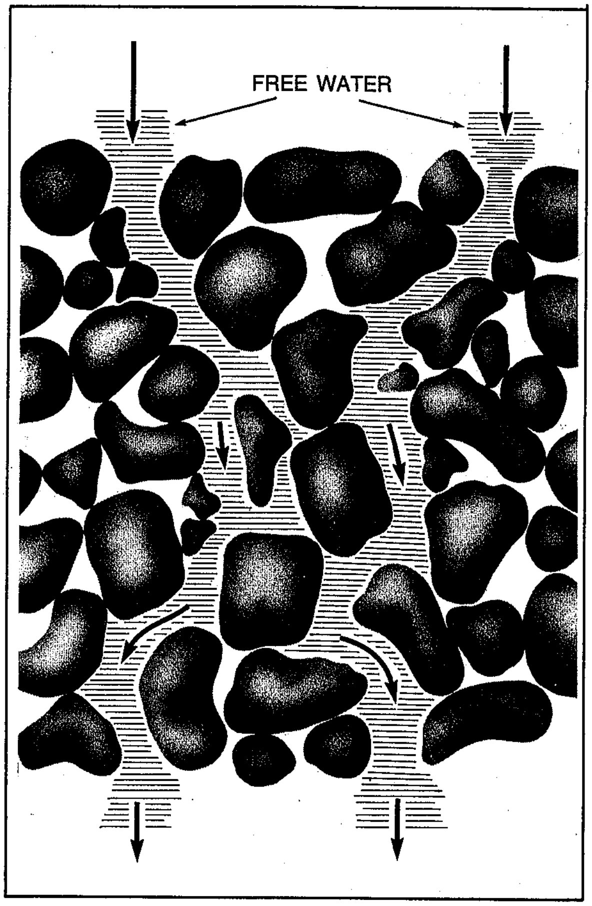


Figure 4.17. Illustration of free water flow through snow. In general, air, ice (snow grains), and free water may be present.

the overall strength to increase. Once densification occurs, the cohesion component of strength may also increase.

LOOSE SNOW AVALANCHE FORMATION

Loose snow has little or no cohesion. Loose snow avalanches form near the surface and they involve near-surface snow on initiation. Once the descent starts, subsurface snow beneath the surface may be swept along, particularly if the snow is wet (Figure 4.17). Snow of low cohesion may be either dry or wet, but the important point with respect to water content is that wet loose snow avalanches can be much more massive than dry ones. For either dry or wet loose avalanches, th basic mechanism is the same: The slope angle exceed the critical angle (called the *angle of repose* or *stati friction angle*) necessary to cause motion. A stati friction angle may be defined for each type of snow initiate downslope motion depending on grain geom etry, temperature, cohesiveness, and water content.

Loose snow avalanches are easily recognizable b cause they start from a point and the mass of sno displaced forms a triangular pattern on descent. The involve a small initial volume of surface snow, whi slips out (usually less than 10^{-4} m^3). Natural loose sno avalanches are triggered by a local loss of cohesion d to metamorphism or the effects of sun or rain (Fig 4.18). Often the initiation is near rock outcrops, whi cause locally high snow temperatures. Of course, na ral or artificial disturbances to surface snow are al important triggers of loose snow avalanches (e.g., s ers, falling rocks, or snow).

Wet loose avalanches are usually triggered by he melt due to warming by the sun or rainfall on

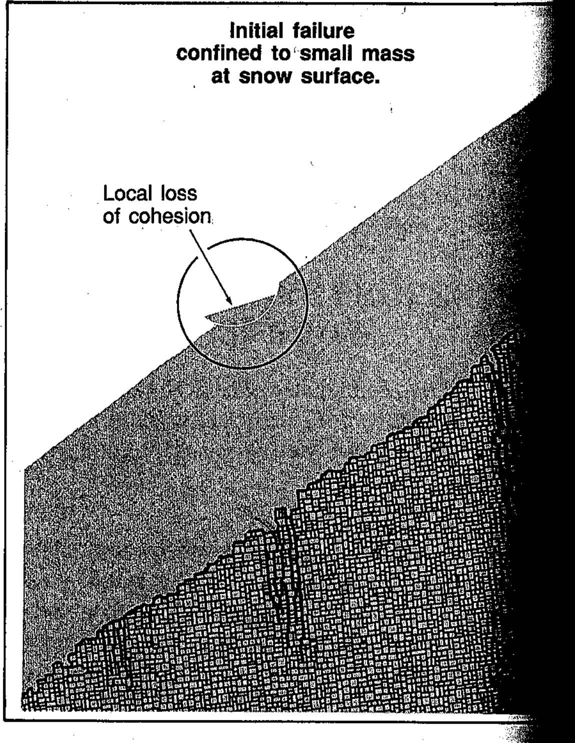
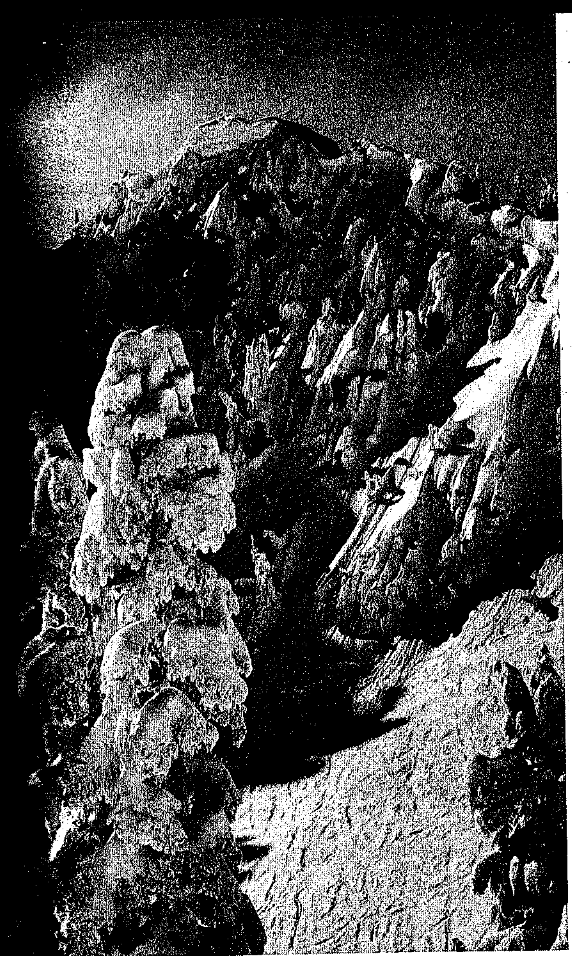


Figure 4.18. Mechanism of loose snow avalanche fai



ure 4.19. Moist snow has a small amount of strength and cling to very steep slopes. (Photo by R. Emetaz)

owpack. The cohesion of wet snow decreases with ter content to provide the basic cause of wet loose alanches. Wet loose avalanche activity is highest en the water content of the near-surface snow is reasing, and activity slows down when the water ntent is decreasing. Wet loose avalanches can occur at y time during the snow season and they can involve ow of quite high density. The strength of wet snow pends not only on water content, but also on the grain ms and bonding characteristics (Figure 4.19). New ow can, for example, fail at a lower water content than der snow if its initial strength is less. If snow has a all enough water content to be classified as moist (see Table 3.4), surface tension and bond formation between ains may develop to give the snow modest cohesion, hich allows it to cling to very deep slopes and surfaces. Loose snow avalanches often present the greatest probms when midwinter rainstorms strike a mountain nge (frequently in maritime climates).

Dry loose snow avalanches commonly form under cold, relatively windless conditions. Cold temperatures retard bond formation so that the snow remains cohesionless. Also, snow falling through a cold atmosphere tends to be unrimed. It has been suggested that the conditions for multiple-bond formation for stellar or dendritic crystals are less favorable for unrimed crystals, thus limiting increased cohesion (bond formation). If the wind is not blowing, the snow will tend to be less cohesive due to absence of windpacking and breakage effects. Dry loose avalanches tend to involve snow of very low density when they form in snow composed of dendritic or stellar crystals (unrimed). Dry loose avalanches can also involve heavily rimed crystals such as graupel with fairly high initial density. In fact, it has been suggested that these two extremes—unrimed dendritic and stellar crystals and fully rimed crystals (graupel)—form the two main prototypes for loose snow avalanche formation. A further—and persistent—observation is that dry loose avalanches can release a day or two after a storm stops in cold weather. Possibly, initial metamorphism by decomposition (disappearance of crystal branches) can decrease cohesion. Laboratory tests show that the critical angle of repose decreases as the initial stage of metamorphism (destructive) takes place.

With respect to crystal forms, general guidelines are available from laboratory studies of the angle of repose for dry disaggregated snow. Dendritic or stellar crystals have the highest angle of repose (up to 80°), decreasing to 35° for rounded forms. For wet snow, more emphasis is placed on the water content: The angle of repose decreases rapidly as water content approaches saturation. However, it is known that slush can avalanche off of slopes of 15° or less. Slush avalanches usually involve snow much deeper than surface snow and they are generally classified as slab avalanches (discussed later). Alpine snow is so porous it is difficult to maintain fully saturated (slush) conditions in near-surface snow unless some impermeable layer (such as an ice crust) lies below (Figure 4.20).

When snow moves, motion is resisted by kinetic friction, which may be expressed as an angle depending on the same variables as the static friction angle. If the slope angle exceeds the kinetic friction angle, loose snow in motion will continue in motion. However, once the slope angle is less than the kinetic friction angle, deceleration will begin to slow and eventually stop the mass—provided it is moving slowly. Laboratory studies show that the kinetic friction angle is about 10° less than

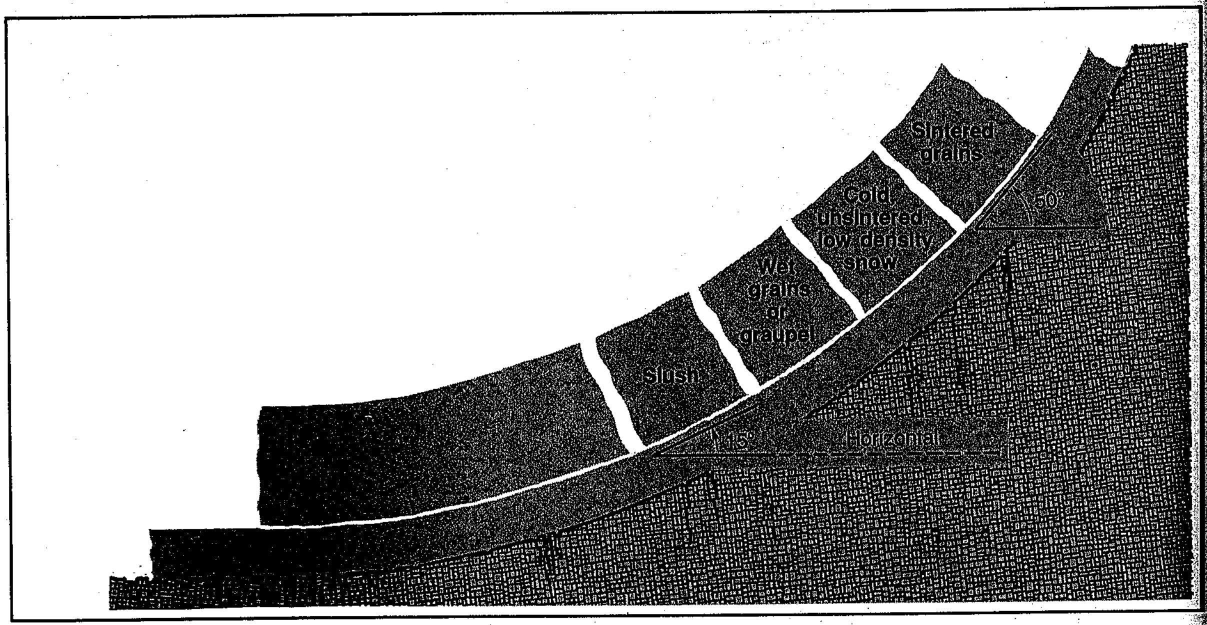


Figure 4.20. Schematic of angle of repose as a function of snow type.

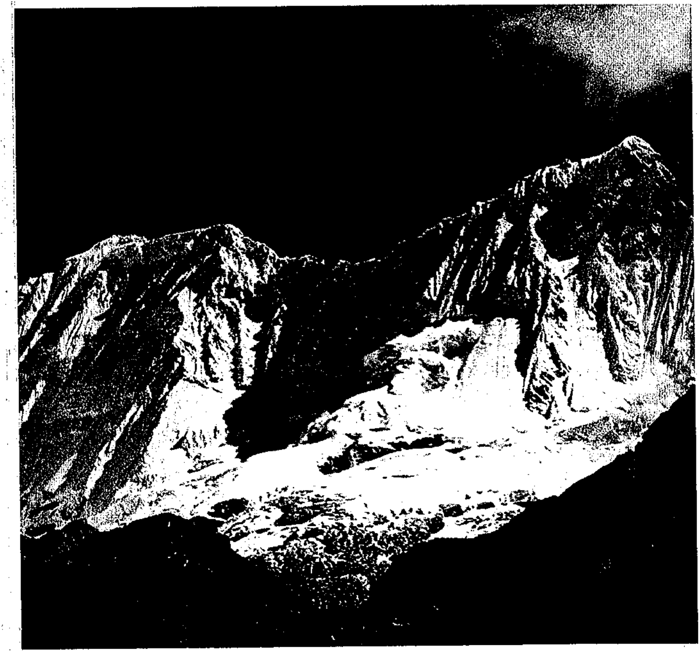
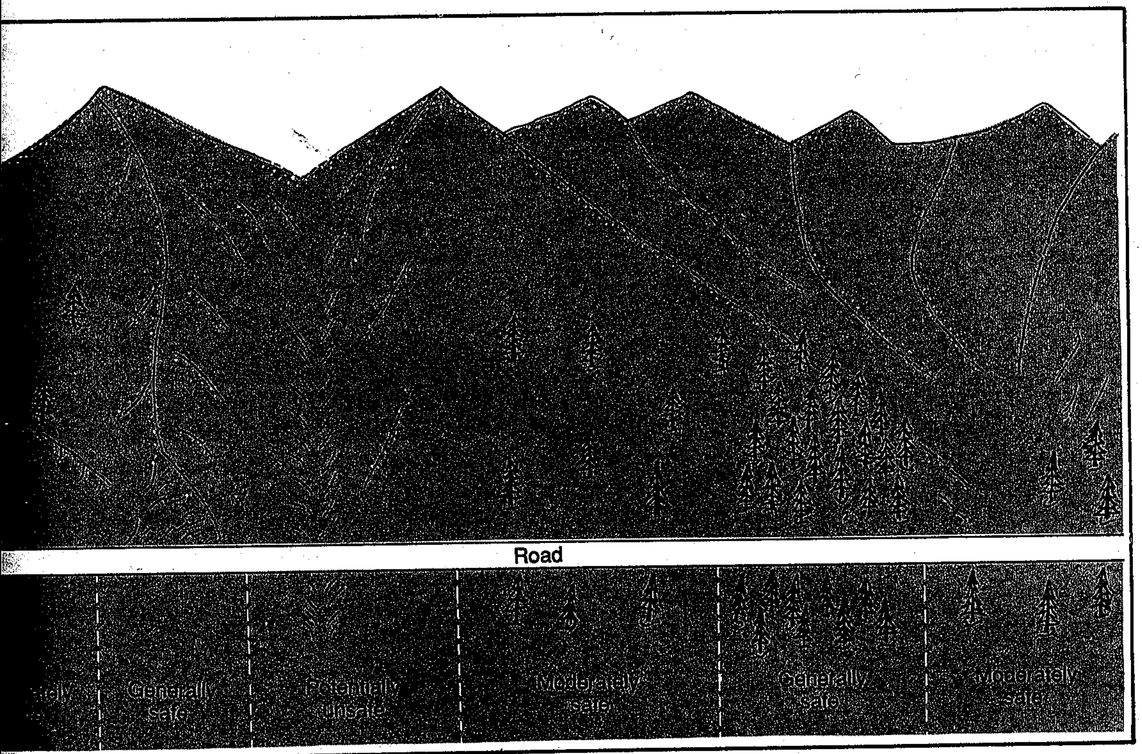


Figure 4.21. The steep faces preferred by ice climbers are swept frequently by dry loose avalanches. (Photo by D. McClung)

the static friction angle (angle of repose) for most crystal forms. If the mass is moving rapidly (more than a few meters per second), other mechanisms dominate the braking action due to kinetic friction.

Dry loose avalanches are usually not massive or dense but they can be hazardous to people in precarious situations such as mountaineers climbing steep ice faces. However, wet loose avalanches are potentially more threatening to mountaineers on steep faces or gullies during warm weather or rain since they can be more massive with much higher snow density than dry loose avalanches. When noncohesive snow is present or expected, it appears that these two extremes in weather (cold or very warm) form the prototypes for loose snow avalanche formation (Figure 4.21).

Large wet loose avalanches can and do affect highways with adjacent steep slopes and they can be large enough to damage vehicles and structures. Loose snow avalanches have two other important effects: (1) They tend to prevent slab avalanche formation on steep slopes by sluffing activity and (2) they may serve as a trigger for slab avalanches on slopes below.



5.20. Terrain above a road.

steep slopes, including cut slopes; below slopes sed to wind; and below a thin forest on a steep . Other moderately safe areas are at avalanche on the other valley side and at through-cuts and at ottoms of narrow valleys.

nsafe areas when snow is unstable are below gul- below long steep slopes that are open or covered small, scattered trees (Figure 5.21); and below ces and snow pillows.

any potential avalanche paths can be recognized by en slope bordered with dense forest (Figure 5.22). etimes when the frequency of major avalanches is forests can be dense with old growth and a path is ally unrecognizable. In the high mountains, vegeta-will not be present. In this case, experience and an eciation for the expected scale of avalanche runout d on terrain variables may be the only available aids.

KCOUNTRY ANALYSIS

ne of the important steps in backcountry avalanche rd evaluation (see Chapter 7) is to *analyze* the terrain. One must ask the question: Can avalanches occur on the terrain in question? A checklist of some, but not all, of the important factors to watch for is given here. The reasoning was explained in the preceding sections.

Slope Angle

- Slope angles between 25° and 60°; 35° to 40° are most common for skier-triggered slabs (see Table 5.1 and also Chapter 4).
- For high or extreme instability, it is possible to generate propagating shear fractures while moving on gentle or flat terrain to produce an avalanche on a slope above.
- Degree of instability usually increases as the slope angle increases.
- Increased instability appears on *convex* slopes.

Slope Orientation (Aspect)

- Lee, wind-loaded slopes
- Lee slopes under cornice roofs

Figure 5.21. Weak snow and a fracture line formed near small trees. (Photo by Swiss Federal Institute for Snow and Avalanche Research)

- North-facing slopes (persistence of instability)
- South-facing slopes (direct exposure to sunlight)

Terrain Roughness and Vegetation

- Open slopes or thinly forested areas
- Deep snowpacks (bury anchors)
- Smooth slopes (without anchors)

Terrain Traps

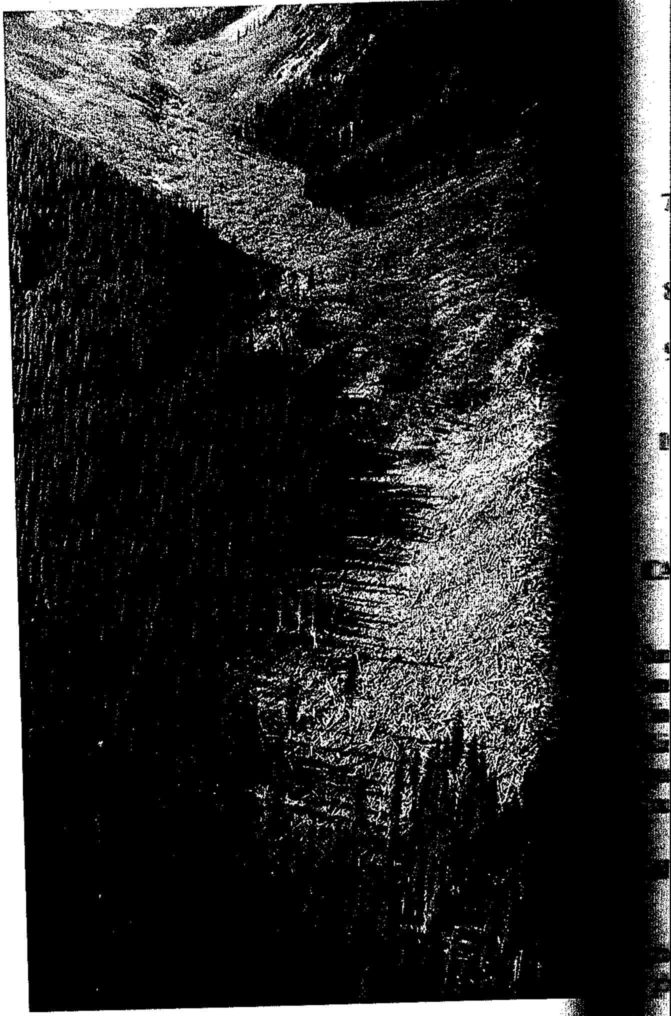
- Drop-offs
- V-shaped valleys and gullies

IDENTIFICATION OF AVALANCHE PATHS

Avalanche paths need to be recognized when housing, industrial developments, ski areas, roads, railway lines, transmission lines, and other facilities are planned in mountainous terrain. The following procedures have been found useful:

1. Determine from contour maps, aerial photos, and ground observations whether the slopes meet the conditions for avalanche formation—incline, exposure, orientation.
2. Using the same sources, estimate the location of tracks and runout zones below previously identified starting zones.
3. Using aerial photos or visual confirmation, look for signs of past avalanche activity such as sharp trimlines in treed areas, new tree growth, differen species (Figure 5.22). A comparison of earlier aerial photos is useful, particularly for areas disturbed by logging or fires.
4. Evaluate the climate to determine whether maxi-

Figure 5.22. The trimline in the forest indicates the width o track and the maximum runout distance. (Photo by P. Schaere



mum snowfalls, including drifting snow, could cover surface roughness.

nvestigate clues to earlier avalanche activity using a ground-vegetation survey (discussed later in this chapter). Look for younger, different species of trees and broken trunks, limbs, and scars on the uphill side of trees. Other clues are broken wood, needles, and twigs outside the forest area; leaning trees; and fallen trees aligned with the expected direction of avalanche flow.

Clues applicable to open areas include rock debris perched on boulders and scattered on roads; gullies and creeks filled with avalanche snow; "brushed" shrubs; and rock cones, mounds, and pseudo-moraines deposited by avalanches.

Observe avalanches during the winter and spring. It might be sufficient to make an inspection in the spring when half the snow has melted and avalanche debris is visible on the surface. Avalanche snow is harder and coarser than fallen snow; it is usually contaminated with debris. Other signs of activity are fracture lines, flow marks in gullies, and snow plastered on the uphill sides of trees.

7. Collect information on historical avalanche events from local residents, road maintenance crews, and newspapers.
8. Calculate runout distances for maximum avalanches (see section later in this chapter).
9. Compare inclines, slope lengths, exposures, and runout distances with known avalanche terrain in the area.
10. Report conclusions about the width and runout distances of expected average and maximum avalanches *using all of the collected information.*

ATALOGING AVALANCHE PATHS

Operators of permanent facilities identify the ava- nche paths in their areas by name, number, or aspect d elevation. On roads, railways, and transmission es the identifier is usually the running kilometer. ists, maps, and aerial photos may refer to avalanche ath locations using these identifiers. Avalanche paths ay also be described in an avalanche atlas.

VALANCHE ATLAS

An avalanche atlas is a catalog with descriptions of he avalanche paths in an area. It is compiled from aerial hotos, ground observations, surveys, and on-site observations. The atlas may contain the following information.

Introduction

- Area referred to by the atlas
- Area climate including snowfall and snow on ground
- Volume of winter road traffic
- Topographical map showing avalanche paths with their identifiers (name, number)
- Definition of terms
- Method of compilation and time span of observations

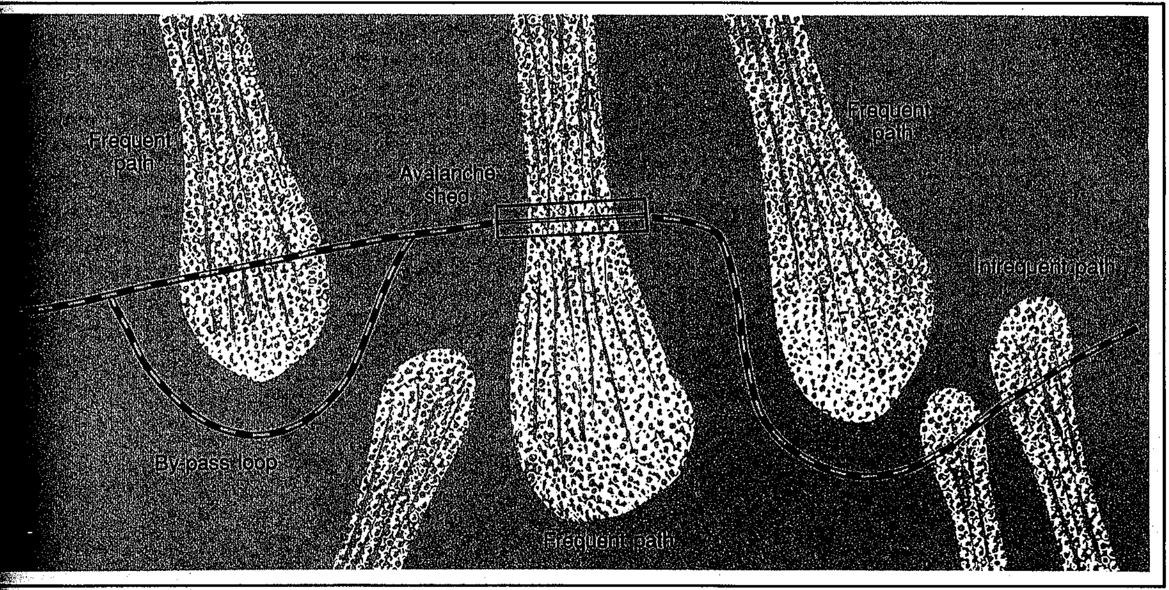
Avalanche Paths

- Identifier
- Photo of entire path (preferably in winter)
- Description of starting zone(s) (elevation, incline, aspect, and general topography)
- Description and incline of track for significant avalanches
- Description of runout zone(s) for significant avalanches, including incline, ground cover, and stopping location for small, medium, and large avalanches
- Catchment area (maximum area that can contribute avalanching snow)
- Effect on roadway where applicable
- History; observed past avalanches classified according to size, stopping location, frequency, and whether wet or dry
- Measurements of terrain variables needed for calculation of runout distances (see later section in this chapter for details)

AVALANCHE MOTION AND EFFECTS

Knowledge of avalanche motion (avalanche dynamics) is important when estimating avalanche speeds because the speed has an effect on the design and placement of structures that may be in the path of flowing snow. The principles of avalanche dynamics are also useful when considering route selection in mountain travel, camp placement in mountaineering ventures, and survival when one is caught in an avalanche.

The mathematical problem of describing the interaction of flowing snow over complex mountain terrain to predict avalanche speeds along the incline has not been solved. However, some descriptive features of the problem are available from field observations and measurements.



re 9.12. Location of mountain highways.

STABILIZATION BY COMPACTION

The strength and stability of a snowpack can be oved by compaction. Compacted dense snow usu- retains adequate strength even during melting (see pter 3). However, due to terrain steepness, machines ot usually be applied in avalanche starting zones, therefore personnel on skis and foot must be used for avalanche control compaction.

Ski Stabilization

Ski stabilization (also called ski cutting, control, or ective skiing) involves skiing the avalanche starting s frequently, releasing small avalanches, and pack- the snow in the ski tracks. The effect of ski cutting onfined to surface snow layers; deep, weak layers ot be compacted and stabilized. Therefore, ski ilization is best carried out after every light and erate snowfall. The slopes should be tracked densely op up potential starting areas. The distance between s should be 1 to 5 m. Caution must be observed: one on at a time on a potential starting area. Normal lity evaluation safety procedures must also be fol- d (see Chapter 6).

Continuously skied slopes are usually avalanche free except with unskied new snow. It is a good policy to allow skiers to use and ski pack potential avalanche starting zones from the beginning of the winter (Figure 9.14).

Boot Packing

Boot packing involves people walking through avalanche starting zones to make densely spaced footprints (distance about 1 m). Boot packing affects deeper snow layers than does ski stabilization.

Boot packing is generally limited to small, critical areas because of the heavy personnel requirements. It is often applied to strengthen weak snow (depth hoar) that had formed early in the winter before slopes were skied. To prevent avalanche formation, it should be carried out before the weak snow is covered with stronger snow. Packing fresh snow can be very effective for preventing depth hoar formation later.

AVALANCHE CONTROL BY EXPLOSIVES

Detonating explosives in starting zones has two objectives: to release avalanches under controlled conditions and to test the stability of the snowpack (see Chapter 6).

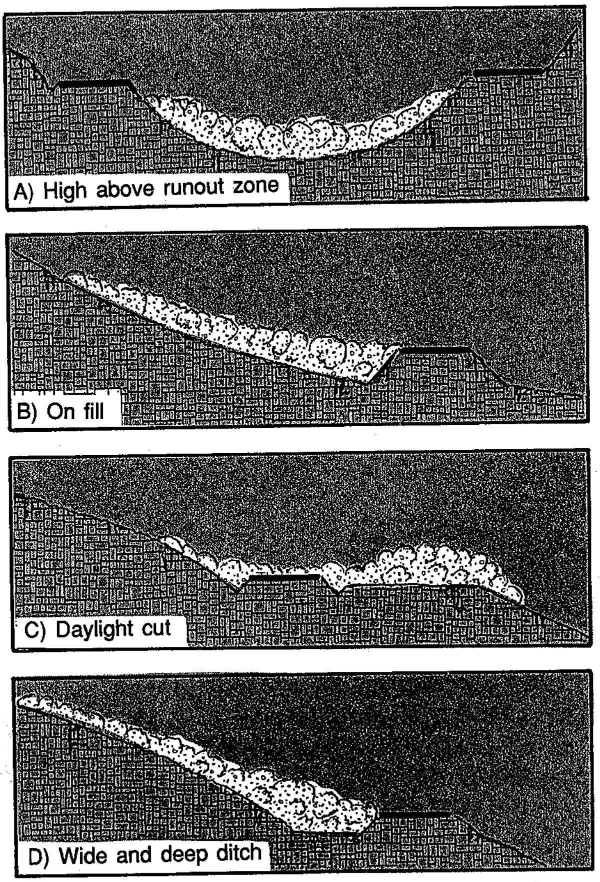


Figure 9.13. Cross section of roads in avalanche paths.

One benefit of releasing avalanches with explosives under controlled conditions is that the avalanche release is chosen when the exposed areas (for example, roads and ski runs) are not occupied. The areas may be opened after avalanches are released; therefore, closures may be kept short. Another benefit is that frequent explosive control usually ensures that snow is brought down in several small avalanches, rather than a single large one. Small avalanches may not reach facilities, and snow removal time on roads can be minimized, making closures short. Also, frequent avalanche release prevents large unpredictable natural avalanches later, for example, with snowmelt.

Effect of Explosions

Explosive charges are used to generate elastic stress waves to initiate shear fracture propagation and dry slab avalanche release. Stress waves attenuate rapidly snow, but propagation is more efficient through the and the ground (Figure 9.15). Explosions above snow surface stress the snow over a wider area t those in the snowpack; therefore, they are more ef tive in activating weak spots to produce failure. S waves in the ground propagate with little attenua over long distances, but their impact on the snowp depends on the quality of the contact between snow ground. Under favorable conditions, ground shock w can be very effective. Artillery shells detonated on r have released avalanches on adjacent slopes and opposite side of ridges, but this effect is not very comm

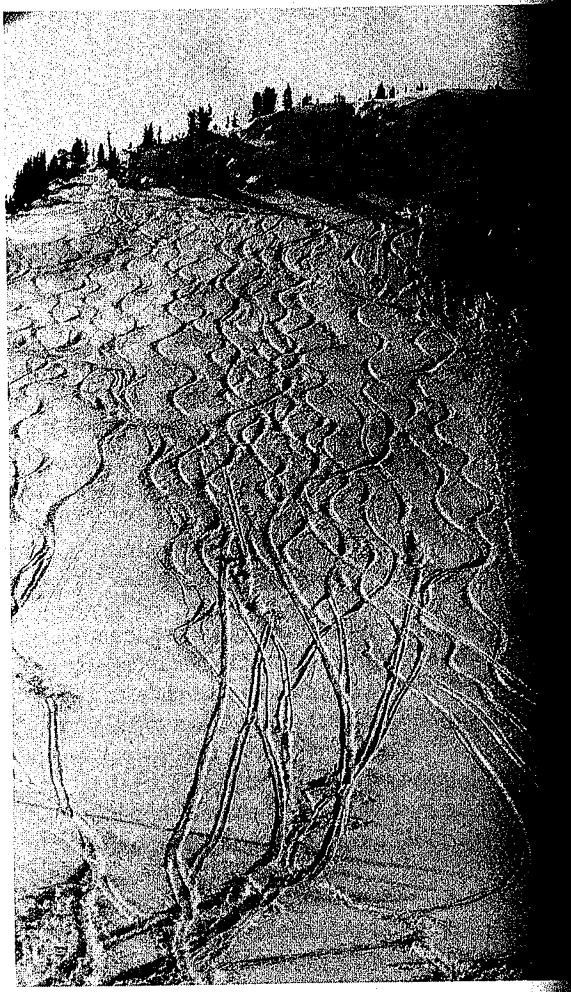
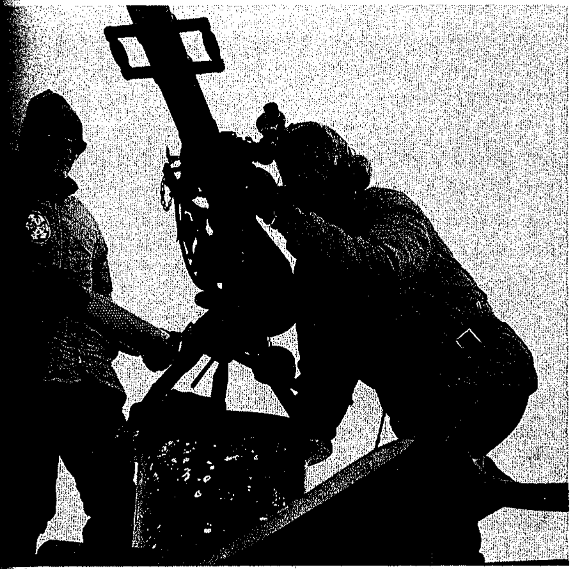


Figure 9.14. Ski-stabilized slope. (Photo by P. Schaerer)



gure 9.27. Sighting for firing artillery.

gulations. The example in Appendix H can be re-rded as one with a minimum set of safety standards.

Helicopter Bombing

Helicopter bombing involves dropping large hand arges while hovering above avalanche starting zones. he bombardier lights the fuse of a prepared charge and ops the charge through the open helicopter door frame igure 9.29A). Assistance (optional) is provided by o other qualified blasters: a recorder who selects the rgets and records the results, and an explosives han-ler who carries the igniters (separate from the bombs), aces the igniters on the fuse, and hands the charge to e bombardier. In some areas, fewer personnel are used side the helicopter; in others, more qualified blasters e involved. An example set of procedures is given in ppendix H. The procedures described there assume the ptional) presence of both a recorder and explosives andler. Often, tasks are combined to yield a crew of ree including the pilot.

Helicopter flying and explosive transport in moun-ins are hazardous, therefore, strict safety rules must be dhered to. Procedures include helicopter safety train-g on the ground, practice flights dropping dummy ombs (of wood), and good communication between the lasting crew, the pilot, and the ground.

Figure 9.28. The Avalauncher is a control weapon with limited range utilizing compressed gas. (Photo by P. Schaerer)

Advantages of Helicopter Bombing

Numerous avalanche paths can be treated within a short time. The cost is reasonable if a helicopter is stationed near the area and numerous avalanches paths close together can be controlled during one flight. In addition, the blasters are not exposed to avalanches, and inaccessible starting zones can be reached (not accessible on ground or reachable with artillery).

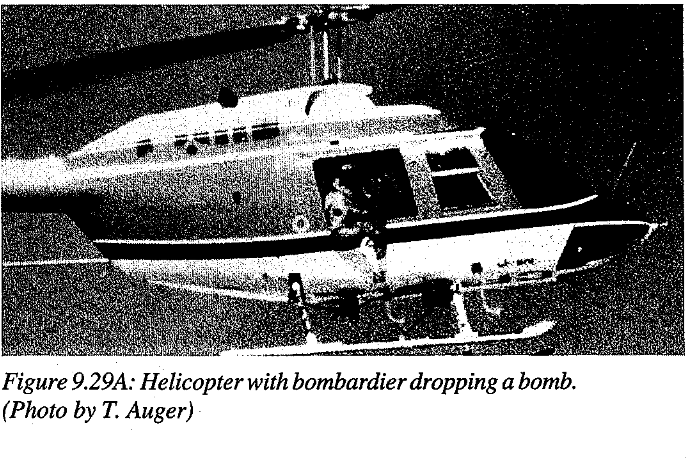


Figure 9.29A: Helicopter with bombardier dropping a bomb. (Photo by T. Auger)

Figure 9.30. Avalanche area accessed by ropeway, Coquihalla, British Columbia. Avalanche paths and targets are shown. (Photo by S. Walker)

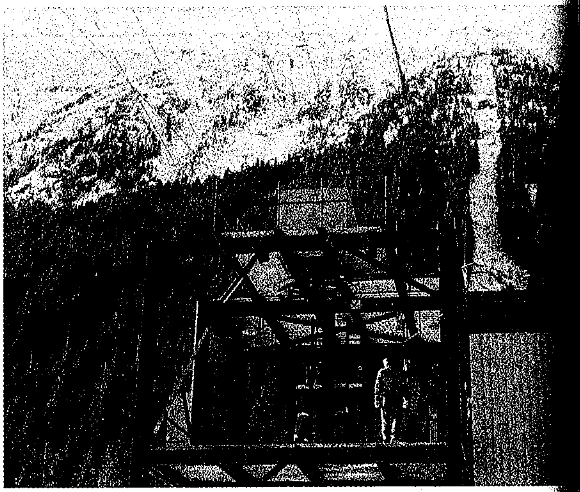


Figure 9.31. Ropeway terminal, Coquihalla, British Colu bia. Cut in forest for ropeway ascent is shown in the bac ground. (Photo by S. Walker)

Preplaced Charges

Preplaced charges are installed on the ground at the beginning of the winter, with individual detonation by coded radio signals. Either a single charge at a critical location may be used or, for a wider range, several charges spread across a starting zone may be detonated simultaneously. A radio receiver-decoder, solar panel, and battery are placed at a safe location next to the avalanche starting zone, and cables connecting the explosives are buried in the ground. The charges are best placed on rocky ground to prevent damage to soil and vegetation.

Advantages of Preplaced Charges

The method is applicable in terrain that is inaccessible for hand charging and artillery. Also, avalanche control is fast because avalanches can be released by pushing a button, the application is not affected by visibility and the weather, and the cost is moderate.

Limitations of Preplaced Charges

Detonation is at the bottom of the snowpack, therefore preplaced charges are not effective in areas with deep snow. This disadvantage may be partially compensated for by large charges (5 to 10 kg).

Precautions must be taken to prevent tampering by unauthorized persons, for example:

- Only avalanche starting zones that are difficult access should be used.
- Charges should be placed as late as possible in the fa
- Warning signs should be placed.
- All unused charges should be detonated in the sprin
- Since the charges are not in an approved magazi special permission is required for legal reasons.

Gas Exploders

With gas exploders, the shock is created by igni a mixture of a gaseous fuel and an oxidant, for examp propane and air. The systems require permanent ins lations with fuel tanks, oxygen or air tanks, pipes to blasting site, a mixing chamber, and an ignition syst The mixing of gases and the ignition may be contro from a remote location. Exploders that direct the b toward or parallel to the snow surface have proven to best. Systems using gas explosions at the bottom of snowpack have not been successful.

Advantages and Limitations of Gas Exploders

Two advantages of gas exploders are that the me is applicable at sites that are inaccessible for h charging and artillery fire, and avalanches can be leased quickly and independently of visibility weather. On the other hand, the capital costs are high there is no flexibility in target choice.

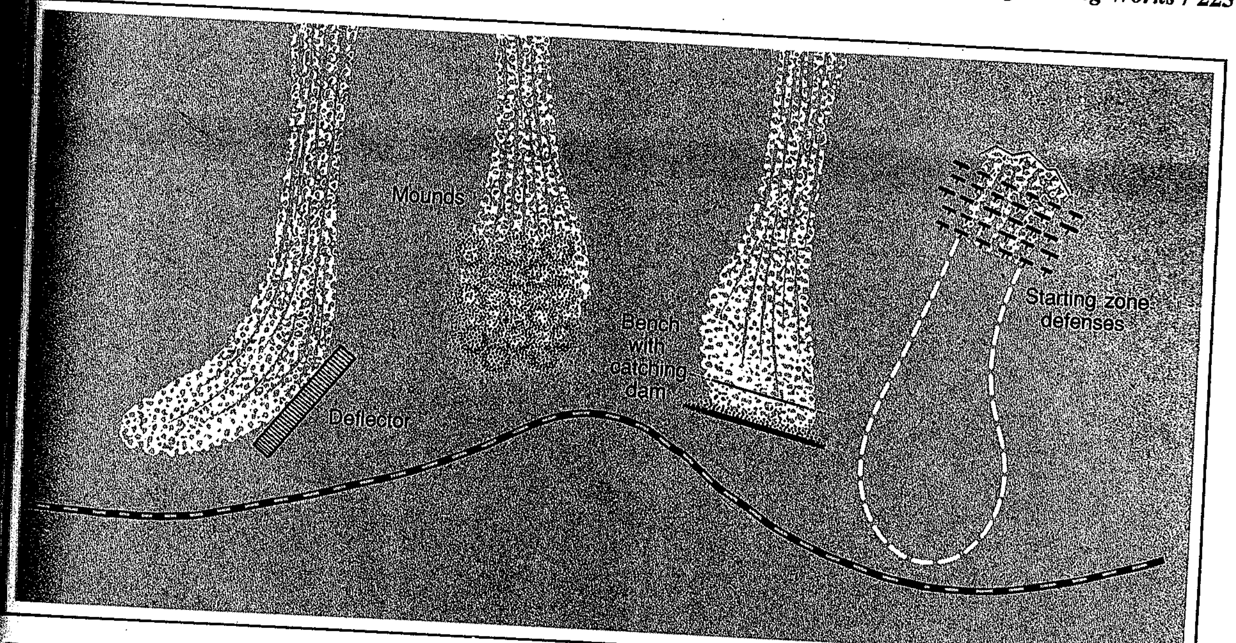


Figure 9.32. Defense structures for protection of mountain highways.

OTHER AVALANCHE TRIGGERING METHODS

Explosives are the common method for the controlled release of avalanches. However, other methods include test skiing, which is discussed in Chapter 6, and loading with snow, in which snowpackers and bulldozers are used to push snow from ridge tops to start avalanches on the slope below.

ENGINEERING WORKS

Engineering works for avalanche protection are permanent structures and earthworks (Figure 9.32). Their functions are avalanche prevention and deflection; facility protection, because avalanches can pass over or under; and deceleration and stopping of avalanches.

Engineering works operate independently of daily avalanche hazard forecasts and operational commitments. Their principal disadvantage is high capital cost. Other disadvantages are inflexibility when operational conditions change, the need for land, and a lack of aesthetic appeal (Figure 9.33). Therefore, engineering

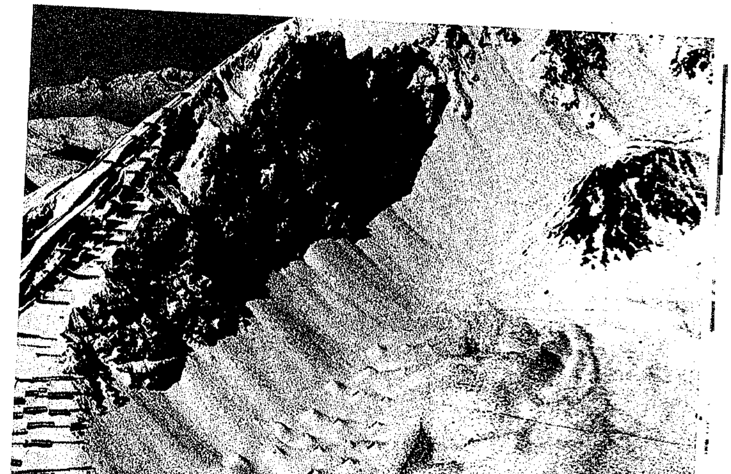


Figure 9.33. The left side shows supporting structures in avalanche starting zones. In the center of the picture, mounds and arrester dikes are visible. (Photo by E. Wengi)

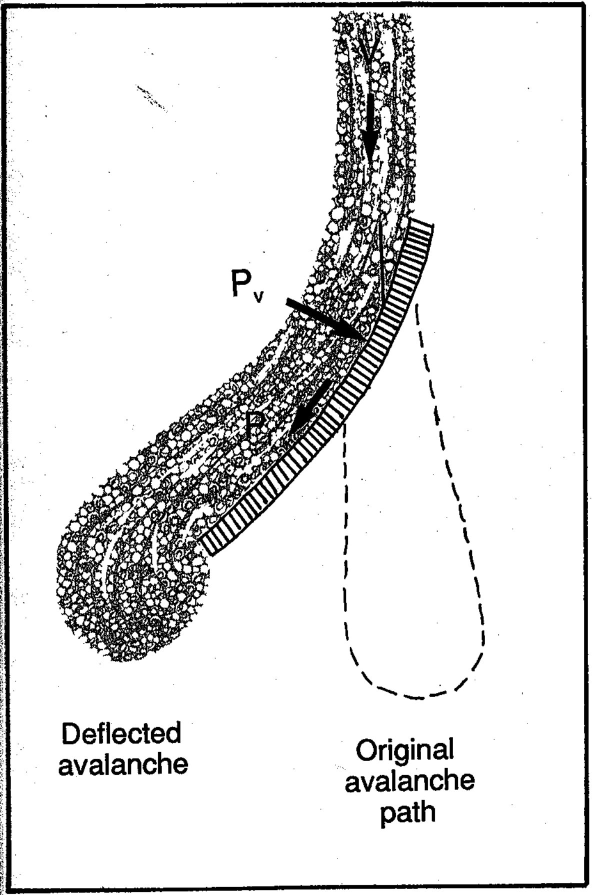


Figure 9.40. Location and forces on a deflector. The initial deflection angle should be less than 20° if possible.

4. The design height H_d of the deflector can be calculated roughly by the relationship (Figure 9.41):

$$H_d = H_s + H_a + H_v$$

where

H_s = depth of snow deposited by snowfall and previous avalanches
H_a = flow depth of the design avalanche
$H_v = (V_a \sin\alpha)^2/2g$ = minimum runup height from flowing snow. Since H_v is derived only from simple energy considerations based on the assumption that the avalanche moves as a point mass, the expression given here must be regarded as a minimum estimate only (Hungr and McClung, 1987). (In practice, H_v may also be larger depending on the details of the avalanche and geometry of the runout zone.)
V_a = approach speed of the design avalanche
α = deflection angle
$g = 9.81$ m/s^2

5. The height H_d of the deflector may be extended partially by excavating the soil in front of the dike. Temporary deflectors are sometimes built during the winter by bulldozing snow into a ridge.
6. The ground behind a deflector should be smooth and free of trees, large boulders, or hummocks. The deflector face should be as steep as possible without sharp corners. The terrain should be surveyed with the location staked out precisely prior to construction.
7. Walls should be designed for avalanche impact

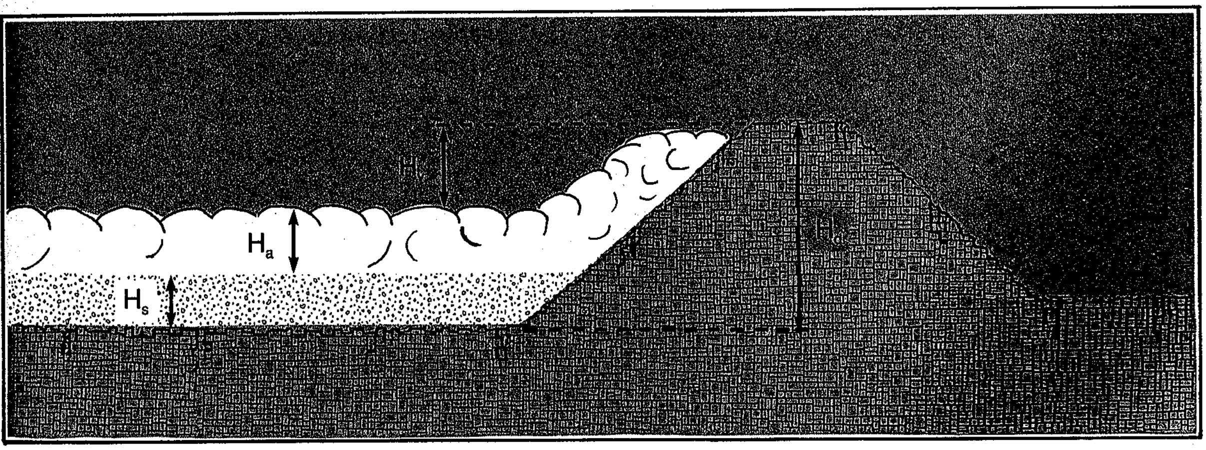


Figure 9.41. Schematic for calculating height of deflectors.

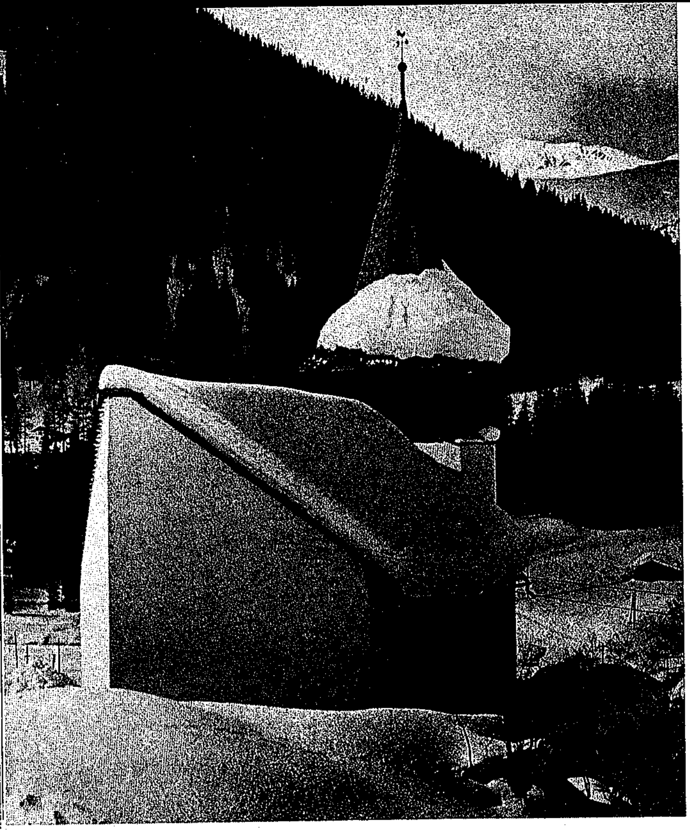


Figure 9.47. Splitter used to protect the Davos-Frauenkirch church. (Photo by E. LaChapelle)

sumed to be 250 kg/m^3 for dry snow and 400 kg/m^3 for wet snow.

- The surface angle of the deposit snow varies between 10° and 25° depending on deposit characteristics.
- Snowfall and plowing require additional ditch capacity but the effectiveness may be maintained by periodic snow removal.

Splitters

Splitters are wedge-shaped dams or walls, earth mounds, or pillars. They are placed directly in front of a single object, for example, a building, a power line tower, or a chairlift tower, to direct the avalanche flow around the structure (Figure 9.46). Splitters can also be incorporated into the structure. For example, a building may be built with a reinforced wall facing the avalanche, or the base of a tower may be encased in concrete or earth (Figure 9.47).

Splitters may also be placed at a strategic location in an avalanche path to divide the avalanches into several small arms. The arms have reduced mass and a shorter runout distance, and they may be controlled easier by retarders than the concentrated avalanche flow.

The flow direction of usual and erratic avalanches should be determined carefully when a splitter is located. The apex of a wedge-shaped splitter should face the principal direction of flow, and the wings should be long enough to cover the object. The apex of the splitter usually has an angle of 60°. The height of splitters and the design forces are determined in a manner similar to that for deflector design. Splitters cannot be built high enough to control powder avalanches. Therefore, when power line and chairlift towers must be protected, a splitter serves to deflect the dense core component, and the tower structure above is designed against forces from the powder component.

In making decisions about the use of splitters, one should be aware that splitters protect only the objects behind them; traffic and other structures downslope and at the sides are still exposed to the deflected flows.

Snow Sheds

Snow sheds (also called *galleries*) are roofs designed to allow avalanches to pass over the object. They are applied on railways and highways and sometimes incorporated into building design (Figure 9.48). Concrete, steel, wood, and combinations of these materials are used. Temporary snow sheds have been built of snow blocks (igloo-style) and by tunneling into deep avalanche deposits.

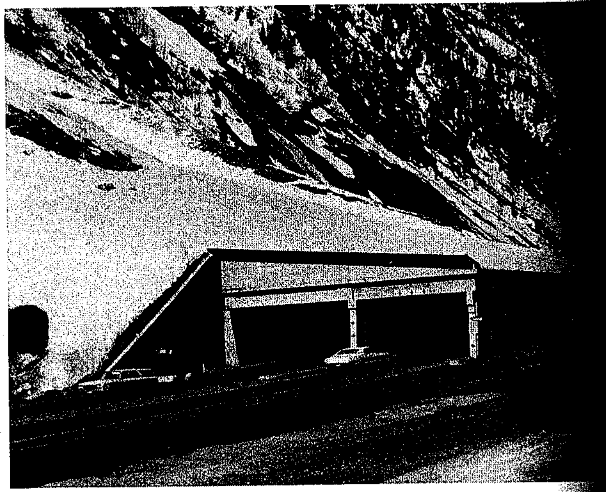


Figure 9.48. Snow shed used to protect highway traffic. (Photo by P. Schaerer)

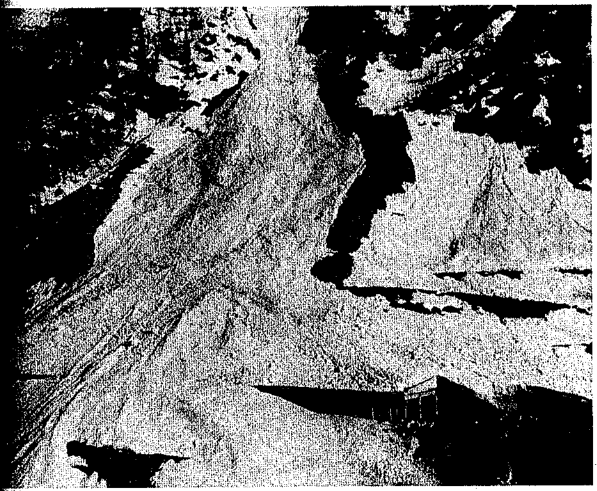


Figure 9.49. Snow shed with dikes that prevent spreading of avalanches. (Photo by P. Schaerer)

Snow sheds are expensive so careful consideration is required for their need, benefits, and alternatives. Sometimes a rock tunnel or a structure in a cut and fill may be a less expensive solution.

A snow shed should be long enough to cover the width of the avalanche path. However, sheds are frequently built shorter with avalanches being allowed to spill over under extreme conditions (for example, once in 10 or 30 years). The length can sometimes be reduced by building guiding dams on top of the shed to prevent spreading of avalanches, but this is not always successful (Figure 9.49). When several avalanche paths are close together, it is often more economical and practical for later operation to build one continuous shed, rather than several short ones.

The following *design forces* are considered:

- Vertical force (weight) of a design avalanche moving over the shed
- Dynamic friction of a design avalanche moving over the shed
- Static weight of snow deposited on the shed from snowfall and avalanches (The weight of deposited avalanche snow at the end of the winter can be very high—comparable to dynamic loads—for snow sheds in the runout zone of frequent avalanches.)
- Dynamic forces if avalanches strike the shed directly due to a sharp transition of slope between the snow shed and the terrain

Figure 9.50. Earth mounds to retard flowing snow at the end of a runout zone. (Photo by P. Schaerer)

- Horizontal snow pressure from avalanche snow deposited adjacent to the snow shed
- Impact, friction, and uplift on protruding roof parts from avalanches that come from the opposite valley side

Not all forces occur simultaneously; each design value must be determined from careful estimates of maximum conditions.

Other considerations for design and operation of snow sheds are that snow sheds reduce the visibility and vertical clearance on roads, and the ground inside the snow shed generally is colder than outside: Ice forms readily on the pavement, creating hazardous driving conditions. Frost action on foundations, retaining walls, and pavement should be considered.

Also, creeks (usually present in avalanche paths) must be diverted to the side, channeled across the shed, or contained in a culvert underneath. The drainage and waterproofing of the roof require special attention, and the shed roof might have to be protected against rockfall (usually with a layer of soil).

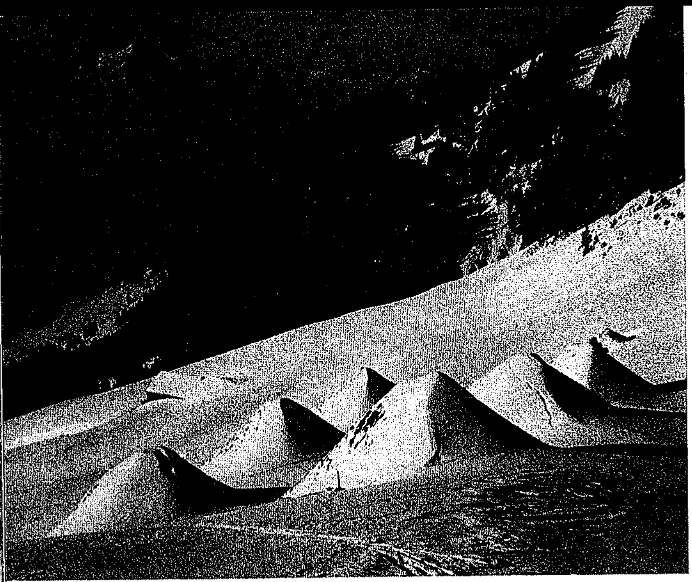


Figure 9.51. Earth mounds in a runout zone. (Photo by H. Frutiger)

Retarders

Retarders are obstacles located in avalanche paths to reduce the runout distance by dissipating motion energy of avalanches. Retarders dissipate energy by spreading the avalanches over a wider area (Figure 9.43). This results in reduced flow depth and greater contact area with the ground. They also create friction against forward motion to slow the moving snow. For example, two rows of earth mounds may reduce the runout distance of avalanches by 20 to 30 m (Figures 9.50 and 9.51).

The effect of retarders is limited and it depends crucially on the type of avalanche snow and avalanche motion. Retarders are most effective when the avalanches are slow and contain dense snow (for example, wet snow avalanches). Retarders have little effect on rapidly moving, dry snow. Above a road, the retarders may reduce the number of avalanches and the amount of avalanche snow on the road, but they must not be counted on to eliminate the hazard to traffic.

Earth mounds built from local soil are low in cost and are, therefore, the most common type. Rock piles, concrete blocks and wedges, cribs, and tripods of steel or concrete (open and covered with wire nets) have been applied.

The following guidelines apply to the *location and design of earth mounds:*

- Mounds are best built on terrain with a slope incline not greater than 15° to 20°.
- Mounds should be built in the avalanche runout zone. One should plan for a storage capacity of more than one avalanche.
- Mounds should be spaced laterally, as close together as possible, with the toe of each mound meeting the toe of the adjacent one.
- At least two rows of mounds in a checkerboard fashion should be built.
- The optimum height is 5 to 6 m, but heights up to 8 m might be needed in areas of deep snow or where more than one avalanche is to be expected. Mounds should be about 2 m wide at their top (across the avalanche path).
- The stability of mounds built from sand-gravel-boulder material (usually found in avalanche runout zones) is adequate against avalanche forces. Surface erosion by avalanches is negligible but planting shrubs and grass helps provide protection against rain erosion.
- Creeks should either be diverted around the mounds or be carried in a culvert underneath mounds. Open creek channels through the mound pattern can provide weak spots.

FOREST CONTROL

Forests control avalanches by preventing large avalanches and retarding avalanches in motion (see Chapter 5). The loss of a forest due to fire, careless cutting,

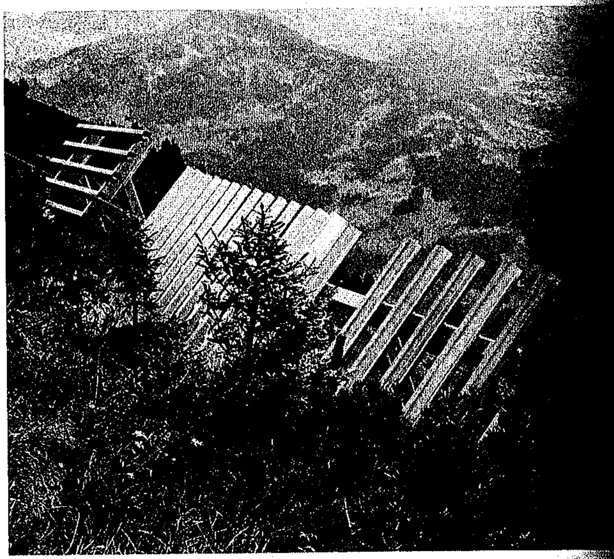


Figure 9.52. Young trees on an avalanche slope in Switzerland with creep and glide control structures. (Photo by H. Frutiger)

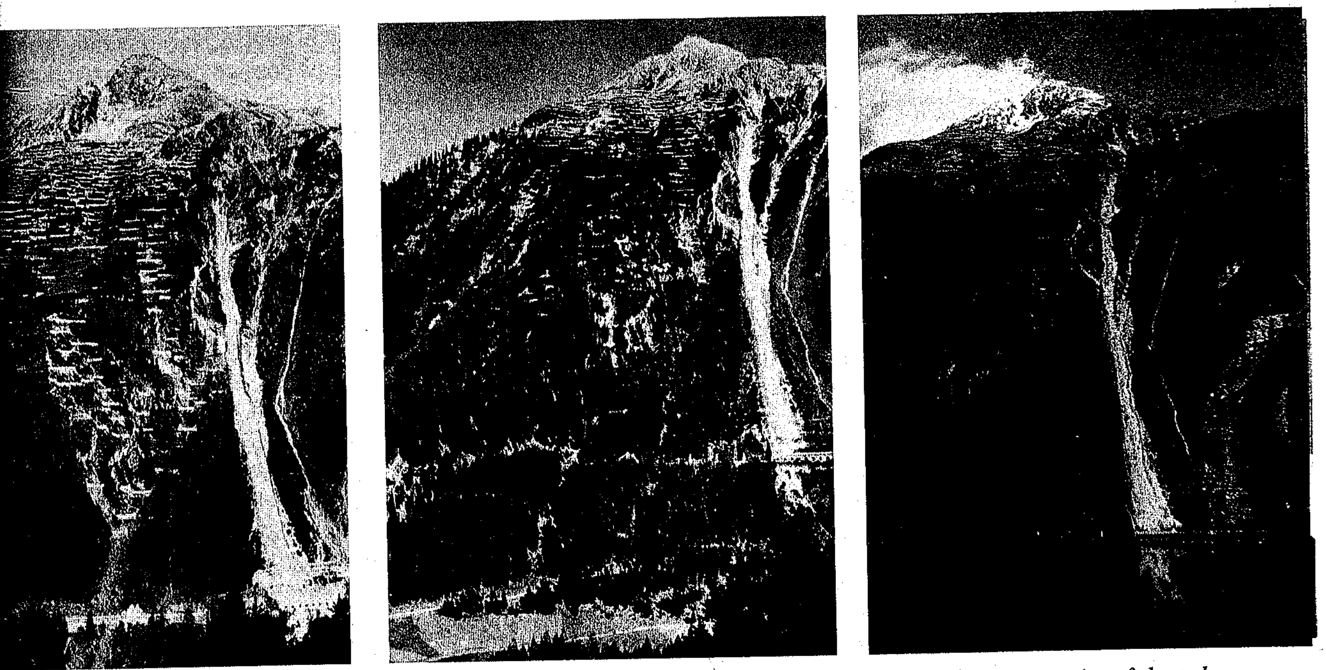


Figure 9.53. Progressive reforestation in avalanche terrain. Left, taken in 1907, shows masonry terraces for protection of planted forest; middle photo taken in 1938; right photo in 1957. (Photos from Swiss Federal Institute for Snow and Avalanche Research with the permission of Rhätische Bahn)

excessive explosive control, disease, or acid precipitation can produce avalanches where none had occurred before (refer to Figure 5.11).

Regrowth of a forest in an avalanche path is difficult, expensive, and slow because the young trees are damaged continuously by avalanches, snow glide, and snow creep. Often reforestation must be combined with supporting structures (Figure 9.52). Supporting structures (often temporary) with a life span of about 50 years are used (100 years for slow-growth conditions and species). Because of the possible damage and the difficulty of repair, logging plans on steep terrain should consider whether new starting zones might be created.

Avalanche paths are usually subject to harsh growing conditions including poor soil, a short growing season, wind and drought conditions, steep ground (which promotes erosion), and persistence of deep snow (which promotes snow mold fungi). Fast-growing native species should be planted whenever possible. Some attempts will have to proceed in stages with the initial use of fast growing successional species (for example, willows and alders). These species have good root systems and they also fix nitrogen (fertilize soil) to provide the

Figure 9.54. Snow fence on a ridge to collect blowing snow. (Photo by H. Frutiger)