. Entrainment of new snow is also simulated by assuming one new particle per meter is entrained into the flow. Deposition is modeled by eliminating particles from the flow when particle velocity becomes insufficient to advance it into the next 1 m sub-segment.

Introduction of entrainment and random-velocity terms produces a stochastic avalanche model in which the entrainment dominates on steep slopes and deposition dominates on gentle slopes. This is consistent with numerous observations of real avalanche deposits. Because the flow of particles arrive at a given point on the profile at different times and at different speeds, the string of particles requires a finite time period (typically 5–20 seconds) to pass though each point on the profile. A typical time, velocity, and "mass" (number of particles), distribution is shown for the Capitol Creek 2 avalanche in Table 11.

Experience with the use of this model provides the following guidelines for its use:

a. The number of particles, N, chosen to represent the released slab should be approximately equal to $L/3$, where L is path length in meters. Thus entrainment will have a similar effect on avalanches of different lengths.

b. The friction coefficient, μ, should be chosen as constant (≥0.2) over the path length. This reduces the introduction of unknowns into the simulation and enables the avalanche to stop on typical runout-zone slopes. The computer model, however, allows for a variable μ.
c. The turbulent drag coefficient, *M/D*, should also be constant over the path length and should be adjusted to force the model to match the observed or predicted runout distance. A small percentage of the total number of particles (5–10 percent) may slightly exceed the pre-determined runout distance without invalidating the simulation. In practice a typical *M/D*-value required to simulate the known runout will be approximately 0.6 to 0.8 times the *M/D*-value used to match a known runout distance with the PCM center-of-mass model.
d. The random-velocity term, *R*, should be 0.2–0.4 depending on whether, in the judgment of the user, the design avalanche will be a dispersed (light-flowing) form (*R* = 0.4) or will be relatively dense and undispersed (*R* = 0.2). Larger *R* will result in a longer time interval of avalanche passage at a given point and a more dispersed runout deposit.

Table 11. Particle simulation of avalanche motion.

(Capitol Creek 2 avalanche, central Colorado)
M/D = 630 m, μ =0.20, N = 500, R = 0.3

Seg	Length (m)	Angle (deg)	*Vavg* (m/s)	*Vmax* (m/s)	*Vsdev* (m/s)	*N*	*T* (sec)
0	150	37.7	(Initial slab region)			500	—
1	100	37.7	24.4	36.5	8.6	500	7.8
2	89	37.7	33.4	44.7	6.6	561	7.2
3	218	26.6	37.8	50.5	7.0	601	8.0
4	137	32.3	38.0	51.5	6.2	652	9.9
5	125	43.0	40.6	53.1	6.5	693	10.7
6	98	29.7	45.7	59.3	6.7	733	11.5
7	118	11.9	44.6	57.5	7.1	758	11.9
8	200	4.3	37.0	51.6	6.6	759	13.2
9	100	4.3	20.9	33.5	6.3	655	15.7
10	100	4.3	15.1	29.6	5.6	437	21.6
11	50	4.3	11.4	21.3	4.6	164	19.4
12	39	4.3	9.3	16.7	3.6	83	15.1

(Maximum runout predicted: 7% of initial slab travels a maximum of 18 m past the observed runout limit)
Vavg—Average particle velocity entering segment
Vmax—Maximum particle velocity entering segment
Vsdev—Standard deviation particle velocity entering segment
N— Number of particles (avalanche size) into segment
T—Total time required for avalanche to enter segment

The results provided in Table 11 should be compared below to those previously obtained when the PCM center-of-mass model was applied to the Capitol Creek 2 avalanche.
a. *Average* particle velocity at beginning of each segment is 10-20 percent less than that predicted by center-of-mass model;
b. *Maximum* particle velocity is substantially more than center-of-mass model velocity, but large predicted velocities are approximately two standard deviations above the mean, thus involve only about 2.5 percent of the total mass or volume.
c. Avalanche size (*N*-value), increases on steep slopes and decreases on gentle slopes.
d. Time required to flow past the beginning of a segment increases rapidly on gentle slopes thus modeling avalanche dispersion in the runout zone.

Additional detail about the modeled avalanche structure is provided at the beginning of each segment. Figure 23 plots the "flow thickness" at the beginning of segment 8, and at the beginning of segment 10, near the center of the runout zone.

Although the particle model does not compute flow thickness, *d*, this can be computed at any point on the profile as

$$d = Q/WV, \quad (3.26)$$

where Q = particles (converted to volume) per second, W is path width, and V is velocity at the point. This calculation assumes constant density flow, similar to the Swiss method, and would not compute powder-blast height, or density decrease and flow height increase within the flowing avalanche core.

Comparison of the two distributions in Figure 23 illustrates how the modeled avalanche has become thinner and more dispersed (longer total time interval required for avalanche passage) at the top of segment 10. Although data on the velocity, mass, and momentum distributions in large avalanches are not available, observations of large, dry-snow avalanches do suggest that most of the material is concentrated toward the front of the flow and probably becomes more dispersed or elongated on gentle gradients. In applications, the number of starting particles, *N*, can be matched to assumed release volume and mass, enabling discharge and momentum calculations to be made, providing additional flow parameters which may be important in design.

Two-Step Procedure for Design-Avalanche Calculations

The previous three sections have discussed and illustrated that avalanche-dynamics models can produce widely-varying results in velocity and runout distance.

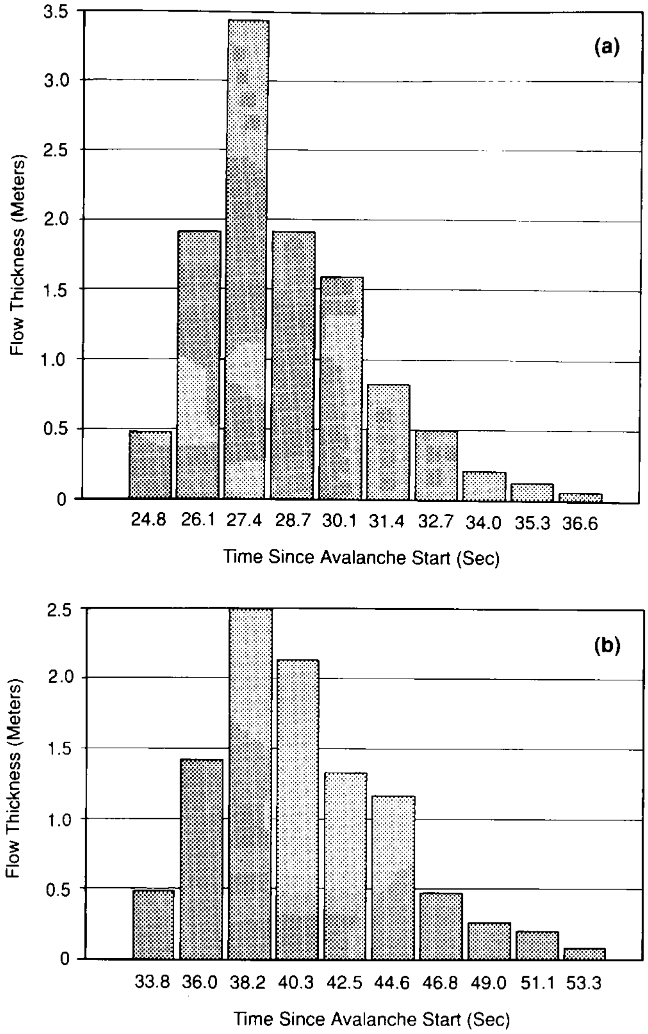


Figure 23. "Flow thickness" time distributions at the beginning of segments 8 (a) and 10 (b), Capitol Creek 2 avalanche, as computed from the particle model (Perla et al. 1984). Although the particle model does not compute flow thickness, d, this can be computed at any point on the profile by equation (3.26). Note lesser maximum thickness and longer duration of flow in segment 10.

More advanced and complicated models (e.g., Tesche 1986; Norem et al. 1989) will produce similar variability in runout distance. Because of the difficulties in objectively choosing the parameters that model avalanche-dynamics and predict velocity, runout distance, and other important design parameters, the use of the PCM model, the Swiss procedure, the particle model or any other more complex model of avalanche flow *is not recommended* for prediction of runout distance. Although avalanche-dynamics models must be used to delineate zones of avalanche impact pressure on avalanche-zoning maps, and to design defense structures, the runout distance should be determined by completely independent methods, as discussed earlier in this chapter.

To obtain avalanche velocities or other flow features along the path profile, the following two-step procedure is recommended.

Step A: First, determine the design-avalanche runout distance. This should be done by *(a)* direct observations, *(b)* path history, *(c)* vegetation analysis, or *(d)* aerial-photo interpretation when the damage from the design avalanche can be reliably documented. Past records of the design avalanche are, of course, far superior to any indirect method of predicting runout. When reliable documentation does not exist, apply a statistical-prediction method based on the performance of major ("100-year") avalanches of various sizes in the particular area of interest. These statistical relationships must be developed for each major mountain region; the results from one region will not necessarily apply in other regions. Apply an appropriate confidence or prediction interval to the Alpha-angle estimate to extend the predicted runout in accordance with accepted statistical procedures.

Step B. Calculate the avalanche velocity and other flow characteristics along the path profile. This should be done by applying an avalanche-dynamics model such as those discussed, but forcing that model to stop at the position determined in Step A. Dynamics models more advanced than those discussed here can be used in Step B to compute velocity, flow height, lateral spreading, energy density (pressure potential) or other characteristics. The dynamics model will provide estimates of avalanche flow characteristics at points along the path which can then be used for mitigation design and hazard-zone delineation.

This two-step method reduces the uncertainties inherent in using one method alone and therefore increases the confidence in the overall analysis. Conclusions about runout will be based in part on observations on regional avalanche performance, and these conclusions can be assigned confidence limits by applying standard statistical methods.

Additional Methods for Computing Velocity and Force

Given all the uncertainties in predicting avalanche runout distances in areas without a long history of avalanche activity, multiple methods should be applied to computation of design-avalanches whenever possible.

Velocity Estimates

Point estimates of avalanche velocity can sometimes be obtained by measuring the superelevation of

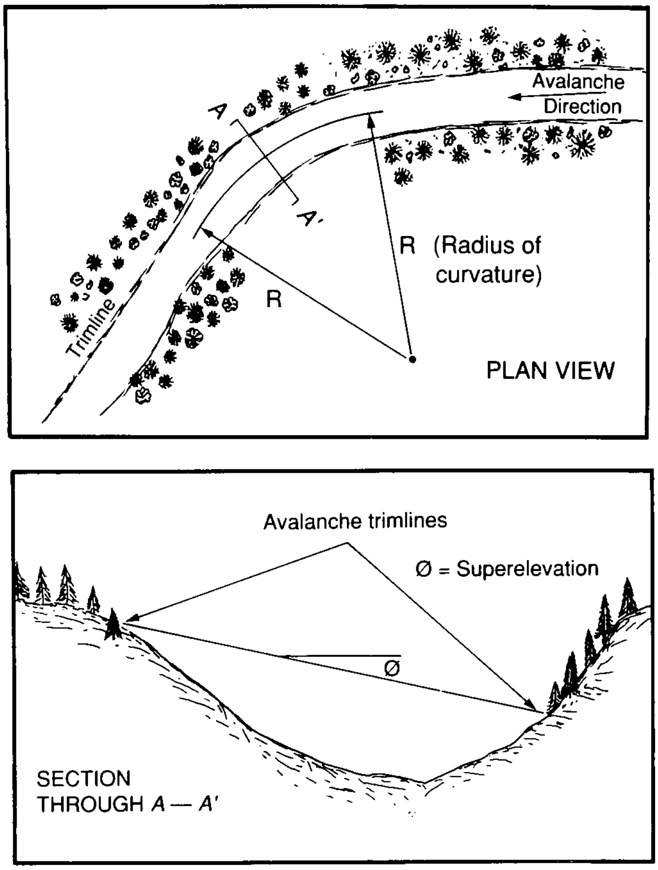


Figure 24. Superelevation measurements used in avalanche channel for velocity calculations.

avalanche flow around corners in a channelized track, (Figure 24). Differences in trimline heights on opposite sides of the channel can sometimes be observed. These height differences depend on mean avalanche velocity over the flow cross section and the mean radius of curvature, R, of the channel measured in map view. When the asymmetry (transverse tilt, or superelevation) of flow cross section across the channel can be expressed as the superelevation angle, $\varnothing$, the equation for mean velocity over the track cross section is written

$$V = (R\, g \tan \varnothing)^{0.5}, \qquad (3.27)$$

where g is the gravitational acceleration.

In order for this method to provide reliable estimates, the following criteria must be satisfied.

a. The curved section must be within a portion of the track where avalanche flow velocity is thought to be fairly constant.
b. The radius of curvature through the curve must also be fairly constant.
c. Trimlines at the edges of the track (e.g., broken tree trunks and limbs), must be well defined.
d. Superelevation measurements must be made at right angles to the avalanche flow direction.

If possible, this velocity calculation procedure should be made at several locations within a single curved section of the track. The various computed velocities should then be compared. If a wide divergence in results are obtained, the method probably is not reliable at the location. If the velocities are similar (perhaps within 10–20 percent of each other), they can be compared with other methods of velocity estimation, such as avalanche-dynamics equations.

Impact–pressure estimates

Avalanche impact pressure can sometimes be estimated by studies of damage to objects that have been broken or moved by avalanches. Probably the most common type of widespread avalanche damage is broken tree trunks or trees with broken limbs in avalanche tracks and runout zones. When the geometry of impacted trees can be assumed to be simple circular cylinders and the impact height can be deduced from limbs trimmed from adjacent trees, lower and upper limits of the avalanche force can be estimated by simple calculations (Mears, 1975). The lower limit of avalanche impact force is determined by calculation of bending-moment capacities of trees in which the main stem has failed in bending, the upper limit by similar analysis of those trees which have received but resisted impact and bending stresses.

In order for this method to be reliable the following conditions must be satisfied.

a. Impact surfaces must be fairly simple. Many branches or other irregularities in the tree truck may complicate the dynamics of avalanche loading so the analysis becomes inaccurate.
b. The tree trunk must have failed in bending at or above the ground surface. Trees uprooted by avalanches indicate failures in the root/soil system where the material strengths were unknown. These trees did not fail in bending.
c. Avalanche flow heights at the broken trees must be estimated by local field evidence.

Tree strengths can be calculated by measurements of broken trunk diameters and tables of wood strength used in timber engineering. However, more reliable estimates of tree-trunk "moment capacities," M_c , can be obtained for a wide range of trunk diameters from standard tables of transmission-line or telephone-pole properties. These tabulate moment capacities for circular cylinders of various tree species.

When bending failure occurred M_c can then be equated to the induced moment, M_I, caused by the avalanche. If the avalanche flow height, H, and exposed tree diameter, D are also known, the applied impact pressure, P, per unit area can be calculated as

$$M_c = M_I = (P)(H)(D)(H/2), \text{ or} \qquad (3.28)$$
$$P = (2\, M_c)/(D)(H^2).$$

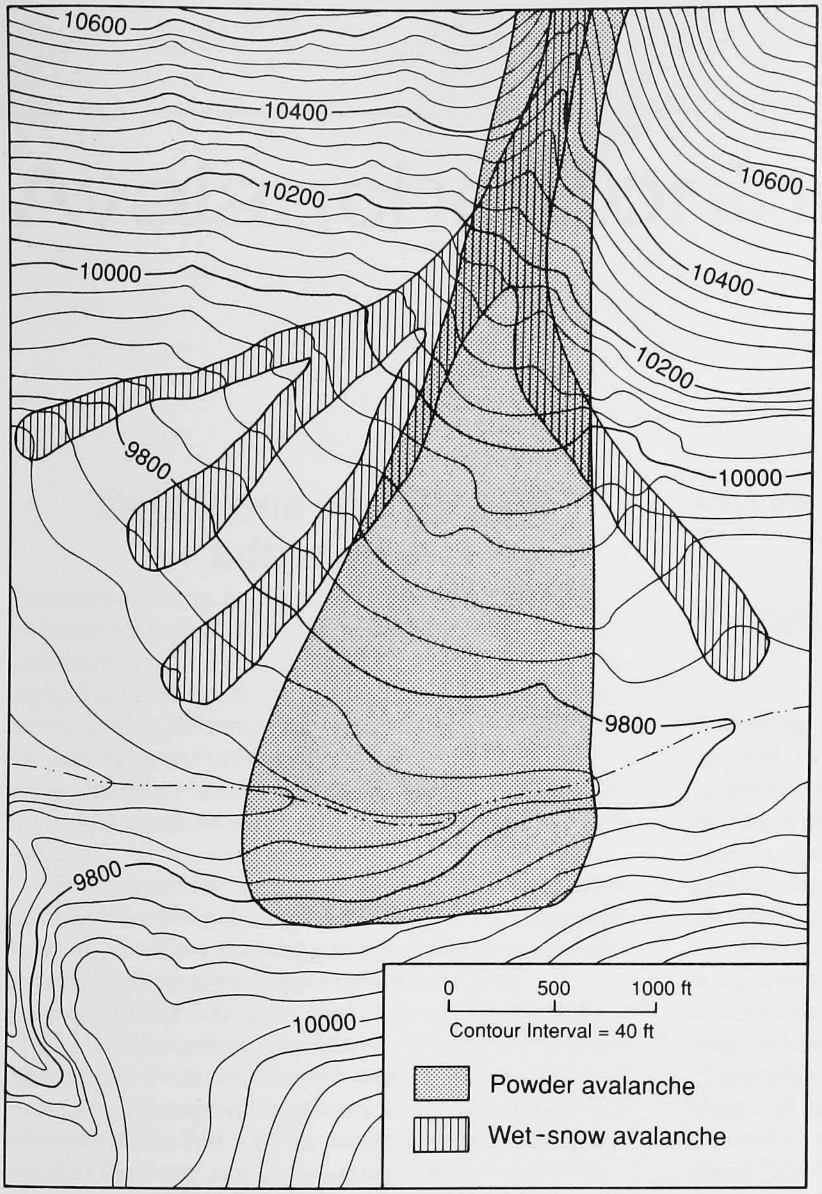


Figure 25. This alluvial fan tends to divert the flow of wet-snow avalanches toward the steepest gradients. Due to their large velocities, dry-snow/powder avalanches advance down the center of the fan in the direction attained in the track.

This method will provide only rough estimates of avalanche impact force. To increase the reliability of the estimates, many tree failures should be sampled and P calculated many times in a given part of the avalanche path. In practice, estimates of P obtained in this way will vary by a factor of at least two in the best-documented cases and may vary by a factor of 5 to 10. The variability may result from tree-strength differences, changes in avalanche impact energy with location, or combinations of these and other factors. However, if the range in calculated P is substantially in excess of normal building loading capacities, this will indicate the necessity for incorporating special design in structures or may indicate that construction of certain structures is not practical at a given location.

Avalanche Width

Estimates of avalanche width cannot be obtained through use of statistical or dynamics models discussed above and usually must be estimated by other methods listed below.

a. Unconfined paths tend to be approximately as wide in the runout zone as in the starting zone and track.

b. Confined paths, especially those discharging onto alluvial fans, may affect an area much wider than the channel. Slow-moving wet-snow avalanches usually turn toward the steepest gradients on alluvial fans, whereas, dry-snow/powder avalanches, because of large velocities, often advance in a direction determined by a projection of the avalanche track. In some cases, the entire alluvial fan may be reached by the design-avalanche runout. Figure 25 illustrates the directional differences resulting from wet and dry-snow avalanches on an alluvial fan.

c. Topographic barriers such as ridges, small hills, gullies, etc. in the runout zone may provide distinct barriers to flow, particularly near the end of the runout zone where velocities are reduced. Small-scale terrain barriers, however, will be overrun by deep, high-velocity powder avalanches because flow depth will exceed the height of terrain barriers.

Chapter 4

Avalanche Zoning

Definitions and General Information

Avalanche zoning has traditionally been defined in two different ways: *(1)* delineation and mapping of areas subject to avalanches and *(2)* application of *zoning* and land-use policies within mapped avalanche areas. Avalanche mapping (also sometimes referred to as "zoning"), may also be necessary within mining areas and other industrial facilities located in remote mountain areas, well beyond the jurisdiction of communities.

Procedures that can be used to map design avalanches have been discussed in Chapter 3 of this publication. Land-use planning and engineering applications usually require consideration of a long (approximately 100-year) avalanche return period (Table 5). Delineation of avalanche boundaries, quantification of avalanche design criteria and mapping of hazard zones requires application of quantitative and objective procedures so the results can be reliably applied to land-use and engineering needs. Subjective estimates of avalanche extents, velocities, and destructive effects are not appropriate and should not be used in design and planning applications.

Strictly speaking, avalanche zoning utilizes the mapped avalanche boundaries and designates, by municipal or county ordinance or state law, land uses and restrictions which are appropriate within the defined avalanche areas. For example, zoning may restrict residential structures from areas subject to either frequent or potentially powerful avalanches and may require special protection for buildings or other valuable objects located in less frequent avalanche areas. Certain land uses may not be permitted in known or potential avalanche areas.

Because avalanche zoning reduces hazard by reducing exposure, it is a form of avalanche mitigation. Because zoning attempts to limit or avoid exposure to avalanches, it is the safest form of avalanche mitigation. Various other forms of avalanche mitigation which are used in place of or in conjunction with zoning are discussed in Chapter 5.

General Definition of Avalanche-Hazard Zones

Following definitions introduced and commonly applied in the Swiss Alps (Frutiger, 1970), avalanche-hazard zones have traditionally been defined in terms of return period and potential impact pressure. Two zones of potential avalanche hazard are usually defined in Switzerland and have been used at many locations in North America:

Red Zone (High potential hazard). The Red zone is an area reached by either frequent or powerful avalanches. In Switzerland "frequent" is defined as a 30-year or less avalanche return period. An avalanche is "powerful," for Swiss zoning definitions, if it produces an impact pressure on a large, flat, rigid surface normal to the flow direction of 30 kPa (630 lbs/ft^2) or more. The Swiss are often able to specify avalanche return periods of 30 years fairly accurately because of a long history in mountain areas. Either the impact or return-period condition will suffice to define the Red zone, therefore large areas within the design avalanche path may be defined as Red because of large potential avalanche pressure, even if the return period within these areas is long.

Blue Zone (Moderate potential hazard). The Blue zone is an area reached avalanches with 30–300 year return periods and in which the design avalanche produces impact pressures of less than 30 kPa (630 lbs/ft^2). Both the return period and the impact conditions must be satisfied in order to qualify as a Blue zone.

The Red and Blue zone definitions used in Switzerland must be modified in North American applications because of the much shorter period of detailed historical record in these areas. As a general rule, avalanche return periods can be defined only to the nearest order of magnitude, or factor of 10. A typical order-of-magnitude definition for the return period, *T*, which can be applied to areas lacking a long historical record is as follows:

10-year return period—$10^{0.5} < T < 10 \times 10^{0.5}$;

100-year return period—$10 \times 10^{0.5} < T < 100 \times 10^{0.5}$.

The above definitions indicate that the actual return period for a "10-year" avalanche may lie between approximately 3 and 30 years and the "100-year" return period may lie between 30 and 300 years. More precise definitions may exist for short return periods at certain locations, but the historical record of avalanches is usually too short to allow a more precise definition for the long return-period events.

Examples of Municipal Avalanche-Zoning Plans

With the accuracy limitations used to define the return-period understood, the Town of Vail, Colorado and the City of Ketchum, Idaho both passed avalanche-zoning ordinances in the late 1970s. Ordinance details are summarized below because they provide useful models for other areas.

Avalanche zoning can have its greatest effect on land-use control and potential hazard reduction at the municipal-government level because within the boundaries of communities human activity is most concentrated. Vail and Ketchum use somewhat different approaches to accomplish what is felt in each community to be the governmental duty of protecting the public safety.

Vail, Colorado

The essential points of the Vail avalanche-zoning plan, which, in some cases severely limits the property owner's use of the land and alters land-use regulations which were in effect prior to avalanche awareness are summarized below. The Town of Vail avalanche-zoning plan has been in effect since 1976.

- The Town of Vail mapped and defined "avalanche influence zones" (AIZ), which are areas in which avalanches may, but do not necessarily constitute a potential hazard. The AIZ are only estimates about avalanche runout distances during extreme conditions; they are not defined by any analytical techniques such as those discussed in Chapter 3, but are simply based on the subjective opinion of specialists trusted by Vail. Nevertheless, building permits are not issued within an AIZ unless more detailed studies are completed.
- If property lies within an AIZ and a building permit is desired, the property owner must determine, at his expense, the details of the design-magnitude avalanche. According to Vail ordinance, this site-specific study must delineate Red and Blue zones and must compute avalanche dynamic and static loads on exposed habitable structures. Furthermore, the Red and Blue zones must be defined, as in Switzerland, in terms of expected return periods and impact pressure. Red zones have a return period of 25 years or less or impact pressures of 600 lbs/ft^2 (29 kPa); Blue zones have return periods of more than 25 years and impact pressures of less than 600 lbs/ft^2 (29 kPa).
- Land use restrictions are also based on the Red and Blue zone definitions. Residential construction is not permitted in the Red zone, however, building is permitted in the Blue zone if design for avalanche forces is provided by an engineer registered in Colorado.

Two important points are implicit in the Vail avalanche-zoning plan. First, in order for an engineered structure to be built, avalanche-design criteria must be provided to the structural engineer and architect. Therefore, it is important that the property owner and builder can show that he used the most reliable methods presently available to derive the design criteria. Secondly, because responsibility for providing safe design lies with the owner, builder, or consultant, the Town of Vail may be relieved of such responsibility.

The avalanche-zoning restrictions have resulted in avoidance of the most seriously-affected avalanche areas within the Town boundaries despite very high property prices. Figure 26 is an aerial photograph of an area within the Town of Vail in which the geometry of residential development is partly controlled by the potential snow-avalanche hazard. Figures 17 and 18 are pre-development photographs of this same area.

Ketchum, Idaho

Portions of the City of Ketchum, Idaho are located below small-to-moderate sized avalanche paths with long return periods. A portion of the exposed residential area is shown in Figure 19. The City of Ketchum was divided over the question of whether building should be restricted in defined hazard zones at the time the ordinance was being considered. Those opposing restrictions claimed that they represent an unfair and possibly illegal "taking" of private property and that they violate the individual's right to do as he wishes with his property. Those in favor of building restrictions similar to those in Vail felt that construction in hazard zones was a matter of "public" rather than "private" interest. They felt a moral responsibility to protect the public, particularly future owners, tenants, and others who may be unaware of the potential hazard.

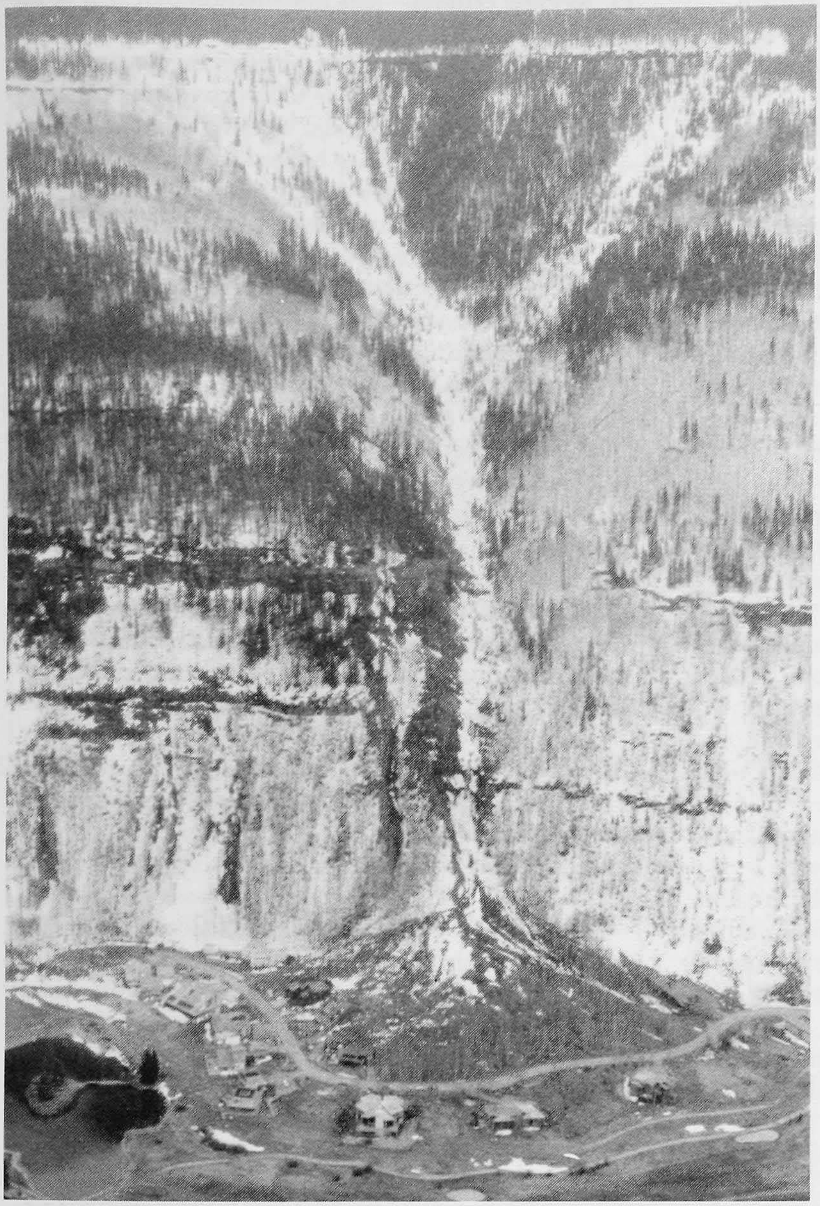


Figure 26. Development along the perimeter of this alluvial fan in Vail, Colorado avoids the area of high avalanche pressure potential and frequency. Some of the homes are located within the Blue (moderate hazard) avalanche zone, and have been reinforced for design-avalanche loads. Compare this with pre-development photographs (Figures 17 and 18).

As a compromise, the following avalanche-zone district was added to the city ordinance with the following provisions.

USE RESTRICTIONS

- All new utilities in avalanche areas will be installed underground.
- Avalanche-defense structures (including buildings reinforced for avalanche loads) will not deflect avalanches toward adjacent property.
- Any building, except a single-family residence will be designed for expected avalanche forces. Design will be certified by an engineer registered in the State of Idaho who will base his design on avalanche studies done by the City of Ketchum or by an independent consultant recognized by the city as an "expert in the field of avalanche occurrence, force, and behavior."
- Any new single-family structure that has not been engineered for avalanche forces will not be leased, rented, or sub-let from November 15 through April 15.
- No further subdivision will take place within the red (high hazard) avalanche zone.

NOTICE REQUIREMENTS

- Subdivision plans will identify lots as lying within red or blue avalanche zones.
- Building plans will identify the proposed building as lying within the red or blue zone.
- Building permit applicants will appear before the city council to receive personal notice of the fact that the proposed building is in an avalanche zone.
- The City of Ketchum will issue any tenant, lessee, or sub-tenant with written notice that the rented property is in the avalanche zone.
- The City of Ketchum will post avalanche-warning signs along public rights of way.
- Real-estate agents, salespersons, or brokers, and each private seller will inform prospective purchasers with notice that the property is in an avalanche zone.

SUSPENSION OF SERVICES

- All city services may be suspended during periods of avalanche danger.

The various provisions in the Vail and Ketchum avalanche zoning ordinances have required a set of avalanche maps which have been defined objectively. Objective procedures in the development of these maps were necessary to ensure a uniform and unbiased treatment of all affected property and to provide a base for hazard designation and mitigation design.

Additional County/Municipal Avalanche Land–Use Controls

As discussed in Niemczyk (1984), municipal and county governments may address several factors that comprise land-use controls in avalanche areas. The factors comprising land-use regulations are listed below.

1. **Purpose**—states the reason for the law, recognizes the potential hazard, and declares the intent to protect people and property.
2. **Definitions**—defines terms which will be used in the proposed ordinance.
3. **Map(s)**—show the known and/or potential avalanche areas and sometimes subdivides the hazard levels into red and blue zones, as discussed on page 37.
4. **Avalanche studies**—requires that all studies that address the avalanche hazard be kept in files.
5. **Applicability**—states the conditions that apply when the law is applicable, usually when a property owner submits a development application in mapped or recognized avalanche areas.
6. **Prohibition**—prohibits the development of land with known or potential avalanche activity.
7. **Districts**—Zoning districts may be established according to the degree of potential hazard if shown on the avalanche map. The most severe zone may prohibit development; less severe zones may require special review.
8. **Restricted uses**—allows some development in hazard zones but normally limits the full potential for development.
9. **Permitted uses**—lists those land-uses allowed in avalanche zones.
10. **Non-conforming uses**—allows continued land use which may be in conflict with the provisions of the ordinance. It may prohibit rebuilding if 50 percent or more of a structure is destroyed by whatever means.
11. **Permit procedure**—requires a permit for development in an avalanche zone and specifies the procedure for acquiring the permit.
12. **Submittal requirement**—lists the information that must be submitted with a permit application. Typically required information includes
    a. Map or maps quantifying hazard;
    b. Report describing the maps and project;
    c. Site plan showing building location, shape;
    d. Calculated avalanche forces on structures;
    e. Mitigation recommendations and specifications;
    f. Discussion of the change in avalanche hazard.
13. **Review criteria**—lists information that will be addressed when reviewing an application.
14. **Criteria for approval**—specifies the findings that government must make to approve the project. Usually the hazard must be eliminated or reduced and must not increase hazard in adjacent areas.
15. **Mitigation**—allows structural mitigation procedures that will eliminate or reduce the hazard.
16. **Design standards**—addresses the design and placement of structures intended to mitigate avalanche hazards.
17. **Map amendment**—allows for the change of avalanche boundaries with submittal of proper evidence such as use of more detailed maps or updated procedures.
18. **Amendment**—allows for changes in the avalanche-zoning regulations.
19. **Variance**—establishes a procedure for granting relief for part of the avalanche-zoning regulations.
20. **Additional studies**—directs the local government to continue studying the avalanche hazard and accumulating data of avalanche effects.
21. **Consultant's qualifications**—sets standards for avalanche consultants.
22. **Referral procedure**—requires review and approval of projects within avalanche zones from appropriate public agencies.
23. **Disclaimer**—states that there exists no guarantee about the accuracy or completeness of the avalanche maps or consultant's recommendations.
24. **Public notice**—requires labeling of all maps, building plans, and other drawings with a notice about potential avalanche hazard. All buyers, renters, tenants, and lessees also require notification.
25. **Suspension of services**—permits the suspension of public services and utilities during times of avalanche danger.

Table 12 lists counties and municipal areas with avalanche-hazard regulations and determines which of the above factors are used at each location. Table 12 illustrates that avalanche-zoning regulations range from being very restrictive (e.g., Vail, Ketchum) to simply providing general information about local avalanche-hazard potential (e.g., Mono County). Passing an avalanche-zoning ordinance has always been difficult. Traditionally, government feels mandated to inform and protect the public, whereas property owners, who may never have seen an avalanche on their property and may have little knowledge about local conditions, are often opposed to any ordinance that may restrict land use and possibly reduce property prices. The more restrictive ordinances are usually found in municipal areas and in particular in those areas in which land prices are high and avalanche mitigation represents a small portion of the cost of development.

Table 12. Land-use factors used in various county and municipal regulations, modified from Niemczyk, 1984.

LAND-USE FACTORS	COUNTY															MUNICIPALITY				
	A	B	C	D	E	F	G	H	I	J	K	L	M	N		AA	BB	CC	DD	EE
1		x	x	x				x		x	x		x	x			x	x	x	x
2			x					x			x		x	x						x
3		x		x			x	x		x			x	x		x	x	x		x
4											x		x	x			x			x
5				x			x			x	x			x						
6	x			x	x	x	x		x		x	x				x				
7		x															x			x
8														x			x			x
9		x					x										x		x	x
10				x							x									
11										x										
12			x	x				x		x	x								x	
13				x			x													
14								x		x										
15					x	x	x			x	x			x		x	x			x
16														x			x		x	x
17				x																
18				x																
19				x																
20														x			x		x	x
21										x	x								x	
22											x									
23										x	x						x			
24																	x			
25																	x			

x —factors used in regulations of each government agency

GOVERNMENT ENTITY

County

A Beaverhead County, Montana
B Blaine County, Idaho
C Gunnison County, Colorado
D Larimer County, Colorado
E Moffat County, Colorado
F Park County, Montana
G Pitkin County, Colorado
H Saguache County, Colorado
I Salt Lake County, Utah
J San Juan County, Colorado
K Summit County, Colorado
L Teton County, Wyoming
N Placer County, California
M Mono County, California

Municipality

AA Breckenridge, Colorado
BB Ketchum, Idaho
CC Ophir, Colorado
DD Sun Valley, Idaho
EE Vail, Colorado

LAND-USE FACTORS

(See previous page.)

Use of Analytical Procedures in Preparing Zoning Maps

Because avalanche-zoning maps must objectively subdivide areas of potential avalanche hazard, will affect the safety of residents, and may be used as input for structural mitigation design, the maps should be developed systematically through application of the best techniques presently available. Avalanche-zoning maps are usually based on avalanche return period and impact-pressure potential (see page 37).

Avalanche return period should be determined by a careful study of the avalanche history, vegetation and geomorphic damage, and study of photographs, including old aerial photos, (Chapter 3). Return periods can usually be placed in three categories:

a. Frequent avalanches (more often than once every 10 years);
b. Ten-year return periods (return periods of 3–30 years);
c. One hundred-year return periods (return periods of 30–300 years).

The longer return-period categories b and c probably cannot be established with greater than order-of-magnitude (nearest factor of 10) accuracy, even with good historic, vegetative, or geomorphic records of avalanches. Avalanches of a given return period are randomly distributed through time, therefore even if a known length of time has elapsed between avalanches at a given location, the true return period will be uncertain. This uncertainty can be expressed by the encounter probability relationship [Chapter 3, equation (3.1), Table 7].

Avalanche impact-pressure potential must be computed by analytical techniques, (Chapters 3 and 5). The impact pressure and total pressure on an exposed object will always be highly dependent on structure location, shape, and orientation, therefore final design forces can never be provided in an avalanche-zoning or mapping study. Reference pressures (for example, on flat surfaces normal to the flow), can be computed. The following steps should be taken to specify the pressure potential for avalanche mapping and zoning studies.

a. The design-avalanche runout distance should be determined by history, study of photographs, geomorphic and vegetative damage, and statistical techniques, (Chapter 3).
b. The design-avalanche width should be determined by techniques similar to those discussed in a, and by detailed study of the terrain barriers and shape in the runout zone. The behavior of previous major avalanches in areas of similar terrain should also be used to estimate avalanche width.
c. The design-avalanche velocity must be computed along the path centerline by application of an avalanche-dynamics model (such as the PCM model, the Swiss procedure or more advanced models). This model should be run between the known top of the starting zone (where velocity is zero) and the tip of the runout zone (where velocity is also zero). If the PCM model is used, the lengths of profile segments in the runout zone chosen should be sufficiently short to define velocity carefully within the decelerating phase of avalanche motion. The Swiss procedure assumes avalanche kinetic energy decreases linearly with distance in the runout zone, therefore

$$V_x^2 = V_P^2\,(1 - x/s), \qquad (4.1)$$

where the beginning of the runout zone is located at the point P (see page 30), x is the distance from P to the design point, s is the runout distance, and V are velocities at the P-point and the design point.
d. Design-avalanche reference impact pressure, P_r , should be computed by applying the relationship

$$P_r = (\rho)\,V^2, \qquad (4.2)$$

where V is the velocity computed along the path profile and ρ is the average flow density. The assumed flow density in most large, dry-snow avalanches will probably range from 50–150 kg/m^3, although densities may be more than 400 kg/m^3 when wet-snow avalanches constitute the design case. Although the densities of wet-snow avalanches will always be large, velocities are small. Dry-flowing avalanche combine velocity and density in such a way as to produce the largest pressure potentials in most cases.

Because avalanche frequency is also used to define the avalanche-hazard zones, the evidence for or against previous avalanches must be carefully considered. However, evidence that avalanches have not occurred for a long time period (a 200-year old forest, for example), does not prove that the "100-year" avalanche cannot reach the site. Application of equation (3.1) illustrates that there exists a 13 percent chance the "100-year" avalanche **will not** occur in a randomly-selected 200 year period.

Avalanche-zoning plans are obviously designed to protect both valuable structures and the people who will use them. However, any development within or adjacent to avalanche areas will increase the hazard potential because of the resulting land use. The persons one wishes to protect may not be inside when the avalanche occurs. This increase in hazard must be accepted by the governmental body, developer, or resident permitting land use in the avalanche areas.

Chapter 5

Avalanche Structural Protection

Overview of Avalanche Mitigation Methods

Avalanche mitigation or control methods are used to eliminate hazard or to reduce it to an acceptable level. Several general categories of avalanche mitigation are discussed briefly below; structural mitigation is discussed in pages 44–51.

Avalanche zoning, (Chapter 4), is the most desirable type of mitigation from the standpoint of safety. When the area affected by the design-magnitude avalanche is mapped, and development avoids the mapped area, mitigation is achieved through avoidance of the potential hazard. However, zoning and avoidance are not always acceptable alternatives for all types of land uses. Transportation, communication, and utility routes often pass through avalanche terrain. In many cases residential structures and other buildings are located in avalanche paths because the building sites are desirable for economic or social reasons and because the avalanche risk can be reduced to an acceptable level by some type of protection.

Evacuation of avalanche paths during periods of potential activity also achieves avoidance with respect to human exposure, but does nothing to protect property or fixed facilities. Furthermore, evacuation depends on a reliable forecast of snowpack stability for the rare, design event. However, little experience has been gained in forecasting for the extreme events, therefore forecasting sometimes is inaccurate. Those responsible for forecasts may not be available when the unusual weather or snow conditions occur, or the avalanche warnings may not reach all people who would be affected by large avalanches. Given all the uncertainties, evacuation is not recommended as an avalanche-protection method to be used at residential areas. At times, however, warning and evacuation must be used when areas are already exposed and may be acceptable for temporary industrial operations such as construction or mining camps if damage to fixed facilities is acceptable.

Artificial release is the most common avalanche-control method used in the United States. This method is fairly economical, and is often accomplished by skilled personnel who are familiar with local conditions. However, in some cases, artificially-released avalanches have been larger than expected and damaged structures or killed people.

The reliability of artificial release is questionable. When large volumes of unstable snow are released by explosive control, and the released avalanches are of manageable proportions, the method is considered to have been reliable. However, at times no avalanche, or only small slides occur after blasting, or the effect of explosive control cannot be observed because of inclement weather or time of day. When these situations result, important questions must be asked with regard to the effect explosives have had on the avalanche hazard:

a. Because no large avalanches have occurred, does this indicate the snowpack is stable?;
b. Have the explosive-control attempts weakened the snowpack, making future avalanches more likely?

Unfortunately, the answers to these questions are not known; the only definite answer with regard to the effect of explosives on the hazard occurs when an avalanche is observed and unstable snow has been released from the starting zones. Even then, avalanches may be much smaller or larger than anticipated. In some cases, artificially-released avalanches have damaged structures and killed people. Due to all the uncertainties about the reliability of artificial release, these methods are not a recommended avalanche-mitigation method above developed areas.

Avalanche-control structures should be used where avalanches cannot be avoided and other control methods such as evacuation, explosive control, and timed avoidance are not applicable because of the reasons discussed above. Structures have various forms and purposes.

a. **Supporting structures**—These structures prevent avalanche release and/or reduce avalanche size.

b. **Snow-drift fences**—Fences reduce the amount of snow blown into starting zones, thereby reducing avalanche frequency and size.
c. **Deflecting berms**—Berms change the direction of avalanche runout in the lower track and runout zone and eliminate or reduce hazard in certain areas.
d. **Catching structures**—Avalanche dams or mound fields reduce avalanche runout distance.
e. **Direct-protection structures**—Structures reinforced for avalanche impact and deposition loads protect isolated buildings and other objects.

Each type of structural avalanche-defense option has advantages and disadvantages, some of which are discussed in subsequent sections of this chapter.

Supporting Structures

Purpose

Supporting structures are intended to anchor the snow slab to the ground in the starting zone, thereby preventing avalanche release. In some cases only the upper portion of starting zones can be anchored by structures because of economic or topographic constraints, thus avalanches are not prevented but are reduced in size. Supporting structures are appropriate when valuable objects or high-risk facilities are exposed to avalanches, when starting zones are small and accessible, and when design snowpack depths are less than approximately 4.5 m. Because supporting structures are expensive, may scar the terrain, and are not 100 percent effective, development in avalanche areas should not proceed with the intention of building supporting structures to protect proposed development unless high construction and maintenance costs are acceptable and residents accept the residual risk.

Figure 27. Supporting structures are built across the avalanche starting zone above this Swiss village. The structures are nearly continuous across the slope to prevent small avalanches from flowing between structures.

Structure forms

Modern supporting structures consist of continuous or closely-spaced fences, vertical rakes, or wire-rope nets built in rows across the slope. Typical supporting structures which have been built to protect Swiss villages are shown in Figures 27 and 28.

Construction materials used include wood, aluminum, steel, and reinforced concrete. Modern structures are built primarily from steel. Structures must resist very large forces that result from downslope creep (internal deformation) and glide (slip at the ground surface) of the snowpack and the impact of small avalanches. The creep and glide forces increase quickly with snow depth, snow density, reduced ground roughness, and slope angle, all factors that must be carefully considered in engineered design. The snow depth is an

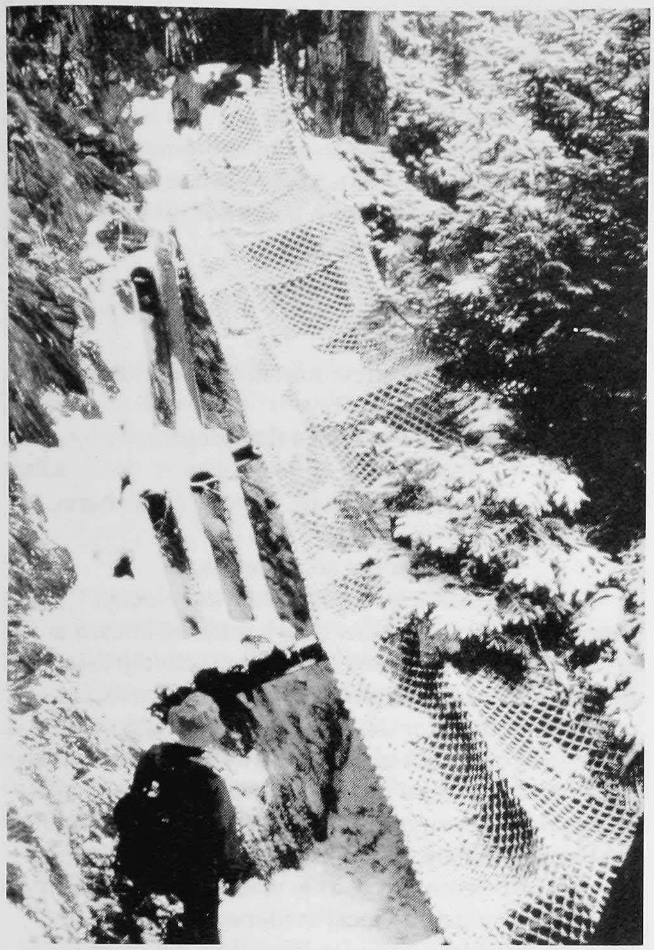


Figure 28. These snow-net supporting structures are designed to resist large creep (internal deformation) and glide (slip at ground interface) forces from the design avalanche.

especially critical design parameter because the supporting structures will not prevent avalanche release when the snowpack depth exceeds the structure height. Furthermore, snow depth often varies considerably across an avalanche starting zone in response to wind scour and deposition, exposure to the sun, and topographic irregularities. Therefore, tall structures may be required in certain areas while only short structures may be needed in adjacent areas.

Guidelines for the design of supporting structures can be found in the translation of the Swiss design guidelines (Frutiger and Martinelli, 1964). More recent research on measurements and calculations of design forces are given in McClung, et. al. (1984). Design forces, in general, have been shown to increase in proportion to the square of the snowpack depth, which, as discussed above, must be determined accurately and objectively in design.

Advantages

A properly designed and maintained array of supporting structures will eliminate large avalanches and will reduce the avalanche hazard in the lower track and especially in the runout zone.

Disadvantages

Supporting structures are expensive. In areas of deep snow cover and steep starting zones with difficult access they may cost \$1,000,000 for every 10,000 m^2 (\$400,000 per acre). Even with ideal conditions, (shallow snowpack, easy access), costs will approach \$500,000 per 10,000 m^2 (\$200,000 per acre). These high costs probably eliminate supporting structures except in small, accessible starting zones. Private development interests rarely will be able to afford these high costs. Extensive arrays of supporting structures (Figure 27) may be visually unappealing, will scar the terrain, and may create erosion or other undesirable environmental effects.

Finally, supporting structures are not 100 percent effective. Studies in Switzerland (Frutiger, 1988) have shown that small avalanches sometimes run through supporting structures. As a result, the Swiss assume that avalanches of reduced proportions will occur even after expensive structures have been erected in starting zones. The assumed hazard in some highly-exposed runout zones, therefore, is assumed to be reduced, but not eliminated.

Snow Drift Fences

Purpose

Wind fences and baffles in and adjacent to avalanche starting zones alter the wind flow over ridges and reduce the amount of snow blowing into starting zones. In addition, fences distribute the snow lower on the slope. Because many avalanches result from snow accumulating in starting zones as a result of wind transport, snow fences can reduce avalanche frequency and size.

Structure form

Snow fences can be located as shown in Figure 29. The fence produces a snow deposit on the windward side of the ridge instead of in the starting zone. This reduces avalanche frequency and size.

Advantages

Snow drift fences are inexpensive (<10 percent of supporting structure cost), and can be erected quickly with a minimum of excavation for foundations. They may be very effective in reducing avalanche frequency in starting zones which are usually subject to strong wind redistribution of snow.

Disadvantages

The fences will not prevent avalanches during storms with unusual wind directions or during storms with light winds. In some cases, these unusual conditions may produce maximum avalanches in some paths. If such unusual wind-loading or storm conditions are considered to be possible during the design period, fences should not be depended upon to provide adequate protection from avalanches. The fences may also have an undesirable appearance in some mountain areas and also will not prevent avalanches resulting from high temperatures or rain.

Deflecting Berms

Purpose

Deflecting berms in the lower track and runout zone intercept and deflect avalanches at a small angle to their natural flow direction and divert snow away from the objects to be protected. They do not necessarily shorten avalanche runout distance.

Structure form and design

Deflectors are usually earthen berms 5 to 12 m high but may also be structural or rock-filled cribbing. Experience has shown that deflecting angles of less than 25° are generally required to deflect avalanches and also keep the avalanches moving, reduce deposition at the base of the berm, and prevent overtopping. Because runout distances are not shortened by deflectors, design must ensure adequate space for the deflected snow. The minimum height, H, of the berm can be estimated by the equation

$$H = H_s + H_a + H_v, \tag{5.1}$$

where H_s = depth of previous snow and avalanche deposits,
H_a = design-avalanche flow depth,
H_v = $(V \sin ø)2/2g$,
V = design-avalanche velocity at the berm,
$ø$ = deflection angle, and
g = gravitational acceleration.

Design-avalanche criteria such as velocity, V, at the design point and flow depth must be known in order to apply equation (5.1) and objectively determine the required height of structures. The recommended method for determining the design velocity is through application of statistical and physical modeling procedures, (see page 23). Because the velocity is an important design parameter, it must be determined in some systematic manner (Chapter 3). The design height can be computed, as is usually done in Switzerland, or estimated by local evidence of damage on trees or structures. Powder-blast flow height may exceed flowing debris height by 10 m or more, (Chapter 2 and 3), therefore, large, dry-snow avalanches cannot be completely diverted by berms.

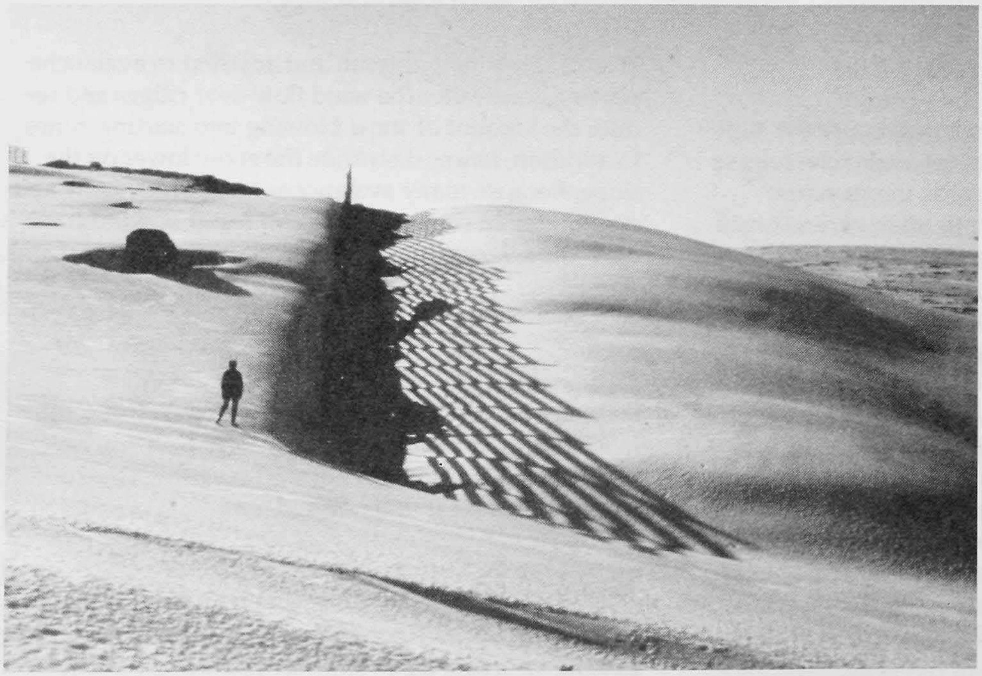


Figure 29. These snow (wind) fences reduce the amount of snow blown into the starting zone and decrease avalanche frequency and size on an avalanche path in western Norway (photo by J. O. Larsen).

Forces on deflecting berms result from the momentum change of the design avalanche. Massive earthen structures are usually stable with respect to large avalanche forces. Structural walls, however, require a careful analysis to determine if they are stable against overturning, sliding, and crushing. Pressures normal to a deflecting wall, P_n, can be estimated by the equation

$$P_n = \rho(V \sin ø)^2, \qquad (5.2)$$

where V and $ø$ are defined above and ρ is the avalanche flow density. Unit uplift, P_v and shear P_s forces also result from avalanche momentum change at the wall and can be estimated by the relationship

$$P_v = P_s = 0.5\, P_n. \qquad (5.3)$$

The height H, over which the forces on the berm act, is determined by equation (5.1). These forces can be assumed to be uniformly distributed with height, however this is probably a conservative overestimate. An alternative assumption is that forces are reduced linearly with height, similar to a hydrostatic load. Berm design height and strength must be rationally based on calculated design criteria.

Figure 30 illustrates the various design criteria required for berm design.

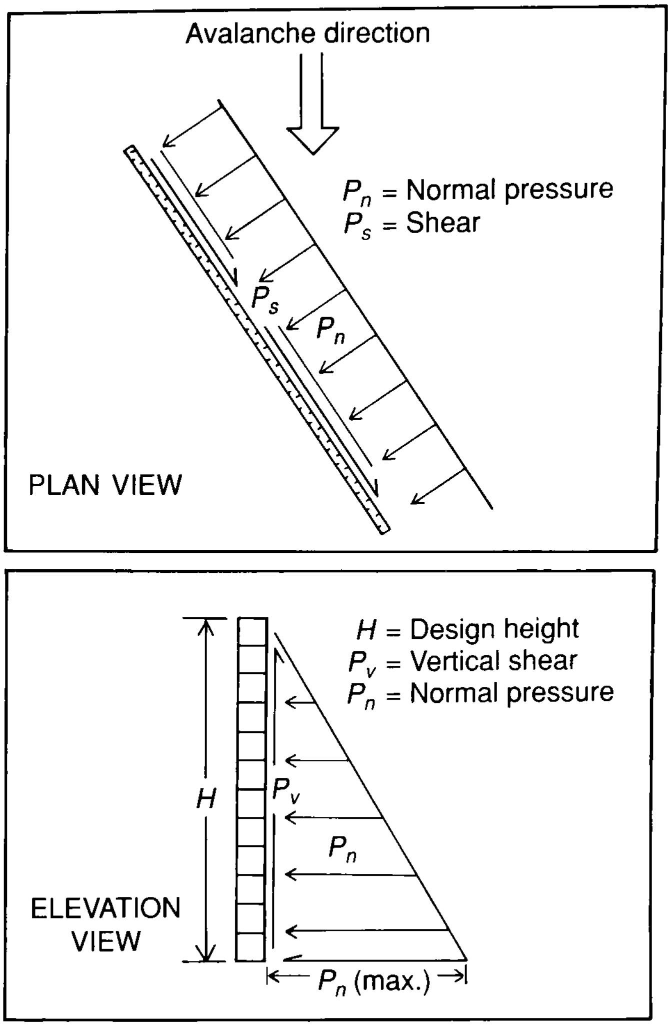


Figure 30. Forces acting on an avalanche deflecting wall.

Advantages

Deflecting berms, especially the earthen variety, are relatively inexpensive. Costs will depend on the size of the defense work which, in turn, depends on the size of the design avalanche and area requiring protection, the availability of material, and heavy-equipment charges. All of these factors will vary considerably from one area to another. When terrain and other factors are suitable, large areas can be made hazard free.

Disadvantages

Berms may not be effective on gentle slopes (<15°), when more than two avalanches per season are expected. In such cases, avalanche deposits will tend to backfill berms, thereby reducing the effective height and enabling subsequent avalanches to overrun them easily. Earthen structures may also require a large volume of material because they will generally be approximately three times as wide as they are high (assuming 1.5:1 side slopes). This means they sometimes can scar the terrain over wide areas and may occupy land that could be used for other purposes. As noted above, deflecting berms probably will not be effective in changing the direction of fast moving dry-snow or powder avalanches. Berms may also increase avalanche runout distance in the direction of deflection.

Retarding Mounds

Purpose

Mounds shorten runout distances by creating additional friction between the avalanche and the ground, spreading avalanches laterally, and reducing the effective flow height. They can be used to reduce the runout distance and volume of flowing avalanches but do little to shorten the runout of fast-moving powder avalanches.

Structure form

Individual mounds are usually conical-shaped earthen structures 4 to 8 m high arranged in a checker-board pattern with the rows placed at right angles to the avalanche flow direction. Construction of the uppermost rows should begin on slopes of less than 20° (less than 15° in large avalanche paths), and should continue downslope as far as is practical or at least as far as the usual runout distances of moderate-sized avalanches. The design height of the mounds should be at least equal to the expected maximum snow depth plus the expected flow height of avalanches during design conditions. An example of an earthen mound system is shown in Figure 31.

Advantages

Mounds can be built easily and quickly, using local material and earth-moving equipment. An array of 20 mounds 5 m high, for example, might require three to five days for one heavy-equipment operator to build, assuming material did not have to be hauled to the site. Construction costs will depend on the size of the area requiring protection and unit costs for labor and heavy equipment. Unlike the berms discussed on page 46, mounds will not change avalanche direction and will not increase the runout distance in any direction.

Disadvantages

Construction of a large mound array may cause considerable damage to the local environment through disruption of the ground surface and changes in and creation of erosion patterns. They will not be effective when large avalanches flow into the mound array more than two times per season. Multiple avalanche events tend to deposit snow between the mounds and reduce the effective height and energy-dissipating capacity of the mound field. As noted above, mounds will do little to stop, slow, or shorten the runout distance of powder avalanches. Therefore, buildings or other facilities located where powder avalanches are thought to comprise the design case should not be located directly below mounds unless additional avalanche protection is incorporated into design.

Catching Dams

Purpose

Catching dams reduce the avalanche runout distances and can sometimes be used in place of or in conjunction with mounds (see page 47).

Structure form and design

Catching dams are similar in form to deflecting berms but are built perpendicular to avalanche flow direction because they are intended to stop, rather than deflect the snow. Most commonly dams are earthen structures, but they can be structural barriers with vertical slopes on the uphill sides and fill on the downslope sides. The design height, H, of catching dams can be estimated by equation (5.1) when it is assumed that the deflection angle, $ø = 90°$. Hungr and McClung (1986) suggest that equation (5.1), which is derived from simple conservation of energy considerations (Voellmy

Figure 31. The uppermost row of mounds are located on a slope of 15°, where avalanche begin to decelerate naturally. Four rows of mounds have been used in this case to provide protection from the "10-year" avalanche.

1955, Mears 1981) tends to underestimate the design height because it does not consider the effect of thrust and momentum which is transferred from the back to the front of the avalanche. They calculate runup heights which are approximately 50 percent larger than those calculated by (5.1). In modern Swiss practice the third term of equation (5.1), H_v, is adjusted by an internal friction factor, k, which reduces the calculated design height, H, which, therefore is written

$$H = H_s + H_a + V^2/2gk. \quad (5.4)$$

The internal friction factor, k, ranges from 1.5 for low-density flowing avalanches to 3.0 for avalanches of dense snow.

Application of equation (5.1) or (5.4) indicates how quickly design height increases with velocity for a barrier normal to the flow direction. In general, it will not be possible to stop avalanches behind berms when the design velocity is greater than 20 m/s. Even this moderate velocity would require a structure approximately 20 m high. In addition to the design-height requirement, sufficient storage volume for avalanche debris must be provided behind the dam, particularly if more than one event per season is expected.

Advantages

Because dams are usually earthen structures, like berms and mounds they are relatively inexpensive to build. When the design conditions are appropriate, dams can reduce avalanche exposure over relatively large areas. Although they do not provide complete protection in all cases, dams can be used to reduce avalanche frequency, exposure to motorists, and clean-up costs at some highway locations.

Disadvantages

Similar to the other earthen structures discussed, dams may require large amounts of earthwork and more space than is available. Furthermore, they may alter the appearance of the terrain considerably. When dams are not built sufficiently high, the design avalanche can be launched over the top and may descend on adjacent unprotected objects. In such cases, dams do not reduce the hazard and are an inappropriate form of structural defense.

Direct–Protection Structures

Purpose

Direct-protection structures are used to provide complete protection for individual objects or areas (e.g., buildings, portions of highways, transmission towers, etc.), that are exposed to avalanches. These are the probably the most important form of structural avalanche mitigation used in the United States because they can be designed on an individual basis and often do not require large amounts of material or space.

Structure form and design

Several forms of direct protection are commonly used, including

a. detached or internal splitting wedges and walls used for protection of buildings, electrical-transmission towers, lift towers, etc.;
b. direct reinforcement of buildings and other objects for avalanche impact and deposition loads; and
c. avalanche sheds over railroads and highways.

One important special case of direct protection which has been used at many sites in western North America is reinforced building design to resist the loads produced by the design avalanche. Much of the avalanche protection in Ketchum, Idaho and Vail, Colorado, and Alta, Utah has been in response to avalanche-zoning ordinances (Chapter 4). Building shapes, sizes and orientations as well as design-avalanche characteristics determine direct-protection design for buildings.

The general procedure for determining the design criteria to be used in direct protection is as follows.

1. The **return period**, of avalanches at the design location must be estimated. This includes avalanches reaching the site which are smaller than design magnitude. As a general rule, return periods of less than 25 to 50 years are too short to allow residential or public buildings, because short return periods increase the probability that persons may be outside when the avalanche occurs. Some mountain communities (e.g., Alta, Utah; Juneau, Alaska) do allow construction where avalanches are known to have return periods of less than 25 years.
2. The **design period** of the avalanche to be considered in direct-protection design must be established. As discussed in Chapter 3, the design period may be 100 years for residential buildings or valuable structures, but may be longer for certain public facilities such as restaurants and hotels where large numbers of people may be concentrated. A decision about what the design period should be is an important part of the avalanche mitigation process; avalanches with longer design periods will have more energy and are more difficult to design for than avalanches with shorter design periods.
3. The **design avalanche characteristics** must be determined at the design point. This requires that analytical procedures be applied (Chapter 3), to determine avalanche velocity, and energy density

(impact-pressure potential) at the site. Specifically, design requires information about

a. Type of avalanche during design conditions (dry, wet, powder, or combinations),
b. Velocity,
c. Flow density,
d. Flow height and width, and
e. Other factors (solid debris in flow, debris deposition, etc.).

Not all of the required design information can be calculated, and calculated results do not always have a high confidence (Chapters 2 and 3). Observations of local field evidence of previous avalanches must be carefully used with the analytical procedures to determine if the results are realistic.

4. **Structural design** must be based on the characteristics determined in step 3. To complete the design, information will be needed by the structural engineer and/or architect about the magnitude, direction, duration, dimensions, and other characteristics of the loads. In general, the forces on exposed structures will differ from the impact-pressure potential at an area because object shape will influence the magnitudes of the loads.

The heights of and forces on direct-protection walls can be estimated by relationships presented in this chapter with appropriate assumptions made about design snowpack depth, avalanche flow depth, and avalanche flow density, and with the Swiss approach, internal friction. Static depositional forces will also occur when avalanche debris is compressed and deposited on top of and against objects. The vertical overburden loads depend on the debris density, which will be 400 to 600 kg/m^3, and the anticipated debris depth. Depth is highly dependent on the shape of the object. Horizontal loads from debris deposition will be triangular, distributed similar to hydrostatic loads, but will be smaller because the shear strength within the snow tends to reduce lateral pressures.

If a large surface changes direction of all the avalanche flow, the normal pressure, P_n, on the surface is

$$P_n = \rho(V \sin \varnothing)^2, \quad (5.5)$$

where V is velocity at the design location, ρ is flow density, and $\varnothing$ is the deflection angle. If the object is small compared to the avalanche cross section only a portion of the avalanche energy is absorbed and the pressure is calculated

$$P = CA(\rho V^2)/2, \quad (5.6)$$

where C is a shape factor (1 for a circular cross section, 2 for a rectangular cross section), and A is surface area exposed to the avalanche.

In addition to the impact and deposition loads discussed above, objects exposed to powder avalanches also receive fluid-dynamic stagnation pressures (drag and uplift) and resulting forces. The stagnation pressure, P_s that results when high-velocity powder avalanches engulf an object is computed

$$P_s = 0.5\,\rho\,V^2, \quad (5.7)$$

where ρ is the powder-avalanche density generally assumed to be in the range of 5 to 15 kg/m^3.

The stagnation pressure must be converted to fluid-dynamic forces consisting of *drag*, F_d, and *lift*, F_l components which are computed

$$F_d = C_d\,A\,(P_s), \quad (5.8)$$

and

$$F_l = C_l\,A\,(P_s), \quad (5.9)$$

where Ps is calculated by equation (5.7). The factors C_d and C_l are drag and lift coefficients which must be determined from an aerodynamic analysis of structure shape, given the fact that powder-avalanche interaction with the structure will be fully turbulent and Reynold's numbers will usually be more than 10^7. For a first approximation, values for C_d and C_l may be taken from those tabulated in building codes. The factor, A, is the cross-sectional area exposed to avalanche drag or lift forces.

Buildings and other large objects will experience the fluid-dynamic forces expressed in equations (5.7), (5.8), and (5.9) well above the height, H, [equation (5.1)] which will be exposed to flowing-avalanche forces. Drag and lift forces from powder avalanches may be larger than those resulting from flowing avalanches because powder avalanches may subject a large surface area to avalanche loads whereas the flowing component may affect a smaller area.

Advantages

Direct-protection structures can often be designed and built on an individual basis and may not require large amounts of space. In the special case of reinforced building design, reinforcement may require no more room than the original structure. Design can be architecturally acceptable and can provide complete protection from all types of avalanches, including powder avalanches. Avalanche sheds provide complete protection for highways and railroads, and are justified when avalanche hazard is high, the length of road covered is short, and other types of avalanche defense are of limited effectiveness.

Disadvantages

Direct protection may not be possible when closely-spaced buildings are exposed to avalanches because one reinforced building may deflect the snow laterally or vertically onto adjacent buildings. Direct protection can be very expensive for property owners. Experience in several North American resort communities indicate the additional expense of direct protection may be 10–20 percent of the total building cost. Finally, direct protection may increase the overall avalanche hazard by increasing human activity within avalanche areas, a fact considered and accepted in many avalanche-zoning ordinances. Avalanche sheds are also expensive. Recent costs of sheds over modern highways range from $3,000 to $9,000 per foot of highway covered.

Some Examples of Direct Protection

Some examples of methods that have been used to reduce avalanche forces and protect buildings are shown in Figures 32, 33, and 34. The 300-year old Swiss church (Figure 32) uses a splitting wedge that deflects avalanches through a small angle and reduces the magnitude of avalanche forces. This church has survived avalanche impact, although it suffered minor damage when reached by a large avalanche in 1968.

The duplex structure (Figure 33) in Ketchum, Idaho was designed with a reinforced ramp roof facing toward the avalanche flow direction. Avalanche

Figure 32. The splitting wedge on this Swiss church deflects avalanches laterally, reducing normal forces.

Figure 33. This ramp roof in Ketchum, Idaho faces toward the avalanche direction. The small deflection angle reduces avalanche dynamic loads.

Figure 34. The reinforced uphill corner of this house near Aspen, Colorado is oriented toward the avalanche direction and acts as a splitting wedge.

forces on the roof consist of avalanche deflection, normal and shear forces and avalanche depositional loads. Calculations have shown that a small portion of the design avalanche will climb over the peak of the ramp and produce small avalanche loads on sections on the downhill side of the building, therefore these sections were also reinforced.

Figure 34 shows a single-family house near Aspen, Colorado built just beyond the limit of known avalanches but within the potential avalanche area. The building was oriented with the uphill corner facing into the avalanche and the uphill building walls were designed for flowing and powder avalanches.

References

Bakkehoi, S., Cheng, T., Domaas, U., Lied, K., Perla, R., and Schieldrop, B., 1981, On the computation of parameters that model snow avalanche motion: Canadian Geotechnical Journal v. 18, no. 1, p. 121–130.

Bakkehoi, S., Domaas, U., and Lied, K., 1983, Calculation of snow avalanche runout distance: Annals of Glaciology v. 4, p. 24–29.

Burrows, C. and Burrows, V., 1976, Procedures for the study of snow avalanche chronology using growth layers of woody plants: University of Colorado Institute of Arctic and Alpine Research Occasional Paper 23, 54 p.

de Quervain, M., 1975, Avalanche formation, *in* U.S. Forest Service, 1975, Avalanche protection in Switzerland: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report RM-9, p. 6–18.

Dent, J. D., and Lang, T. E., 1980, Modeling of snow flow: Journal of Glaciology v. 26, no. 94, p. 1311–40.

Fitzharris, B., 1981, Frequency and climatology of major avalanche winters at Rogers Pass, 1909 to 1977: National Research Council Canada, DBR Paper No. 956, 42 p.

Frutiger, H., 1962, Avalanche control in the starting zone (translation of Swiss guidelines:. U.S. Department of Agriculture, Forest Service Station Paper No. 71. 60 p.

Frutiger, H., 1970, Der Lawinenzonenplan (LZP), Schweizerische Zeitschrift für Forstwesen, 121 Jahrbuch, Nr. 4, p. 246–276. (The avalanche zoning plan Translation No. 11: U.S. Department of Agriculture, Forest Service, Alta Avalanche Study Center.)

Frutiger, H., 1988. On the effectiveness of avalanche control by supporting structures, Interpraevent-Graz, p. 137–188.

Frutiger, H., and Martinelli, M., Jr., 1966, A manual for planning structural control of avalanches: U.S. Department of Agriculture, Forest Service Research Paper RM-19. 68 p.

Gubler, H., 1987, Measurements and modeling of snow avalanche speeds: International Association of Hydrological Sciences Publication 162: p. 405–420.

Gubler, H., 1989, Comparison of three models of avalanche dynamics: Annals of Glaciology v. 13. p. 82–89.

Hungr, O. and McClung, D. M., 1987, An equation for calculating snow avalanche run-up against barriers: International Association of Hydrological Sciences No. 162. p. 605–612.

LaChapelle, E. R., 1966, Encounter probabilities for avalanche damage: U.S Department of Agriculture, Forest Service, Alta Avalanche Study Center Miscellaneous Report No. 10, 10 p.

Lied, K. and Bakkehoi, S., 1980, Empirical calculations of snow-avalanche run-out distance based on topographic parameters: Journal of Glaciology, v. 26, no. 94, p. 165–178.

Lied, K. and Toppe, R., 1989, Calculation of maximum snow avalanche runout distance based on topographic parameters identified by digital terrain models: Annals of Glaciology, v. 13.

Martinelli, M., Jr. 1974, Snow avalanche sites, their identification and evaluation: U.S. Department of Agriculture, Forest Service, Agriculture Information Bulletin 360, 26 p.

McClung, D. M., Larsen, J. O., and Hansen, S. B., 1984, Comparison of snow pressure measurements and theoretical predictions: Canadian Geotechnical Journa,. v. 21, no. 2, p. 250–258.

McClung, D. M. and Schaerer, P. A., 1983, Determination of avalanche dynamics friction coefficients from measured speeds: Annals of Glaciology v. 4, p. 170–173.

McClung, D. M. and Schaerer, P.A., 1985, Characteristics of flowing snow and avalanche impact pressures. Annals of Glaciology, v. 6, p. 9–14.

Mc Clung, D. M., Mears, A. I., and Schaerer, P. A, 1989. Extreme avalanche runout: Data from four mountain ranges: Annals of Glaciology, v. 13.

McClung, D. M. and Lied, K., 1987, Statistical and geometrical definition of snow avalanche runout: Cold Regions Science and Technology, v. 13, p. 107–119.

McClung, D. M., 1990, A model for scaling avalanche speeds: Journal of Glaciology, v. 36, no. 123, p 107–119.

McClung, D. M. and Mears, A. I., 1991, Extreme value prediction of snow avalanche runout: Cold Regions Science and Technology, v. 19, p. 163–175.

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

Mears, A. I., 1976, Guidelines and methods for detailed snow avalanche hazard investigations in Colorado: Colorado Geological Survey Bulletin 38, 125 p.
Mears, A. I. 1980, Municipal avalanche zoning: contrasting policies of four western United States communities: Journal of Glaciology, v. 26, no. 94, p. 355–362.
Mears, A. I., 1980, A fragment-flow model of dry-snow avalanches: Journal of Glaciology, v. 26, no. 94, p. 153–164.
Mears, A.I., 1981, Design criteria for avalanche control structures in the runout zone: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-84, 28 p.
Mears, A. I. ,1988, Comparisons of Colorado, Eastern Sierra, coastal Alaska, and Western Norway runout data: Proceedings of the International Snow Science Workshop, p. 232–238.
Mears, A. I., 1989, Regional comparisons of avalanche-profile and runout data: Arctic and Alpine Research, v. 21, no.3, p. 283–287.
Moore, S. and McCabe, P., 1989, Introduction to the practice of statistics: W. H. Freeman and Company, 790 p.
Norem, H., Irgens, F., and Schieldrop, B., 1989, Simulation of snow-avalanche flow in run-out zones: Annals of Glaciology, v. 13, p. 218–225.
Norem, H. and Kristensen, K., 1986, The Ryggfonn project—avalanche data from the winter 1983–84: Norwegian Geotechnical Institute Report 58120-07, 14 p.
Norem, H., Kvisteroy, T., Evensen, B. D., 1985, Measurements of avalanche speeds and forces—Instrumentation and preliminary results of the Ryggfonn project: Norwegian Geotechnical Report 58120-05.
Norem, H., Kristensen, K., and Tronstad K., 1986, The Ryggfonn project—avalanche data from the winter 1984–85: Norwegian Geotechnical Institute Report 58120-08.
Norem, H., Kristensen, K., and Tronstad, K., 1987, The Ryggfonn project—avalanche data from the winter 1985–86: Norwegian Geotechnical Institute Report 58120-10.
Norem, H., Kristensen, K., and Tronstad, K., 1988, The Ryggfonn project—avalanche data from the winter 1987–88: Norwegian Geotechnical Institute Report 581200-13.
Norem, H., Kristensen, K., and Tonstad, K., 1989, The Ryggfonn Project—avalanche data from the 1988–89 winter: Norwegian Geotechnical Institute Report 581200-15.
Norem, H., Kristensen, K., and Tronstad, K. 1991, The Ryggfonn project—avalanche data from the 1989–90 winter: Norwegian Geotechnical Institute Report 581200-21, 18 p.
Niemczyk, K., 1984, Factors comprising county/municipal land-use controls addressing snow avalanches: Proceedings of the International Snow Science Workshop, Aspen, Colorado, p. 90–94.
Perla, R. and Martinelli, M., Jr., 1976, Avalanche Handbook. U.S. Department of Agriculture, Forest Service Agriculture Handbook No. 489.
Perla, R., Cheng, T. T., and McClung, D. M., 1980, A two-parameter model of snow-avalanche motion. Journal of Glaciology v. 26, no. 94, p. 197–208.
Perla, R., Lied, K., and Kristensen, K., 1984, Particle simulation of snow avalanche motion: Cold Regions Science and Technology, v. 9, p. 191–202.
Salm, B., 1975, Principals of structural control of avalanches, *in* U.S. Forest Service, 1975, Avalanche protection in Switzerland: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report RM-9, p. 45–55.
Salm, B., Burkard, A., and Gubler, H., 1990, Berechnung von Fliesslawinen eine Anleitung für Praktiker mit Beispielen: Mitteilungen des Eidgenossischen Instituts fur Schnee-und Lawinenforschung No. 47, 37 p.
Sommerhalder, E., 1965, Lawinennkraeft und Objectschutz: Winterbericht des Eidg. Institut fuer Schnee-und Lawinenforschung, Nr. 29. [English translation: Avalanche forces and the protection of objects. U.S. Department of Agriculture, Forest Service, Alta Avalanche Study Center Translation No. 6.]
Tesche, T. W., 1986, A three dimensional dynamic model of turbulent avalanche flow, *in* Proceedings of the International Snow Science Workshop, Lake Tahoe, Calif., October 22–25, 1986, p. 111–137.
Voight, B., ed., 1978, Rockslides and avalanches, 1: Natural phenomena: Amsterdam, Netherlands, Elsevier Scientific Publishing Co.
Voellmy, A., 1955, Uber die Zerstorungskraft von Lawinen: Schweizerische Bauzeitung, Jahrg. 73, No. 12, p. 159–162. [English translation: On the destructive force of avalanches: U.S. Department of Agriculture, Forest Service, Alta Avalanche Study Center Translation No. 2, 1964.]
Williams, K., 1975, The snowy torrents: avalanche accidents in the United States, 1967–71: U.S. Department of Agriculture,Forest Service, Rocky Mountain Forest and Range Experiment Station,General Technical Report RM-8, 190 p.

Other Publications on Snow Avalanches Available from the Colorado Geological Survey

Information Series 36
Snow and Avalanche: 1991–92 Annual Report, Colorado Avalanche Information Center, 1992, Colorado Avalanche Center, 54 p.

Miscellaneous Information 30
The Avalanche Book, B. Armstrong and K. Williams, 1986, revised 1992, 212 p.

Special Publication 7
Colorado Avalanche Area Studies and Guidelines for Avalanche-Hazard Planning, A. I. Mears, 1979, 124 p.