6. AVALANCHE HAZARD MITIGATION

6.1 General

From the standpoint of safety, avoidance of avalanche areas is the best form of mitigation. This can be achieved in the Anchorage area by building beyond the limits of avalanche blue hazard zones, thereby reducing exposure to all but the very rare event. This, the safest alternative, is not always economically feasible.

When building occurs within the blue zone, the avalanche encounter probability with structures varies considerably depending upon whether the structure is near the red/blue boundary (a "10-year" return period), or near the distal limit of the blue zone (a "100-year" return period). Thus application of encounter probability theory (LaChapelle, 1966), shows that a building exposed continuously for 30 years in the blue zone stands a 26% to 96% chance of being reached depending on its position in the blue zone.

Such high encounter probabilities dictate that avalanche hazard be reduced by some form of mitigation, or "avalanche control." Several types of control are possible, including (1) artificial avalanche release, (2) supporting structures in starting zones, (3) diverting avalanches in the lower portion of the path, and (4) direct protection and structural reinforcement of objects.

6.2 Artificial Release

When mobile objects such as automobiles, railroad trains, and skiers are exposed to severe avalanche conditions only occasionally, hazard can often be reduced by restricting use of the threatened areas until the avalanches can be released artificially by explosives. This reduces the possibility of damage or injury. Such procedures are common but are not always reliable because the required information about snowpack structure is usually not available. Nevertheless, skiers, automobiles, railroad trains, and other endangered objects can be removed while control attempts are made.

Artificial release is usually an unacceptable control alternative for eliminating the hazard to immovable objects such as buildings because avalanches released in this way may be larger than expected and can destroy unprotected structures.

6.3 Supporting Structures

The objective of supporting structures is to prevent, or to limit, the size of avalanche release. Supporting structures anchor the snow to the mountain and alter the stress and deformation within snowslabs. They are designed primarily for static loads resulting from creep and glide of the snowpack and the small dynamic loads resulting from small slides between the structures. The Swiss have gained considerable experience in the design, construction, and maintenance of supporting structures and have engineering guidelines for their construction (Swiss Federal Institute for Snow and Avalanche Research, 1961).

Construction of supporting structures usually begins in the steep upper terrain where avalanches occur most often. This prevents the smaller slides that may trigger the larger avalanches that are capable of reaching developed areas. Construction over a period of years can anchor entire starting zones with slopes in the 30- to 50-degree range.

Supporting structures may be desirable when starting zones are small, well defined, and accessible, and the objects to be protected are numerous and valuable. Such structures may be the only remaining alternative if advanced hazard planning has not taken place and the objects needing protection are already located in hazardous areas. However, the cost of supporting structures ranges from $100,000 to $200,000 per acre in Switzerland (pers. comm., Hans Frutiger), and would be considerably higher in Alaska because of increased material costs and lack of engineering and construction experience.

6.4 Criteria Used for Structural Design in Runout Zones

Since artificial release is unacceptable and supporting structures are usually not feasible because of high cost, the only remaining forms of defense include protection of objects in the runout zones. The two types of defenses that would be most useful in the Anchorage area include deflection structures, and direct protection structures. Both types of structures require information about avalanche characteristics in order to be designed properly. This information is known as the "design criteria."

The term design criteria refers to the physical characteristics of the avalanche that must be considered when specifying defense structure position, orientation, size, strength, and material. The following avalanche characteristics must be known in order to provide the proper design:

Avalanche type (wet or dry snow, loose snow, or slab),

Type of avalanche motion (powder, flowing, or mixed),

Avalanche velocity (the mean velocity at the front of the avalanche),

Avalanche flow height,

Avalanche flow density,

Avalanche discharge (volume per unit time at some location),

Avalanche impact or stagnation pressure,

Avalanche deposit volume, and

Number of avalanches per winter.

These characteristics are obtained through field observations at the area of interest, comparison of this area with other avalanche paths of known characteristics that are located in a similar climate and have similar orientations, terrain configurations, and sun exposures, and through application of equations.

Avalanche researchers recognize that none of these characteristics can be specified with a high degree of precision because we are only learning about avalanche dynamics through present research efforts. Nevertheless, it is essential that we make use of the body of knowledge as it exists today.

In order to design structures to withstand, deflect, or stop moving avalanches, we must have information about the following: the total static and dynamic force on the structure, the required size (height, width, and length) of the structure, the volume of avalanche debris in the deposition area, or in the area where the structure will be built, and knowledge of any change in the avalanche direction as a result of the defenses.

This information can only be obtained through analysis of the design avalanche and determination, through calculation, of the avalanche characteristics discussed previously.

Voellmy (1955) derived the fluid-dynamic basis of snow avalanche motion and impact. His original equations have been modified through subsequent research, but the basic equations and assumptions of Voellmy are widely applied in Austria, Switzerland, Canada, and the United States.

Sommerhalder (1965, revised in 1971 and 1978) summarized the avalanche dynamics equations commonly applied in the Swiss Alps.

Mears (1976) presented various methods for computing and otherwise determining avalanche hazard through analytical and observational methods.

Leaf and Martinelli (1977) summarized the state of the art in avalanche dynamics equations as developed in the preceding 22 years.

Perla (1980) summarized avalanche release, motion and impact from a theoretical and practical standpoint.

Mears (1981) summarized avalanche dynamics as they are applied to defense structure design.

These publications should be consulted for details on computational techniques and for the theoretical justifications of various assumptions used in computations.

We have not computed avalanche characteristics for all of the paths in the study area, but instead, as discussed in Section 5, we have selected representative paths and computed velocities and runout distances for these paths because they are similar to others in each area. Therefore, detailed design criteria are not available in all of the areas in which avalanche protection is recommended. If avalanche defenses are to be built, we recommend design of the defenses according to the technique discussed in the publications cited above. The following two sections summarize major considerations in the design of deflecting structures and direct protection structures.

6.5 Deflecting Structures

Deflecting structures are intended to change the direction of flowing avalanches, thereby limiting the area of the natural runout zone. Powder avalanches are generally too deep and are of too high a velocity to be deflected; they tend to override deflecting structures. Deflecting structures have proven to be most useful in cases where an avalanche confined to a gully discharges onto an alluvial fan at the base of the gully. In such cases, uncontrolled dry-snow avalanches would tend to spread laterally across the fan. Wet-snow avalanches may assume a digitate form on an alluvial fan as each advancing finger of snow is deflected to new directions by small-scale terrain irregularities.

In the Anchorage area, deflecting structures would be most useful in avalanche paths that are confined to deeply-incised erosion gullies. Avalanche terrain of this type is found on the north side of Eagle River, on slopes above Mirror and Edmons Lake, at selected locations of the South Fork of Eagle River, and on the western side of Indian Creek. As noted earlier, if deflection structures are to be built in any of these locations, advanced planning must consider if the new areas to which avalanches are to be deflected will contain buildings at some future time. Deflection structures would not be useful below the large, unconfined avalanche paths of the South Fork, Girdwood, and Crow Creek areas.

Although large areas can be made relatively hazard-free by carefully designed and located deflecting structures, planners should identify the most desirable locations for the protected objects. Runout distance may actually be increased in the direction to which the snow is deflected because the avalanche flow depth may be increased in this direction.

Deflecting structures will be most effective on runout zone and lower-track slopes of 12-20°. On slopes steeper than 20°, dry, flowing avalanches of design size may flow at high velocities and tend to override deflecting structures. In contrast, on slopes less than approximately 12°, even large avalanches tend to deposit much of their mass. Deposition of snow against a structure reduces its effectiveness because such deposition reduces the effective height of the structure. Deposition and overtopping are serious design problems with all structures located in the lower track and runout zone including catching, retarding, and direct-protection structures. No clearcut guidelines can be given as to the optimum steepness of terrain upon which structures should be placed. The small design avalanches typical of small paths, such as those of Eagle River, will begin to decelerate and deposit debris on steeper slopes, perhaps of 15-25^o. In such cases, because of lower maximum velocities, the flow may be deflected on slopes steeper than 20^o. In contrast, very large design avalanches on major paths may only begin to decelerate and deposit on slopes of less than 15^o. Thus, design-avalanche parameters must be calculated before defenses can be located or sized, and the expected area of avalanche deposition must be determined.

If avalanches smaller than design size frequently deposit debris against structures, it may be necessary to clean debris away periodically in order to maintain the effectiveness of the structure.

When the momentum of an avalanche is changed, as by altering the flow direction with a deflecting wall, the flow depth will increase at the object. This flow-depth increase is the climbing height h which is a function of velocity V, deflecting angle ϕ, and acceleration of gravity g. The design height H_o of the structure is the sum of climbing height h, flow height h', and snowpack depth h_o. Design height is computed by

$$H_o + h_o + h' + h$$

climbing height is calculated as $h = (V \sin \phi)^2/2g$. Thus, equation becomes

$$H_o = h_o + h' + (V \sin \phi)^2/2g$$

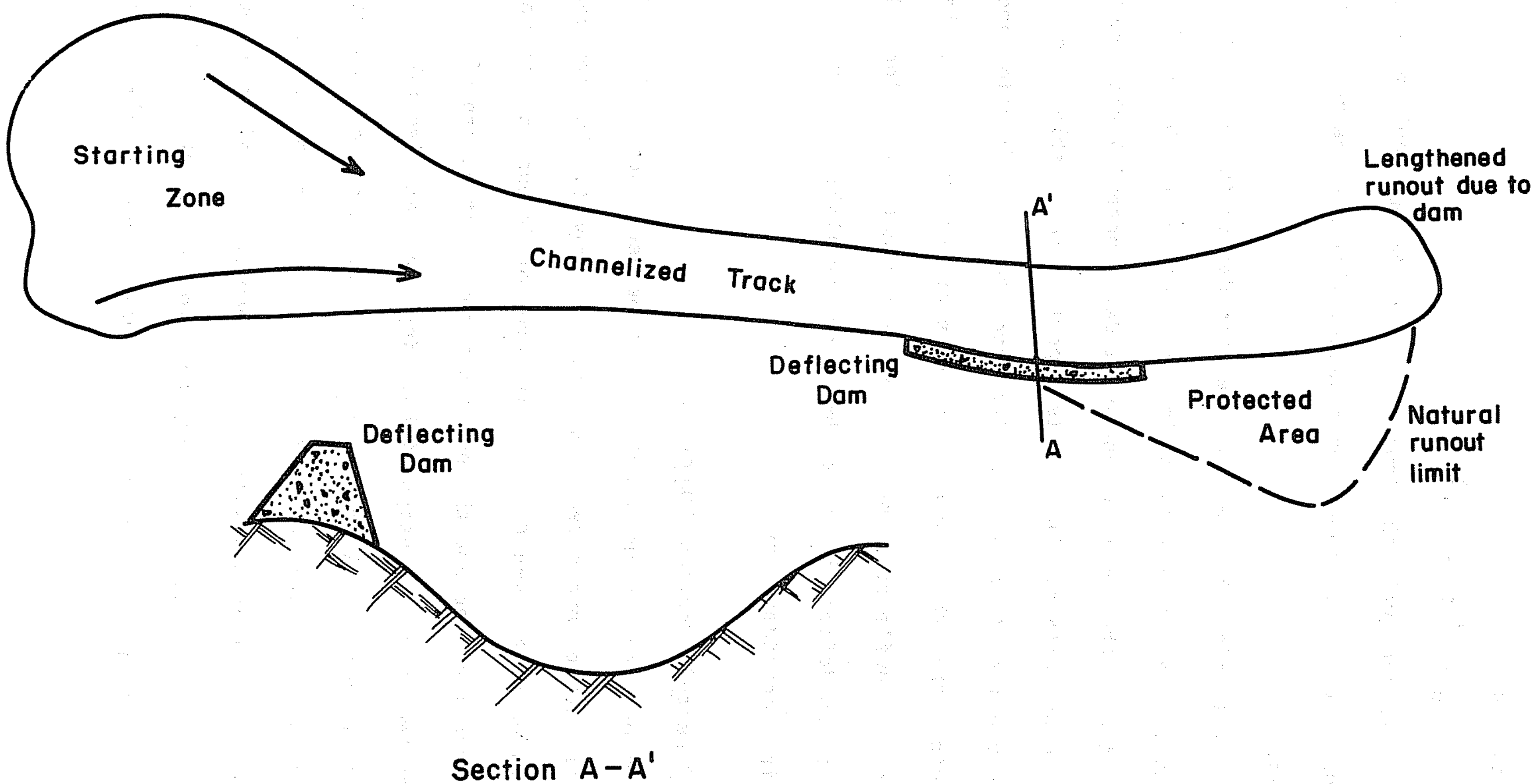
When ϕ is zero, there is no deflection and the wall behaves as a guiding wall. If ϕ equals 90^o, the wall acts as a dam or a catching structure.

The design height increases rapidly with both velocity and deflecting angle; consequently, it is often recommended that ϕ be kept as small as possible. Consider, for example, a design avalanche with the following characteristics: $V = 25$ m/s, $h' = 2.0$ m, $h_o = 1.0$ m, and $\phi = 15^o$. In this case, $H_o = 4.74$ m, but if ϕ is increased to 30^o, then H_o increases to 10.97 m. Figure 6-1 illustrates a deflecting structure in plan and cross-section views.

Deflection forces result when the momentum of an avalanche is changed by an object. The following discussion of deflection forces is applicable to vertical structural walls and to the splitting-wedge type of direction-protection structure (discussed further in the section on Direct Protection Structures). Earthen structures are inherently overdesigned for deflecting forces because of their large mass. The magnitude of the deflection force depends on the avalanche velocity and density, the deflection angle ϕ and the area of the impact surface.

The specific deflection force (i.e., the force per unit area of impacted surface) can be defined in terms of three mutually perpendicular components: normal, shear, and uplift. In the view of the uncertainties that exist regarding the details of avalanche impact, it should be assumed that $0.5\ P_n = P_s = P_v$, where P_n is the normal pressure, P_s is shear, and P_v is uplift. The normal pressure P_n is

FIGURE 6-1
DEFLECTING STRUCTURE



calculated as

$$P_n = \rho'(V \sin \phi)^2$$

where ρ' is the avalanche density. Thus, for $\phi = 90^o$, $P_n = \rho' V^2$, the expression for fluid impact on a large, flat surface normal to the flow direction.

It will often be true that earthen deflecting walls will be more economical than structural walls. The cost of earthen walls is mainly a function of the amount of unconsolidated material that must be moved during construction; thus, it is important to be able to relate wall volume required to protect a given area to the deflection angle. It is recognized that the same area can be protected by a short, high wall with a high deflection angle as can be protected by a long, low wall using a low deflection angle, but space available is usually the principal consideration.

6.6 Direct-Protection Structures

Direct-protection structures can be used when individual, isolated objects must be protected from avalanche impact. In many cases in the United States and Europe, this type of defense has proven to be most practical because the necessary construction can often be incorporated into the design of buildings and can also take place on private property. Although direct protection may often appear to be the simplest and most economical means of avalanche protection, it is not appropriate in all situations. When several adjacent buildings need to be protected, diverting the flow by use of certain types of direct-protection structures may actually increase the avalanche hazard by changing the runout zone to a location not normally reached by the avalanche. Care must be taken in advanced planning to avoid such complications. In general, direct protection is probably not suitable for closely spaced buildings.

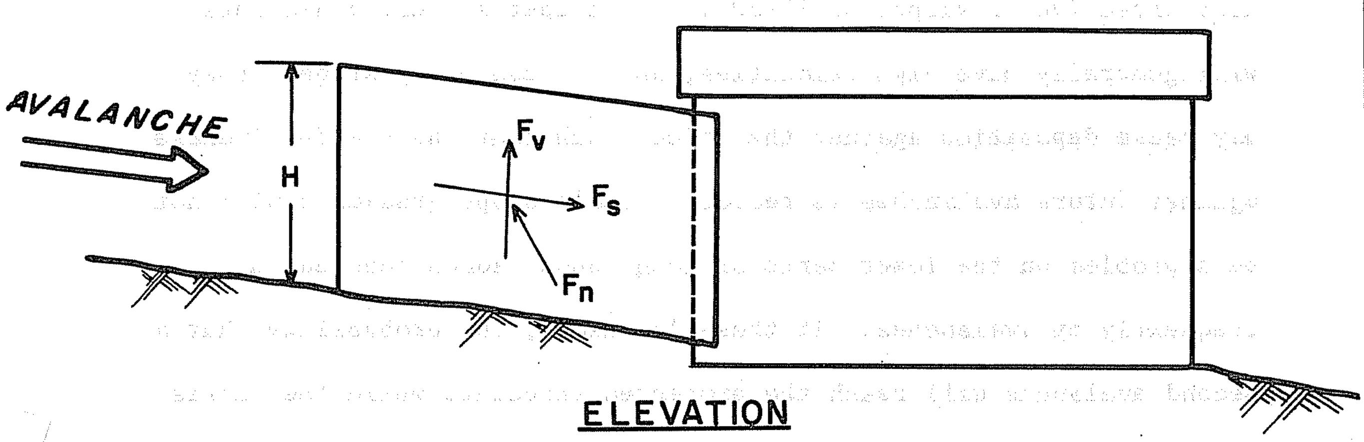
As with deflecting structures, direct-protection structures are most effective on slopes of 12-20^{o}. On steeper slopes, avalanches will generally have high velocities, and on less steep slopes, they may cause deposition against the object such that their effectiveness against future avalanches is reduced. Small slope gradients will not be a problem on the lower parts of long runout zones reached infrequently by avalanches. At these locations, the probability that a second avalanche will reach the protected structure while the debris from previous avalanches is still present can usually be disregarded.

Direct-protection structures should be designed for fluid-dynamic stagnation pressures and for impact pressure from the dense, lower portion of flowing avalanches, or both.

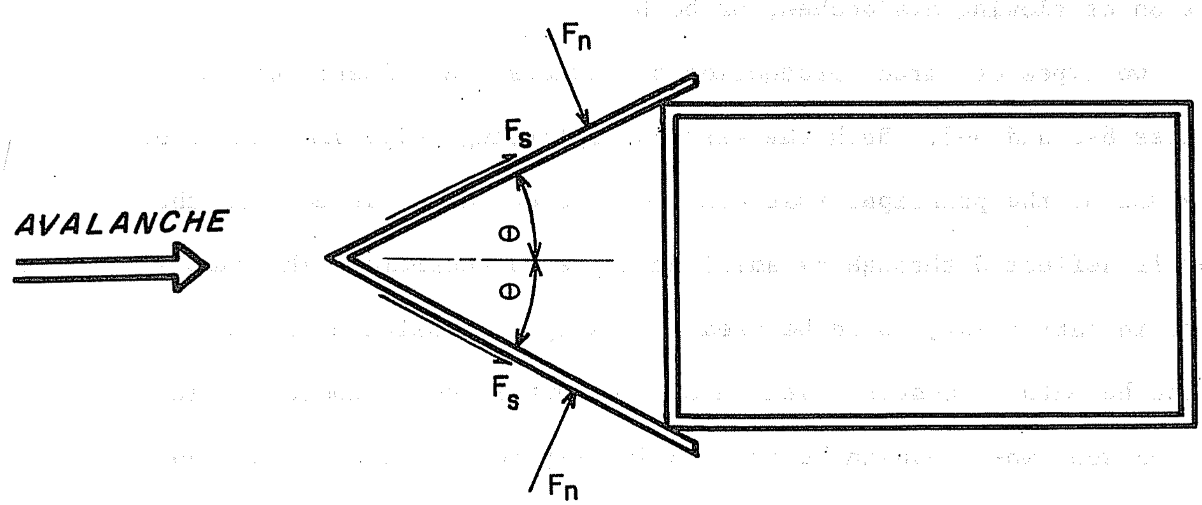
Two types of direct-protection structures are illustrated in Figures 6-2 and 6-3. Both the vertical splitting wedge and ramp roof make use of the principal that avalanche forces are reduced when the flow is deflected through as small an angle as possible. The ramp roof, in particular, could be used at nearly any position in the avalanche path. However, even this structure is not recommended in the red zone where avalanche frequencies may be high and deposition of snow on top of and against structures can be a problem.

As with the other types of structures already discussed, the natural characteristics of the design avalanche must be determined prior

FIGURE 6-2
DIRECT PROTECTION WEDGE



ELEVATION

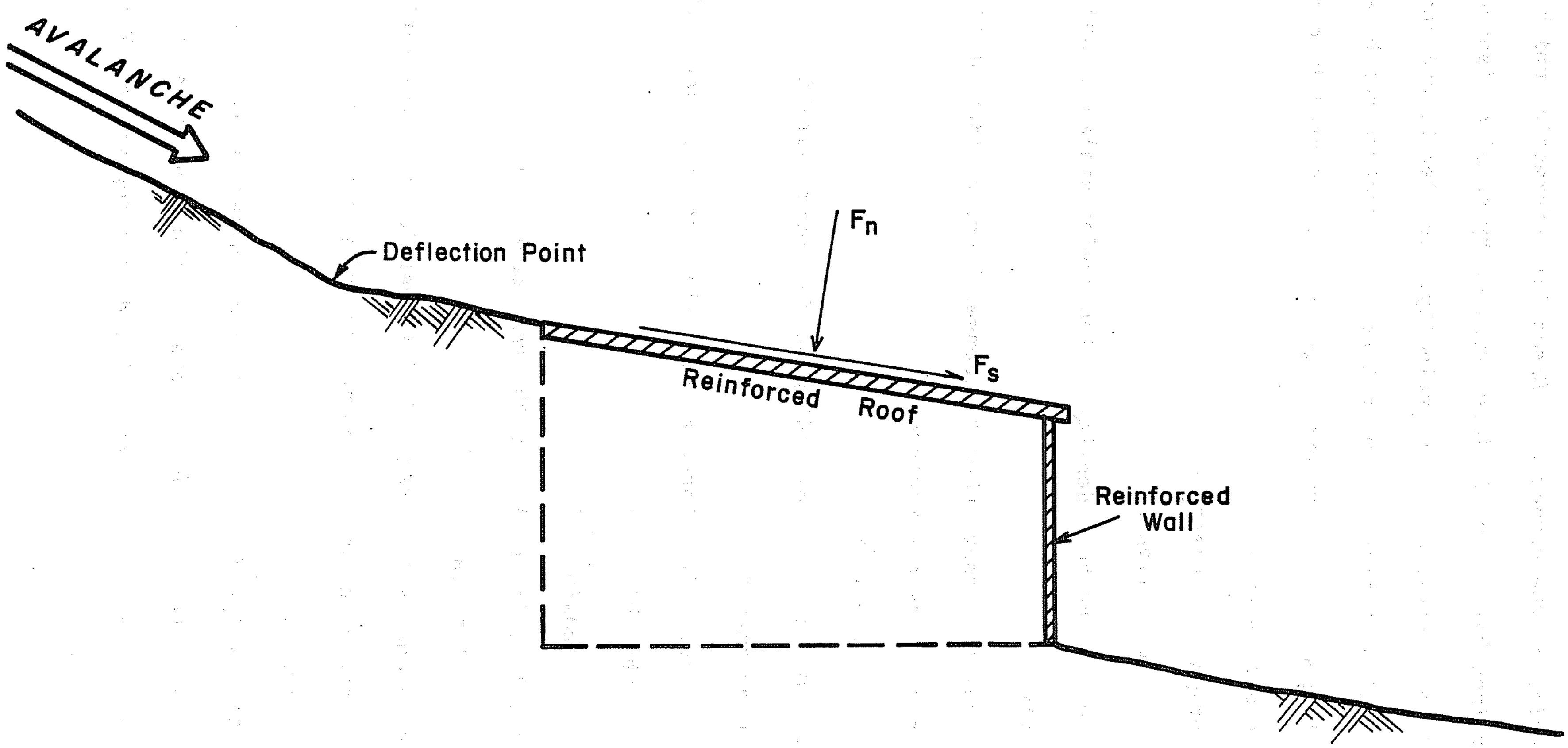


PLAN VIEW

FIGURE 6-3

DIRECT PROTECTION RAMP

(Shed Roof)



to design of the structure. Essential information which should be determined beforehand includes type or types of avalanches reaching the defense site, avalanche velocity, flow depth, and density. This information enables design in terms of structure height and strength.

In summary, the relevant equations to be used in direct-protection design are as follows:

Stagnation pressure,

$$P_s = 1/2\rho' V^2$$

where ρ' is the bulk density of the powder avalanche and V is avalanche velocity.

Impact pressure when the dense, lower portion of flowing avalanches hits a structure,

$$P_f = K\rho' V^2$$

where $1.0 < K < 2.0$, depending on the compressibility of avalanche snow upon impact.

The total drag force F_d resulting from a powder avalanche that engulfs the object is

$$C_d A_d (\rho' V^2/2)$$

and the lift force, F_1, on the same object is

$$F = C_1 A_1 (\rho' V^2/2)$$

where C_d and C_1 are drag and lift coefficients, respectively, and A_d and A_1 are areas exposed normal to and parallel to the avalanche flow, respectively.

The design forces on a vertical surface exposed to avalanche impact must be determined in exactly the same way as previously described for vertical, straight, deflecting walls. Design height

H_o is

$$H_o = h_o + h' + (V \sin \phi)^2/2g$$

where h_o is the snowpack depth, h' is the avalanche flow depth, V is the avalanche velocity, and ϕ is the deflection angle. Normal pressure P_n is

$$P_n = \rho'(V \sin \phi)^2$$

Shear in the avalanche direction P_x and vertical shear P_v are related to normal pressure P_n by the following expression:

$$0.5\, P_n = P_x = P_v$$

Obviously, the equations given above can only be applied if the designer has knowledge of design avalanche velocity, density, and snow type (the latter related to compressibility). Furthermore, final design loads cannot be specified without knowledge of the size, shape, orientation, and location of the building or object to be protected. In general, this information will not be known until buildings are in the final design stage and architectural details are known.

At the present time, direct protection appears most feasible in the South Fork of Eagle River where the design avalanche occurs on unconfined slopes and consists of dry-snow avalanches of low density (see Section 3). Direct protection would also be useful in portions of Eagle River where buildings are not closely spaced, and possibly on the fringes of avalanches in the Crow Creek area.