CHAPTER

2

SNOW AND ICING PROBLEMS

2.1 Characteristics of Snow Covers

The characteristics of snow covers vary greatly depending upon the location. In structural design and construction the factors that should be considered include snow precipitation, snow depth, snow properties, length of snow season, snow transport, and snow drifting. In mountainous terrain the risks of avalanches and snow creep should also be assessed.

Information about snow precipitation, snow thickness, snow loads, and the length of the snow season is often available in local codes and their commentaries. Figure 2.1 gives a rough idea of the existence of snow cover. The properties and characteristics of the snow covers in subarctic and arctic areas, however, differ. The key factor is snow transport, which depends, among other things, on wind speed, snow density, and how well the snow particles have bonded (Fig. 2.2). When the wind velocity is below 10 m/s (20 mi/h), the transport of even fresh falling snow is not very significant. However, blowing of loose surface snow is an important design consideration in flat treeless terrain when the wind speed exceeds 15 m/s (30 mi/h).

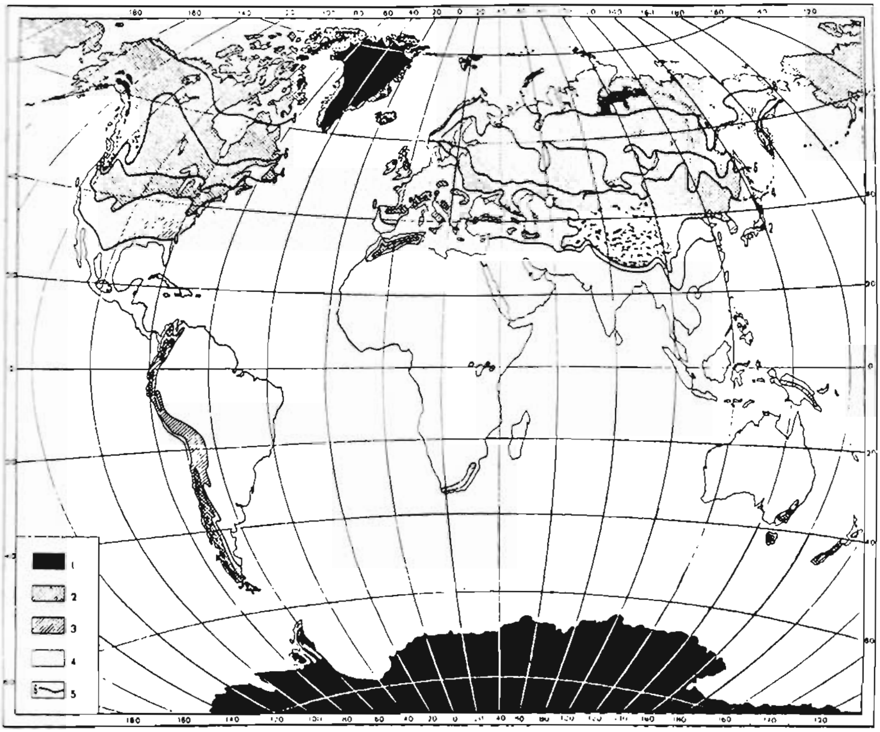

Figure 2.1 Extent of snow cover on the world surface. 1—permanent cover of snow and ice; 2—stable snow cover of varying duration forms every year; 3—snow cover forms almost every year, but is not stable; 4—no snow cover; 5—duration of snow cover (months). *(Mellor, 1964.)*

Snow particles travel close to the snow surface in areas of laminar flow, and they are deposited especially in low-wind-speed regions in the vicinity of flow disturbances. Knowledge of airflow characteristics is thus important when snowdrifts are studied. When wind is associated with snowfall, snowdrift patterns are changed, especially at and near higher locations such as the roofs out of the reach of the normal snow transport path. The snow already deposited on the roof is only a limited source of drift accumulation, but during a snowstorm the supply is greatly increased.

In subarctic conditions the amount of snow transport is typically limited mostly because of vegetation. The density of freshly fallen snow in freezing temperatures is approximately 100 kg/m^3 (6 lb/ft^3) or less. When the snow cover reaches its maximum thickness, its average density will increase to about 200 to 300 kg/m^3 (12 to 20 lb/ft^3) due to the combined effect of compaction, moisture absorption, evaporation, and

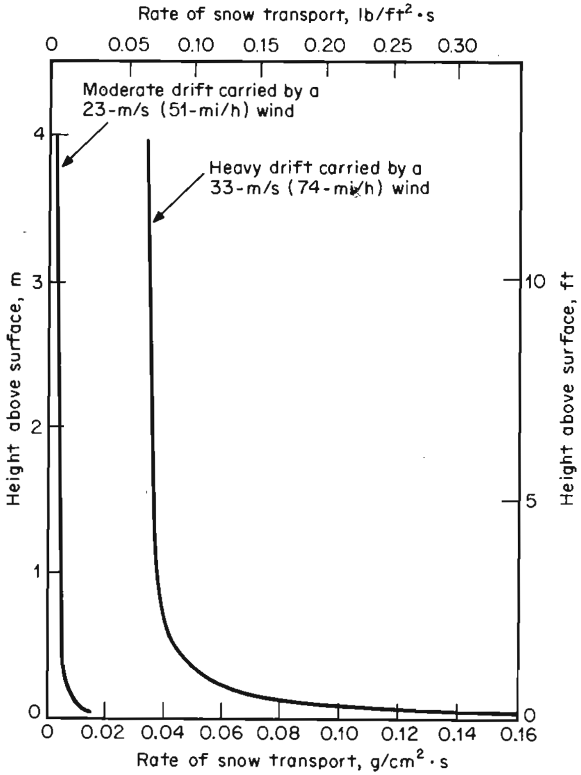

Figure 2.2 Typical arctic snow-transport profiles. *(Mellor, 1965.)*

melting. The density of compacted snow or old melting snow may exceed 500 kg/m³ (30 lb/ft³).

In arctic, treeless tundra, and high mountain regions, the snow particles are rounded because of the constant snow transport during the long winter. Even if the annual precipitation is small, snowdrifts may reach considerable dimensions. The average density of snowdrifts is high, on the order of 300 to 500 kg/m³ (20 to 30 lb/ft³). Due to the steep temperature gradients depth hoar, which is the result of vapor diffusion from a warm lower layer to colder layers above, is typical for arctic snow covers.

2.2 Snow Loads

The snow loads on individual structural elements, such as wires or elevated pipes, may be found based on the width and shape of the structures

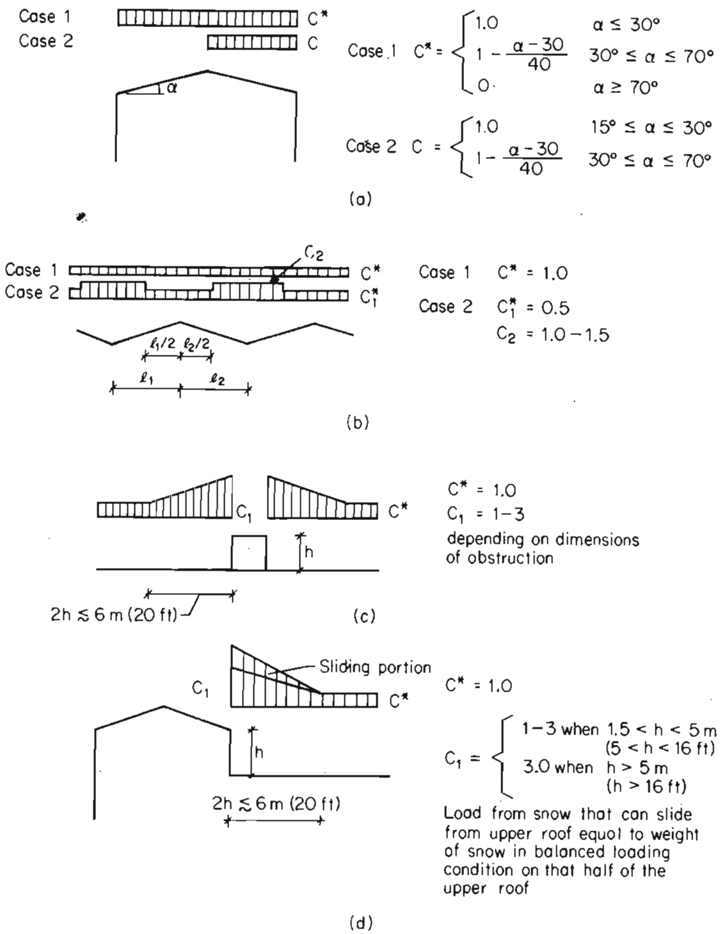

Figure 2.3 Typical snow accumulation coefficients for roofs. Wind reduction factor k may be used together with C^{*} values. (*a*) Simple cable and hip roofs. (*b*) Multispan sloped roofs. (*c*) Major obstructions on flat roofs. (*d*) Two-level roofs.

rather than on local climatological conditions, but usually the snow load of a structure is given in the following form:

$$S = kCg \tag{2.1}$$

where S = snow load
g = ground snow load based on snow thickness and average density
C = snow accumulation coefficient

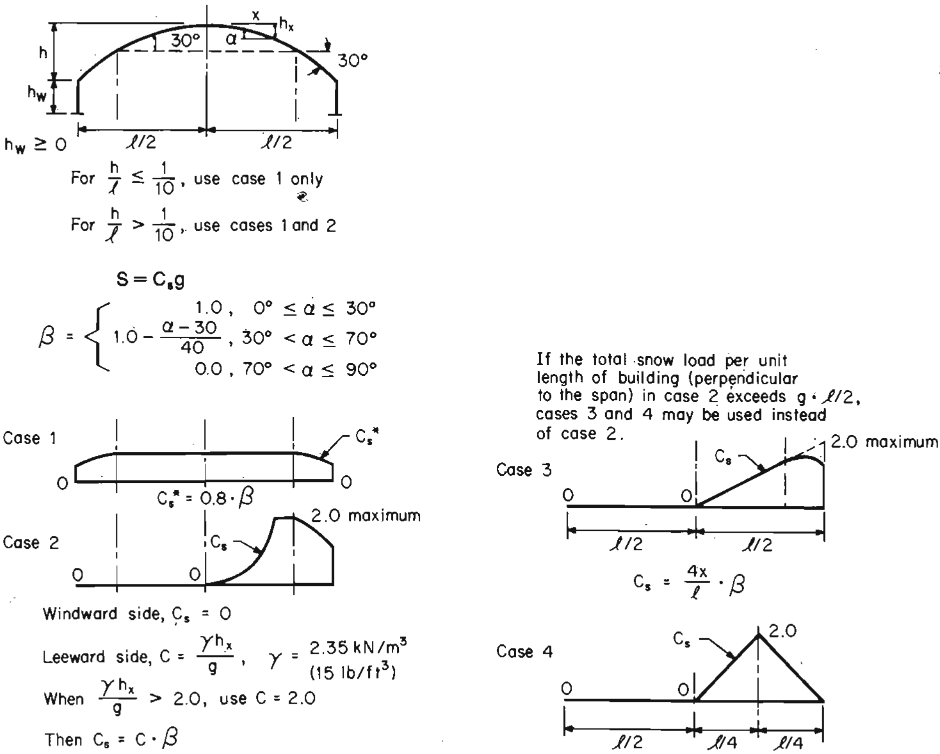

Figure 2.4 Proposed snow loading on arches. For roofs exposed to wind on all sides, all values of C_s^* may be reduced by 25%. *(Adapted from Taylor, 1981.)*

k = wind reduction factor, accounting for snow transport off the elevated and exposed roofs

The structural importance factor and the thermal factor that account for the possible melting of snow can also be recognized in Eq. (2.1).

The ground snow load is given in local codes, and it usually has a value of between 0.5 and 4 kPa (10 to 80 lb/ft²). However, one should keep in mind that the average ground snow load normally increases with elevation because of longer winters and other meteorological effects. Thus in a mountain area the ground snow load given by a code may be exceeded.

The snow loads on roofs are generally smaller than the ground loads because of the effect of winds. The reduction factor k has a typical value

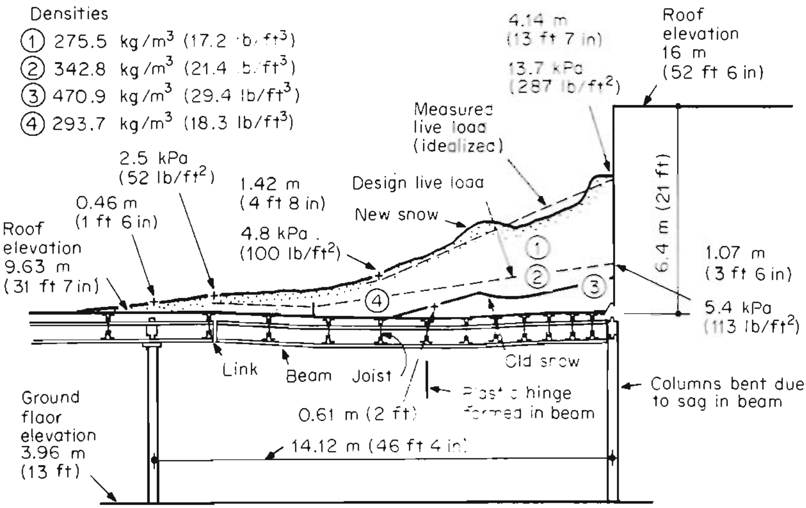

Figure 2.5 Snow drifts on large warehouse in Boston, Mass. *(Courtesy Maurice A. Reidy Engineers, adapted from Templin and Schriever, 1982.)*

of 0.8 for not very well sheltered and 0.6 for well exposed roofs. However, because of the effects of snow accumulation, the average load may be exceeded. Some examples of typical accumulation coefficients are given in Figs. 2.3 and 2.4.

There are some situations where snow loads may catch the designer off guard, as shown in Figs. 2.5 and 2.6. In addition to ordinary code provisions, practical considerations based on local conditions must be allowed for. For example, in design one should pay full attention to the role of unbalanced snow loads as well as to the possibility of snow sliding from an upper roof to a lower one (Fig. 2.7). In the design of special structures, such as large domes, snow accumulation can be studied by small-scale model tests.

Water pressure combined with snow load is one important roof design consideration. The design snow load may be temporarily exceeded on flat roofs when heavy rain falls on snow and does not drain away rapidly. The problem may be greatly magnified in valleys and low areas of the roof due to snow meltwater and rain ponding if there is no adequate slope to the drain or if the drains are blocked with ice. These areas tend to deflect increasingly, allowing even deeper ponds to form. Local roof failures have been experienced due to such combined snow, meltwater, and rain loads. Leakage problems are even more common. Drains are often heat traced to prevent ice formation. Gutters and roof valleys may be provided with heating cables to secure proper drainage. An alternative solution is to cut the roof insulation locally and utilize thermal leaks.

Figure 2.6 Parking shelter collapsed in spring under the weight of accumulated wet snow. *(Courtesy of Lehtikuva Oy.)*

Figure 2.7 Example of heavy snow loads, Fort Wainwright, Alaska. Note how falling snow may increase load on patio roof. *(Courtesy of W. Tobiasson.)*

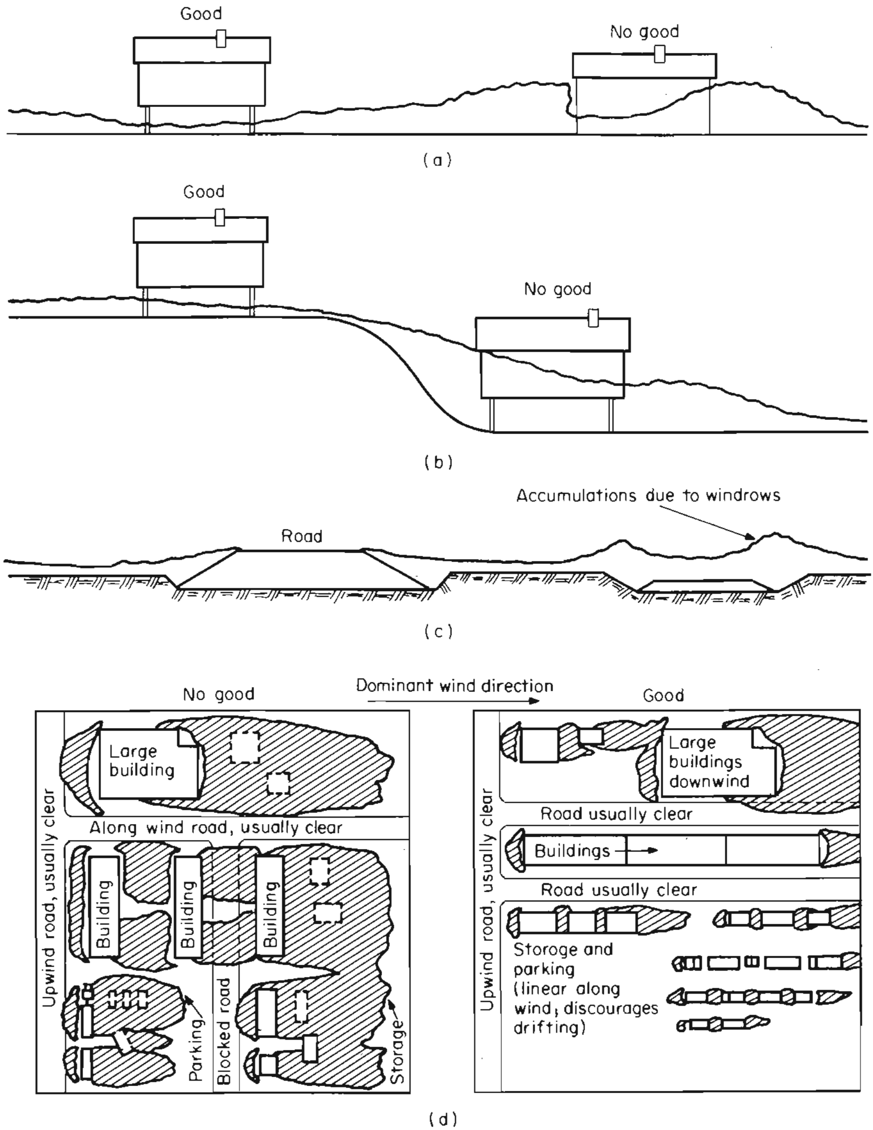

Figure 2.8 Passive methods to control snow drifting. *(Adapted from Rice, 1975.)*

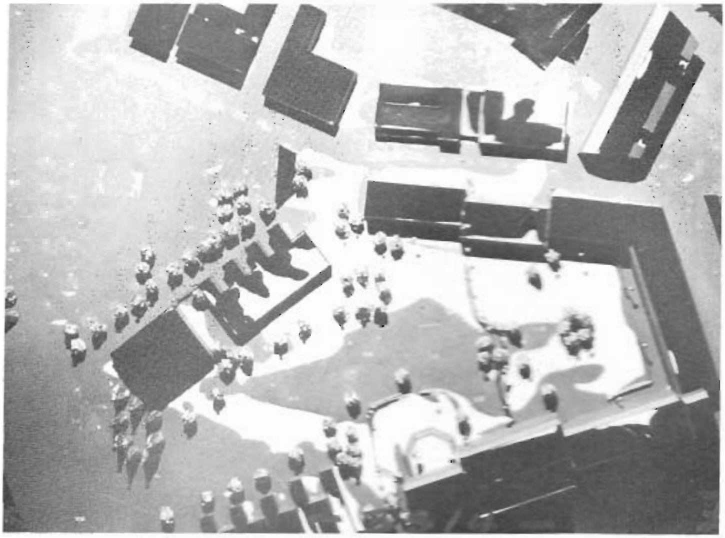

Figure 2.9 Snow accumulation and wind climate around a northern community, studied with small-scale model in wind tunnel. *(Courtesy of Technical Research Centre of Finland.)*

Lateral snow pressures have also caused some structural failures. The plowing of streets may, for example, damage traffic sign poles. In Alaska snow creep has caused failures of power transmission poles in steep slopes (Shira, 1978).

2.3 Snow Control

A variety of measures can prevent or minimize the structural, functional, or maintenance problems caused by snow deposits or drifting. These include site selection, special design considerations, erecting control structures, and snow melting. In subarctic regions snow drifting is only of local importance, but in treeless arctic tundra, where snow transport and drifting are almost continuous, control measures should be given great emphasis.

Some general design considerations in snow control are illustrated in Fig. 2.8. One should by all means avoid locating houses, roads, or other structures in depressions. Exposed plains or ridge tops should be considered in site selection in spite of the inconvenience caused by high winds. The common practice of using elevated structures in arctic permafrost areas is also helpful from the viewpoint of snow control.

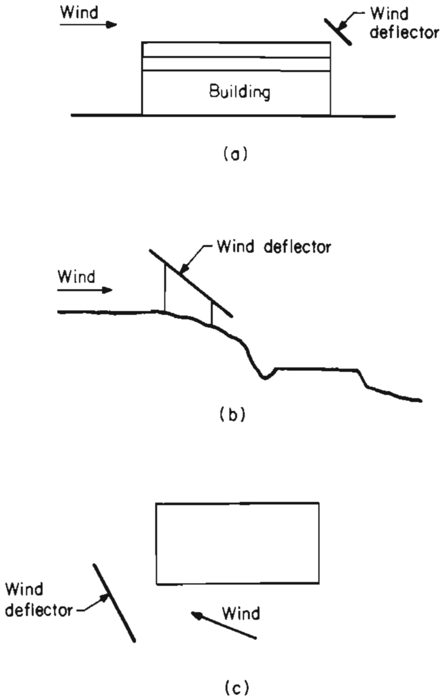

Figure 2.10 Use of wind deflectors to prevent snow accumulation where undesirable.

In road construction one should avoid sharp bends and use high subgrades. Thus the initial rate of snow deposition is minimized, and even if some snow has to be plowed from the road, the windrows do not reach such dimensions that the snow accumulation rate is significantly increased. In the design of communities the maintenance efforts are reduced if the structures are located parallel to the prevailing wind direction and no roads or structures are located immediately on the downwind side of large structures. The design of northern communities with respect to snow is further discussed in Velli et al. (1977). Small-scale model tests may prove useful in design (Fig. 2.9). Modeling techniques have been discussed in Anno (1984), Williams (1978), and Odar (1965), among others.

One can also use active methods in snow control. Snow drifting can be prevented in unfavorable locations, such as in front of doors, by using different kinds of wind deflectors (Fig. 2.10). Snow fences have been used to help in road maintenance (Fig. 2.11). These fences can also be used to gather snow for winter road construction. To be effective, snow fences should have sufficient height. Different kinds of strong cold-weather-resistant plastic strips are gradually replacing wood as the pri-

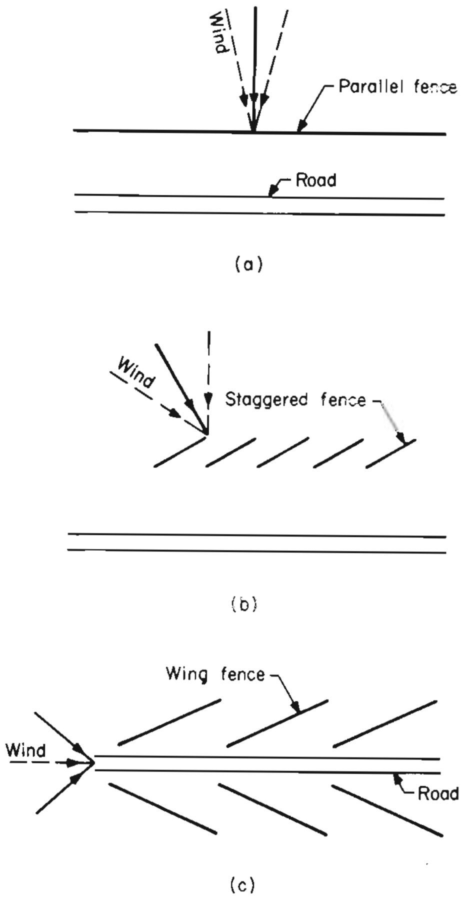

Figure 2.11 Basic arrangements of snow fences for protecting roads or railways. *(Pugh and Price, 1954.)*

mary fence material (Fig. 2.12). The fences do not have to be of the high-density type to be effective, as shown in Fig. 2.13.

Mechanical snow removal using different types of plowing equipment plays a dominant role in snow control measures aimed at maintaining the serviceability of roads, airfields, parking areas, and so on (Fig. 2.14). Salt is often used to melt the hard-packed snow and ice left on the road after plowing (Fig. 2.15). Some restricted areas such as bus terminals, bridges, or important crossroads can also be kept free of snow and ice by thermal methods using a heating cable network or hot fluid circulation in a pipe network (Fig. 2.16). A typical heat input requirement to overcome heat losses by convection, radiation, and evaporation and to melt the falling snow is on the order of 500 W/m^2 [150 Btu/(ft^2·h)]. For further discus-

Figure 2.12 Traditional wooden snow fence in background is replaced by plastic strip fence at left. *(Courtesy of Finnish Roads and Waterways Administration.)*

sion of the different ice and snow control methods, the reader is referred to Gray and Male (1981), and for thermal control system design to the ASHRAE handbook (1980).

2.4 Construction on Snowfields

In the continental ice shelves of Greenland and Antarctica and in some other ice caps and glacierized areas the snow does not melt but slowly

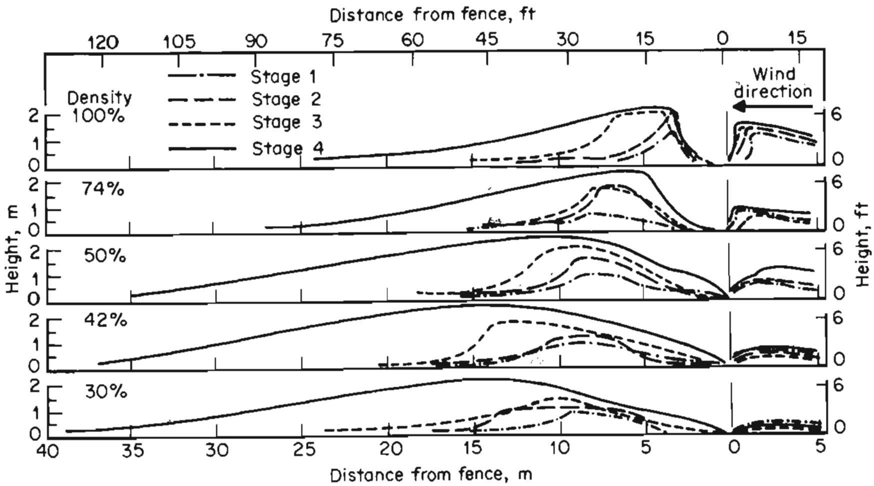

Figure 2.13 Snowdrifts generated by solid snow fences and vertical slat fences of various densities, all 1.87 m (6 ft 2 in) high with a gap of 20 ± 5 cm (8 ± 2 in) underneath. *(Price, 1961.)*

Figure 2.14 Snowplowing. *(Courtesy of D. Minsk.)*

turns into ice as the overburden pressure increases. The construction problems on these snowfields are unique. In addition to the severe climate conditions there are virtually no local resources available. Furthermore, the structures have to be founded on the thermally and mechanically unstable snow, and the typically extensive snowdrift phenomena have to be controlled. In foundation and tunnel design one must take into consideration the movements of snow layers in both the vertical and the horizontal direction. The movements are absolute as well as relative (with respect to the snow surface) as the snow undergoes viscoelastic deformation under overburden pressure. The natural process may be

Figure 2.15 Sand and salt spreading on road to increase abrasion and melt ice. *(Courtesy of Finnish Roads and Waterways Administration.)*

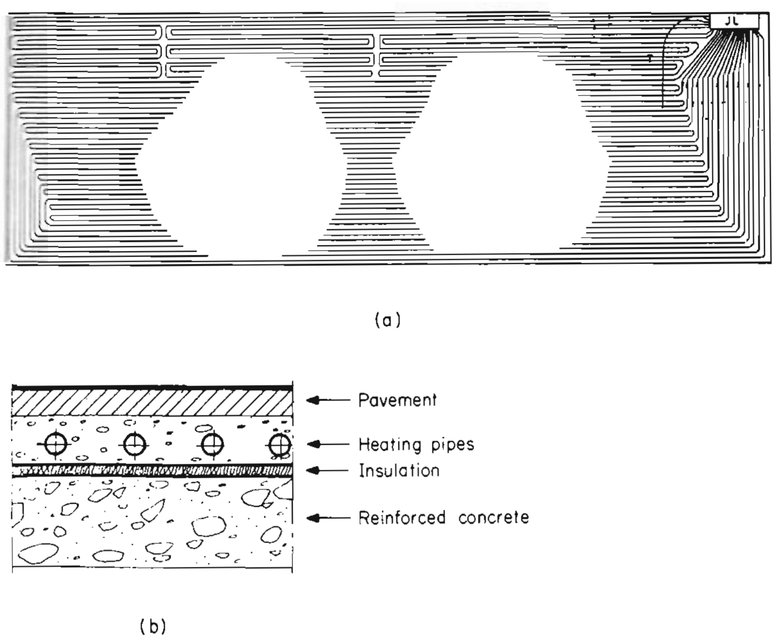

Figure 2.16 (*a*) Typical heating pipe network in slab construction. (*b*) Cross section of slab. *(Matilainen and Suontausta, 1970.)*

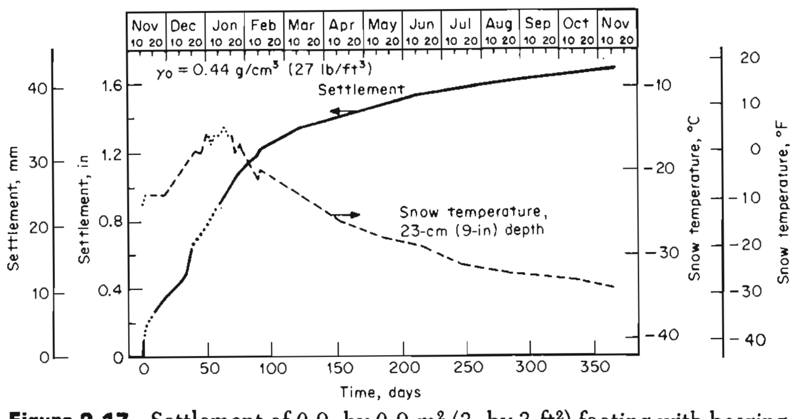

Figure 2.17 Settlement of 0.9- by 0.9-m² (3- by 3-ft²) footing with bearing pressure of 48 kPa (7 lb/in²) at Antarctica. *(Mellor, 1969.)*

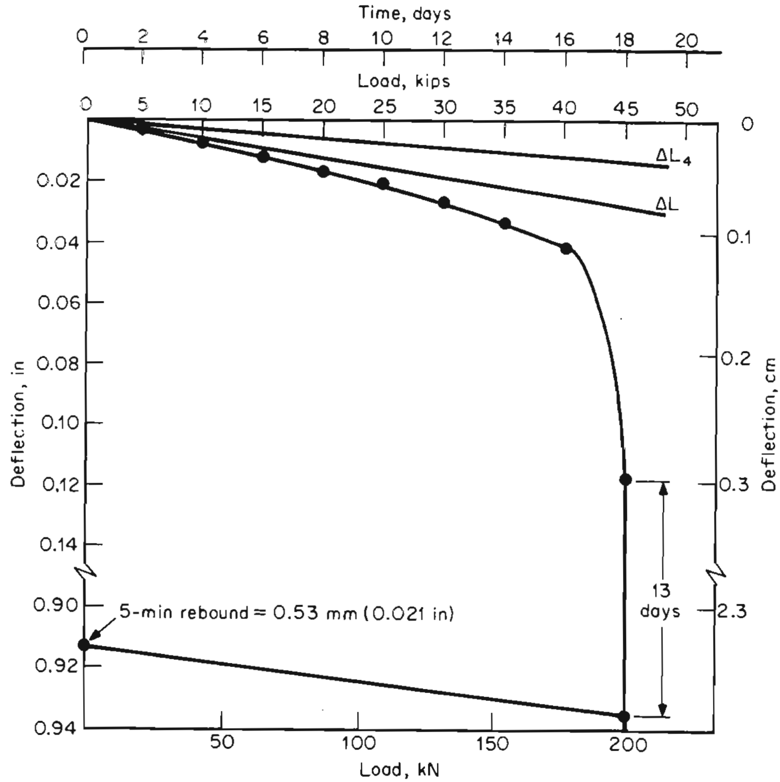

Figure 2.18 Deflection of closed-end steel pile installed into polar snow in Greenland. ΔL—elastic shortening of pile assuming pure end bearing; ΔL_4 — elastic shortening of pile assuming uniform skin friction. Pile diameter 0.25 m (10 in); embedded length 5.5 m (18 ft); bearing capacity was reached at 180 kN (40 kips). *(Kovacs, 1976.)*

disturbed as a result of construction activities. Snow undergoes accelerated creep under concentrated loads, and complex stress and strain fields form around any kind of mechanical or thermal disturbance (Mellor and Reed, 1967).

Separate or strip footings and friction piles are typical foundation structures used on snowfields. Bearing pressure values for moderate relative settlement rates are usually less than 50 kPa (7 lb/in^2), and footings may be tied together to avoid separation (Fig. 2.17). For piles the allowable long-term skin friction values may be on the order of 10 kPa (1.5 lb/in^2) (Fig. 2.18). It is interesting to note that negative skin friction may result at the upper portions of the pile when the new snow

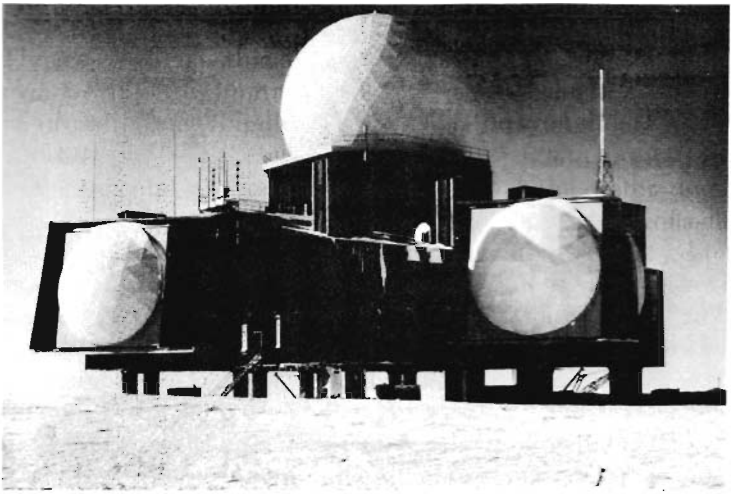

Figure 2.19 DEW line station DYE-3 in Greenland. *(Courtesy of U.S Army Cold Regions Research and Engineering Laboratory.)*

settles faster than the pile. Snow density and temperature are the most important parameters in foundation design, but snow properties and foundation size should also be considered (Mellor, 1969; Kovacs, 1976). Because experience with foundation behavior on snowfields is limited, long-term bearing tests may be necessary for large-scale construction.

Some basic design alternatives for construction on snowfields are shown in Figs. 2.19 to 2.22. If snowdrifts are to be controlled, the structures have to be lifted well above the ground level. Small or temporary buildings can be removed when the surface of the snow cover reaches levels that are not acceptable. Larger buildings should be provided with a lifting mechanism that can also be used to balance the structure in case of uneven foundation settlements (Fig. 2.20). Airflow disturbances due to buildings, parked cars, and equipment can cause large snowdrifts in the surrounding areas, which may have to be leveled off occasionally.

In the alternative shown in Fig. 2.21, snow is allowed to drift around and eventually bury the structure. The thermal stability of the snow is maintained by ventilating the airspace between the protective steel arch and the heated facilities. The effective lifespan of any undersnow structure is limited, especially if the protective arches or possible steel tube linings are not designed to resist the total overburden pressure as the surrounding snow deforms.

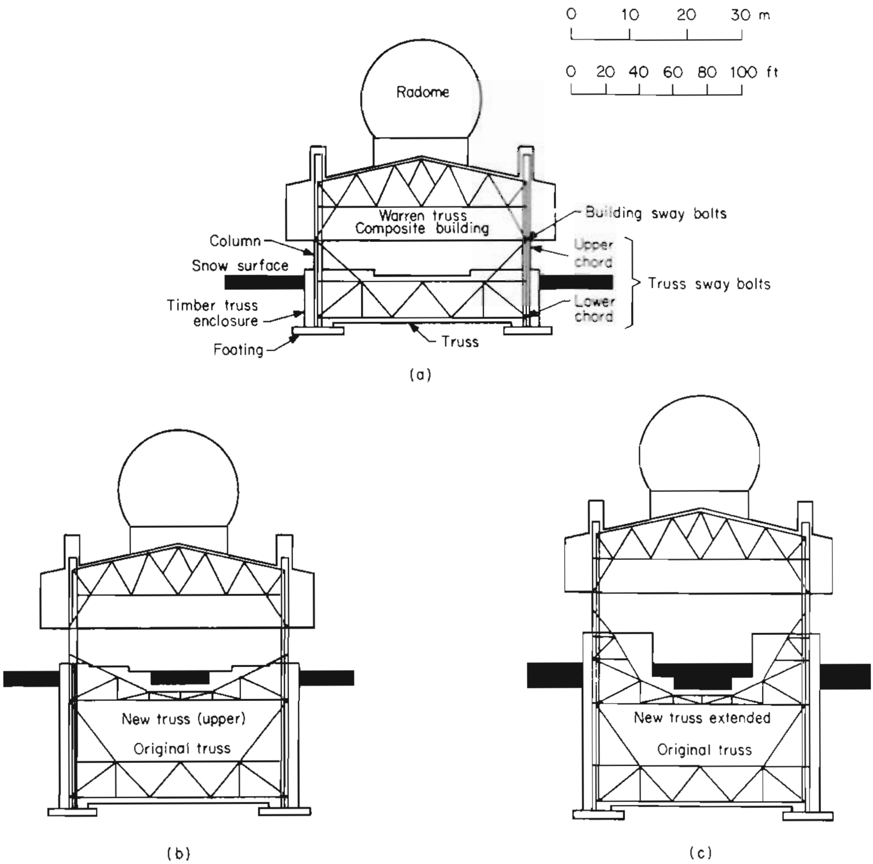

Figure 2.20 Cross sections of structural frames of DEW line ice-cap stations. (*a*) DYE-2 and DYE-3 as built in 1959–1960. (*b*) DYE-2 since fall 1970. (*c*) DYE-3 since fall 1972. *(Tobiasson et al., 1974.)*

2.5 Avalanches

An avalanche may be a small trickle of loose snow, a huge devastating slide of snow, ice, and rock, or anything in between (Fig. 2.23). An avalanche is initiated when the shear strength of the snow cover is exceeded over a sufficiently large area. This may occur when the creep of snow reaches the tertiary stage, but often the reason is an outside factor, such as a significant change in temperature, strong winds, heavy snowfall, an earthquake, or falling snow, rock, or ice. Avalanches have also been triggered by human activities such as skiing, blasting, or even by sound waves.

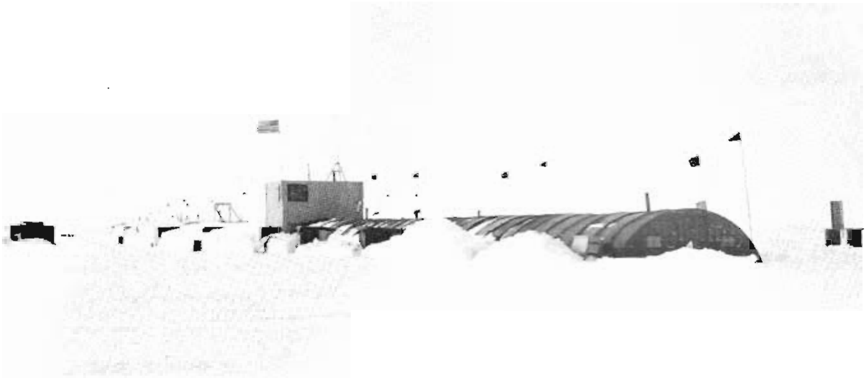

Figure 2.21 Arch-shaped structures at Byrd Station, Antarctica. *(Mellor, 1965.)*

A typical avalanche terrain has a deep snow cover and steep slopes. The characteristics of the slopes also have an important effect on avalanche occurrence. Uneven slopes and trees tend to anchor the snow cover in its place, whereas smooth slopes favor avalanches. Large snowslides occur usually when the slope angle is between 25 and 50°. There are usually no significant snow accumulations on steeper slopes. On gentle slopes only smooth wet slush runs occur sometimes. Most of the avalanches occur in well-defined areas. Central Europe is maybe the best known avalanche area, but there are also large avalanche areas in the western part of North America and in Asia.

The most important characteristic of an avalanche is its magnitude. The reaches of the largest observed avalanches have been measured in kilometers, and the volumes have exceeded 10^6 m^3 (3.5×10^7 ft^3). Such avalanches destroy everything in their path and may create impact pressures approaching 1 MPa (150 lb/in^2). The typical volume range of

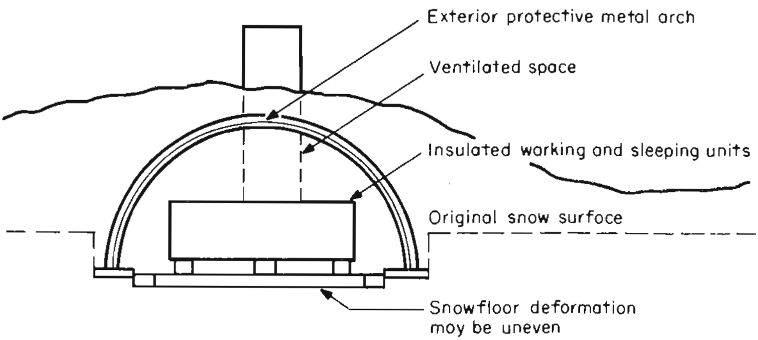

Figure 2.22 Schematic cross section of arch-shaped structure.

Figure 2.23 Dry slab avalanche. *(Courtesy of U.S. Forest Service.)*

an avalanche is between 10^3 and 10^5 m^3 (3.5×10^4 and 3.5×10^6 ft^3), and the corresponding impact pressures are on the order of 20 to 200 kPa (3 to 30 lb/in^2), although higher peak pressures may be experienced (Fig. 2.24). In loose snow the avalanche may begin in a small area, but the rupture of hard snow usually occurs over an extended area (sliding slabs), either along a layer boundary in the snow or along the ground surface. Different types of avalanches can be described by the U.S. Forest Service avalanche classification shown in Fig. 2.25. For a more detailed discussion of the characteristics and dynamics of avalanches the reader is referred to Mellor (1968) and Colbeck (1980).

Avalanches represent a serious potential hazard to human life and property. When necessary, they will have to be controlled. It is possible to trigger avalanches in advance by using explosives. For more permanent protection, structural solutions are available.

Some structural solutions for avalanche control are shown in Fig. 2.26. An extensive snow accumulation at the initial failure areas can be prevented using wind deflectors. Cut and fill terraces and supporting structures can be used as avalanche barriers. Supporting structures are typically arranged 15 to 30 m (50 to 100 ft) apart, depending on slope angle, slope smoothness, and snow depth. The snow force component parallel to the slope is approximated in Swiss practice (Mellor, 1968) by

$$P = \tfrac{1}{2} K N \gamma_s \left(\frac{h}{\cos \alpha}\right)^2 \qquad (2.2)$$

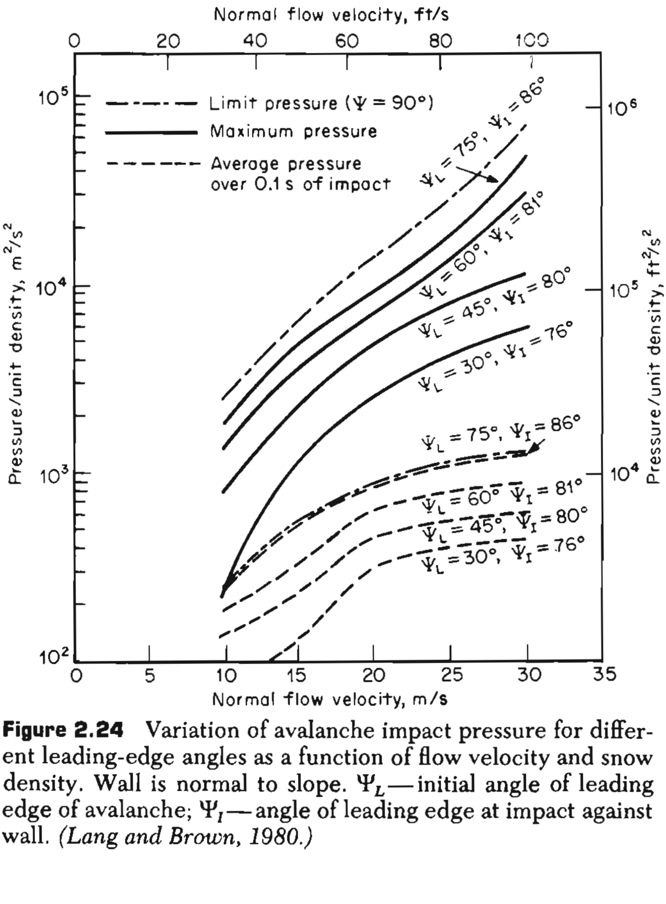

Figure 2.24 Variation of avalanche impact pressure for different leading-edge angles as a function of flow velocity and snow density. Wall is normal to slope. Ψ_L—initial angle of leading edge of avalanche; Ψ_I—angle of leading edge at impact against wall. *(Lang and Brown, 1980.)*

where N = glide factor (1.2 to 3.2, depending on slope smoothness and direction)

K = creep factor (typically 0.7 to 1.0, depending on slope angle and snow density)

γ_s = snow density

h = snow thickness

α = slope angle

Instead of preventing release of the slide, the control can also be accomplished by using deflective or protective structures. The most important loads on the avalanche gallery shown in Fig. 2.26 are the weight of the avalanche, the possible dynamic effects in case of a changing slope, the weight of the snow cover and previous avalanche debris in case they are not swept away, and the shear or friction force along the roof. Typical design values for normal roof loads may be up to 50 kPa

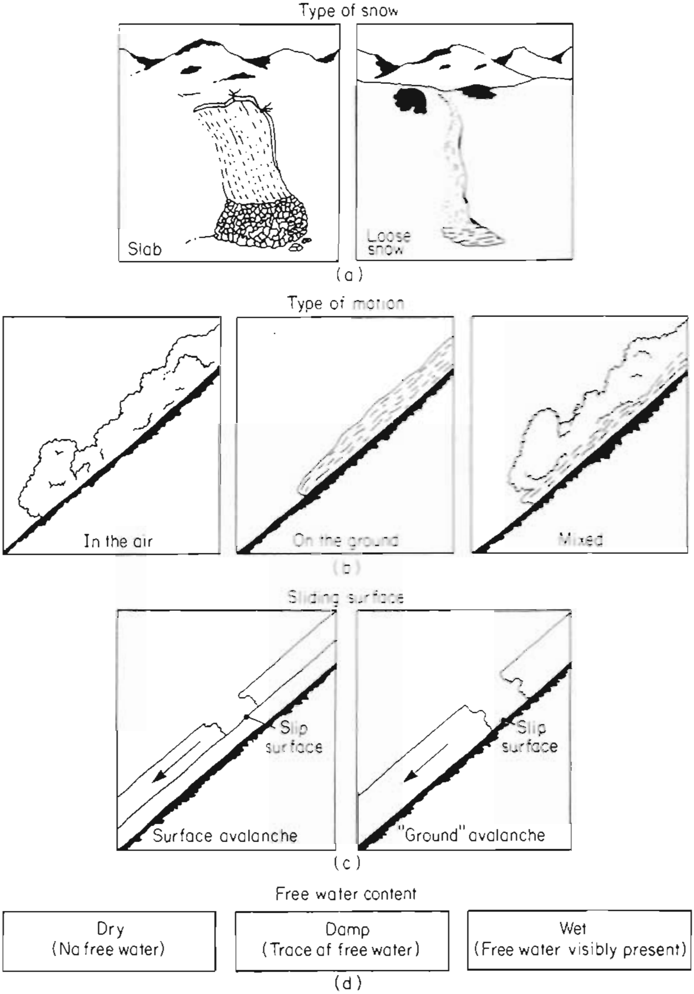

Figure 2.25 Avalanche classification. *(U.S. Forest Service, 1961.)*

(1000 lb/ft^2). The friction force along the roof is often considered to be 50% of the normal force caused by the sliding avalanche. The design principles of avalanche control measures are discussed thoroughly in Mellor (1968).

2.6 Icing on Structures

Icing on structures is caused by freezing of water droplets in subsequent layers on the surface of a structure exposed to the atmosphere. The

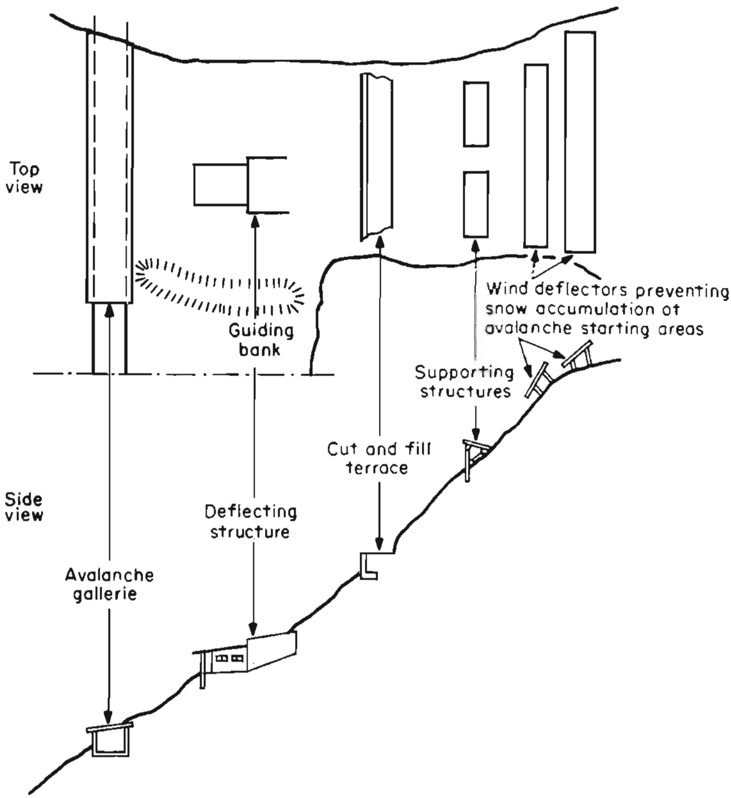

Figure 2.26 Avalanche control measures.

source of this ice buildup may be fog or clouds containing tiny supercooled water droplets, freezing rain, wet snow, or spray from breaking waves and wave crests. Icing can occur anywhere in cold regions, but the frequency and severity vary greatly with the location.

Icing on pavements is maybe the most familiar type of icing in cold regions. This occasional event may cause extremely hazardous driving conditions. Ice may form on the pavement under several conditions, but in a typical case the temperature of the pavement is significantly below the freezing point and the water droplets are supercooled or near the freezing point. A comprehensive analysis of the event is presented in Jumikis (1966).

Heavy atmospheric icing combined with strong winds may be the dominant factor in the design of slender structures such as radio antennas or power transmission lines (Figs. 2.27 and 2.28). Numerous collapses of such structures have been experienced. In the case of ships and ocean

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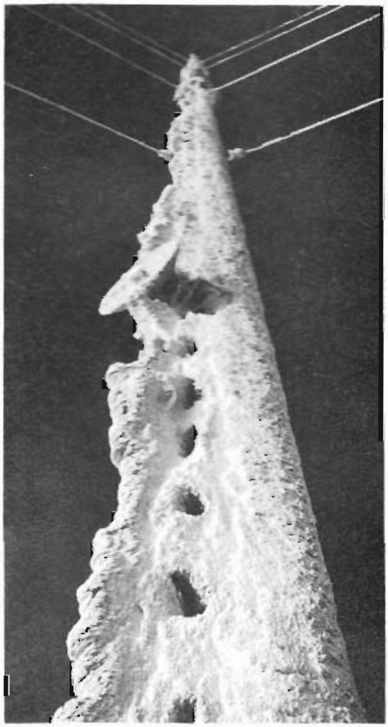


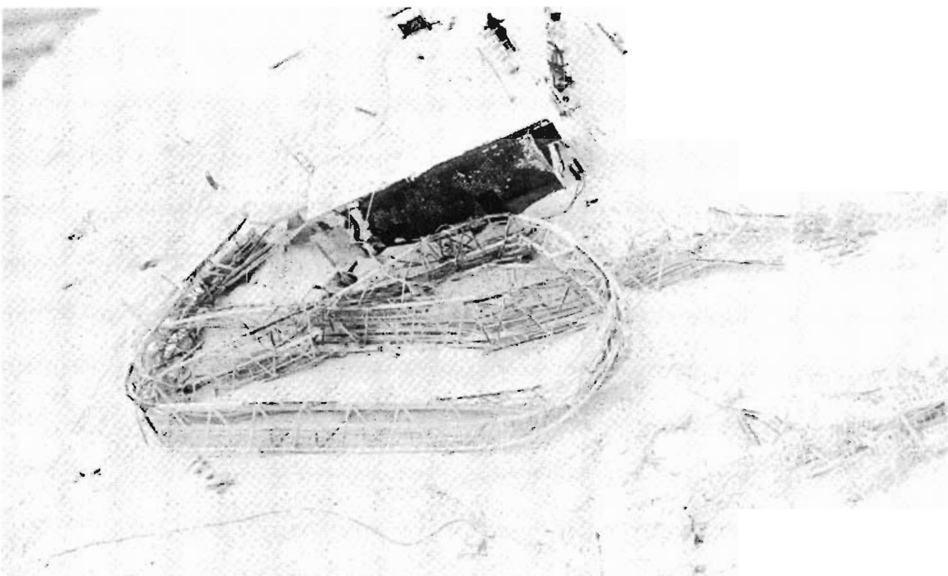
(b)

structures the source of icing is generally sea ice spray. Icing causes mainly operational difficulties, but in extreme cases also safety hazards (Fig. 2.29).

Ice can deposit on the surface of a structure in different forms and densities. Well supercooled tiny water droplets in fog or a cloud freeze very rapidly when they get in contact with a structure. As a result, very-low-density ice, known as soft rime, is formed. Hard rime forms when the freezing of droplets occurs slowly so that some flow of water has time to occur before crystallization. It has a density of 100 to 600 kg/m^3 (6 to 40 lb/ft^3). When water droplets have sufficient time to wet the surface of the structure before freezing, a glaze with densities running from 700 to 900 kg/m^3 (45 to 55 lb/ft^3) is formed. Icing deposits may also be combinations of these different forms and snow. When icing is formed from seawater, it contains brine, pockets of unfrozen saltwater.

The occurrence, severity, and type of atmospheric icing depend very much on temperature, wind speed, total water content of the air, and water droplet dimensions. The general principles of different forms of atmospheric icing are illustrated in Fig. 2.30. The formation of glaze is

Figure 2.27 Heavy icing on a radio tower (*a*), (*b*) and structure after collapse due to combined effects of ice and wind (*c*). *(Courtesy of Finnish Broadcasting Company.)*



(c)

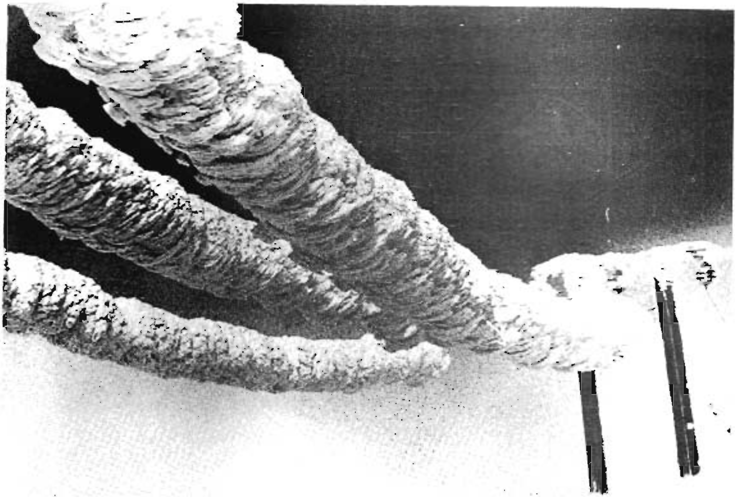


Figure 2.28 Exceptionally heavy ice buildup on conductors in a power transmission line. *(Courtesy of Horn Tron Ab.)*

most probable at temperatures between 0 and −3°C (32 and 27°F). Lower temperatures and low wind speeds favor the formation of soft rime.

Similar approximate relationships can also be established for the severity of icing occurring at sea, as shown in Fig. 2.31. Naturally the peculiarities of the local wave climate and the structural considerations have some effect on the icing intensity. Sea icing is usually caused by spray

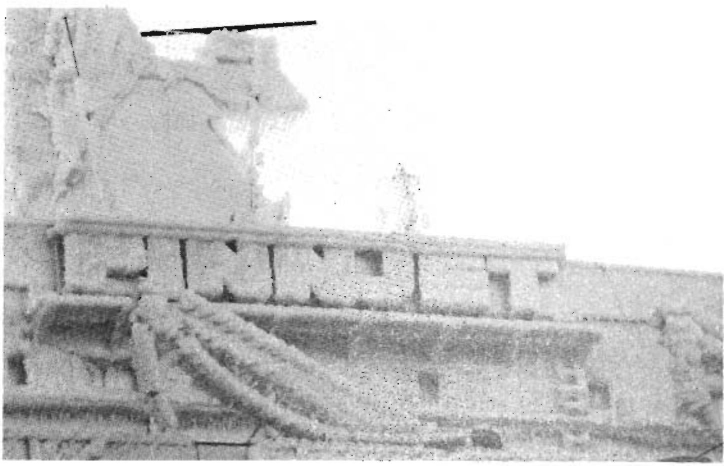


Figure 2.29 Heavy sea icing on a ship. *(Courtesy of Oy Wärtsilä Ab.)*

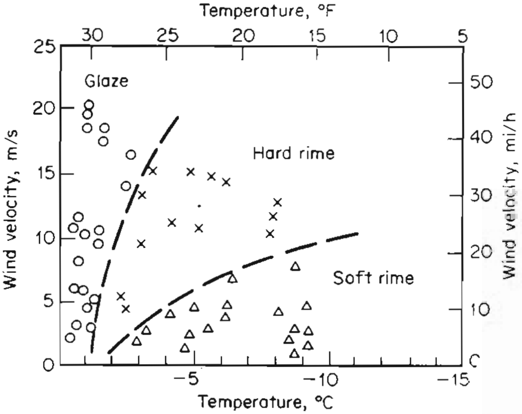
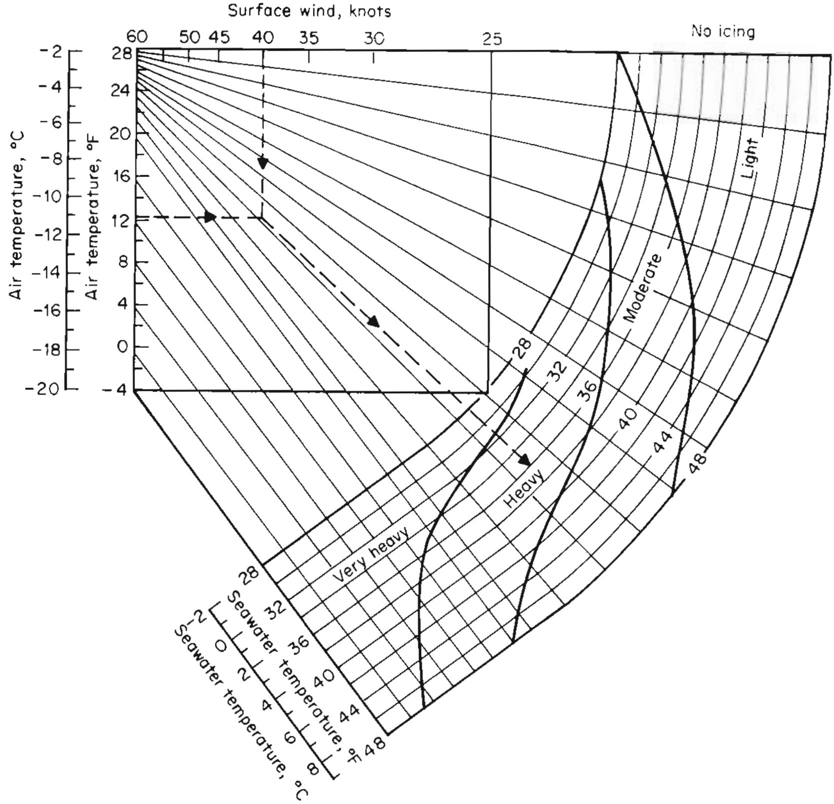


Figure 2.30 Relationship between meteorological conditions and type of icing. *(Kuroiwa, 1965.)*



Category	Rate of icing per 3 h, mm (in)
Light	1–5 (0.05–0.2)
Moderate	5–8 (0.2–0.3)
Heavy	8–19 (0.3–0.75)
Very heavy	19+ (0.75+)

Figure 2.31 Nomogram giving the severity of sea icing as a function of wind speed, air temperature, and seawater temperature. *(Wise and Comiskey, 1980.)*

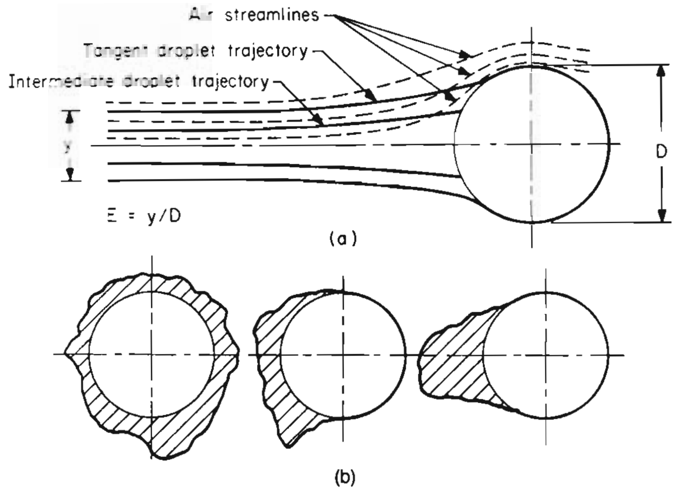


Figure 2.32 (*a*) Collection efficiency *E* and (*b*) typical ice accumulation shapes on cylindrical structures.

from waves breaking against ship hulls or other solid objects. Spray from wave crests is a significant source of icing at very high wind speeds. Contrary to atmospheric icing, the bulk of sea icing occurs at low elevations, generally less than 15 m (50 ft) above the peak water level, although waves breaking against structures may raise significant amounts of droplets above this elevation.

Theoretically speaking, the amount of icing on a structure, or the so-called icing efficiency, can be estimated by

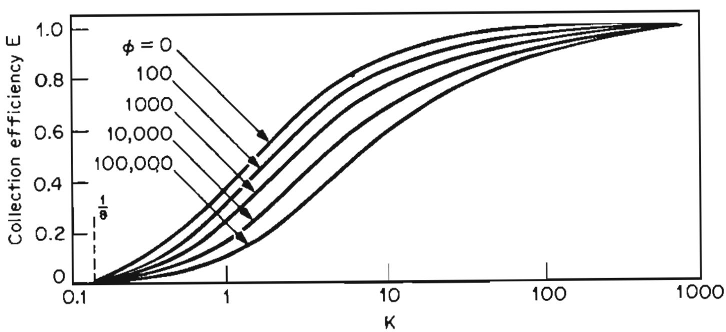


Figure 2.33 Collection efficiency *E* as determined by inertia parameter *K* and parameter ϕ. *(Langmuir and Blodgett, 1946.)*

$$\frac{dM}{dt} = ECDVW \tag{2.3}$$

where M = mass of ice deposited in time t
E = collection efficiency coefficient
C = capture coefficient
V = wind velocity
W = liquid water content in air
D = width of structure

The collection efficiency coefficient corresponds to the fact that water droplets are deflected from their linear trajectories as they approach the structure (Fig. 2.32). It is the ratio of the mass of droplets striking the structure to the total mass of droplets that would have hit the structure if they had not been deflected. In Fig. 2.33 the collection efficiency E is given for a cylinder with radius R as a function of two variables, the inertia parameter K and parameter ϕ,

$$K = 1290\frac{Vr^2}{R} \qquad \left[\frac{\text{cm}^2}{\text{s}}\right] \tag{2.4}$$

$$\phi = 0.175VR \qquad \left[\frac{\text{cm}^2}{\text{s}}\right] \tag{2.5}$$

where r is the radius of the droplets. It can be seen that theoretically no icing occurs when $K < 0.125$.

Not all the water droplets that strike the structure will necessarily freeze. Especially at high wind speeds, the heat of fusion of all incoming water droplets may not be dissipated before they flow to the outer surface and are carried away by the airflow. Data in Glukhov (1971) illustrated that while the capture coefficient is close to 1 at wind speeds ranging from 0 to 5 m/s (0 to 10 mi/h), it may decrease to about 0.2 at wind speeds exceeding 10 m/s (20 mi/h).

In practice there is not enough information available for theoretical icing computations to be used. Attempts have been made to describe areal risk and severity of atmospheric or spray icing on a large scale (for example, Bennett, 1959; Tattelman and Gringorten, 1973). In any case, icing design loads should be based on local codes and experience [for example, in Finland the ice load on a conductor is at least 12.5 to 25 N/m (1 to 2 lb/ft)] along with rational considerations given to site location, elevation, and exposure; the influence of the structural shape on the magnitude of icing; and the asymmetrical and uneven character of ice formations.

There are no easy solutions to control icing. Heat and freezing point depressants have been applied with some success, but generally this kind of protection requires too great an effort except in power conductors, where losses are adequate to melt the ice. In some cases, structures can be protected by flexible sheetings. Space truss structures can be enclosed by corrugated plastic sheets in order to control icing. Site selection is in many cases very important. For example, elevated power-line routing above treeline should be avoided, while valleys shielded from dominant moist wind directions are preferred. In coastal areas, protected structures should be located out of the reach of droplets from major wave-breaking elements. Sometimes this distance may be over 100 m (300 ft). If ice has to be removed mechanically, it is desirable to use simple structural shapes and act quickly before a strong bond can form between ice and structure. Coating with low-adhesion materials, such as some plastics, may also be used.

For further discussions on icing phenomena and their regional occurrence the reader is referred to the extensive summary reports by Minsk (1977, 1980) and to McLeod (1977).