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Design Guidelines for the Control of Blowing and Drifting Snow

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For further information on the U-clips (page 85) and on general snow control, contact: Ronald D. Tabler, principal, Tabler & Associates, 7505 Estate Circle, Longmont, CO 80503. The Snow Fence Guide *(SHRP-H-320) and a 21-minute video, "Effective Snow Fences" (Tape 2), are available from the Transportation Research Board, Box 289, Washington, D.C. 20055; telephone (202) 334-3214; fax (202) 334-2519.*

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Abstract

Blowing snow is a problem because it

- forms drifts on roads that stop traffic and cause accidents,
- increases snow removal costs,
- reduces driver visibility,
- causes slush and ice,
- leads to pavement damage.

Blowing snow can be controlled, but to be successful, control measures must be carefully engineered. Drift control measures should be designed as carefully as other highway appurtenances because improperly designed measures can endanger the travelling public.

This book provides all of the information needed to design effective and economical measures for controlling snowdrifts and reducing the concentration of snow in the air.

1. Executive Summary

Blowing snow is a problem because it

- forms drifts on roads that stop traffic and cause accidents,
- increases snow removal costs,
- reduces driver visibility,
- causes slush and ice,
- leads to pavement damage.

The objectives of controlling blowing snow, therefore, are to

- collect snow in drifts before it reaches the highway,
- improve visibility by reducing the concentration of snow in the air,
- reduce snow removal and highway maintenance costs.

Blowing snow can be controlled, but to be successful, control measures must be carefully engineered. Drift control measures should be designed as carefully as other highway appurtenances because improperly designed measures can endanger the traveling public.

1.1 Who Should Read This Book?

This book provides all of the information needed to design effective and economical measures for controlling snowdrifts and reducing the concentration of snow in the air. Snow control is as technically complex as other areas of civil engineering. The guidelines for drift control are derived from mathematical analyses of the evaporation of wind-transported snow particles, turbulent mixing behind barriers, turbulent diffusion processes, and boundary layer mechanics. For this reason, control measures should be designed by individuals with an engineering background. It is for such an audience that this book has been prepared. Because this specialty involves material not included in most civil engineering curricula, sufficient background information is presented to make this a self-contained "bootstrap" reference. Many of the guidelines can be applied by users who lack technical training. These guidelines are summarized in the *Snow Fence Guide* (Tabler 1991).

Drift control problems should be evaluated and resolved by a snow control specialist who is trained in drift control and who is familiar with maintenance operations and basic engineering concepts and procedures. A snow control specialist at the county or administrative subdivision level could significantly reduce blowing snow problems.

Kaminski and Mohan (1991) have developed an expert system (PASCON) using many of the concepts and guidelines presented in this book. Their main objective was "... to provide a tool for highway design and maintenance personnel to use in evaluating snow problem locations and identifying possible solutions, without requiring an extensive knowledge of passive snow control methods." One of the reasons the material in this book is presented in such detail is to stimulate and facilitate the continued development of computer-assisted snow control technology.

1.2 Content and Organization

Chapter 2, "Benefits of an Engineering Approach," describes the importance of drift control, and the benefits to be derived from properly designed control measures. A brief history explains why past drift control efforts were often disappointing. Case studies illustrate both the effectiveness and benefits of properly designed control measures. Results from an economic analysis illustrate the high benefit-to-cost ratios possible with snow fences, and show how this information can help justify future drift control projects.

Chapter 3, "How Snow Moves and Forms Drifts," describes the characteristics of drifting snow that must be considered if drift control measures are to be successful. In addition to providing the basis for guidelines presented later in this book, this information helps in evaluating drifting problems and devising innovative solutions.

In chapter 4, "Quantifying the Blowing Snow Problem," procedures are described for evaluating problems, and collecting and analyzing data as initial steps in designing control measures. Computational methods for estimating the quantity and directional distribution of seasonal snow transport are presented.

Guidelines for specific control measures are presented in chapter 5,: "Design and Placement of Structural Snow Fences," chapter 6,: "Living Snow Fences," and chapter 7,: "Designing Drift-Free Roads."

Familiarity with the information in chapters 2, 3, and 4 is essential before proceeding to the chapters presenting specific design guidelines.

Highlights at the beginning of each chapter summarize the most important points, and provide the reader with an idea of what material is covered.

References at the end of each chapter describe the sources of additional information on specific subjects.

Terms likely to be unfamiliar to the reader are defined where first introduced, and are also compiled in a glossary at the end of this guide.

The book's focus is on control measures for roads and highways. However, the information can also be applied for controlling blowing snow for railroads, airports, residential developments, and industrial facilities.

1.3 References

Kaminski, D. F. and S. Mohan. 1991. PASCON: An expert system for passive snow control on highways. *Transportation Research Record* 1304: 193-201.

Tabler, R. D. 1991. *Snow fence guide*, Report No. SHRP-H-320. Strategic Highway Research Program, National Research Council. Washington, D.C. 61 pp.

2. Effectiveness of Measures to Control Blowing Snow

This chapter identifies the problems caused by blowing snow, describes the potential benefits that can be derived from an engineering approach to drift control, and provides economic justification for control measures.

2.1 Highlights

- The quantity of snow that blows onto a road can be hundreds of times greater than the precipitation that falls directly on the road. This adds significantly to snow removal costs.
- Snowdrifts create serious safety hazards, including loss of vehicle control, reduced sight distance on curves and at intersections, reduced effectiveness of safety barriers, and reduced effective road width.
- Blowing snow reduces visibility and can cause slush and ice to form on road surfaces.
- Snowdrifts contribute to pavement damage by promoting the infiltration of water under pavement. Snow removal equipment can also damage road surfaces.
- Drift control has been overlooked because improved snow removal equipment; favored mechanical removal; effective guidelines for drift control did not exist before 1970; and the effectiveness of control measures is not always appreciated.
- Snow fences can eliminate snowdrifts, improve visibility, and reduce slush and ice formation. To be effective, these control measures must be properly engineered.
- A 10-year study on Interstate Highway 80 in Wyoming showed that snow fences reduced snow removal expenditures by one-third to one-half. The savings in property damage due to reduced accidents could amortize the initial cost of the fences in 15 years.
- The beneficial effects of a snow fence can extend for great distances downwind.
- Benefit-to-cost ratios for permanent snow fences, based only on reduced costs for snow removal typically range from 10- to 35:1 depending on the quantity of blowing snow.

2.2 The Importance of Drift Control

Snow Removal Costs Snowdrifts can add significantly to the cost of winter maintenance. In exposed, windy locations, the quantity of snow that blows onto a road can be hundreds of times greater than the precipitation that falls directly on the road, with the result that most plowing time is spent removing wind-deposited snow. Although costs vary widely, mechanical snow removal typically costs about $3 per metric ton (2,205 lb). For comparison, a snow fence 1.2 m (4 ft) tall can retain 12.5 metric tons per meter of length (4.2 tons/ft).

Safety Hazards Snowdrifts can be serious safety hazards. They can cause loss of vehicle control, reduce sight distance on curves and at intersections, obscure signs, promote ice formation, reduce effective road width, and render safety barriers ineffective. Blowing snow reduces visibility and promotes the formation of slush and ice on road surfaces.

Effects on Pavement By promoting the infiltration of water under pavement, snowdrifts can contribute directly to pavement damage. In addition to serving as a water source, drifts can adversely affect drainage by blocking ditches, drains, and culverts. Snow removal equipment can also damage road surfaces.

2.3 Why Drift Control Has Been Overlooked

2.3.1 Historical Use of Snow Fences

The earliest known written reference to snow fences was by the Norwegian G. D. B. Johnson in 1852. Widespread use of snow fences probably began with the railroads, because confining vehicles to rails eliminated the option of detouring around snowdrifts. Some of the first snow fences in the U.S. were rows of stone blocks placed on the upwind side of cuts during construction of the first transcontinental railroad in 1868-69 (Figure 2.1). By 1880, a tourist guidebook reported "innumerable" wooden snow fences along the Union Pacific Railroad in Wyoming (Crofutt 1880). These early wooden fences (Figure 2.2) were 2 m (6.5 ft) tall. The same basic design was used by the Union Pacific Railroad and the Wyoming Department of Transportation as late as 1971.

The picket snow fence, made of vertical wood slats held together by wire, has also been in use since the early 1900s. Taller fences were first built in 1900 on the Yukon and White Pass Railroad between Skagway, Alaska, and Whitehorse, Yukon Territory (Figure 2.3).

After automobiles came into general use, the construction of snow fences expanded rapidly. In 1930, the 7th Biennial Report of the Wyoming Highway Commission reported 101 km (63 mi) of fence along Wyoming's highways, and commented: "Intelligent use of snow fences in windy districts accomplishes more per dollar expended than any other feature in maintaining the highways free from snow" (Wyoming Highway Commission 1930). Just two years later, the length of snow fence along Wyoming roads had grown to 169 km (105 mi) (Wyoming Highway Commission 1932).

In the United States, research on snow fences and drift control methods also began in the 1930s with F.A. Finney's wind tunnel experiments at Michigan State College (Finney 1934). His two publications provided some of the first guidelines for using snow fences and road design to prevent snowdrifts.

Figure 2.1. Rock snow fences protecting railroad cuts in southeast Wyoming were probably built in 1868 (Tabler 1986).

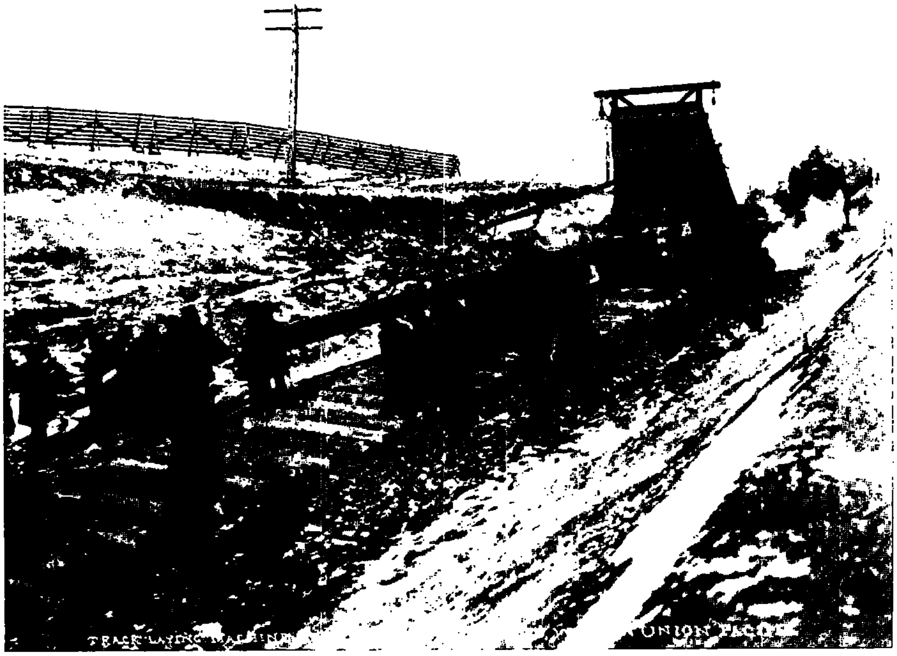


Figure 2.2. Photograph in 1901 by J. E. Stimson shows snow fence protecting Union Pacific Railroad about 25 km (16 mi) southeast of Laramie, Wyoming (Tabler 1986). Photo courtesy Wyoming State Museum.

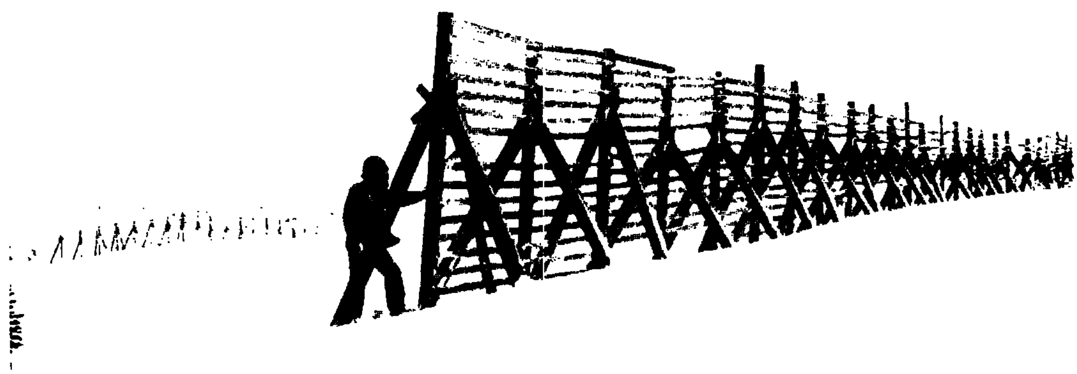


Figure 2.3. Snow fences on the White Pass and Yukon Railroad, approximately 25 km (16 miles) north of Skagway, Alaska. Built in 1900, they were 4 m tall (13.5 ft).

2.3.2 *Why the Use of Drift Control Measures Declined*

Replacement with Brute Force Despite the enthusiasm for snow fences in the 1930s, drift control progressed little over the next half century because improvements in trucks, locomotives, and snow plows, in addition to inexpensive fuel and manpower, favored a brute force approach to snow control. With little incentive to improve passive drift control measures, research came to a standstill, and much of the experience with snow fences was lost through changes in personnel.

Lack of Effective Guidelines In the past, drift control measures often provided disappointing results because guidelines were misleading or lacking. The placement of snow fences recommended in a 1908 textbook on railway engineering, for example, would clearly result in the snowdrift burying the track (Tratman 1908). This error apparently arose from the mistaken belief that snow is only deposited on the upwind side of a porous snow fence, when in fact most of the snow is deposited on the downwind side.

The disparity among guidelines in the past arose because early snow control technicians were unable to predict the shape of snow fence drifts, or how much snow a fence would hold. Finally, although snow fences must have sufficient snow storage capacity to be effective, no guidelines for this factor existed until they were introduced by Soviet scientists in the 1950s (Komarov 1954).

Attrition of Appreciation After a problem snowdrift is eliminated by using a snow fence or modifying a road cross-section, there may be little evidence that a problem ever existed in the first place. When the maintenance workers who remember the original problem and its solution move or retire, their replacements often have no basis for judging the effectiveness of existing control measures. This attrition of appreciation weakens support for additional drift control work and leads to deferred maintenance of existing snow fences.

2.4 A Case Study in Wyoming

Current drift control technology is based on research conducted by the U.S. Forest Service in the 1960s and 1970s (Martinelli, Schmidt, and Tabler 1982). Results from that research were used to solve a severe drifting problem on a newly completed section of Interstate Highway 80 (I-80) in Wyoming the year after it was first opened to traffic in 1970.

The I-80 application provides the only documented quantitative evaluation of the effectiveness of snow control measures. The background and results of the I-80 study are summarized here as a case study that can justify snow control projects on other highways. More detailed information can be found in references listed at the end of this chapter.

The route selected for I-80 closely followed U.S. 30 across southern Wyoming. Between Laramie and Walcott Junction, however, a new location was selected along the foot of the Medicine Bow Mountains to save nearly 24 km (15 mi). No snow fences were in place when this new 124-km (77-mi) section of I-80 was first opened to traffic in October, 1970.

Three months later, snowdrifts as deep as 5 m (16 ft) encroached on the traffic lanes at 27 different locations, and 6 bulldozers were working around the clock, 7 days a week, to remove these drifts. Winds commonly averaged more than 50 km/h (30 mi/h) for days at a time, and the road had to be closed for a total of 10 days because of poor visibility and accidents. As a result of this first winter, snow fences were designed to protect all of the locations where drifts reached the road that first winter, using the progenitors of the guidelines presented in this book. The initial contract consisted of 18.3 km (11.4 mi) of snow fence that ranged in height from 1.8 to 3.8 m (6 to 12.4 ft), constructed at a cost of $480,000.

Careful monitoring of these first fence systems during the 1971-72 winter proved their effectiveness in preventing drifts (Figures 2.4 to 2.7), but the improved visibility and road surface conditions in fence-protected areas (Figures 2.8 to 2.11) were even more impressive because these latter effects were unexpected.

The dramatic effectiveness of those first fences led to many more being installed over the next 18 years. At present, the system on this same section of I-80 consists of 63.6 km (39.5 mi) of fence protecting about 64 km (40 mi) of highway, built at a total cost of $2,260,000.

Ten years after the first fences were constructed, a study was undertaken to quantify their effectiveness. The gradual increase in fence protection over the 10-year period afforded a unique opportunity to quantify the reduction in accidents (Figure 2.12). In a winter with average snowfall and traffic volume, statistics suggest the fencing in place in 1980 prevented 54 accidents and 35 injuries. The original construction cost of the I-80 fences was amortized in less than 15 years by savings in property damage alone. In addition, eliminating drifts reduced winter maintenance expenditures by one-third to one-half.

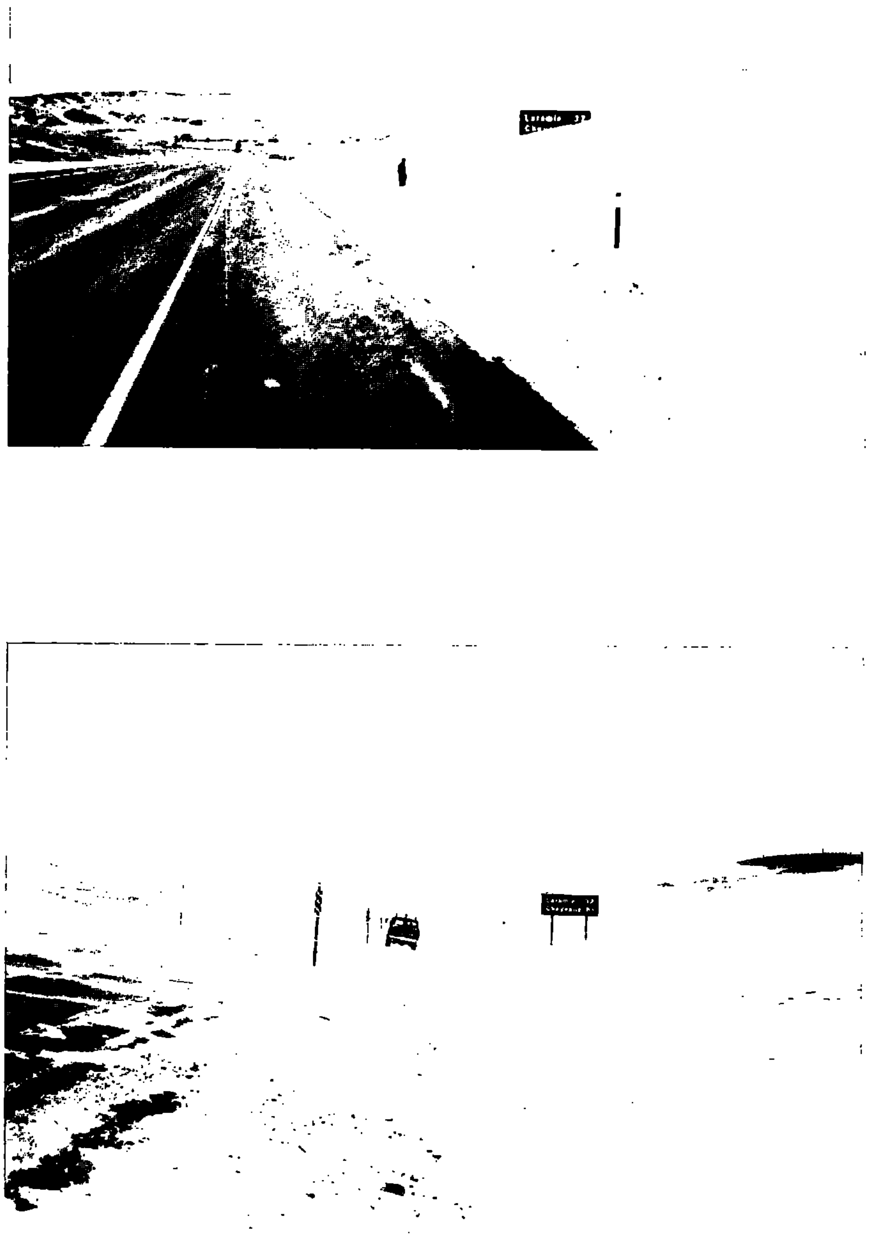


Figure 2.4. Snow accumulation at Mile 280.8, Wyoming I-80, before snow fencing (top), and conditions as they have appeared throughout the 21 years after building snow fences (Tabler 1973a).

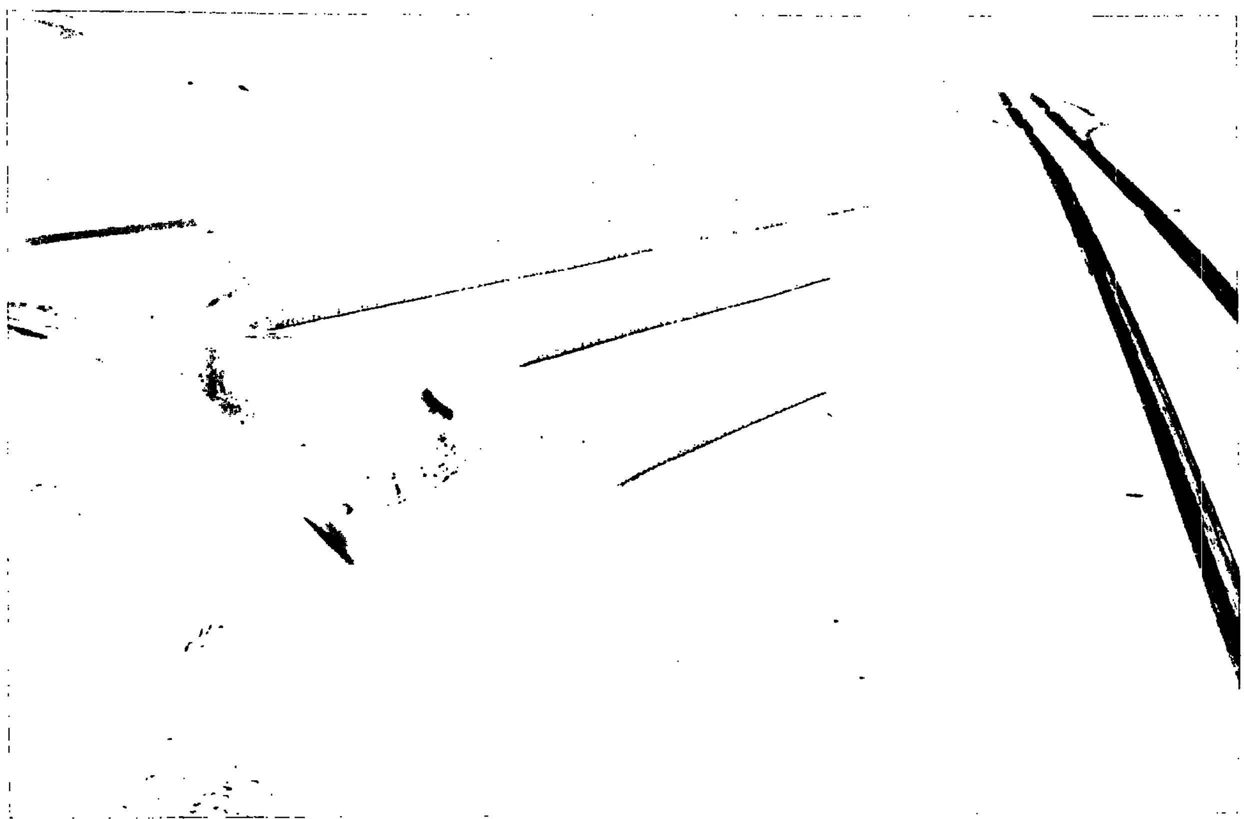


Figure 2.5. Aerial view of the fence system that protects the location shown in Figure 2.4 (Tabler 1986).

Figure 2.6. Snow accumulation at Mile 274.9, Wyoming I-80, in 1970 before fencing (top), compared with conditions typical of the 22 years since fences have been in place (middle). At the time of the bottom photo, the drift formed by the 3.8-m-tall (12.4 ft) fence at this site was 6 m (20 ft) deep and contained about 80 t per meter of fence length (27 tons/ft). From Tabler (1973a).

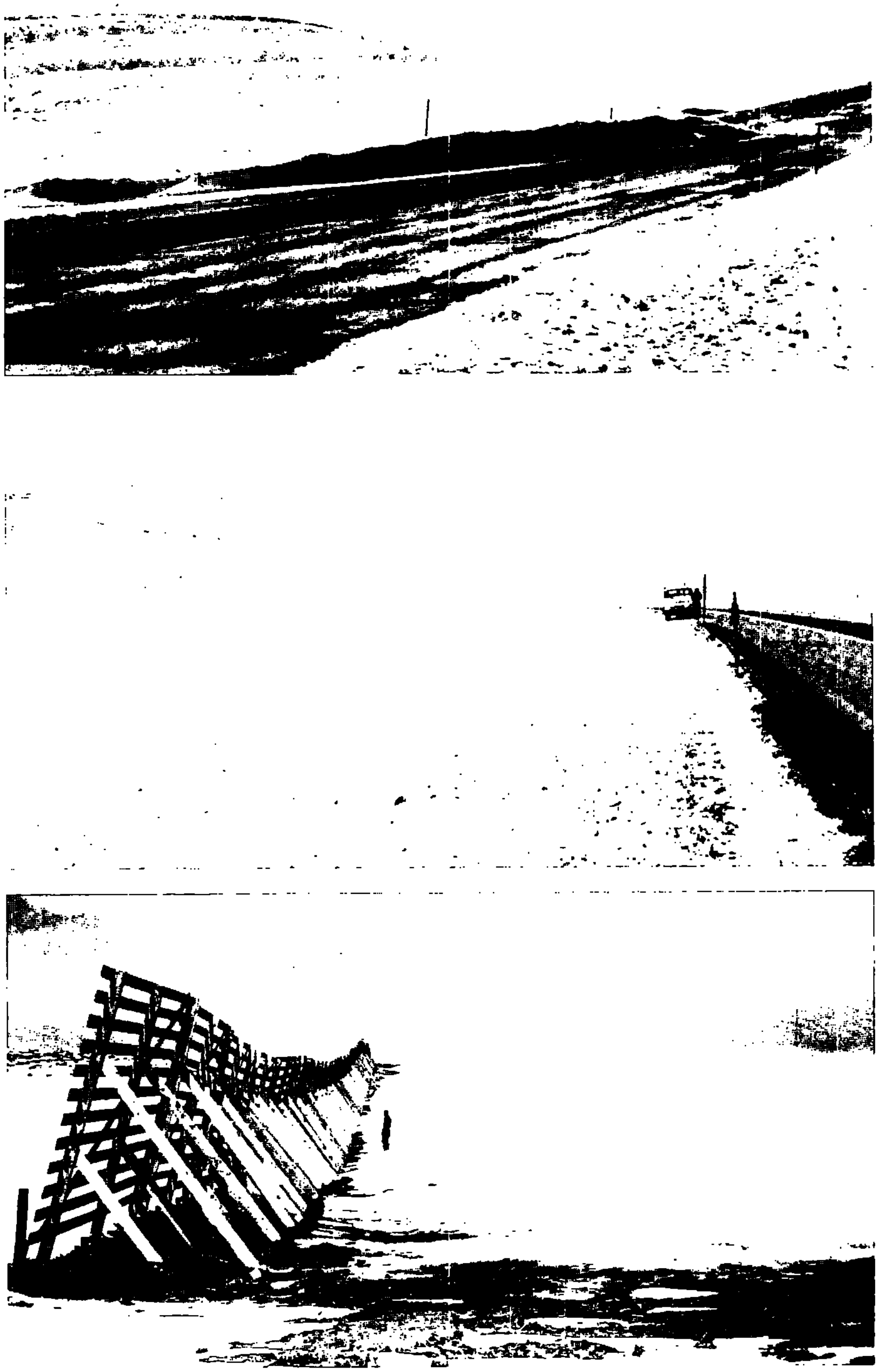
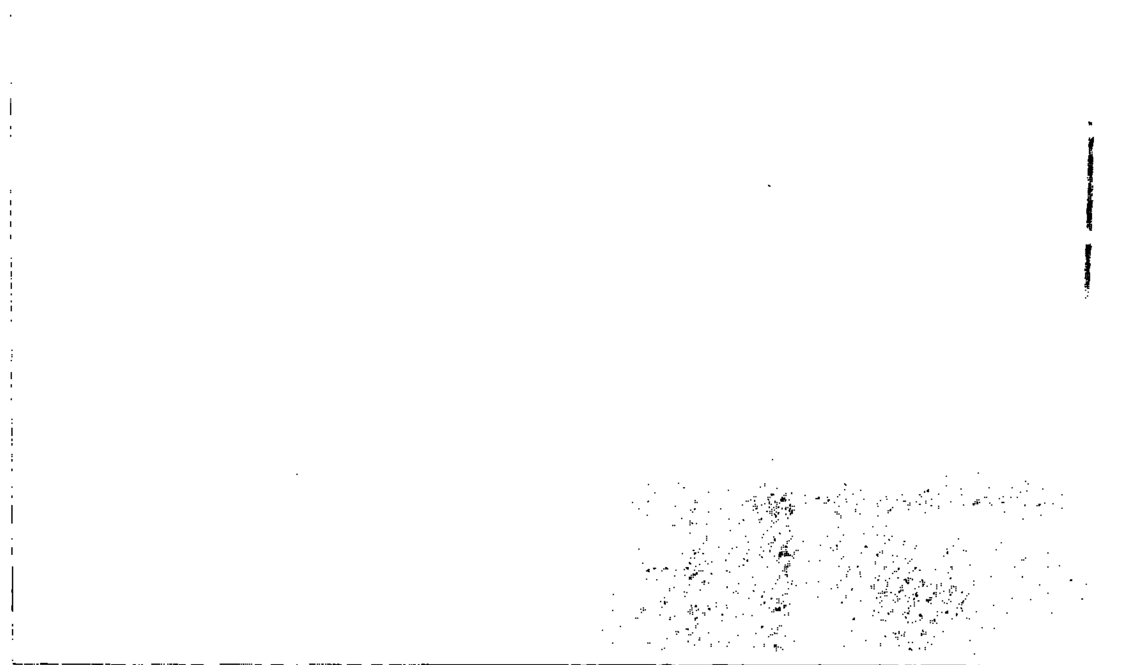


Figure 2.7. Snow accumulation at Mile 269.5, Wyoming I-80, in 1970 before fencing (top), compared with conditions typical of the 22 years since fences have been installed (middle). The bottom view shows a 3.8-m (12.4-ft) Wyoming fence at this location. From Tabler (1973a).

Figure 2.8. Very little blowing snow is seen escaping the two 3.8-m (12.4-ft) fences at Mile 263.0, Wyoming I-80 (Tabler 1973a). At the time of this photo, the lead fence was about 60% full. Photo by Robert L. Jairell.

Figure 2.9. This transition from frozen slush to wet pavement corresponds to the beginning of the area protected by a 3.8-m-tall (12.4-ft) snow fence located about 150 m (500 ft) upwind (Tabler and Furnish 1982). The upper corner of the fence, which extends to the left but is hidden behind the drift, is visible near the center of the picture. The area on the right side of the transition is unfenced (Mile 247.6, Wyoming I-80).



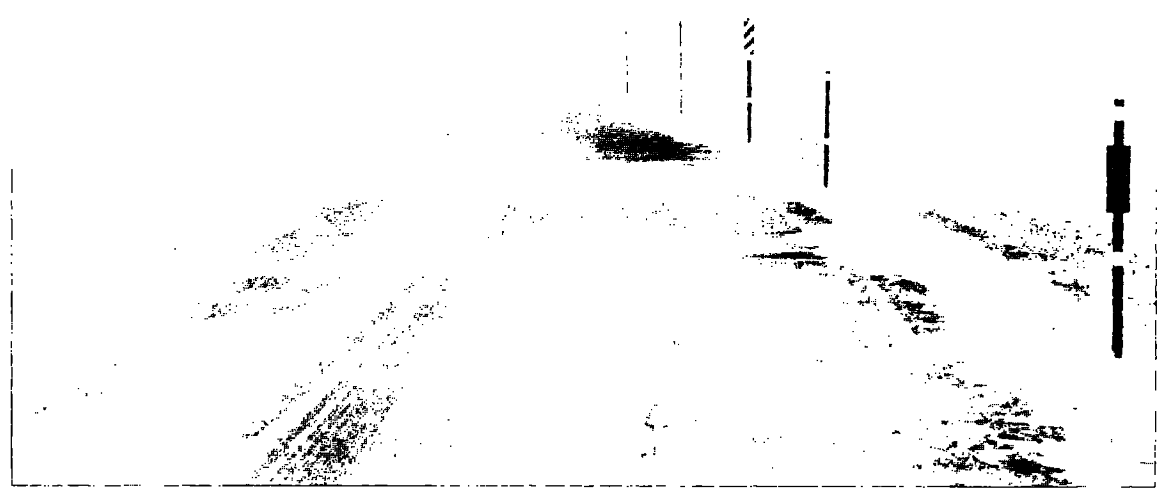


Figure 2.10. Improved visibility downwind of a 3.8-m (12.4-ft) snow fence during moderate drifting. The upper photo was taken 60 m (200 ft) outside of the protected area. The lower photo was taken a few minutes later, standing at the boundary of the protected area. Photos by Keith Rounds, Wyoming Department of Transportation. From Tabler (1973a).

Figure 2.11. This photo taken from the center of the protected area shows the improved visibility downwind of 3.8-m (12-ft) fences, located outside of the field of view to the right (wind is right to left). The end of the fence system coincides with the abrupt change in conditions just beyond the information sign (Mile 254, Wyoming I-80). From Tabler (1986).

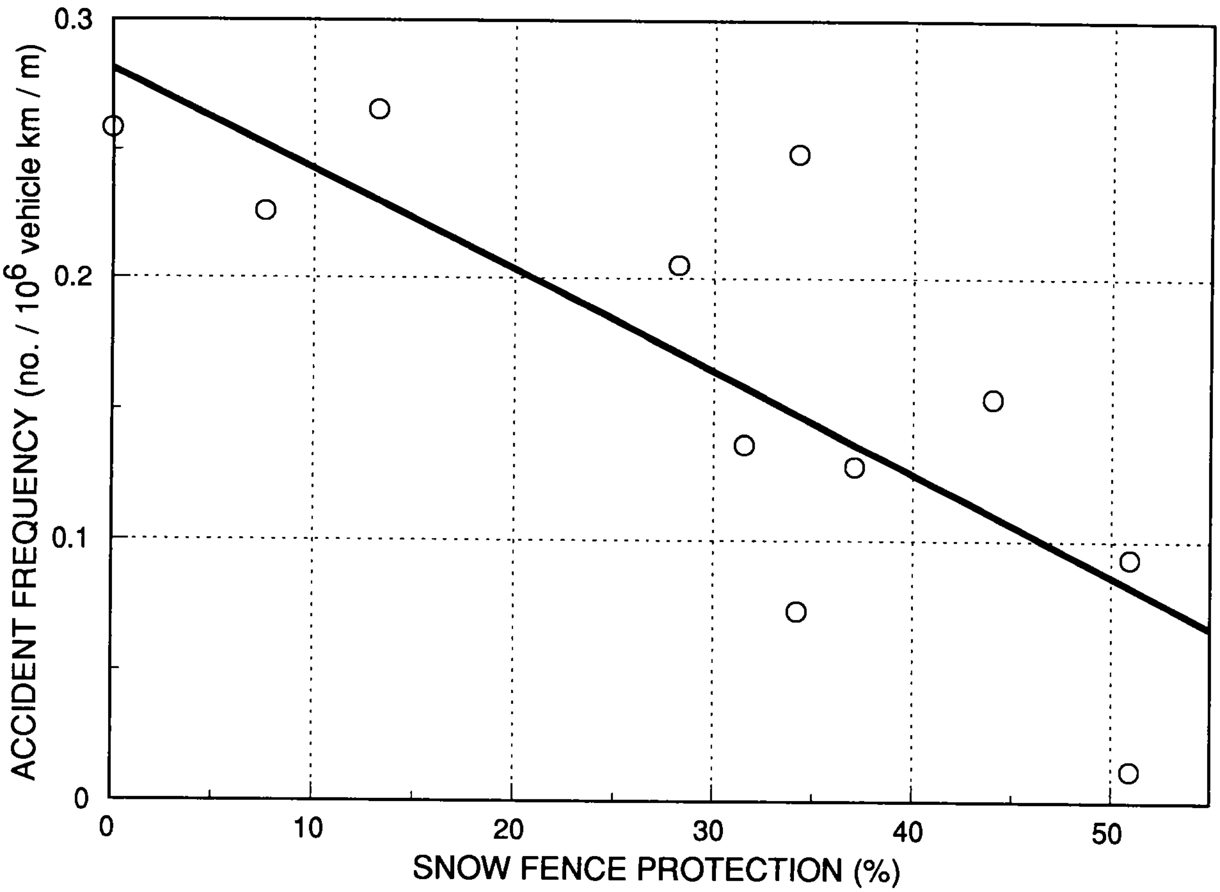


Figure 2.12. Accident rate in blowing snow conditions on Wyoming I-80, Mile 235 to 295, in relation to snow fence protection. To account for yearly variations in snowfall, accident rate is expressed per meter of snowfall over the period October 1 to April 30 (after Tabler and Furnish 1982).

2.5 Other Examples

Many other successful projects have proven that properly engineered snow fences are effective (Tabler 1992). One example is the village of Wainwright, Alaska, where 4.6-m-tall (15 ft) snow fences, 800 m (2600 ft) in length, eliminated drifts that previously damaged buildings and made streets impassable to conventional wheeled vehicles (Figure 2.13).

The examples presented here demonstrate that the benefits of snow fences can extend for considerable distances downwind. This is in part attributable to the pressure gradient from the wake region to the outer undisturbed flow, which retards the influx of snow into the wake. As a result, the boundaries between protected and unprotected areas may be visible for great distances downwind. The deposition of blowing snow behind a fence increases the eroding capability of the wind, resulting in a tendency for snow to be scoured out downwind of the fence. The advance of this snow erosion "front" extends the effect of the fence downwind (Figure 2.14).

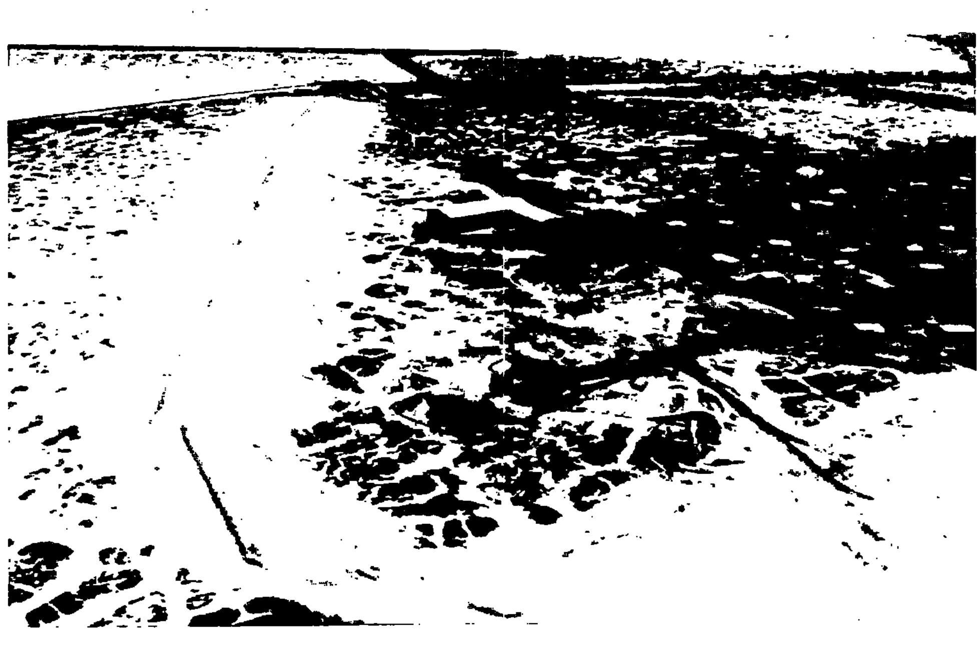


Figure 2.13. Conditions at Wainwright on Alaska's North Slope before (top) and after (bottom) a 4.6-m (15-ft) snow fence was built in 1982 (top photo by Robert L. Jairell, U.S. Forest Service Research; bottom photo by Dr. Carl S. Benson, Geophysical Institute, University of Alaska — Fairbanks).

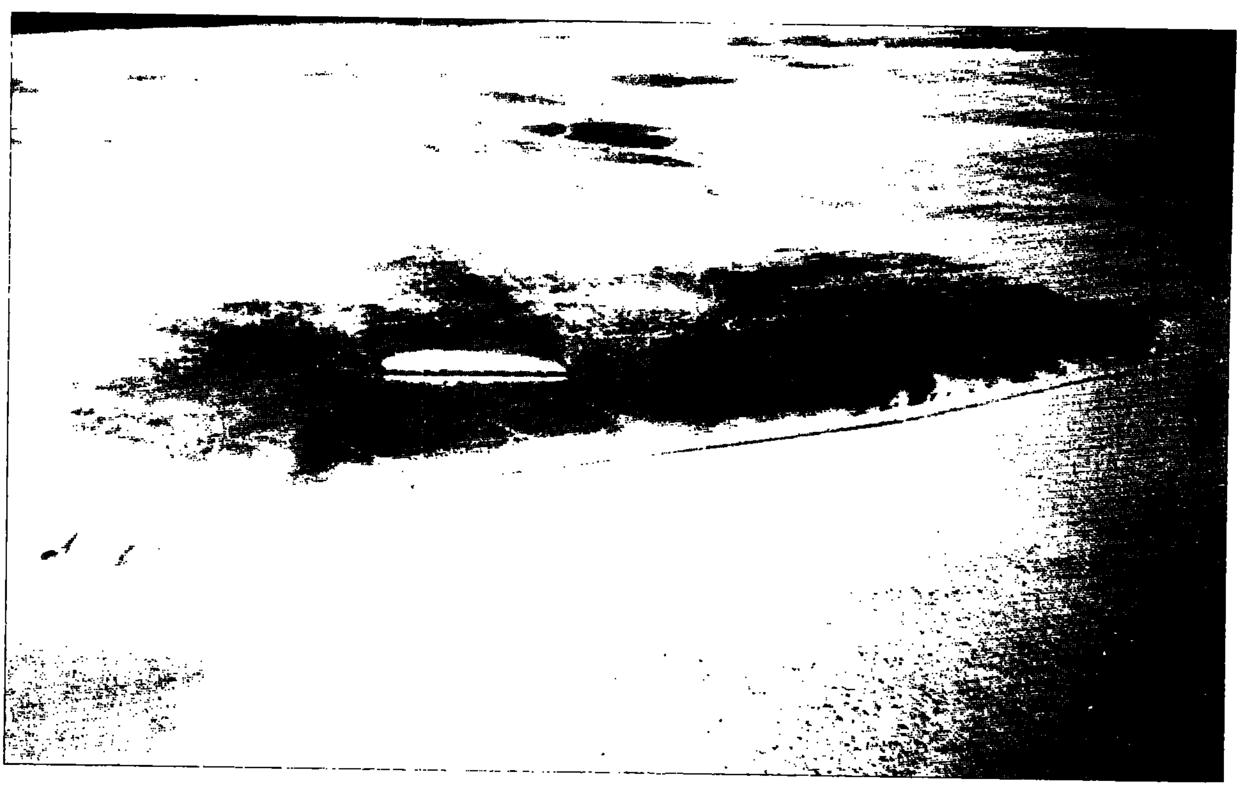


Figure 2.14. This aerial view shows that the effect of a snow fence can extend for great distances downwind. A 3.8-m (12-ft-tall) fence in the foreground is trapping most of the incoming snow. The increased eroding capability of the wind has scoured out snow for nearly a kilometer downwind. U.S. Forest Service photo by A. Loren Ward.

2.6 Benefits from Snow Fences

The above examples show that snow fences can be effective in preventing snowdrifts, improving visibility, and reducing slush and ice. Benefits include reductions in

- Snow removal costs
- Accidents
- Property damage
- Road closures
- Pavement maintenance costs

Using information presented in chapter 5, it is possible to perform an economic analysis to determine benefit/cost ratios for snow fence projects. The benefit from reduced accidents was described for the case study in section 2.5. Benefits in the form of reduced snow removal costs can be illustrated by considering these benefits equal to the reduction in the quantity of blowing snow arriving at the road. Figure 2.15 shows how the ratio of snow removal benefits-to-cost for snow fences varies with the cost of mechanical snow removal, and with the seasonal *snow transport* — the quantity of blowing snow that is transported by the wind in the first 5 m (16 ft) above the ground, per unit of width across the wind. The following assumptions were made for this analysis:

Total cost for snow fence equal to $15 per square meter of fence frontal area,
25-year amortization,
7% interest rate,
Annual cost of fence maintenance equal to 5% of initial capital investment,
Design capacity equal to the quantity of blowing snow expected over an average winter.

Because costs for easements or right-of-way acquisition vary, these are not included in the analysis. In most cases, however, such costs are less than those for the snow fence. Although costs for mechanical removal vary widely, $3 to $5/ton is typical, and similar to costs for earth excavation and wasting.

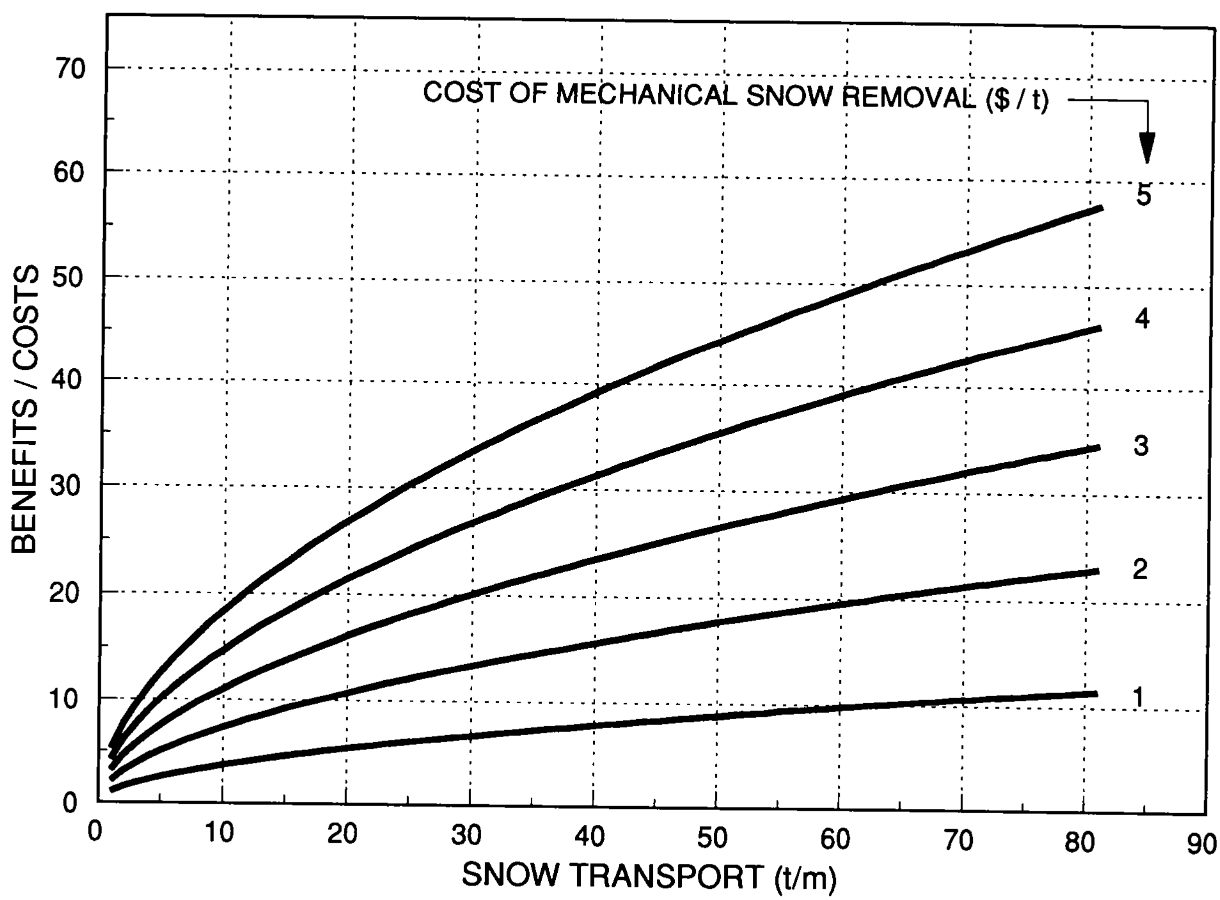


Figure 2.15. Benefit-to-cost ratios for permanent snow fences in relation to seasonal snow transport and costs for mechanical snow removal.

2.7 Benefits from Road Design

It has long been recognized that proper road design can be effective in preventing snowdrifts (Finney 1939; Fowler 1930; Schultz 1930). However, this method of drift control cannot be expected to improve visibility and road surface conditions to the extent possible with fences. Although roads should be designed for drift-free conditions to the extent possible, this control method should not be construed as eliminating the need for snow fences. Snow fences are invariably a less expensive solution to snow drifting problems than reconstruction to change the cross-section of an existing road.

2.8 Conclusion

The potential for eliminating drifts, improving visibility, and reducing slush and ice, are compelling reasons for controlling drifting snow. The evidence of how effective fences can be is irrefutable, and it is incumbent on public officials to apply this technology to improve the safety and convenience of the public. Proper application requires attention to engineering detail, as summarized in this guide.

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3. How Snow Moves and Forms Drifts

3.1 Scope

This chapter describes the characteristics of drifting snow that are the basis for the guidelines presented in this book.

3.2 Highlights

- Blowing snow particles have diameters on the order of 100 to 200 μm.

- Snow moves by *creeping*, *saltation*, and *turbulent diffusion*. Creeping particles roll along the surface and form dunes and snow waves. Saltating particles appear to jump along the surface. Most saltation occurs within the first 10 cm or so (4 in.) above the surface. Turbulent diffusion refers to the process whereby smaller particles are carried to greater heights by turbulent eddies.

- Although wind-transported snow can be present at great heights above the surface, the concentration above 5 m (16 ft) is negligible for purposes of drift control.

- The concentration of snow particles at a given height above the surface increases with wind speed. At wind speeds of 100 km/h (62 miles/h), for example, 50% of the total blowing snow is more than 1 m (3.28 ft) above the surface, and 30% is above 2 m (6.56 ft). The vertical distribution of blowing snow has important implications for optimum height of snow fences.

- Total transport in the first 5 m (16 ft) above surface varies as the 3.8 power of the wind speed at 10 m (33 ft).

- Visibility in blowing snow varies inversely with the fifth power of wind speed at 10 m (33 ft) above the surface.

- Blowing snow particles evaporate whenever relative humidity is less than 100%. This phenomenon occurs even at temperatures well below freezing.

- Evaporation from wind-transported snow particles can be significant because of the large ratio of surface area to mass, and the exposure of the particles. More than half of the relocated snow evaporates over a transport distance of 3 km (1.9 miles). Quantifying the evaporation of blowing snow provides the basis for estimating snow transport, and hence the required storage capacity of snow fences.

- Subtracting evaporation loss from total relocated precipitation provides an estimate for total seasonal snow transport.

- Snow is deposited where surface shear stress decreases with distance downwind, and erosion occurs where shear stress increases.

- Wind-deposited particles freeze together on contact. The bond strength approximately doubles in 24 hours.

- The density of wind-deposited snow increases with snow depth.

- Snow is deposited in a topographic feature until the snow surface achieves a balance between erosion and deposition. By the end of the winter, snow surfaces represent shapes formed at lower wind speeds because interparticle bonding resists erosion by stronger winds.

- A snow fence reduces wind speeds and changes the shape of the wind profile. These changes cause creeping and saltating particles to come to rest. As the drift behind the fence grows, its shape changes.

- There is a limit to how much snow a fence can hold. When the drift reaches equilibrium with existing wind conditions, no more snow is caught by the fence. The dimensions of equilibrium drifts are proportional to fence height, and the cross-sectional area is proportional to the square of the fence height. Snow storage capacity is proportional to fence height raised to the 2.2 power because of the relationship between snow depth and snow density.

- Dimensions of snow fence drifts vary with the porosity of the fence. Fences that have 50% porosity have the largest snow storage capacity.

- For the case of a fence with a porosity ratio of 0.5, about 85% of the snow is deposited on the downwind side of the fence. When such a fence on flat terrain is filled to capacity, the length of the downwind drift may approach 35 times the fence height.

- For non-porous barriers, snow accumulates on the upwind side first. Deposition on the downwind side begins when the upwind drift reaches the top of the fence. Solid fences trap only about 35% as much snow as fences with a porosity ratio of 0.5.

- The terrain surrounding a fence can have an overriding influence on drift shape.

- The trapping efficiency of a snow fence is the proportion of incoming snow over the height of the barrier that is permanently retained by the fence. Trapping efficiency at the beginning of the season is on the order of 90 to 95%. Efficiency declines as a fence fills with snow, reaching 80% when the fence is half full, and 60% when the fence is 80% full.

3.3 Snow Particle Characteristics

Blowing snow particles resemble tiny grains of sand, and range in size from infinitesimally small to 0.5 mm (0.02 in.) in diameter (Figure 3.1). Particle size decreases with height above the surface, with mean diameters ranging from about 0.2 mm (0.008 in.) at a height of 5 cm (2 in.), to about half this size at 1 m (3.3 ft). There is little entrapped air in the ice, and the specific gravity of the particles is typically about 0.9.

Snow particles derived from freshly fallen snow are smaller than those originating from a snowcover that has remained undisturbed for a few days. As snow particles are transported by the wind, they become progressively smaller and more rounded from fragmentation, abrasion, and evaporation. As described in section 3.4.6, evaporation of wind-transported snow particles can be appreciable even at temperatures well below freezing.

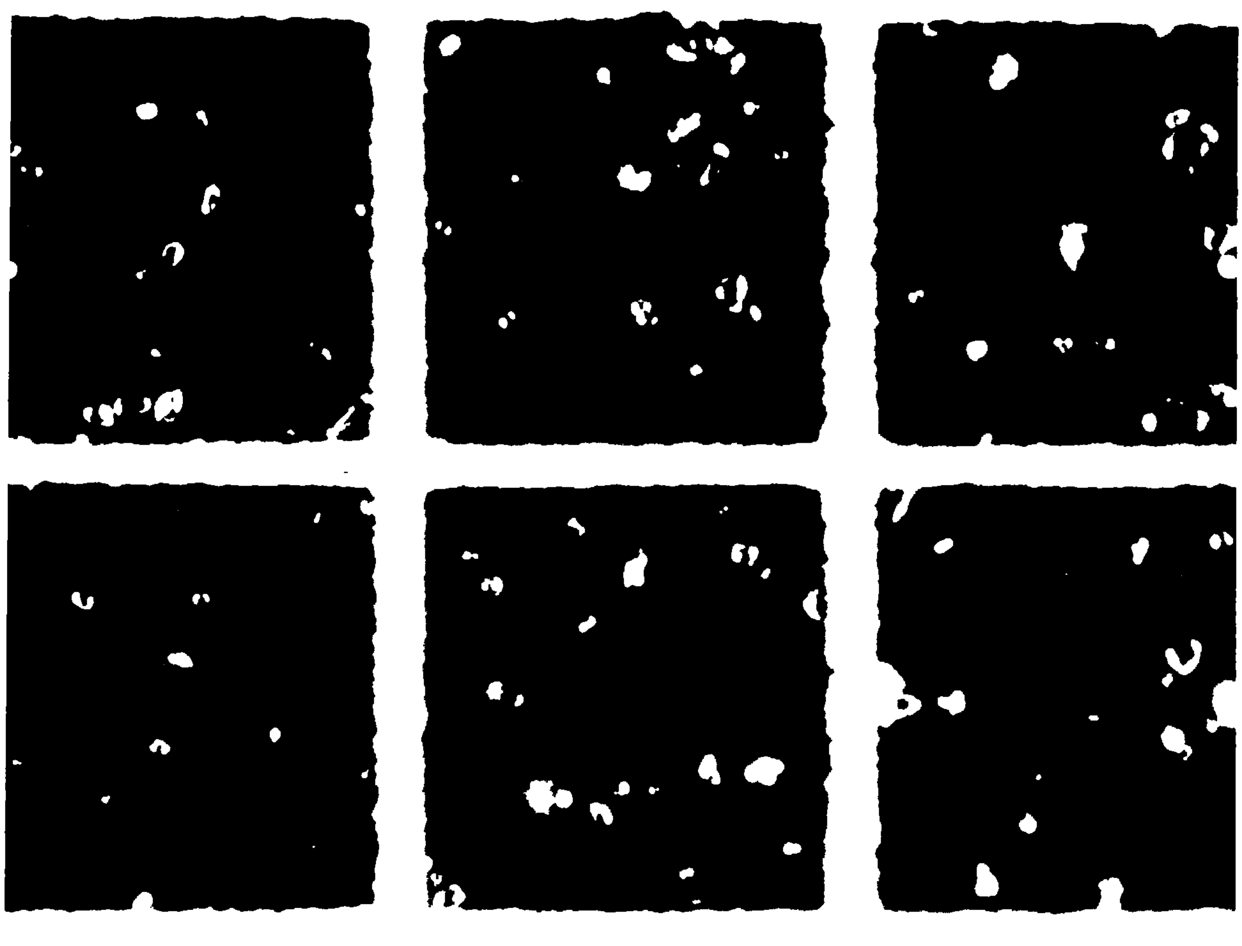


Figure 3.1. Blowing snow particles collected 1 m (3.3 ft) above the snow surface (Tabler 1986). Grid scale is 2 mm (0.08 in.). Photo by Dr. R.A. Schmidt.

3.4. Snow Transport

3.4.1 Definition

Snow transport is the mass of snow transported by the wind over a specified time and width across the wind. Although blowing snow particles can be found thousands of meters above the surface, their concentration above 5 m (16 ft) or so is negligible from the standpoint of drift control. Unless otherwise specified, snow transport refers to the total within the first 5 m (16 ft) above the surface, per unit of width across the wind.

3.4.2 Modes of Snow Transport

There are three types of snow movement: creep, saltation, and turbulent diffusion (Mellor 1965). Particles that are too large to be lifted off the surface under existing wind conditions roll or *creep* along the surface, forming snow waves or dunes that migrate downwind (Figure 3.2). Snow waves disappear when average wind speeds exceed 55 km/h (35 miles/h) or so (Tabler, 1986). Creeping particles comprise up to one-quarter of total transport at low wind speeds. Creeping particles are easily trapped by a snow fence or topographic feature.

Lighter particles may *saltate*, appearing to jump along the surface, but such particles are still too heavy to remain suspended in the air. Although trajectories of saltating particles vary with particle size, wind speed, and surface conditions, a typical "jump" is a parabolic arc 1 cm (0.5 in.) high and 25 cm (10 in.) long. Most saltating particles are contained within 5 cm (2 in.) of the surface (Figure 3.3). Saltating particles dislodge other particles, especially those that have frozen to adjacent particles (Figure 3.4).

After winds remove snow from most of a landscape, remaining snow patches provide sources for streams of saltating snow particles that can extend downwind for several kilometers (Figure 3.5). Snow streams can coincide with drainages (Figure 3.6) because more snow tends to accumulate in topographic depressions than on surrounding uplands, and winds can be channelled by topography.

Snow shadows, the opposite of snow streams, are regions downwind from features that disrupt the flow of saltating particles by deflection or deposition (Figure 3.7). Saltating particles are easily trapped by a snow fence. Removing the saltating particles from the airstream can disrupt the erosion of the snow surface and reduce transport for great distances downwind. This is one reason why snow fences can be so effective.

The existence of snow streams and snow shadows suggests that local variations in snow transport should be considered when planning the location and capacity of measures to control drifting snow.

Turbulent diffusion refers to the mechanism by which particles are suspended in the airstream without the periodic surface contact that typifys saltation (Figure 3.8). A snow particle becomes suspended in the airstream when the gravitational force on the particle is less than the average lift force caused by the drag of the upward-moving air. Turbulent diffusion favors smaller particles than those that move by saltation. As the suspended particles become smaller through evaporation, they tend to be carried higher above the surface. This sorting process causes particle size to decrease with increasing height above the surface.

Recent research suggests that most blowing snow is transported in the turbulent diffusion mode, but the greatest portion of the total suspended particle mass is contained 1 m (3.3 ft) or so above the surface (Pomeroy 1988, 1989). For suspended particles to be caught by a snow fence, they must settle to the surface in a region sufficiently sheltered to prevent subsequent dislodgement.

Figure 3.2. Migrating snow waves moving about 5 m/h (16 ft/h) with a wind speed of 40 km/h (25 miles/hr)(Tabler 1986).

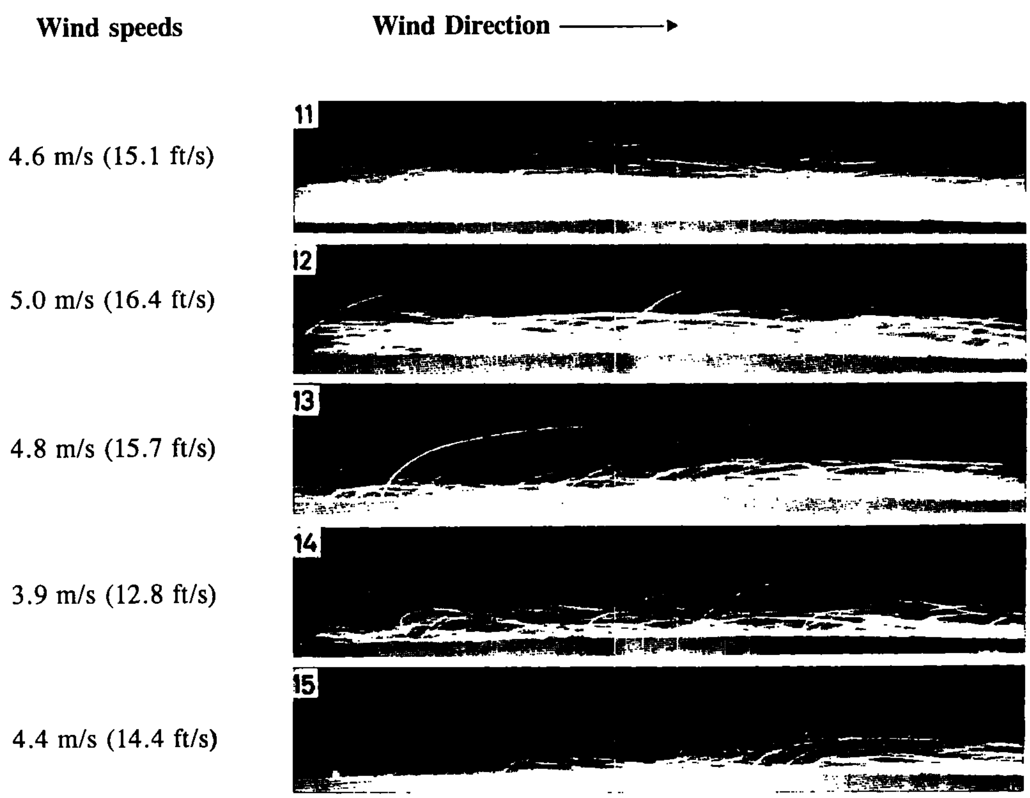


Figure 3.3. Saltating snow particles without snowfall. Field is 25 cm (10 in.). Wind speeds are at 1 m (3.3 ft). Photos by Dr. Daiji Kobayashi (1972).

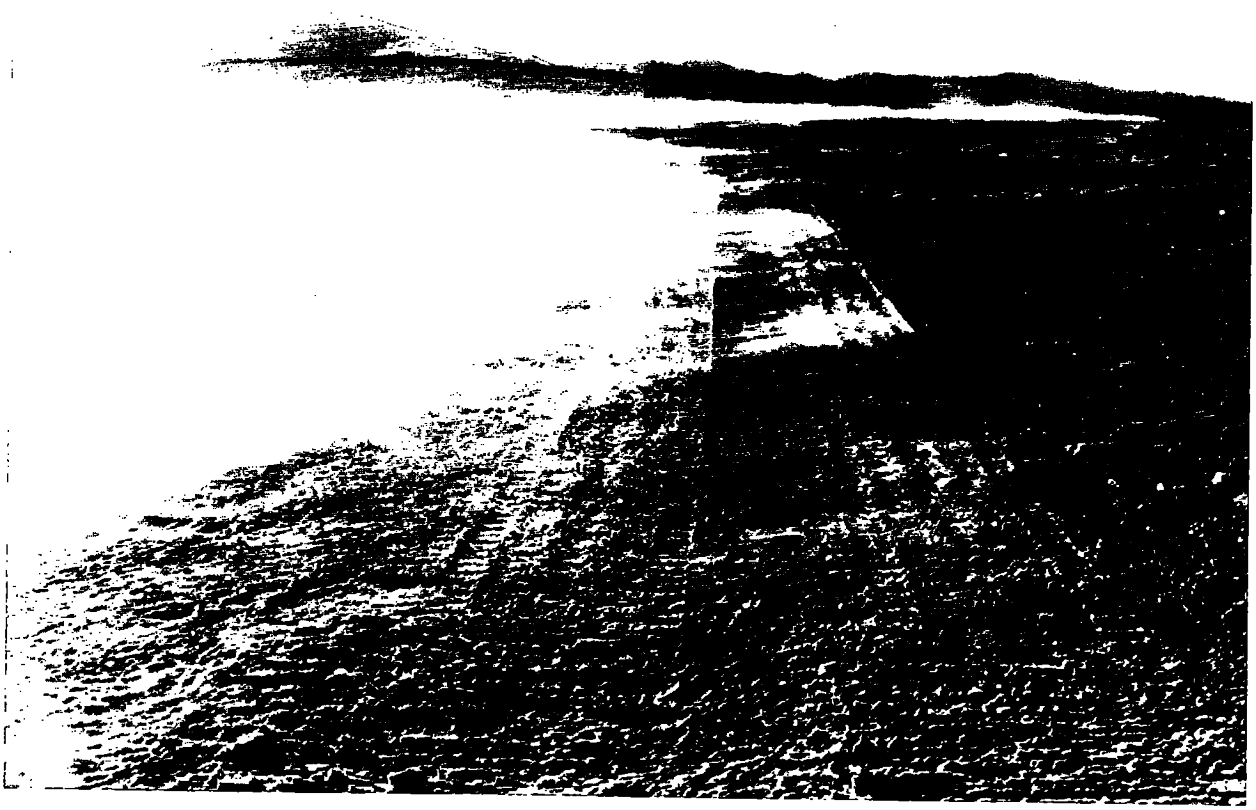


Figure 3.4. Chain reaction of saltating snow particles downwind from where tractor treads broke the snow crust (wind from right). Such disturbances act as sources of blowing snow that can persist over long distances downwind (Tabler 1986).

Figure 3.5. Snow stream downwind of a source of blowing snow. The boundaries of this stream were uniform for at least 3 km (1.9 miles)(Tabler 1986).

Figure 3.6. Snow stream that coincided with a drainage channel (facing wind)(Tabler 1986).

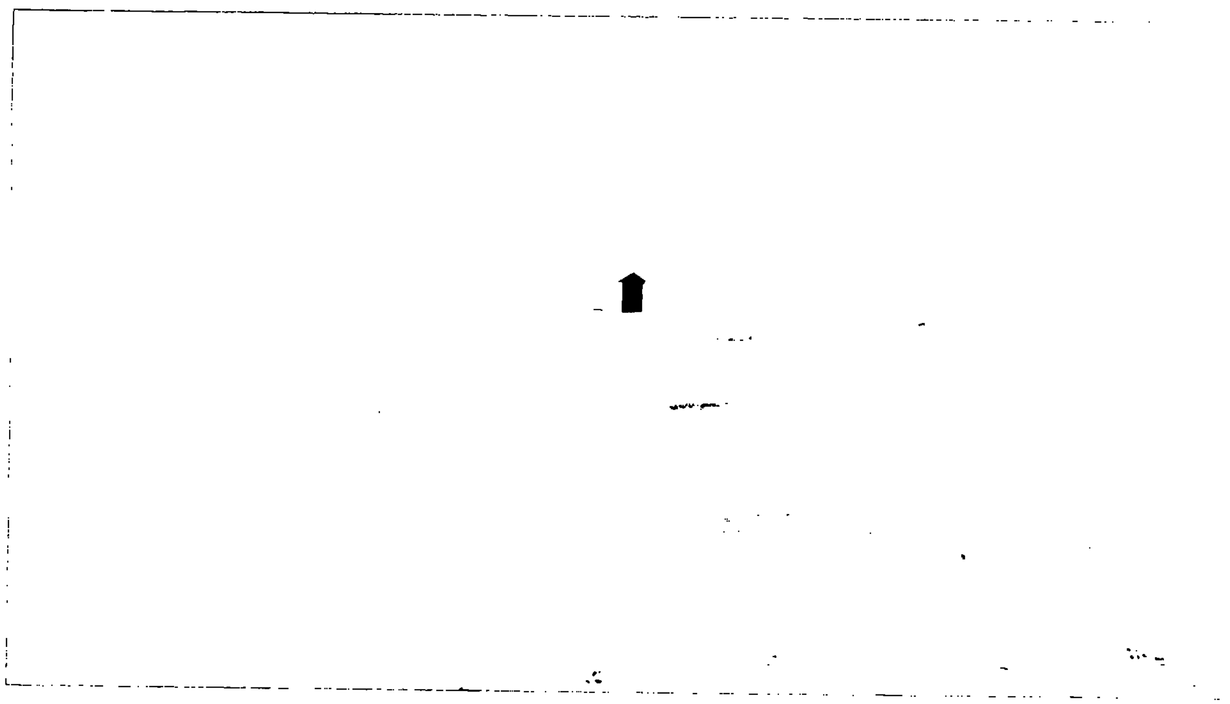


Figure 3.7. Snow shadow formed by a cylindrical shelter 1.2 m (4 ft) in diameter and 2.1 m (7 ft) tall (Tabler 1986). This view is from a point 150 m (500 ft) directly downwind. Photo by Robert L. Jairell.

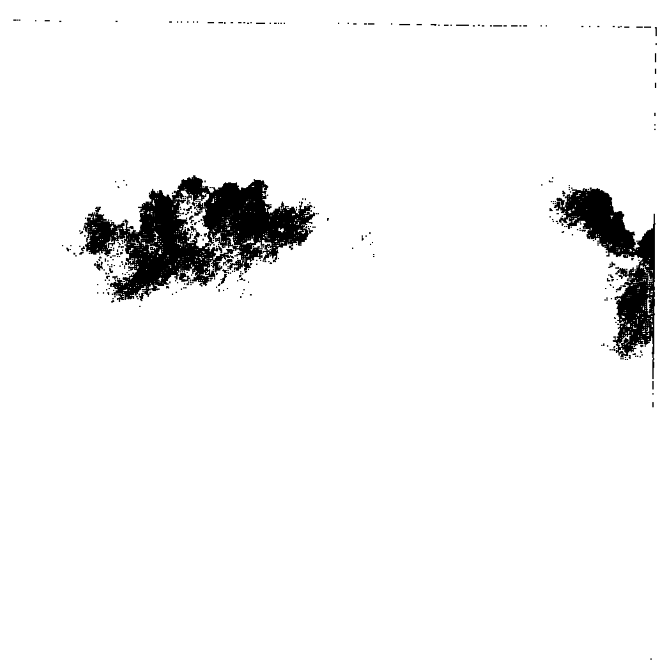


Figure 3.8. Turbulent diffusion of snow particles (wind from right).

3.4.3 *Wind Profile*

Wind speed increases with height due to the diminishing drag of the earth's surface. This vertical distribution of wind speed must be known in order to calculate wind loads on snow fences. In general, snow surfaces are aerodynamically rough (no laminar sublayer), and airflow is fully turbulent for all wind speeds above the threshold for blowing snow. On flat, unobstructed surfaces the wind profile is reasonably well described by

$$U = (2.5\ U_*)\ln(Z/Z_o) \tag{3.1}$$

where U = wind speed at height Z above the surface,
U_* = shear velocity (defined as the square root of the surface shear stress divided by the air density),
Z_o = aerodynamic roughness height (i.e., the height at which wind speed is zero),
ln = natural logarithm (to the base 2.71828...).

For blowing snow conditions on snow-covered flat terrain, over the range of wind speeds most often encountered, U_* is typically about 4% of the wind speed at a height of 10 m (33-ft). The value of Z_o depends on the nature of the surface, ranging from 0.001 cm (0.0004 in.) over smooth ice, to 30 cm (12 in.) for forest vegetation (Budd, Dingle, and Radok 1966; Liljequist 1957; Tabler 1980b). Z_o increases with wind speed due to roughness contributed by the saltating particles (Owen 1964). Although this relationship varies with surface roughness, the following approximation is sufficient for engineering applications.

$$Z_o = U_*^2/31250 \tag{3.2}$$

where velocities are in centimeters per second, and heights are in centimeters (Tabler and Schmidt 1986). The presence of blowing snow therefore has a significant effect on the wind speed profile.

The wind speed profile in the form of Equation (3.2) is used to estimate wind loads on fences. Conservative estimates are provided by assuming the existence of a snowcover without blowing snow, for which Z_o = 0.02 cm (0.008 in.). To estimate wind speeds at heights other than the height of measurement when snow cover conditions are unknown, it is standard practice to assume that the wind speed at height Z is related to the wind speed at a height of 10 meters according to

$$U_Z/U_{10} = (Z/10)^{1/7} \tag{3.3}$$

As used in this book, wind speed refers to that at the standard height of 10 m (33 ft), and is denoted by U_{10}. As estimated from Equation (3.3), the wind speed at this standard height is 28% greater than at 1.8 m (5.9 ft).

3.4.4 Snow Transport Rate and Vertical Distribution

The wind speed at which snow particles start to move depends on the condition of the snow cover and density of the air. Fluffy snow will begin to move when the wind speed reaches about 20 km/h (13 miles/h), while a snow surface hardened by wind and sun can resist erosion at speeds in excess of 85 km/h (53 mph). Snow typically ceases to blow when wind speed falls below about 24 km/h (15 miles/h)(Schmidt 1981; Tabler, Pomeroy, and Santana 1990).

Although blowing snow particles can be transported thousands of meters above the surface, most of the snow transport takes place relatively close to the surface. For purposes of drift control, transport above 5 m (16 ft) can be ignored. Snow transport in the first 5 m above the surface varies with wind speed according to

$$Q_{0\text{-}5} = U_{10}^{3.8}/233847 \tag{3.4}$$

where $Q_{0\text{-}5}$ is snow transport in kg/s per meter of width across the wind, and U_{10} is wind speed in m/s (Tabler 1991b). This relationship was derived from a regression equation relating mass flux to wind speed and height above the surface (Mellor and Fellers 1986). The rate of snow transport is therefore very sensitive to wind speed — doubling the wind speed results in almost a 14-fold increase in snow transport (Figure 3.9). This explains why snow fences can be so effective: reducing wind speeds by 50% would reduce snow transport rate by 94%. In reality, however, the aerodynamic effects of fences on transport and deposition are much more complex.

Although most of the snow transport occurs within 1 m (3.3 ft) or so above the surface, the vertical distribution of blowing snow in the first 5 m (16 ft) has important implications for blowing snow control. Because most of the blowing snow passing over the top of a snow fence is not caught by the fence, the vertical distribution of blowing snow is an important factor in deciding how tall a fence should be. As shown graphically in Figure 3.10 and quantitatively in Table 3.1, the vertical distribution of blowing snow becomes more uniform as wind speed increases. Less than 10% of the snow is transported at heights above 1.5 m (5 ft) with a wind speed of 35 km/h (22 miles/h). At 108 km/hr (67 miles/h), however, about 38% of the snow is transported above this height. Other things being equal, then, the effectiveness of a fence increases with its height.

Throughout this book, the total seasonal transport Q_t is assumed to be equal to $Q_{0\text{-}5}$ which is the snow transport in the first 5 m (16 ft) above the ground.

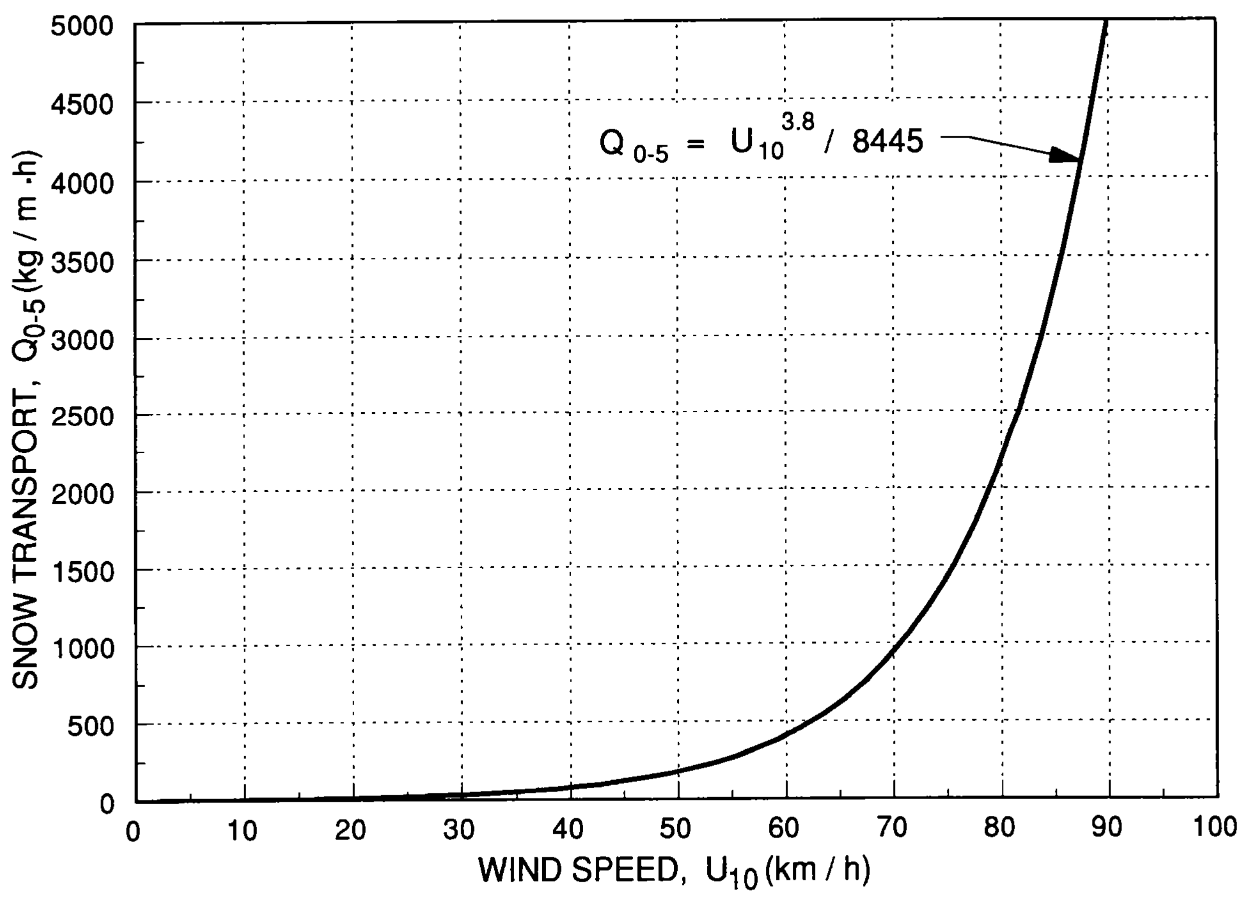
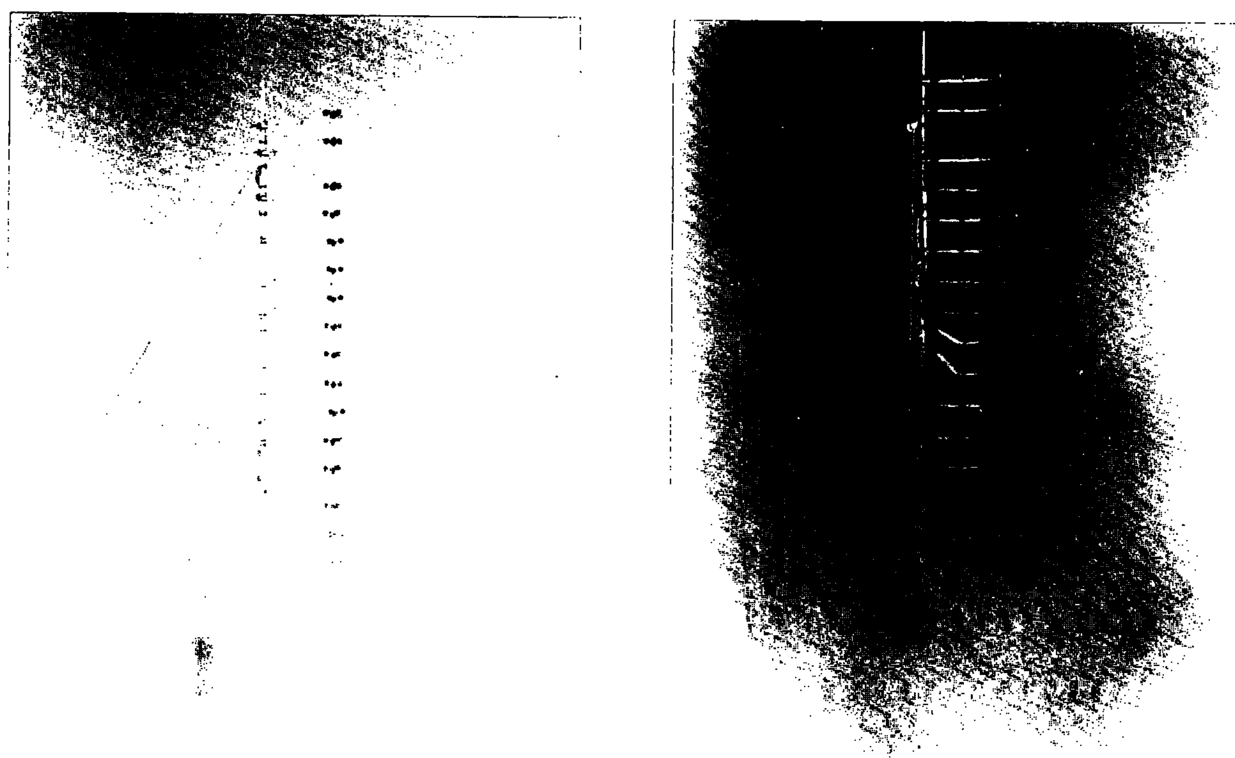


Figure 3.9. Snow transport in the first 5 m (16 ft) above the ground, as a function of wind speed at a height of 10 m (16 ft)(Tabler 1991b).



a. Blowing snow at 40 km/h (25 miles/h)

b. Blowing snow at 80 km/h (50 miles/h)

Figure 3.10. Visual demonstration of how the vertical distribution of blowing snow changes with wind speed. This array of anemometers, spaced 30 cm (12 in.) apart, was set in a field of wood posts 1.2 m (4 ft) tall (Tabler 1986).

Table 3.1. Vertical distribution of snow transport as function of wind speed. Values are $Q_{0\text{-}z}/Q_{0\text{-}5}$. The snow transport within the first 5 m (16 ft), in (g/m·s), is shown in parentheses (Tabler 1991b).

Height Z (m)	Wind speed (m/s) 10	15	20	25	30
0.1	0.822	0.487	0.251	0.126	0.056
0.2	0.853	0.579	0.365	0.239	0.160
0.3	0.868	0.628	0.431	0.312	0.233
0.4	0.878	0.661	0.480	0.366	0.290
0.5	0.885	0.687	0.519	0.411	0.338
1.0	0.909	0.768	0.645	0.563	0.505
1.5	0.925	0.818	0.725	0.662	0.616
2.0	0.938	0.857	0.786	0.737	0.701
2.5	0.950	0.888	0.834	0.797	0.770
3.0	0.961	0.915	0.876	0.849	0.828
3.5	0.971	0.940	0.912	0.893	0.879
4.0	0.981	0.961	0.944	0.933	0.924
4.5	0.991	0.981	0.973	0.968	0.964
5.0	1.000	1.000	1.000	1.000	1.000
	(32.3)	(114.9)	(375.0)	(902.0)	(1711.8)

m/s = 0.447 (miles/h)

3.4.5 Visibility in Blowing Snow

The vertical distribution of blowing snow illustrates the advantage of tall delineator markers, and explains why truck drivers have better visibility than motorists in passenger cars during blowing snow conditions (Figure 3.11).

Knowing how visibility in blowing snow varies with wind speed can be useful for quantifying "whiteout" problems to justify construction of snow fences. This information also allows better interpretation of wind forecasts in relation to maintenance operations and highway safety.

When the ground is completely snow covered, a motorist's visibility varies with wind speed in a predictable way. Visibility in blowing snow conditions is even more sensitive to wind speed than is mass transport, because it is inversely proportional to the fifth power of wind speed. The coefficient of proportionality in Equation (3.5) varies with snow availability. For unlimited snow on the ground, however, this relationship is approximated by

$$V = 1.1 \cdot 10^8 / U_{10}^5 \tag{3.5}$$

where V is visibility in meters, and wind speed is in meters per second (Tabler 1979, 1984). Table 3.2 shows values for visibility at selected wind speeds, in the absence of concurrent snowfall. Because visibility is so sensitive to wind speed, fluctuations in wind speed make driving in blowing snow hazardous. Over a period of 10 minutes or so, wind speed typically varies 30 to 50% from the average, which causes extreme variations in visibility. For example, if wind speed averages 60 km/h (37 miles/h) with a variation of ±40%, visibility could vary from 1100 m (3609 ft), to 16 m (52 ft).

Table 3.2. Visibility versus the wind speed at 10 meters for unlimited snow on the ground and without precipitation, assuming a 40% gust factor.

Wind speed	Motorist visibility (meters)		
(km/h)	Minimum	Maximum	Average
30	509	35200	2737
40	121	8353	650
50	40	2737	213
60	16	1100	86
70	7	509	40
80	4	261	20
90	2	145	11
100	1	86	7
110	0.8	53	4
120	0.5	34	3
130	0.3	23	2
140	0.2	16	1
150	0.2	11	0.9
160	0.1	8	0.6
170	0.1	6	0.5

km = miles· 1.61
m = ft· 0.305

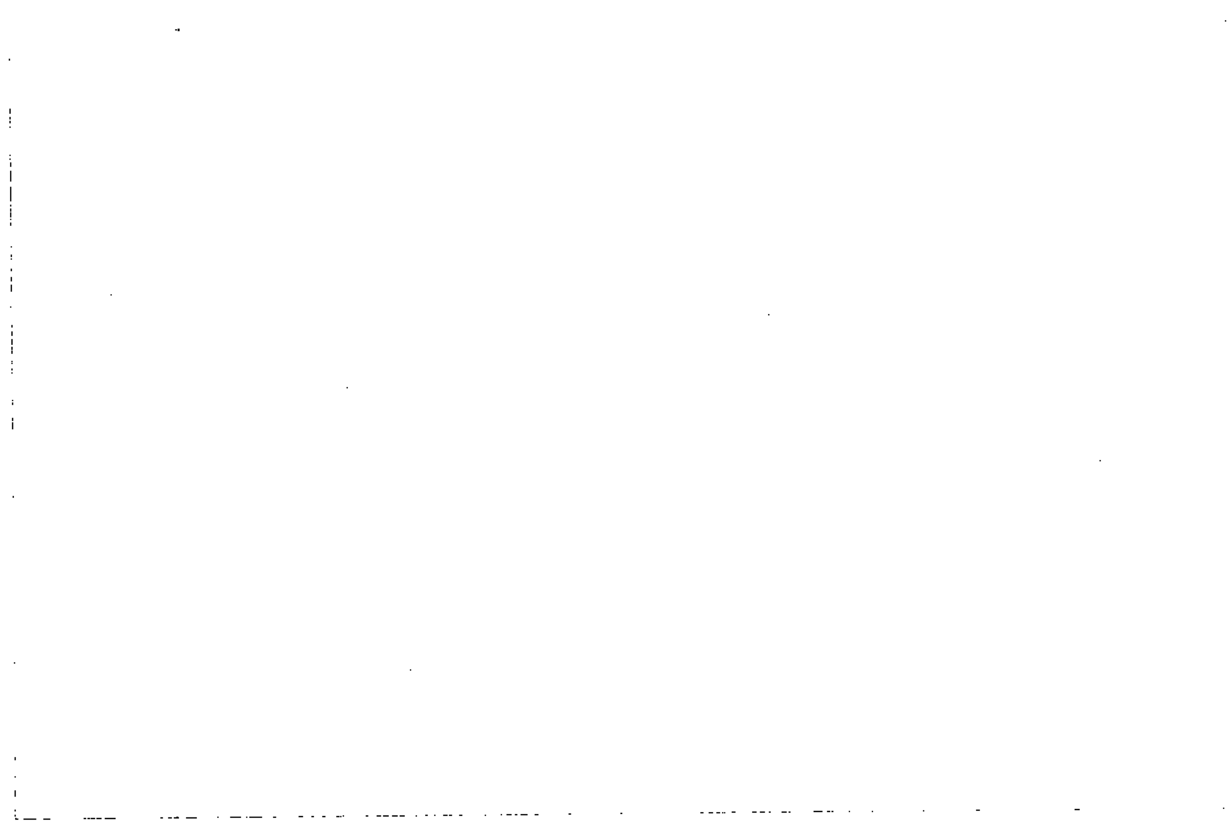


Figure 3.11. Vertical distribution of blowing snow when wind speed averaged 90 km/h (55 miles/h).

3.4.6 Evaporation of Blowing Snow

The common experience that ice cubes evaporate during sub-freezing storage, and the large ratio of surface area to mass presented by blowing snow, leads to an intuition that evaporation of blowing snow particles is significant. This idea was first proposed by Dyunin (1954, 1956, 1959) and Komarov (1954). Evaporation of wind-transported snow has been substantiated by process-based energy-balance models (Schmidt 1972; Lee 1975; Pomeroy 1988), analysis of atmospheric conditions during drifting (Schmidt 1982b), hydrologic evidence (Tabler and Johnson 1971), and mass balance studies (Benson 1982; Tabler 1975a). Graphic evidence for evaporation at subfreezing temperatures is shown by the condensation of water vapor above a column of blowing snow in Figure 3.12. According to Schmidt (1972), relative humidity is the dominant factor affecting evaporation. At a temperature of -15 °C (+5 °F) and a wind speed of 88 km/h (55 miles/h), for example, the evaporation rate is more than 5 times greater at 40% relative humidity than at 90%. Other things being equal, therefore, locations that have high humidities, such as areas prone to lake-effect snowstorms, have more blowing snow.

Other significant factors that determine evaporation from individual particles are particle size, atmospheric pressure, solar radiation, and air temperature. The evaporation rate approximately doubles for every 10 °C increase in temperature.

Although evaporation cools the air and increases humidity, the turbulent diffusion of heat and water vapor keeps the process from being self-limiting. The increase in turbulent diffusion with wind speed implies that the rate of evaporation may also increase with wind speed.

These mathematical models provide the necessary insight to develop a simplified method for estimating total evaporation over a winter. Subtracting that amount from the precipitation gives an estimate of snow transport needed to design the capacity of snow control measures. A conceptual model (Tabler 1975a) that relates evaporation from a typical size distribution of snow particles to the distance the particles are transported by the wind shows that over a travel distance F, the ratio of residual mass M to initial mass M_o is closely approximated by

$$M/M_o = e^{-2(F/T)} \approx 0.14^{(F/T)} \qquad (3.6)$$

where T is the *maximum transport distance* — the distance that the average sized particle can travel before completely evaporating. F is the *fetch* that contributes blowing snow to a downwind location (Figure 3.13).

The differential equations utilizing Equation (3.6) allow evaporation to be computed over increments of fetch having different snow retention characteristics. For a fetch having uniform conditions

$$Q_{evap} = 1000\ S_{rwe}F - 500\ T\ S_{rwe}(1 - 0.14^{F/T}) \tag{3.7}$$

where
Q_{evap} = evaporation loss (kg per meter of width across the wind),
S_{rwe} = relocated snow water-equivalent (depth, in meters),
F = fetch distance (m), and
T = maximum transport distance (m).

The relocated snow, S_{rwe}, is that portion of the winter's snowfall relocated by the wind, and excludes snow retained by vegetation and topographic features, or snow that hardens or melts in place. The *relocation coefficient* θ is therefore defined as the proportion of winter snowfall water-equivalent S_{we} relocated by the wind:

$$\theta = S_{rwe} / S_{we} \tag{3.8}$$

Studies in Siberia and Wyoming show that even on flat areas with low-growing vegetation θ seldom exceeds 0.7 over a winter. In the northeastern United States, θ typically ranges from 0.2 to 0.3.

The upwind end of the fetch is any boundary across which there is no snow transport, such as forest margins, deep gullies or stream channels, rows of trees, and shorelines of unfrozen bodies of water (Figure 3.14).

The maximum transport distance varies greatly from one storm to the next (depending on relative humidity, air temperature, and wind speed), but season-long averages appear to be relatively stable. Studies in Wyoming show that the maximum transport distance averages about 3000 m (10,000 ft). Although it is expected that the seasonal average would vary with location, other compensating factors make the 3000-m value generally applicable. For example, a similar value seems to apply in arctic Alaska where lower relative humidity may compensate for the colder temperatures.

The evaporation rate varies greatly from storm to storm, but the net loss over a winter is much less variable. Equation (3.7) with T = 3000 m provides a reasonable approximation. For continental climates, evaporation loss increases with fetch as shown in Figure 3.15, with about 57% of the relocated snow evaporating over a distance of 3 km (1.9 miles) and 85% over a fetch of 10 km (6.2 miles).

Figure 3.12. Condensation of water vapor above a column of blowing snow. Maximum temperature for the day was -5.6 °C (+22 °F) (Tabler 1986).

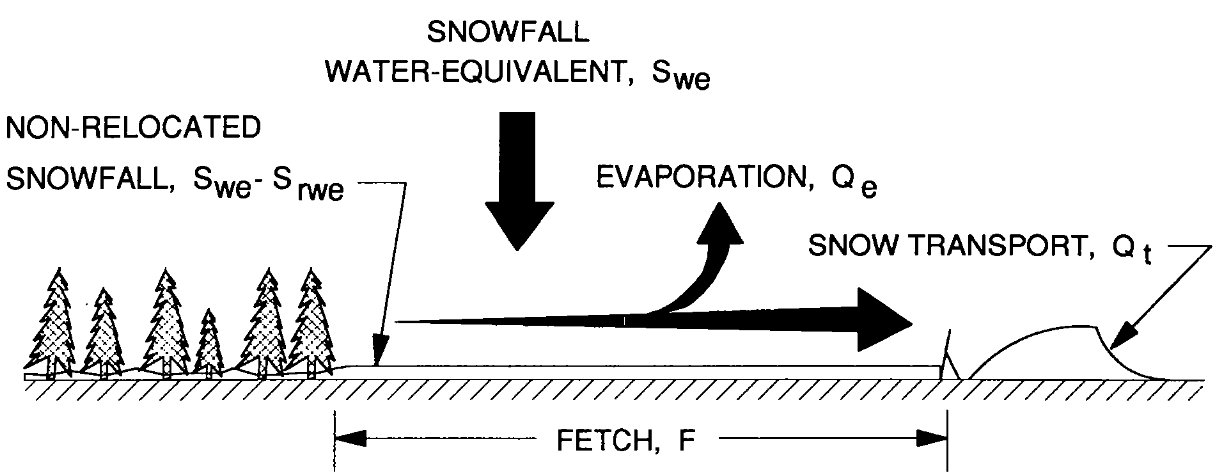


Figure 3.13. Diagram of the transport distance concept used to estimate evaporation loss from wind-transported snow (Tabler, 1975a).

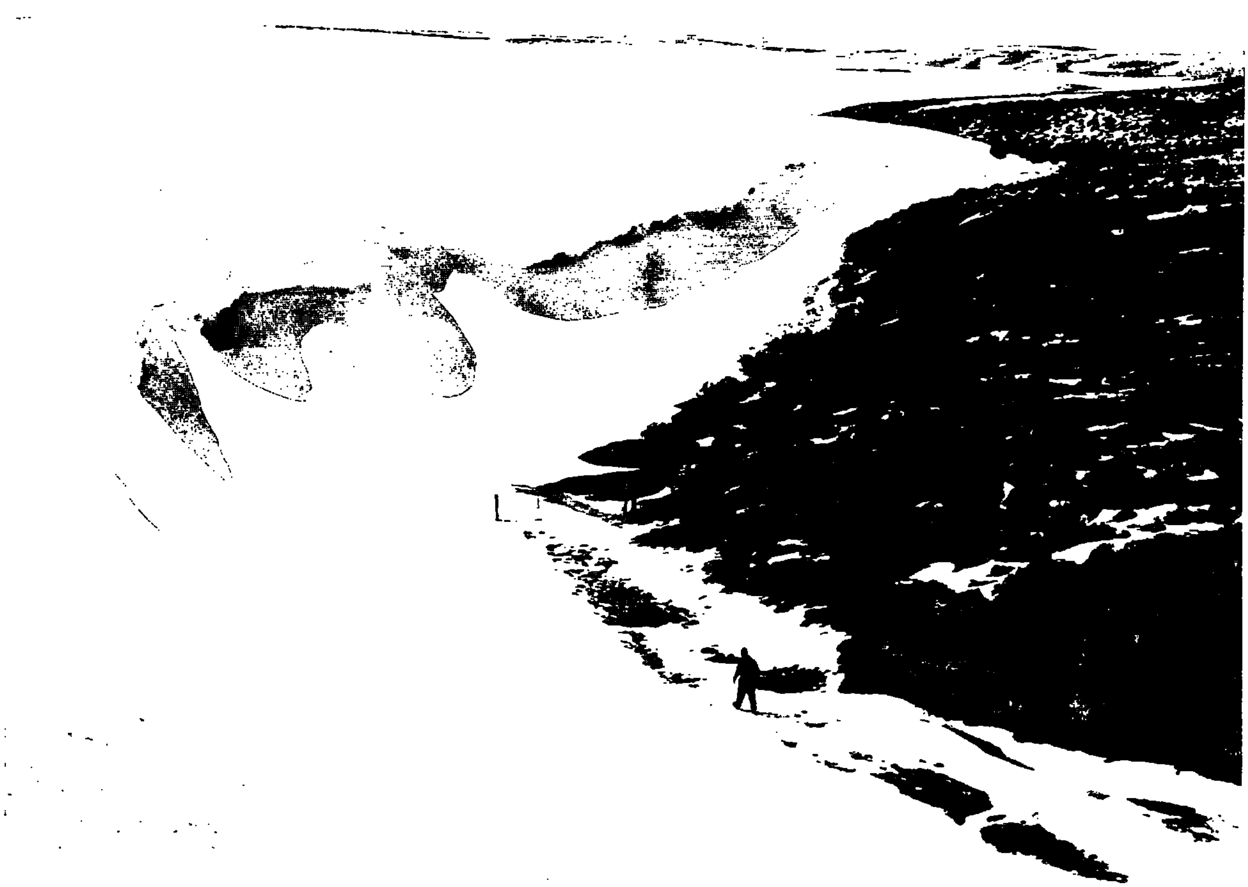


Figure 3.14. This valley is an example of an upwind boundary that defines the fetch distance for downwind locations (wind left to right)(Tabler 1986).

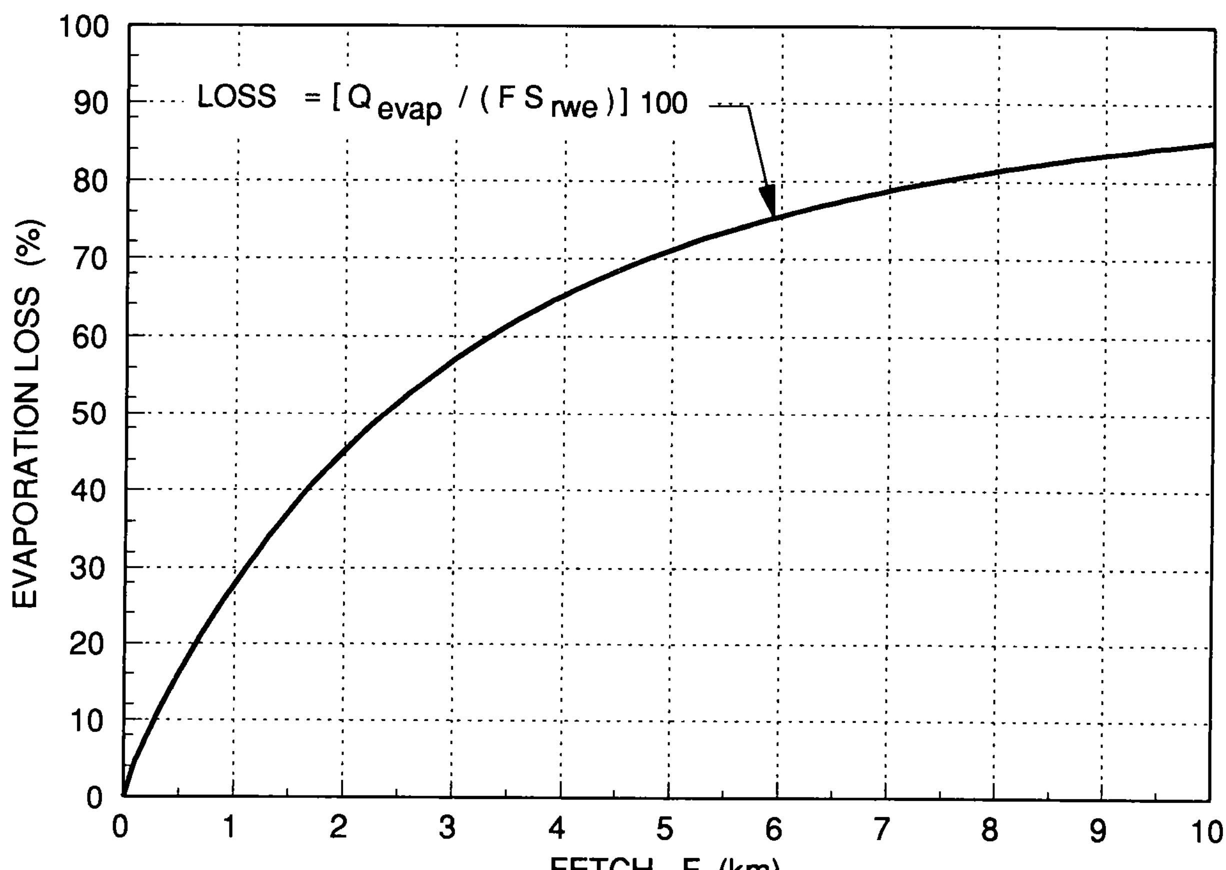


Figure 3.15. Evaporation of relocated snow as a function of the fetch.

3.4.7 Snow Transport Versus Fetch and Relocated Snow

Subtracting the evaporation loss from the total relocated precipitation provides an estimate for the total seasonal transport Q_t (kg/m). Again, assuming uniform snow retention over the fetch

$$Q_t = 500\ T\ S_{rwe}(1 - 0.14^{F/T}) \tag{3.9}$$

where S_{rwe} is in meters water-equivalent, and distances are in meters. When a long-term mean value is used for S_{rwe}, Q_t is replaced with $Q_{t,ave}$ to denote mean annual snow transport. Figure 3.16 illustrates the functional relationship represented by this equation.

Equation (3.9), with a value of T = 3000 m (10,000 ft), has been used to design many successful snowdrift control projects, and provides an excellent first approximation for general engineering use. If future experience in new locations indicated a discrepancy between predicted and measured transport, however, Equation (3.9) could be calibrated by using a different value for the maximum transport distance, T.

Equation (3.9) can also be written as

$$Q_t = Q_{inf}(1 - 0.14^{F/T}) \tag{3.10}$$

where Q_{inf} represents the snow transport that would occur downwind of an infinitely long fetch, and the terms in the parentheses constitute a correction for fetch distance. Figure 3.17 shows the general relationship between fetch and the snow transport that uses the usual assumption that T = 3000 m (10,000 ft).

If the relocated snowfall water-equivalent is known,

$$Q_{inf} = 500\ T\ S_{rwc} \tag{3.11}$$

where S_{rwe} is in meters. Usually, however, it is necessary to estimate Q_{inf} from wind speed records using Equation (3.4), as described in section 4.7.

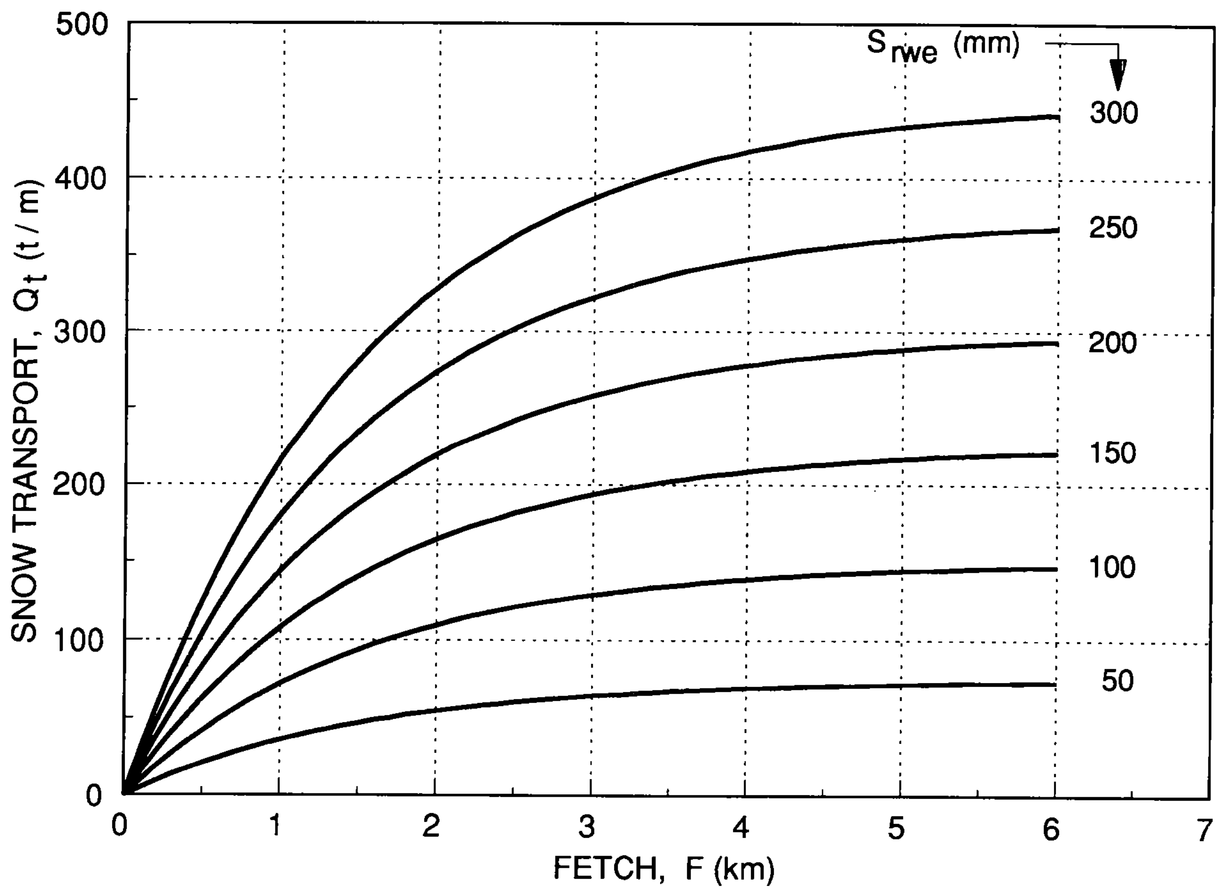


Figure 3.16. Snow transport as a function of fetch distance and relocated snow water-equivalent, as calculated from Equation (3.9), using T = 3000 m (10,000 ft).

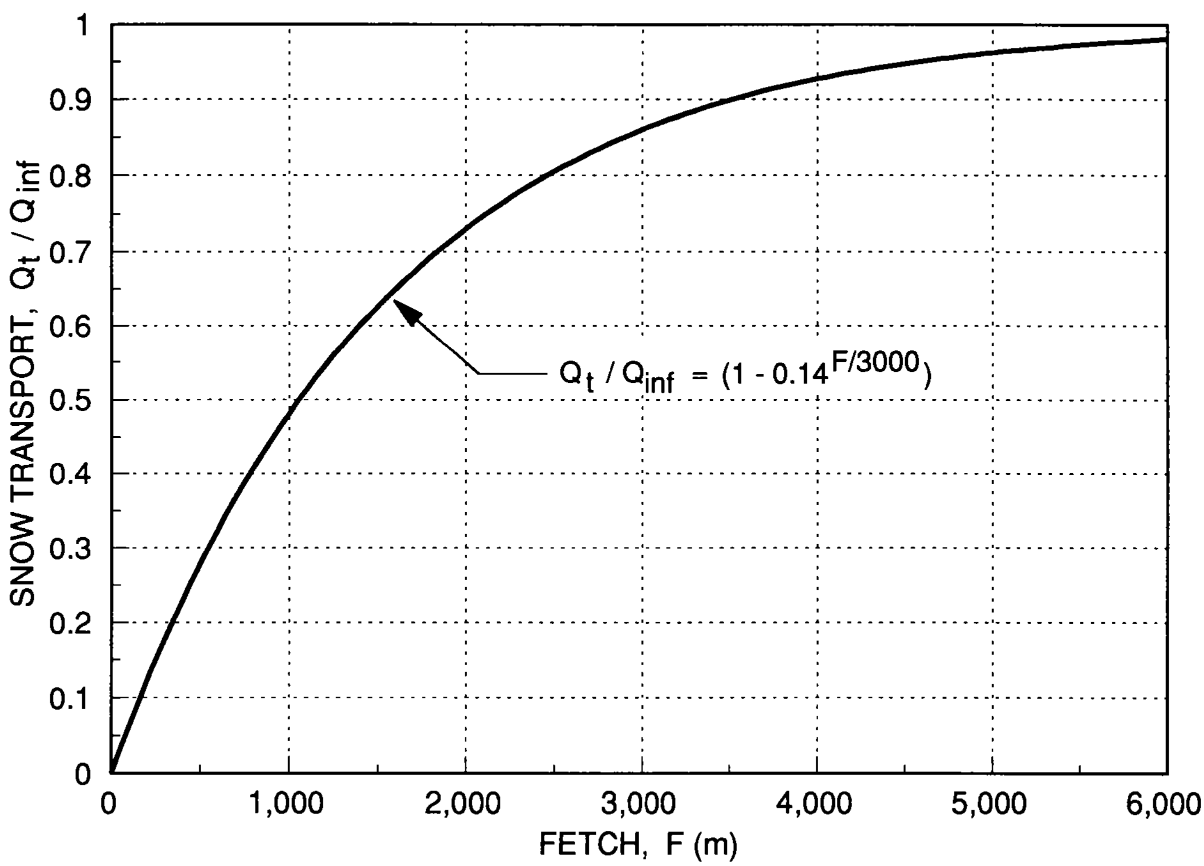


Figure 3.17. How snow transport increases with fetch distance, as given by Equation (3.10) assuming T = 3000 m (10,000 ft).

3.4.8 Snow Surface Features

Features caused by erosion and deposition range from ripples and pits measurable in centimeters, to V-shaped dunes and *sastrugi* having dimensions on the order of meters. Familiarity with the larger features can be useful for determining wind directions from aerial photos. The presence of dunes on a snowdrift also indicates that the drift surface is at equilibrium for the existing winds.

Snow dunes resemble their sand counterparts. The most common ones are V-shaped or crescent-shaped, are 10 to 30 cm (4 to 12 in.) high, and have horns that are several meters long, with the apex pointing into the wind (Figure 3.18). Snow waves, dunes that resemble rounded water waves, typically attain heights of 20 to 40 cm (8 to 16 in.), lengths up to 10 meters (33 ft) or more, and are oriented perpendicular to the wind direction (Figure 3.19). Because dunes and waves both require the presence of relatively large snow particles creeping along the surface, they develop best at lower wind speeds and from older snow, that can provide a source of larger ice fragments.

Dunes and waves migrate downwind at a rate proportional to the wind speed. Those shown in Figure 3.2 were moving about 5 m/h (16 ft/h) under a wind speed averaging 40 km/h (25 miles/h). The rate of snow transport by these waves was 45 kg/h per meter of width across the wind (30 lb/h·ft), or about 30% of the transport in the first 5 m (16 ft) above the surface, as given by Equation (3.4). Snow waves are often a conspicuous feature on aerial photographs, and can be used to determine the wind direction because these features are oriented across the wind.

Sastrugi (singular *sastrug*, from the Russian *Zastrug*), can refer to a number of different snow surface features, but Mellor (1965) states that sastrugi are "generally regarded as being the sharp-edged longitudinal ridges" that form on the surface of a wind-swept snowfield. Wind erosion exposing soft snow beneath a harder surface forms tongue-shaped features 25 to 40 cm (10 to 16 in.) tall that face into the wind (Figure 3.20). Although sastrugi are often difficult to see on aerial photos, their orientation can provide an indication of wind direction for field observations.

Figure 3.18. Crescent-shaped snow dune (wind from left)(Tabler 1986).

Figure 3.19. Snow waves (facing wind). The snow fence is 3.7 m (12 ft) tall (Tabler 1986).

Figure 3.20. A sastrug, with 12- × 20-cm (5- × 7-in.) field book for scale (wind from left).

3.5 Snow Erosion and Deposition Processes

3.5.1 Erosion

The erosion and transport of snow particles is driven by the shear stress, τ_o, exerted on the snow surface by the wind. For the turbulent flow conditions associated with blowing snow,

$$\tau_o = \rho_a |du/dz|^2 \lambda^2 \tag{3.12}$$

where

ρ_a = air density,
du/dz = vertical gradient of wind speed, and
λ = mixing length.

This relationship is presented to show that the *shape* of the wind profile is a determining factor in the erosion, transport, and deposition of snow.

Snow begins to blow when the surface shear stress becomes strong enough to dislodge a few of the snow particles. As these particles saltate, they dislodge more particles. This chain reaction continues until the force of the wind drops below that required to sustain the process (Figure 3.4).

Distances of 150 to 300 m (490 to 980 ft) are required for transport rates to reach equilibrium, and about 500 m (1600 ft) is required for a fully developed blowing snow profile in the first 5 m (16 ft) above the surface (Takeuchi 1980). *This implies that there is a tendency for the snow surface to erode over this distance downwind of any boundary that initiates a fetch, including a snow fence.*

For blowing snow to fully develop to a height of 5 m (16 m) or so over a flat surface, the surface erosion rate should equal the evaporation rate, provided that the transport rate is in balance with momentum transfer into the drifting layer. Although transport rates fluctuate and corresponding erosion and deposition patterns develop, on a uniform extensive surface the average depletion of snow cover balances the total evaporation from the blowing snow particles and from the snow surface.

3.5.2 Deposition

Deposition occurs if the rate of momentum transfer to the saltation layer decreases to a value less than that to which the transport rate has adjusted. If a barrier or change in topography causes the wind speed to decrease, some of the transported snow will be deposited. Where the wind accelerates, more particles will be picked up, causing erosion. This is a dynamic balance because the energy level of the wind is constantly fluctuating as a result of natural turbulence. Averaged over time, however, deposition occurs where surface shear stress decreases in a downstream direction, and erosion occurs where shear stress increases.

3.5.3 *Inter-Particle Bonding*

Wind-deposited snow particles freeze together upon contact. These bonds grow and strengthen through sintering. The rate at which these bonds strengthen increases the work required for disaggregation, which doubles within 1 day and triples within 3 days (Figure 3.21). Because wind-deposited snow becomes quite resistant to subsequent erosion within only a few hours of deposition, there is a tendency for drift shape to reflect the maximum attainable profile associated with lower wind speeds.

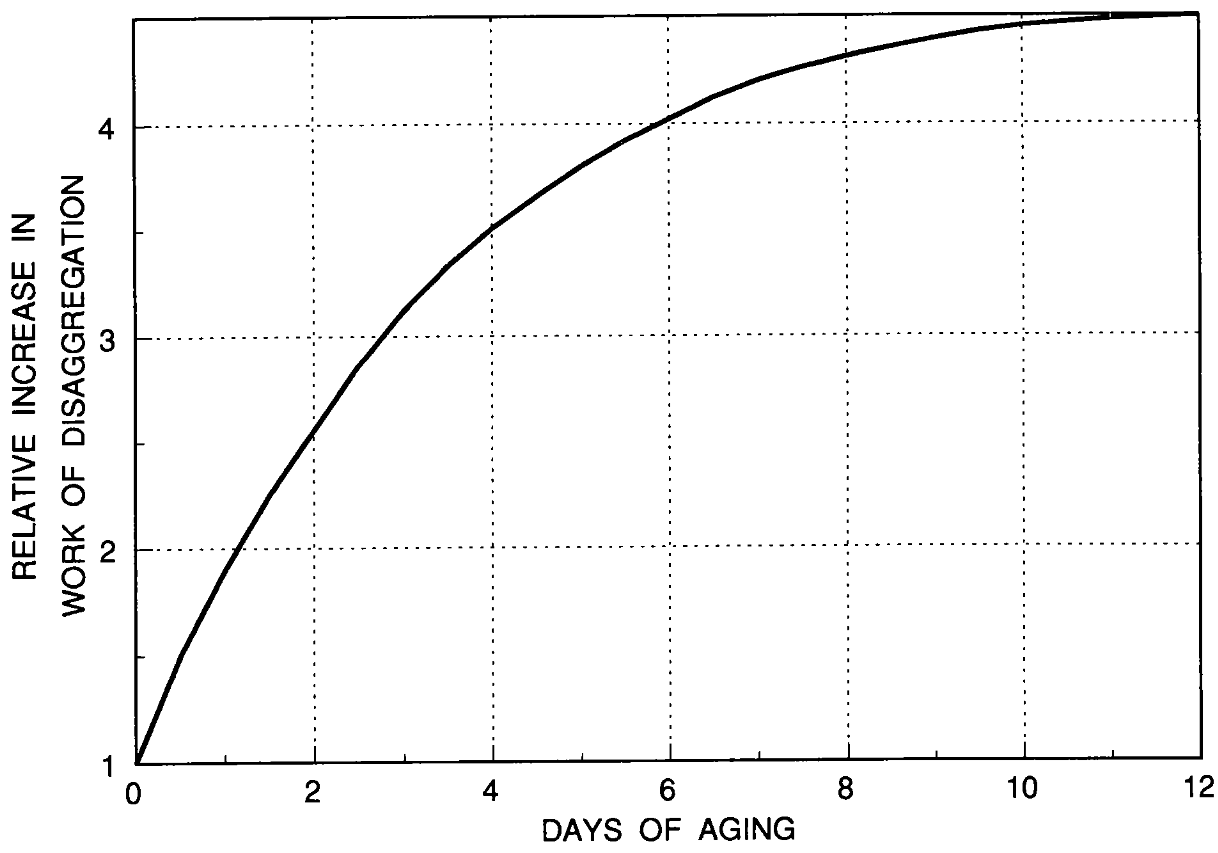


Figure 3.21. Change in the strength of bonds among deposited snow particles with time, as indexed by work of disaggregation (after Jellinek 1957).

3.5.4 *Snow Densification*

The density of newly fallen snow averages about 100 kg/m^3 (6.2 lb/ft^3). The density of the snowpack increases with time due to the compaction of overlying snow, and the changes that occur as a result of vapor movement within the snowpack.

Drifted snow is usually more dense than undisturbed snow because the particles are initially smaller and more compact. Density of newly deposited snow varies with weather conditions, however, and concurrent snowfall is a dominant factor. The density of a newly deposited layer of blowing snow can be as low as 100 kg/m^3 (6.2 lb/ft^3) in the presence of snowfall, or as high as 300 kg/m^3 (18.7 lb/ft^3) in its absence.

The pressure of overlying snow compacts and rearranges snow particles by plastic yielding, particle fracture, and sliding. Before the onset of melt, the density of drifted snow (ρ_s, expressed as kg/m^3) is approximated by

$$\rho_s = 522 - (304/1.485Y)\,(1 - e^{-1.485Y}) \tag{3.13}$$

where Y is snow depth in meters and e is the base of natural logarithms (2.71828...) (Tabler 1985). The 522 kg/m^3 asymptote in the equation, determined by least-squares analysis, reflects some plateau in the densification process, such as the closest possible packing attainable by compressive loading with limited metamorphism. The maximum density that can be attained experimentally by packing alone is about 550 kg/m^3, corresponding to the critical density where densification rate abruptly decreases. The functional relationship given by Equation (3.13) is shown graphically in Figure 3.22.

Excluding the basal ice layer typical under melting drifts, density of actively melting snowdrifts on well-drained sites is essentially independent of snow depth, averaging about 600 kg/m^3 (Tabler 1985).

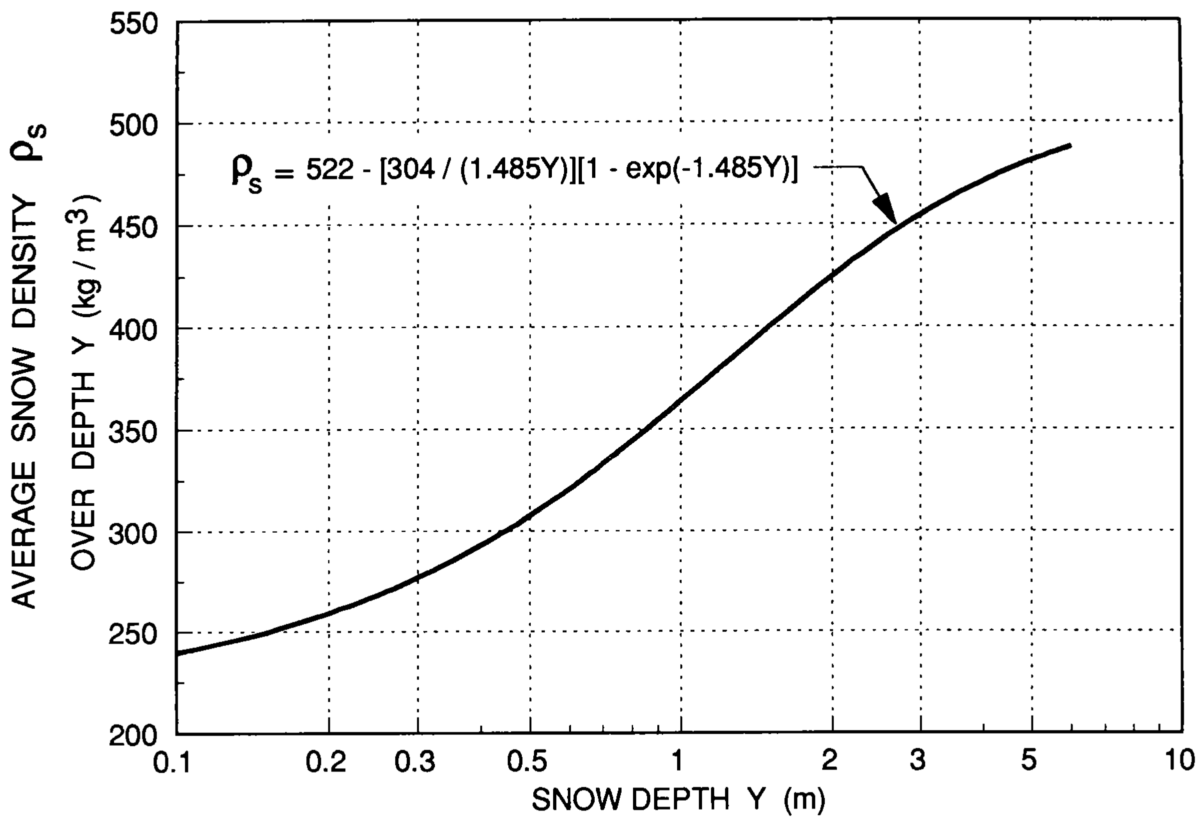


Figure 3.22. Density of wind-deposited snow as a function of depth, before the onset of melt (Tabler 1985).

3.6 Snow Deposition and Retention Due to Vegetation

Because blowing snow is deposited so as to reduce the aerodynamic drag of the surface, drifts fill in surface depressions (Figure 3.6), streamline objects protruding from the surface, and fill in spaces between surface roughness features such as vegetation (Figure 3.23). Snow is retained by low-growing vegetation because vegetation protruding above the snow surface reduces the shear stress on the intervening surface.

In areas that have sufficient wind to relocate all of the snowfall, snow transport is inversely related to the height and cover density of vegetation over the fetch. In such areas, information on the vegetative cover can be used to estimate relocated snowfall as required to estimate snow transport from Equations (3.9) to (3.11).

In some instances, blowing snow problems can be reduced by rows of standing corn or by stubble (Tabler 1991a).

Figure 3.23. Snow retained in a field of posts 130 mm in diameter, 1.2 m tall (5 in. in diameter, 4 ft tall) at different spacings illustrates how the geometry of surface roughness controls snow deposition.

3.7 Deposition in Topographic Depressions and Road Cuts

3.7.1 How Drifts Grow

As indicated by Equation (3.12), any factor that changes the velocity gradient will affect surface shear stress. Wind passing over a curved surface, such as that shown in Figure 3.24, is slowed by the adverse pressure gradient, promoting the deposition of blowing snow in the region where the flow is decelerating. If the curvature change is great enough, the airflow separates from the surface and forms an eddy in which the wind near the surface moves in a direction opposite to that of the approaching wind. This condition, which also occurs over the wing of an aircraft when the stall angle is reached, greatly increases the resistance to the airflow and promotes deposition upwind of the eddy area, which in turn contributes to the growth of the recirculation region. In this way, relatively small changes in surface curvature can create large drifts.

In areas where the terrain drops suddenly, such as a road cut, the rapid change in the vertical gradient of velocity triggers the deposition of blowing snow. Because most of the snow is transported near the surface, there is a preferential deposition near the slope break where the velocity first changes. Snow continues to be deposited at this point until the snow surface reaches an elevation where the surface shear stress is the same as that immediately upwind. As this condition is approached, deposition shifts downwind so that the drift elongates with little increase in depth upwind (Figure 3.25)(Tabler 1975b). The abrupt change in the slope of the snow surface marks the top of the *slip face*, so named because of its resemblance to the leeward slope of sand dunes where deposited sand slips to an angle of repose. The run-to-rise ratio of the steeper upper part of the slip face typically ranges from 1:1 to 1.5:1.

The flow separates at the top of the slip face, with the formation of a vortex immediately downwind. This recirculation zone extends downwind for a distance equal to 6 to 7 times the height of the slip face from the ground surface. Most snow particles that settle in this region are sufficiently protected from the wind that they are not carried downwind.

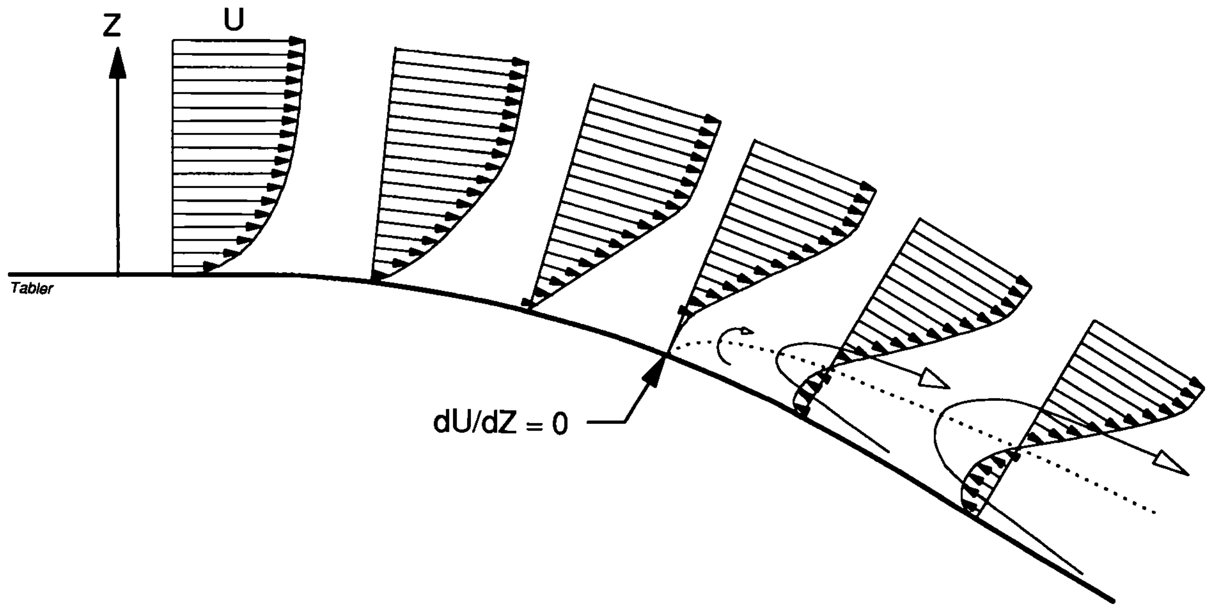


Figure 3.24. Wind profile changes over a curved surface, and the formation of an eddy area caused by separation of the airflow. ***du/dz*** **is the vertical gradient of the wind speed.**

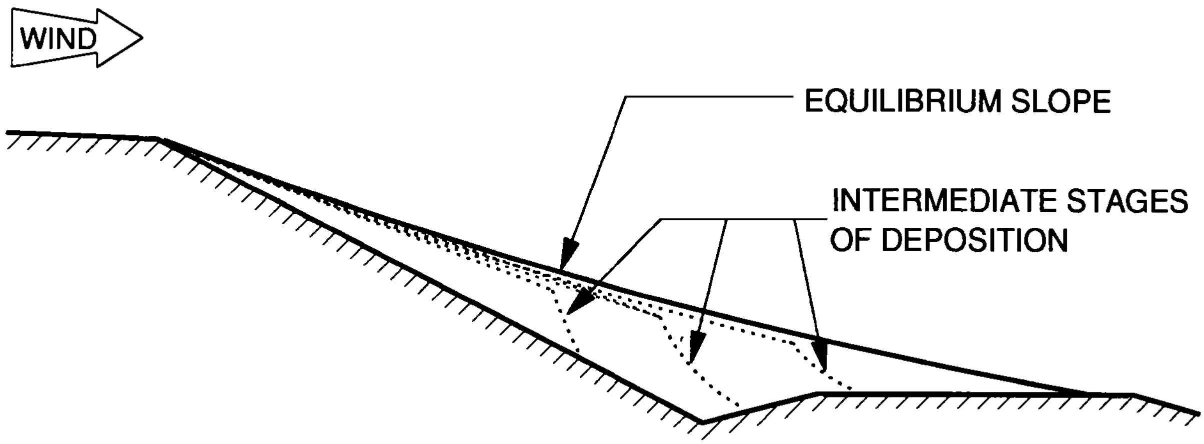


Figure 3.25 Stages of drift growth in a topographic catchment (Tabler 1975b).

3.7.2 *Equilibrium Slope*

It is reasonable to suppose that for a given wind speed and direction, a particular terrain feature has a maximum snow retention capacity that cannot be exceeded regardless of the quantity of blowing snow. The snow surface corresponding to this maximum drift is referred to as the equilibrium slope (Figure 3.25). If the development of a snowdrift follows the so-called law of natural growth, so that at any given time the growth rate is inversely proportional to the total snow accumulation up to that time, then the snow-trapping efficiency of the terrain feature would decline in some manner as it fills with snow. The true equilibrium profile then may be approached as a limit, but may not be attained with a finite quantity of snow transport. There is no way to be certain that true equilibrium has been attained for any given terrain feature observed in the field, because snow transport is always limited in nature. The greater the snow storage capacity of a terrain feature, the greater the potential disparity between the apparent and true equilibrium profiles. For engineering applications, however, it can be assumed that the difference between the two is insignificant.

Because wind velocity fluctuates, there are periods when snow is deposited, and other periods when snow is eroded away. Although no quantitative relationship is available, the equilibrium slope increases somewhat with wind speed; that is, the stronger the wind, the steeper the slope. The ice bonds that form among newly deposited particles helps to stabilize previously deposited snow, however, with a resulting tendency for snow surfaces to represent lighter wind conditions. The angle of the equilibrium slope is always less than the critical angle required for separation of the airflow — that is, the angle required to form a region of recirculating airflow immediately above the surface. This critical angle varies from 10° to 12°, although the equilibrium slopes might be steeper in areas such as mountainous terrain where background turbulence is greater.

3.7.3 *Trapping Efficiency*

The trapping efficiency of a topographic feature is the proportion of the incoming snow within 5 meters (16 ft) of the ground that is permanently retained by the feature. A major factor that affects trapping efficiency is the slope of the surface immediately upwind of the slip face. Figure 3.26 shows how snow trapping efficiency varies with approach slope for two heights of step-like terrain configurations analyzed by computer simulation (Schmidt and Randolph 1981). The trapping efficiency increases rapidly as this slope steepens, and at an angle of about 10°, trapping efficiency is at a maximum. This angle is approximately the same as the equilibrium snow surface. Figure 3.26 also shows that the height of the slip face above the ground has little effect on trapping efficiency.

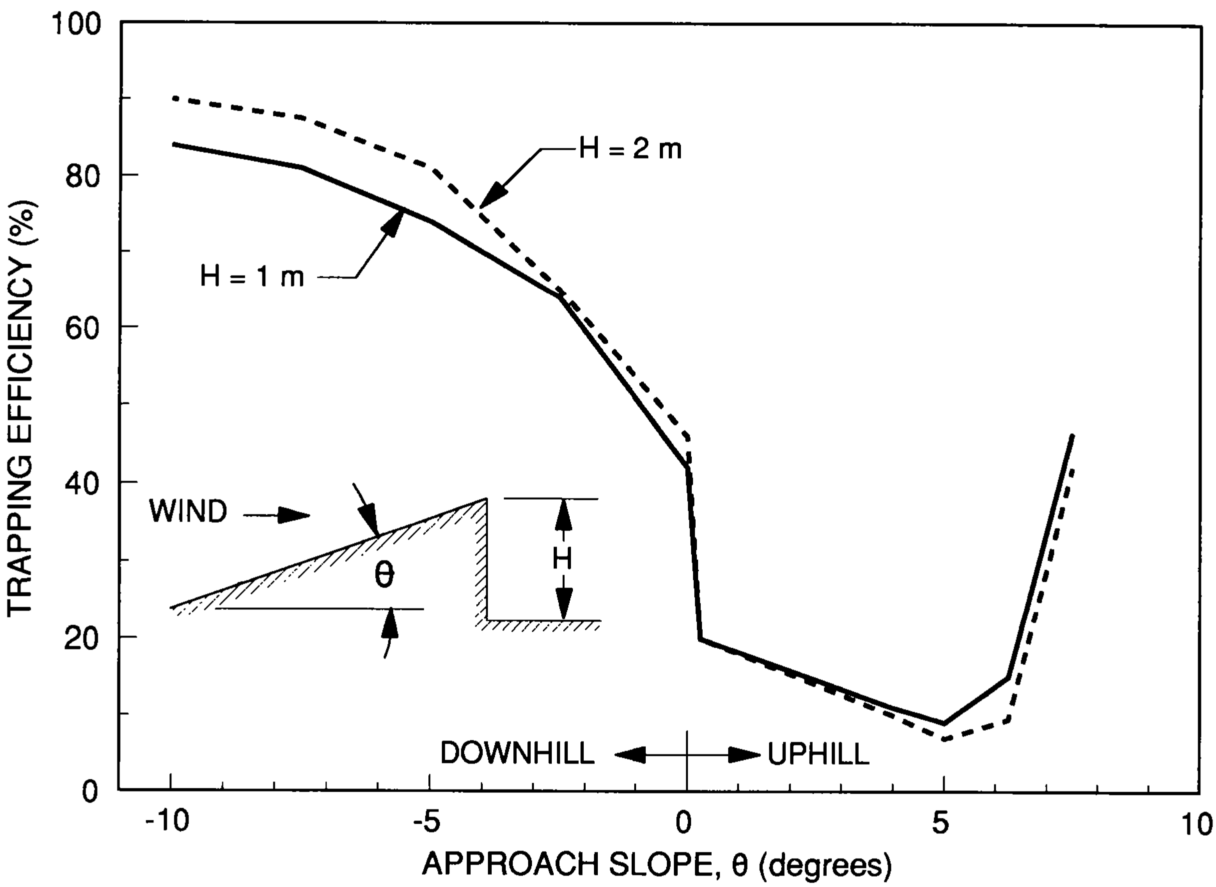


Figure 3.26. Initial trapping efficiency of downwind-facing steps in relation to approach slope and step height, as determined by Schmidt and Randolph (1981).

3.8 Deposition at Snow Fences

3.8.1 Fence Height, Porosity, and Bottom Gap Defined

Fence height is the vertical distance from the ground to the top of the fence, and is represented by *H*. Distances and heights referenced from a barrier are often expressed as multiples of fence height. A distance equal to 5 times the fence height, for example, is written as *5H*.

The *bottom gap* is a space between the ground and the bottom of the snow fence. Its purpose is to reduce snow accumulation at the fence and thereby maintain trapping efficiency.

The *porosity* of a fence is the ratio or percentage of open area to the total frontal area excluding the bottom gap. Porosity is represented by *P*. Fences that are 40 to 50% porous store the most snow.

3.8.2 Effect of Porous Fences on Wind and Blowing Snow Particles

A snow fence reduces wind speeds and changes the wind profile. A typical profile near the fence consists of the following regions, shown in Figure 3.27 (Tabler and Schmidt 1986):

Region 1 is where wind speeds are retarded by the aerodynamic resistance of the surface, with the velocity distribution given by Equation 3.1. The height of this developing boundary layer increases with downstream distance.

Region 2 is a zone of nearly uniform wind speed that constitutes the core of retarded flow immediately behind the fence.

Region 3 is where the retarded flow behind the fence mixes with the faster-moving flow that passes over the top of the fence. The upper boundary of this region coincides with the center of the accelerated flow over the top of the fence, the height of which increases as the square root of the distance from the fence. This region widens linearly with increasing distance downwind until the lower edge of the mixing region reaches the lower boundary of Region 2. Thereafter, the widening continues in a non-linear fashion.

Region 4 is a zone of turbulent mixing between the accelerated flow over the top of the fence and the outer undisturbed flow (Region 5). This region is readily apparent in wind profiles taken within 5 times the height of the fence, but at greater distance this region becomes indistinguishable from Region 3.

Wind speeds near the surface decelerate over a distance downwind from the fence equal to about 7 times the fence height (Figure 3.28), which reduces surface shear stress and allows creeping and saltating particles to come to rest. Some of these particles are deposited upwind from the fence as approaching surface winds decelerate. A significant portion of the suspended particles passing through a snow fence do not reach the ground before they are carried beyond the sheltered area.

Wind speed reduction is approximately scaled with height (Tabler and Jairell, 1993), so that the representation in Figure 3.29 is a reasonable approximation for all heights and ambient wind speeds.

When snow first begins to accumulate, the aerodynamic effect of the fence controls the deposition of snow entering the sheltered region. As the snowdrift develops, however, it exerts an additional influence on the airflow that changes as the drift shape grows and changes.

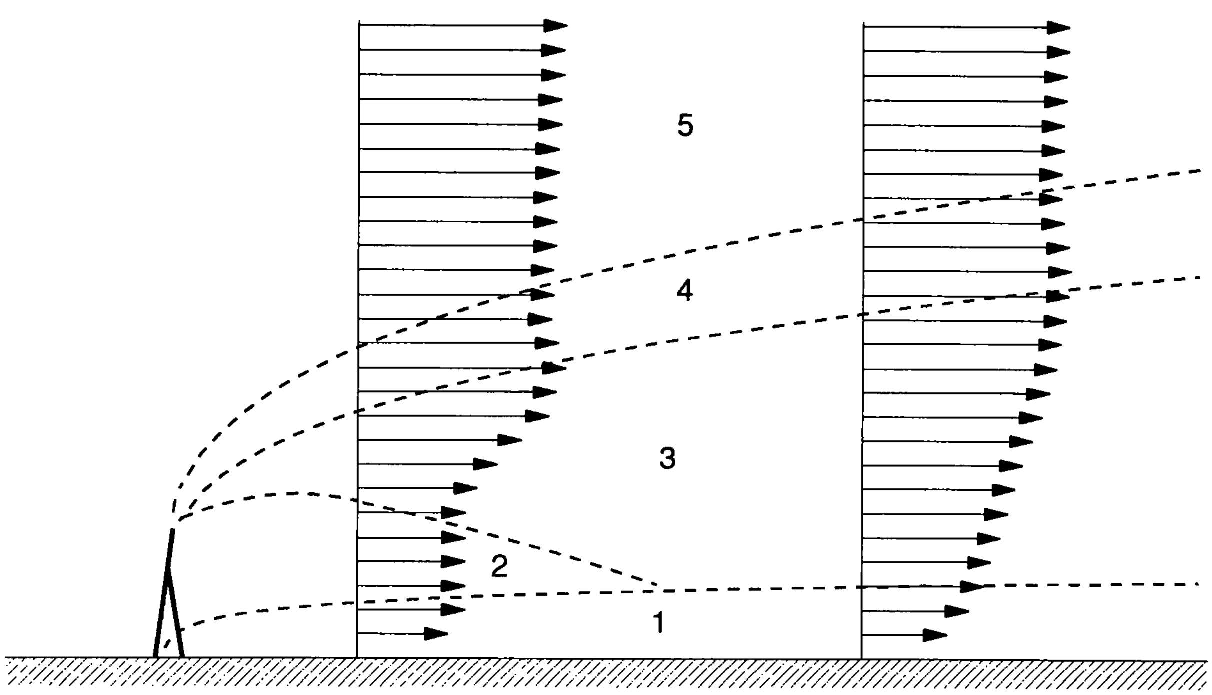


Figure 3.27. Turbulent mixing diagram, showing zones defined by Tabler and Schmidt (1986).

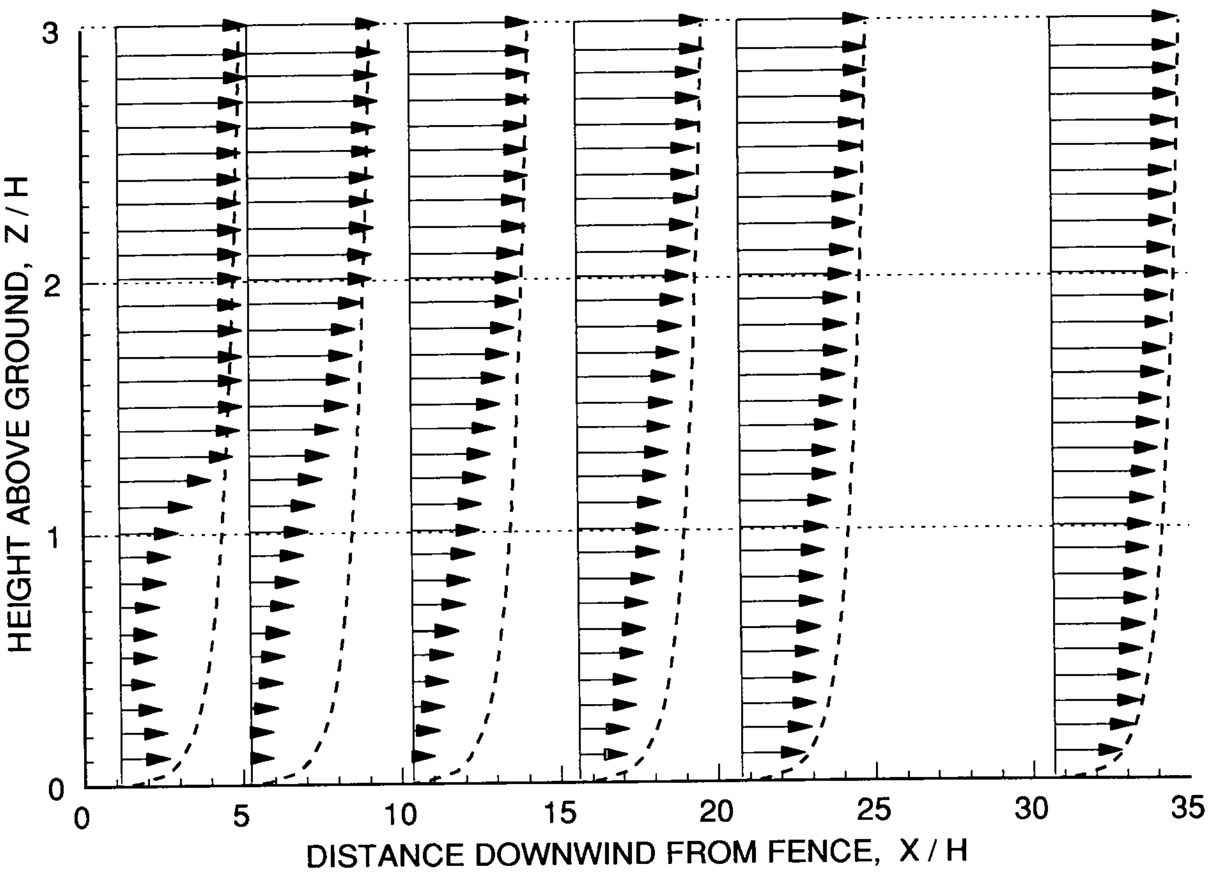


Figure 3.28. Wind speed profiles at different distances (*X*) downwind from a 50% porous snow fence, compared to profile (dashed line) far upwind from fence. *Z* is height above ground and *H* is fence height.

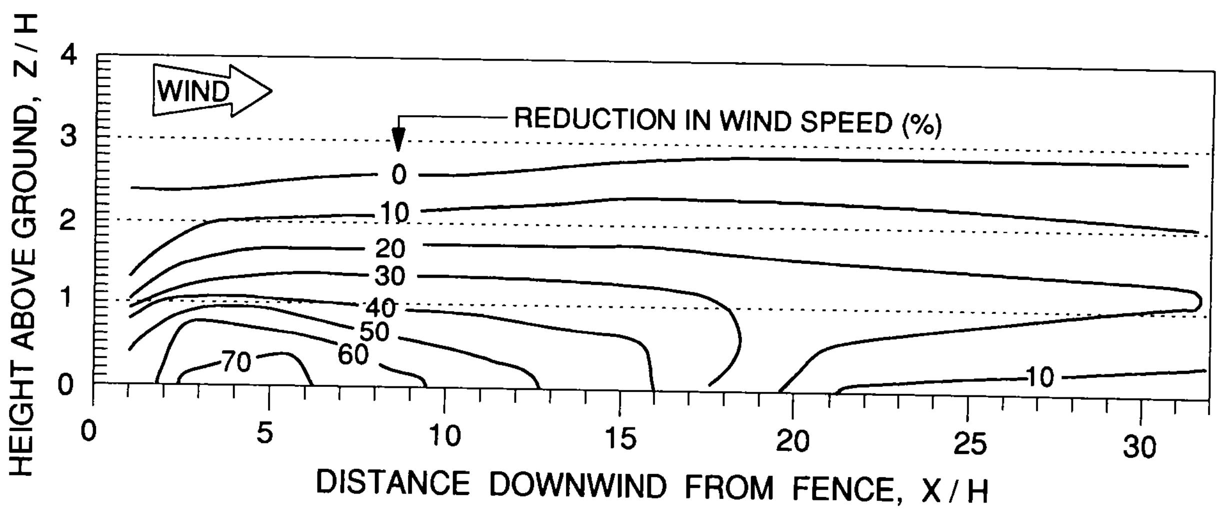


Figure 3.29. Wind speed reduction contours on the lee side of a 50% porous snow fence with height *H* (Tabler 1986). Contour values are percent of ambient (undisturbed) wind speed at an equivalent height.

3.8.3 Stages of Drift Growth at Porous Fences

The stages of drift growth are described by Tabler (1986, 1988a, 1988b). In the initial stages of drift growth, snow particles that pass through a porous barrier encounter a zone of greatly diminished winds and decreasing surface shear stress. This zone extends downwind for a distance equal to 7*H* (Figures 3.28 and 3.29). Most particles that reach the ground within this region come to rest and form a lens-shaped drift that becomes thicker in the middle as deposition continues.

This initial lens-shaped deposit thickens until the airflow cannot follow its curvature. At this stage, the flow separates from the surface, as shown in Figure 3.24. The resulting eddy area extends the effective sheltered region to 12 to 15*H* downwind. This is where most of the snow is deposited until the fence is about 75% full. The formation of the slip face and recirculation zone (Figures 3.30 and 3.31) characterize the second stage of drift growth. The recirculation zone extends downwind for a distance equal to six to seven times the height of the slip face. The run-to-rise ratio of the slope of the upper portion of the slip face typically ranges from 1:1 to 1.5:1.

During this second stage of development, the flow separation aft of the drift adds significant resistance to the approaching wind. This promotes snow deposition on the nose of the drift and reduces surface winds within the recirculation zone to a minimum. As a result, with light to moderate winds, trapping efficiency can be greater than the initial trapping efficiency at the onset of accumulation. Strong winds, however, can cause particles to be carried beyond the recirculation region before reaching the ground.

If the snow cover contains newly fallen snow, or if it is snowing while the wind is blowing, the electrostatic charge on the particles causes them to adhere to the surface and form a snow cornice at the top of the slip face. This enhances the trapping efficiency. The second stage is characterized by an increase in drift depth, with little elongation, and is represented by measurements 1 through 3 in Figure 3.32.

As the depth of the downwind drift approaches its maximum, which for 50%-porous fences is 1 to 1.2 times the height of the fence, the third stage of growth begins. This stage is characterized by snow filling the recirculation zone as the drift lengthens downwind, and is represented by measurements 4 through 6 in Figure 3.32. As long as a slip face is present, however, trapping efficiency remains relatively high.

The fourth stage of growth begins when the drift surface assumes a smooth profile without a slip face or a recirculation zone. At this point the drift is about 20*H* in length, as indicated by measurement 6 in Figure 3.32 where only a trace of the slip face remains. At this stage trapping efficiency declines rapidly and only creeping and saltating particles are deposited. Subsequent growth is therefore relatively slow as the drift reaches its ultimate length of 30 to 35*H*, as represented by measurement 7 in Figure 3.32.

The fourth stage ends when the drift ceases to grow despite the continued influx of blowing snow. The drift at this stage is at equilibrium for the existing wind conditions, but erosion or deposition could result from a change in wind speed or direction. After equilibrium is achieved, trapping efficiency remains at zero.

Equilibrium drifts are always streamlined so that their shape offers a low resistance to the airflow, and porous fences form airfoil-shaped drifts. As will be described in section 3.8.5.2.1, the dimensions of equilibrium drifts are scaled with fence height, as shown in Figure 3.33 for 50%-porous fences.

Figures 3.34 and 3.35 show how the length and depth of a drift change as a 50% porous fence fills with snow. Length of the downwind drift changes with snow accumulation according to

$$L/H = 10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2 \qquad (3.14)$$

where

L = Length of the downwind drift,
H = Fence height,
A = Cross-sectional area of the downwind drift at any time during the winter, and
A_e = Cross-sectional area of the equilibrium drift.

The maximum depth of the downwind drift, Y_{max}, changes according to

$$Y_{max}/H = 6.3(A/A_c) - 13.3(A/A_e)^2 + 12.1(A/A_e)^3 - 3.9(A/A_e)^4 \qquad (3.15)$$

These estimates of drift dimensions prior to equilibrium will be used in chapters 5 and 6, and are also useful for estimating how much snow a fence contains without cross-sectioning the drift.

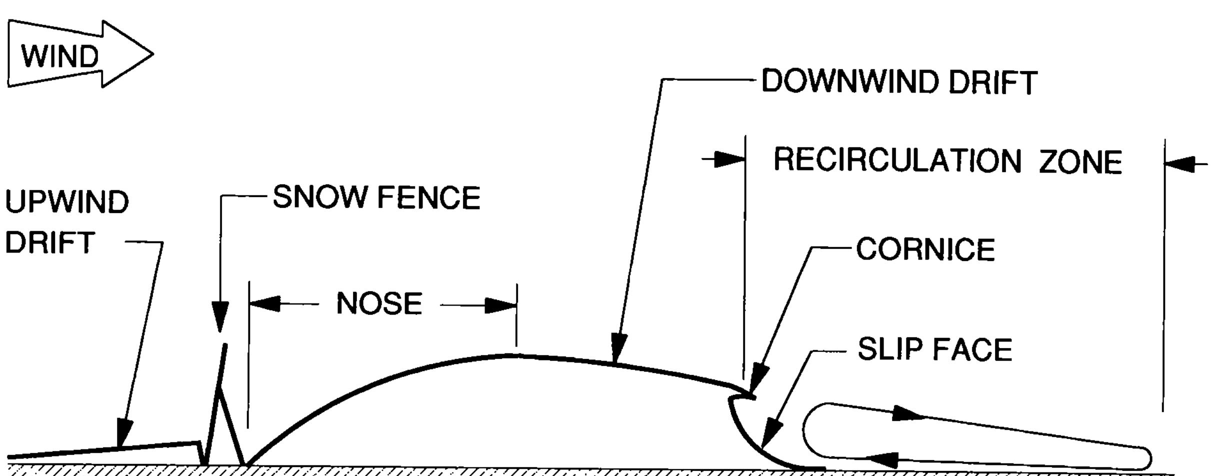


Figure 3.30. Slip-face and recirculation region formed by a 50%-porous snow fence during the intermediate stages of growth (Tabler and Jairell 1993).

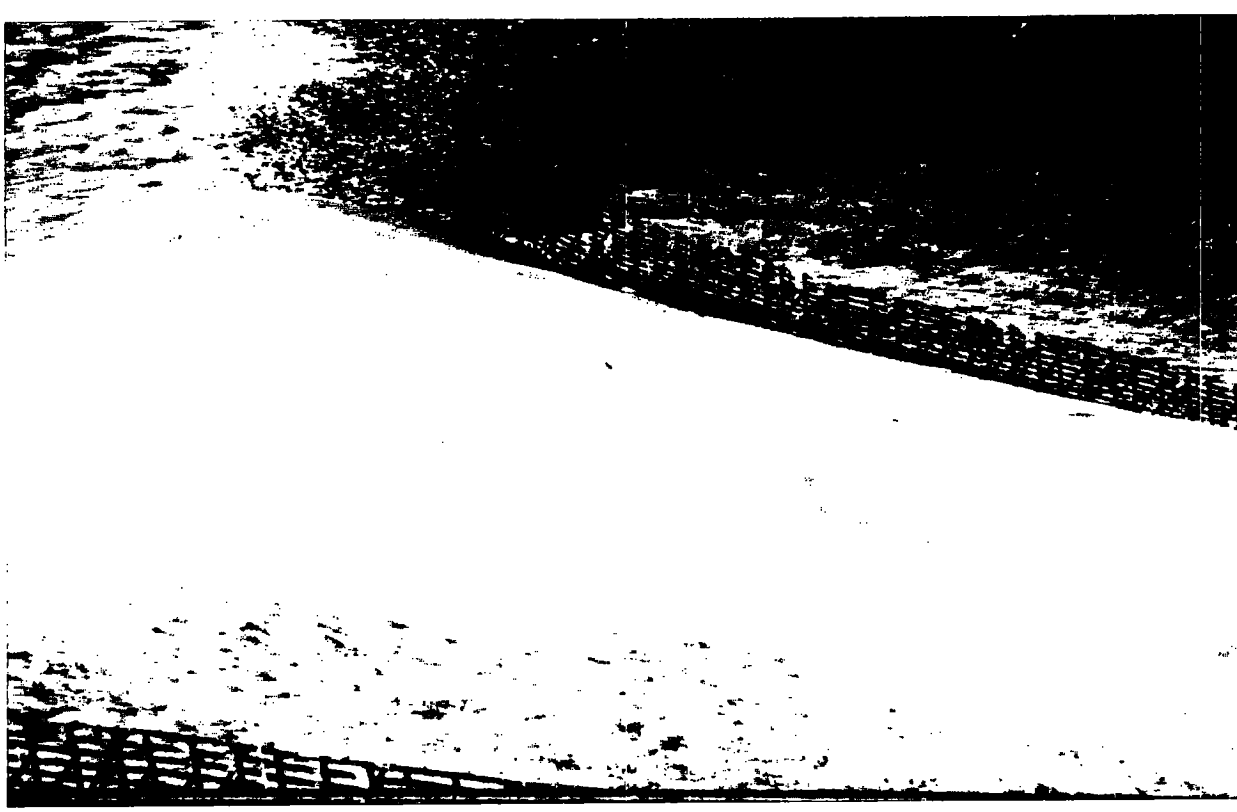


Figure 3.31. Slip face and cornice behind a 3.8-m (12.4-ft) snow fence.

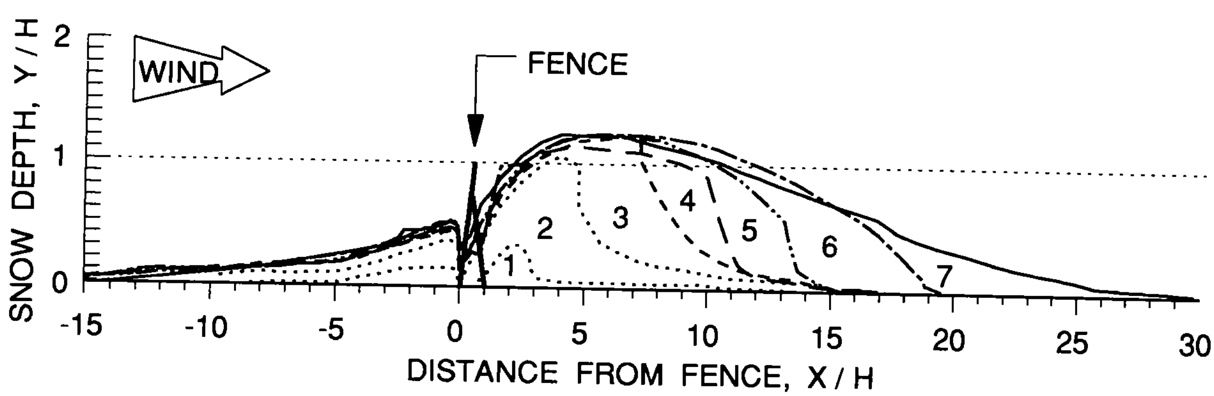


Figure 3.32. Seven profiles of a snowdrift formed by a 12.4-ft (3.8-m) horizontal-board fence that is 50% porous (Tabler 1986).

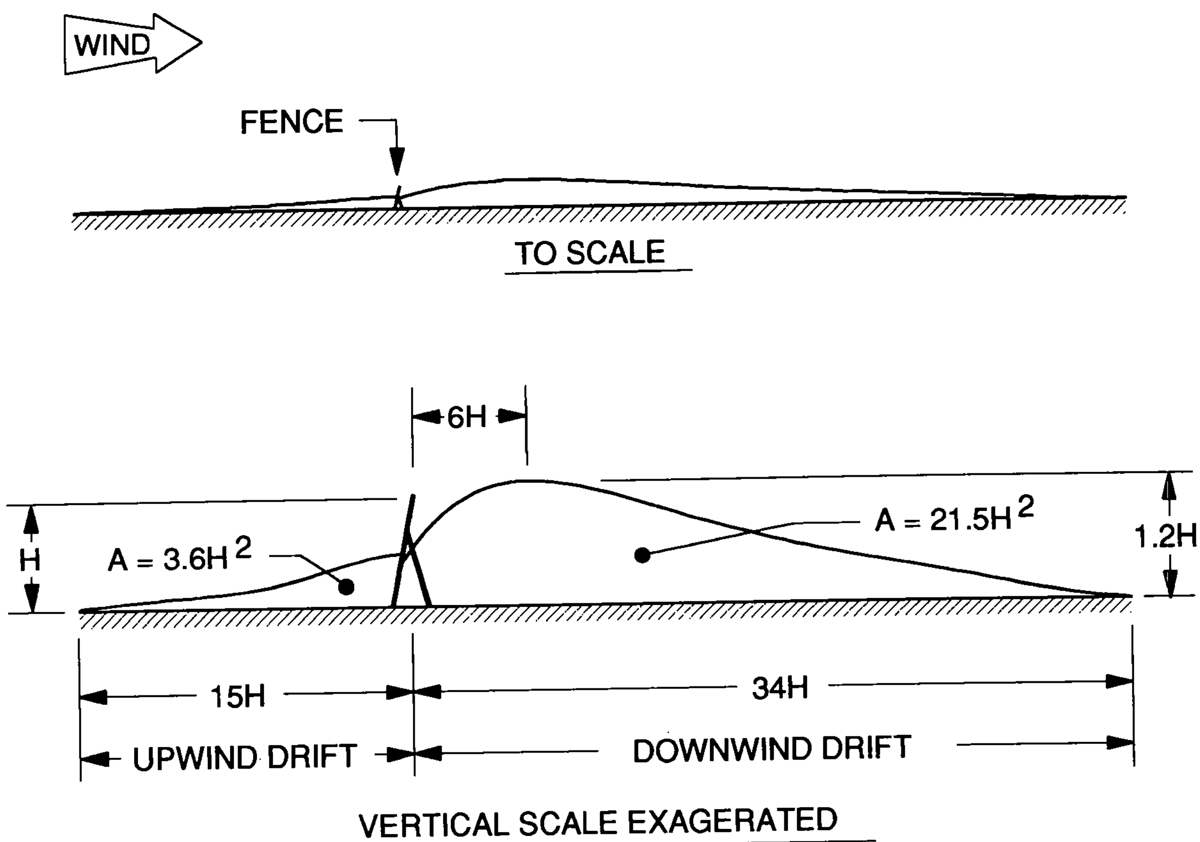


Figure 3.33. The dimensions of an equilibrium drift formed by a 50%-porosity snow fence (Tabler 1989; Tabler and Jairell 1993).

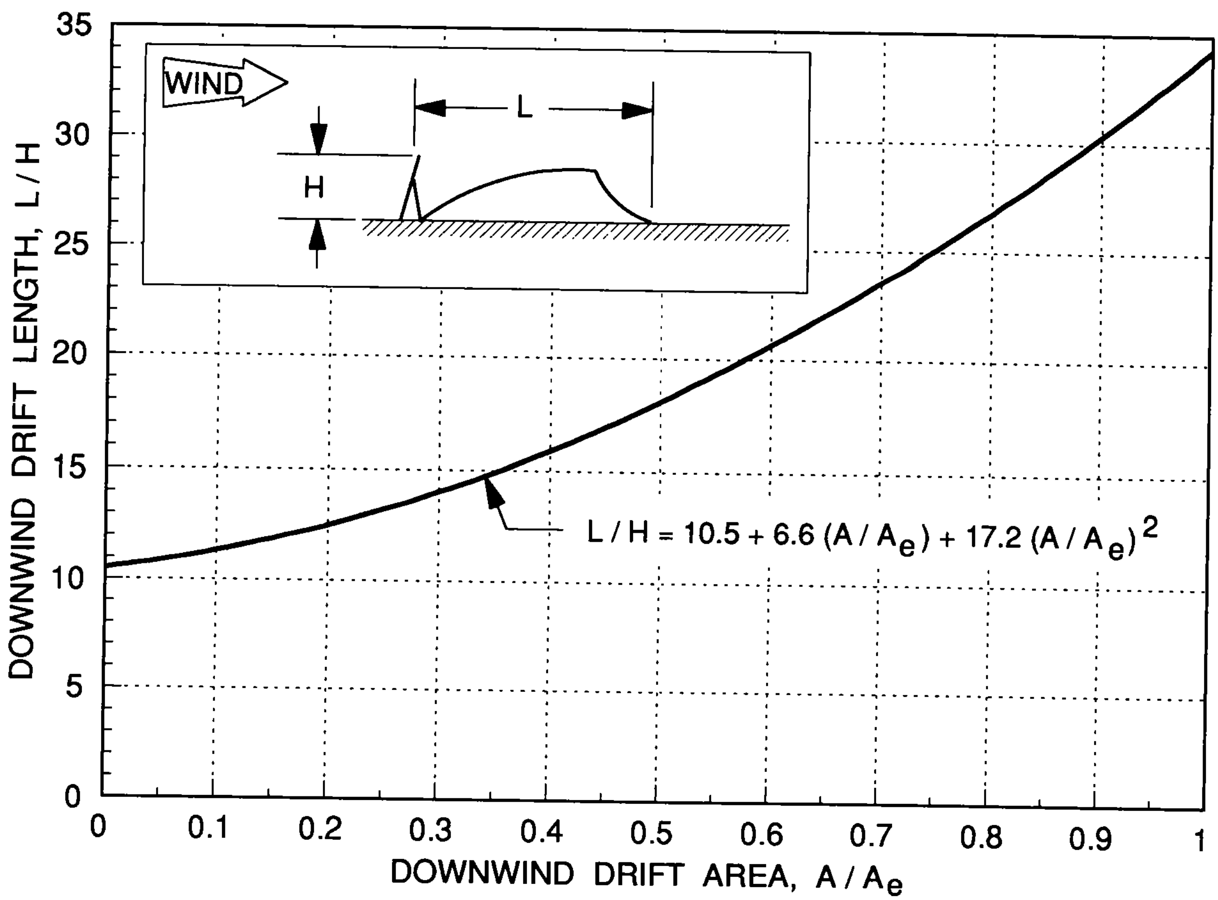


Figure 3.34. Changes in the length of the leeward drift as a 50%-porous snow fence fills with snow.

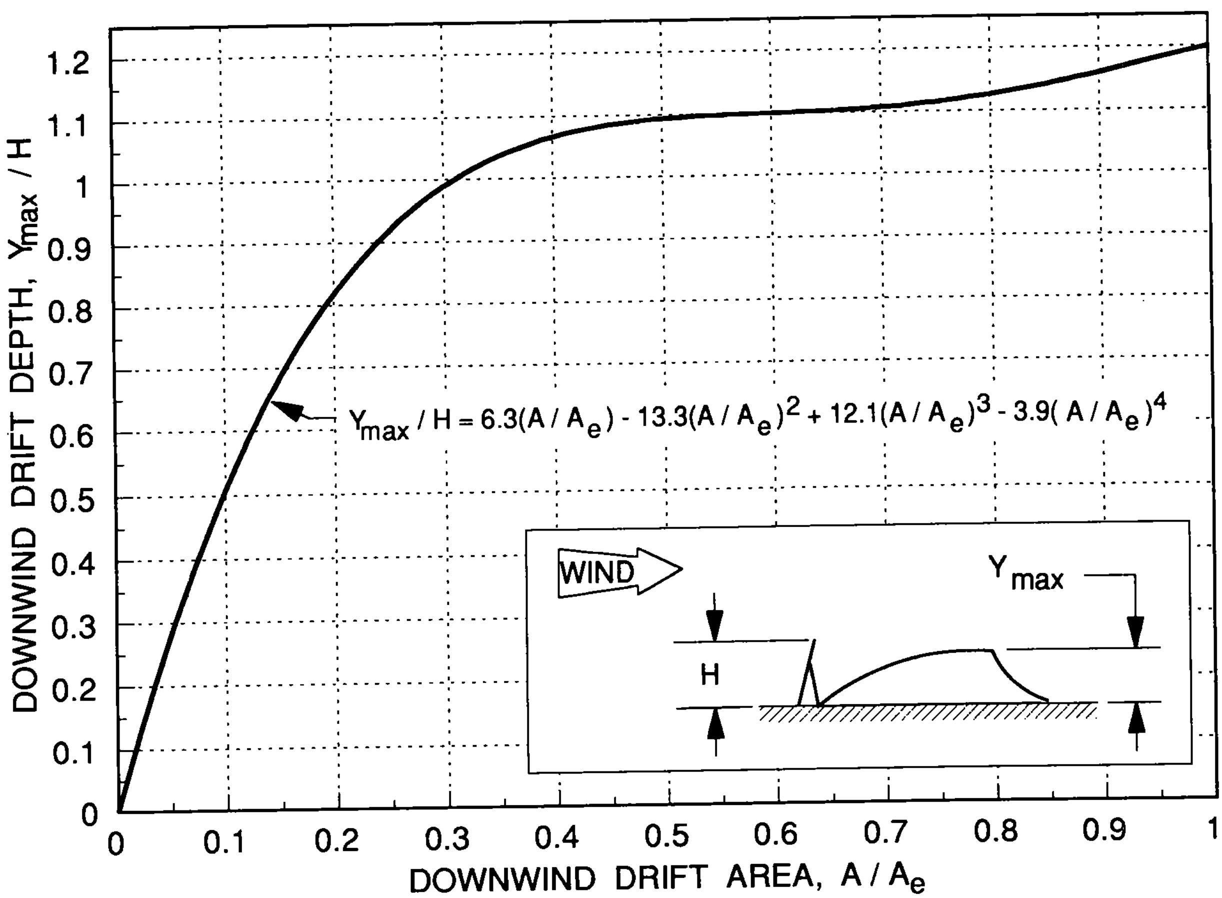


Figure 3.35. Changes in the maximum depth of the leeward drift as a 50%-porous snow fence fills with snow.

3.8.4 *Drift Growth at Solid Fences*

In the case of a solid (non-porous) fence, most of the snow is deposited on the upwind side until the upwind drift reaches the top of the fence (Figure 3.36)(Tabler, 1986). The first stage of growth is typified by the presence of a cavity between the drift and the upwind side of the fence, caused by a vortex that retards deposition near the fence (Figure 3.37). After the snow surface immediately upwind of this vortex reaches an elevation above the stagnation point on the fence (about 0.6*H*), the second stage begins. The vortex weakens sufficiently to allow snow to fill in the cavity. During these first two stages, the downwind drift is comprised primarily of snowfall that is swept toward the fence by the recirculating airflow. After the upwind drift reaches the top of the fence, it stops growing and the downwind drift develops rapidly, filling in the recirculating region behind the fence. As shown in Figure 3.36, the equilibrium drifts on both sides of the fence are concave, and extend about 10 to 12*H* on either side of the fence.

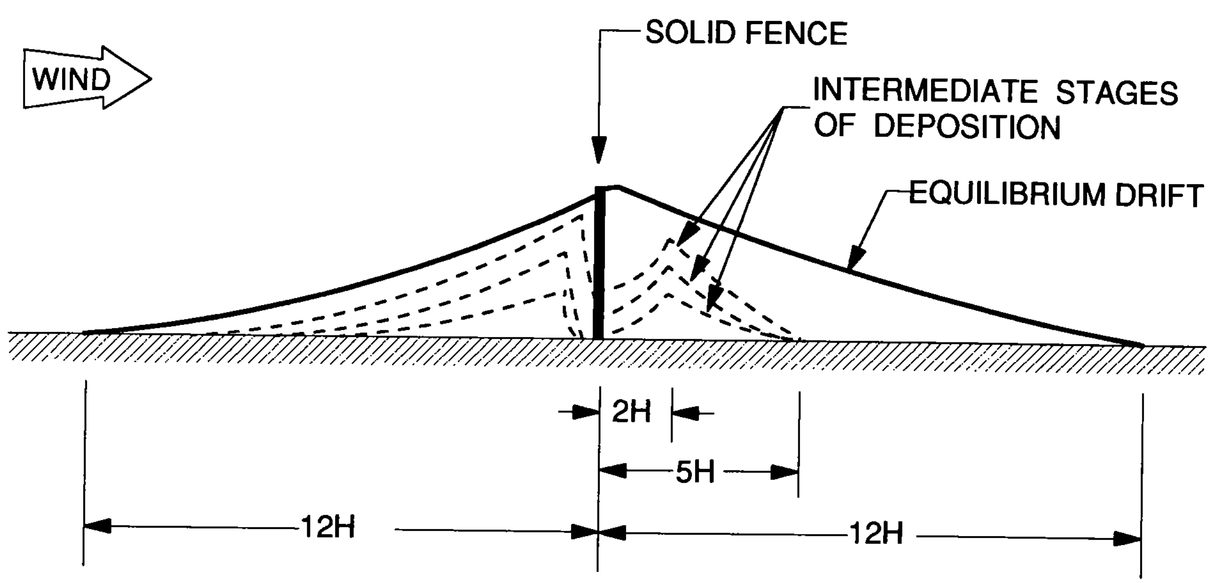


Figure 3.36. Stages in drift growth at a solid (non-porous) fence.

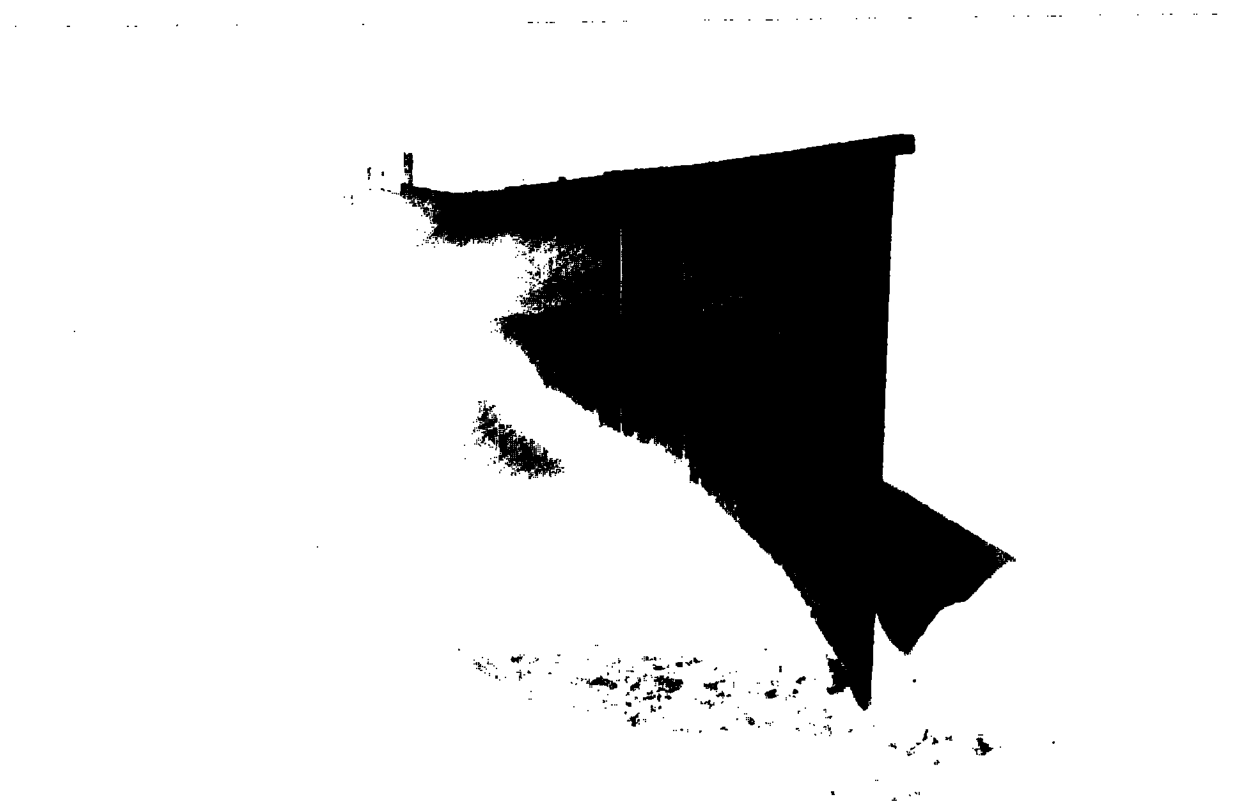


Figure 3.37. The vortex on the upwind side of this solid barrier prevents deposition immediately upwind of the fence until the snow depth reaches about 0.6*H*.

3.8.5 Equilibrium Drifts

3.8.5.1 Importance

The shape of equilibrium drifts is important because many of the guidelines for snow fence systems are based on these characteristics. For example, the length of the downwind drift determines the required setback distance, and the overall profile determines the storage capacity of the fence.

3.8.5.2 Factors that Affect the Shape of Equilibrium Drifts

At equilibrium, the combined wind resistance of the fence and drift is at a minimum, and the drift is shaped so that the surface shear stress is uniform along the path of the wind. The mechanism allowing this uniformity is the turbulent mixing that takes place between regions of air that have different velocities. Drift shape is determined by the rate at which the main mixing region (Region 3, Figure 3.27) expands downwind from a barrier, which in turn is related to the initial difference in velocities behind and above the barrier. As a result, the surface of the equilibrium drift follows the lower boundary of the mixing region (Figure 3.38) so that the snowdrift is shaped like the wind profile that formed it. The nose of the drift resembles the logarithmic profile of the developing wall boundary layer (Equation 3.1), the tail of the drift is shaped like the wind profile in the mixing layer, and the crest of the drift is where the two flow regimes first come together. As a result, the overall shape of the downwind drift is reasonably well represented by an equation analogous to the "law of the wake" (Coles, 1956) for vertical wind profiles:

$$Y/H = B\ln(X/X_o)\{1 - \sin^2(0.5\pi X/L)\} \tag{3.16}$$

where
Y = Snow depth,
X = Distance from the fence,
X_o = Distance from the fence to the upwind edge of the drift,
L = Length of the lee drift,
B = Coefficient of proportionality.

With $B = 0.29$, $X_o = 0.1H$, and $L = 34H$, Equation (3.16) closely approximates the equilibrium downwind drift formed by 50%-porous fences.

The shape of the equilibrium drift therefore depends on fence height and on other fence attributes that affect the rate of turbulent mixing behind the fence such as fence length, porosity, and bottom gap. In addition, the topography of the surrounding terrain can be influential.

For any particular fence, the shape of the equilibrium drift also varies with the speed and orientation of the wind, and with snowcover conditions. In other words, the shape of the equilibrium drift formed by a particular snow fence varies from year to year.

Because the complexity of these interacting factors has precluded specifying drift shape on the basis of theory, field measurements of drifts provide the primary source of information on this subject.

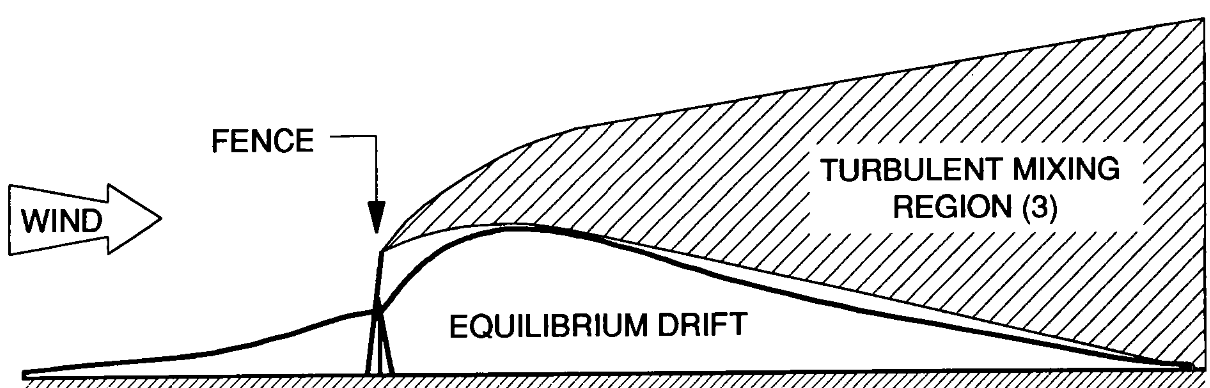


Figure 3.38. The surface of an equilibrium drift follows the lower boundary of the main mixing region (region 3, Figure 3.27) behind a porous fence.

3.8.5.2.1 Fence Height

Other factors being equal, dimensions of equilibrium drifts are approximately proportional to fence height (Tabler, 1980a). This means, for example, that a drift behind a fence 2 m (6.6 ft) tall will be *approximately* twice as long, and twice as deep, as a drift behind a fence 1 m (3.3ft) tall. Although some exceptions will be noted later, this approximation is sufficient for most engineering applications, and greatly simplifies the guidelines for snow fence design. Figure 3.39 shows that the drift formed by a 6-cm (2.5-in.) fence is geometrically similar to that behind the 3.8-m (12.4-ft) fence shown in Figure 3.40. This similarity allows researchers to use reduced-scale models outdoors to study snowdrifting problems (Tabler 1980b; Tabler and Jairell 1980).

The geometric scaling of equilibrium drifts allows their size to be expressed in dimensionless terms. Drift lengths and depths can be expressed as multiples of fence height, H. It is important, however, to distinguish between the structural height of a fence, denoted in this guide as H_s, and the *effective height* — the height of the fence above the surrounding snowcover — denoted by H. As shown in Figure 3.41, drift shape and snow storage change drastically as the effective height decreases.

Drift shape can be approximated with a fifth order polynomial of the form

$$Y/H = A' + B'(X/H) + C'(X/H)^2 + D'(X/H)^3 + E'(X/H)^4 + F'(X/H)^5 \qquad (3.17)$$

where
Y = Snow depth,
X = Distance from the fence,
H = Effective fence height,
A' = Empirical constant, and
$B'...F'$ = Empirical coefficients.

Values for $A'...F'$ are different for various kinds of fences, and are determined by regression analyses.

There is one important exception to the scaling law for snow fence drifts:

Drifts formed by fences 1.5 m (4.5 ft) tall or less are not as deep as those formed by taller fences. The maximum depth for shorter fences is more nearly equal to the height of the fence.

Although this difference suggests that the airflow over the shorter fences may not be deflected to the same degree as that over the taller structures, it should be kept in mind that short fences are usually partially buried by the time equilibrium is attained, which reduces their effective height. The anomalous behavior of the shorter fences can be ignored for most practical purposes.

The lengths of equilibrium drifts are proportional to fence height (Tabler 1980a):

$$L \sim H \tag{3.18}$$

If a fence is half-buried, drift lengths may be shorter than if the fence were fully exposed (Figure 3.41). However, the length of drifts behind partially buried fences depends on the sequence of deposition. If equilibrium is attained *before* the fence starts to become buried, drifts can actually elongate to about 50 times the structural fence height. This is because the pre-burial equilibrium drift forms a downward sloping surface that interacts with the airflow behind the partially buried fence.

Because the depth and length of snowdrifts are proportional to effective fence height, and because the basic shapes of equilibrium drifts can be approximated by right triangles, it is apparent that *the cross-sectional areas of equilibrium drifts are approximately proportional to the square of the effective fence height:*

$$A_e \sim H^2 \tag{3.19}$$

where A_e is cross-sectional area of the equilibrium drift (Tabler 1980a). This implies that a 2.4-m (8-ft) fence would hold four times as much snow as a 1.2-m (4-ft) fence; however, as shown in the following section, the taller fence will actually store 4.6 times as much snow as the 1.2-m fence on a weight basis, because snow density increases with depth (section 3.4.1.4). For example, from Equation 3.13 or Figure 3.22, the density of snow 1.2 m deep (4 ft) is 380 kg/m^3 (23.7 lb/ft^3), compared to 467 kg/m^3 (29.1 lb/ft^3) for a 3.7 m (12 ft) depth. Using Equations (3.13) and (3.17), it can be shown that the storage capacity of fences is therefore related to effective fence height H according to (Tabler, 1980a)

$$Q_e \sim H^{2.2} \tag{3.20}$$

Figure 3.39. Equilibrium drift formed by a 6-cm (2.4-in.) reduced-scale model of a 1.8-m (6-ft) fence (Tabler 1986). Wind is left to right.

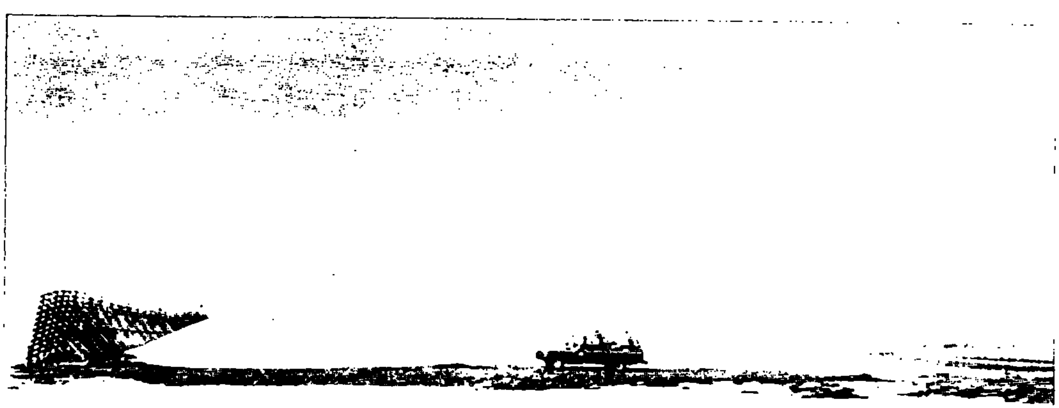


Figure 3.40. Drift formed by a 3.8-m (12.4-ft) fence, near equilibrium. Wind is from left to right (Tabler 1986).

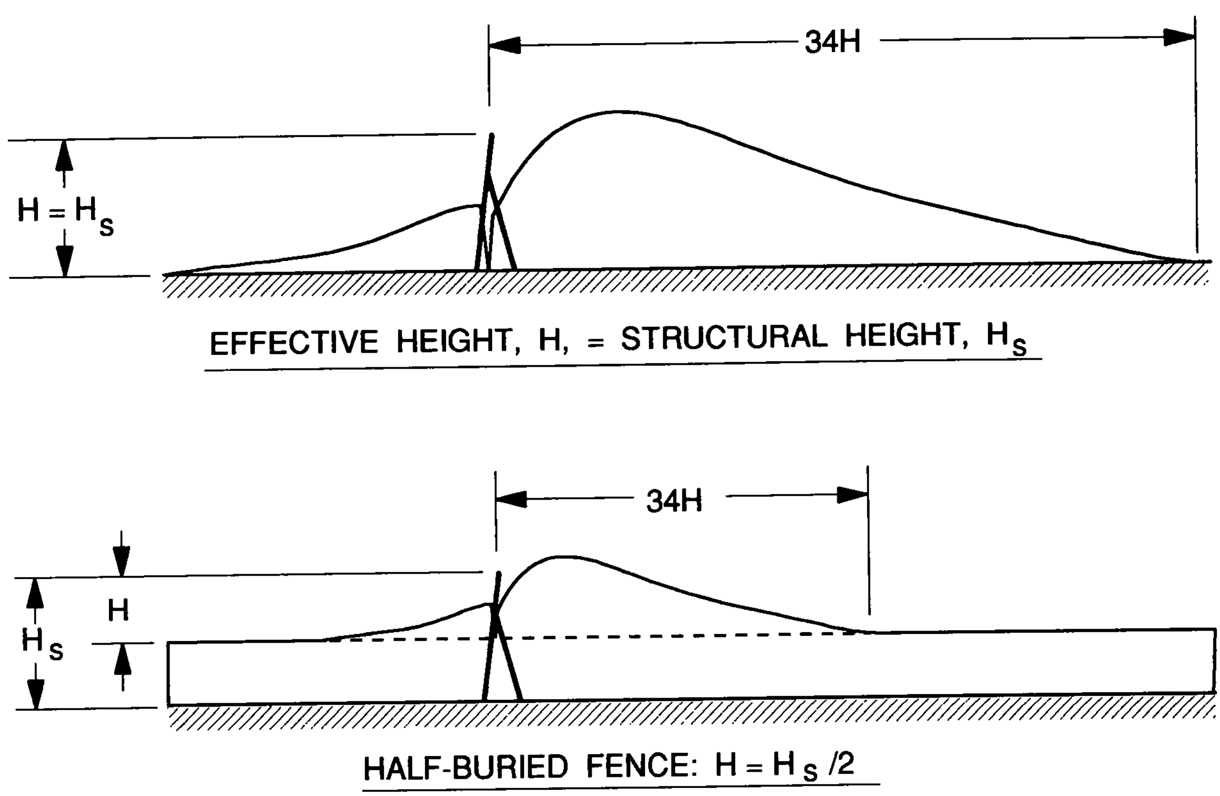


Figure 3.41. Drift dimensions depend on effective fence height *H* which may be less than the structural fence height H_s.

3.8.5.2.2 Fence Length and End Effect

The dimensions described in the previous section apply only to the center of long fences — that is, fences that are 25*H* or longer. Drifts formed by fences that have shorter lengths are reduced by the rounding that extends inward about 12*H* from the fence ends (Figures 3.42 and 3.43)(Tabler 1980a).

This characteristic of drifts, called the end effect, dictates how far fences should extend beyond the area to be protected. In addition, the fact that drifts are shorter near fence ends can be considered in specifying the minimum setback distance of fences placed at an oblique angle to the road. Thus the end effect has important implications for fence system design. Fences should be as long as possible, and gaps or openings should be avoided.

As shown in Figure 3.44, the length of the downwind drift varies with distance from the fence end X_e according to

$$L/L_{max} = \{1 - 0.01[(X_e/H) - 9]^2\}^{0.5}, \quad -1 \leq X_e/H \leq 9 \qquad (3.21)$$

The end-effect also reduces storage capacity and trapping efficiency over the affected portion of the drift. As shown in Figure 3.45, the cross-sectional area of the drift *A* varies with the distance from the fence end, according to

$$A/A_{inf} = 0.23 + (X_e/H)/5.2 - (X_e/H)^2/59.5 + (X_e/H)^3/1961, \quad X_e/H \leq 12 \qquad (3.22)$$

where A_{inf} is the cross-sectional area of the drift at a location unaffected by the end effect (Tabler, 1980a). The capacity at 5*H* from the fence end, for example, is about 84% of that in the center of a very long fence.

When fence lengths are shorter than 20 to 25*H*, the effects of the two ends overlap, reducing drift size and storage capacity to an even greater extent. The relationship between total storage capacity and fence length (Figure 3.46) is approximated by

$$Q_c/Q_{c,inf} = 0.288 + 0.039(L_f/H) - 0.0009(L_f/H)^2 + (L_f/H)^3/133333;$$
$$5 \leq L_f/H < 50 \qquad (3.23)$$

where $Q_{c,inf}$ is the snow storage capacity of an infinitely long fence, and L_f is fence length (Tabler and Schmidt 1986).

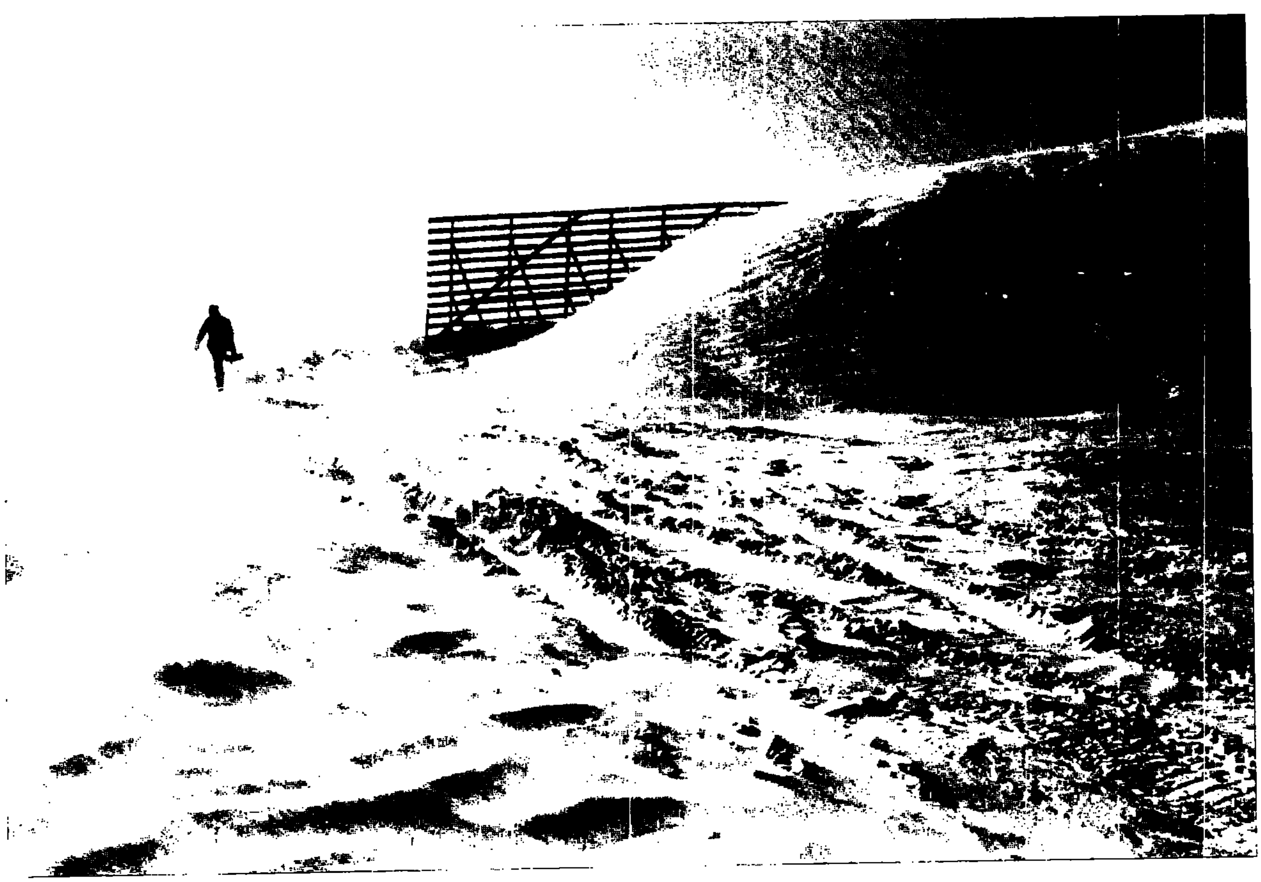


Figure 3.42. Rounding of drift ends, as shown by this 3.8-m-tall (12.4-ft) Wyoming fence, reduces storage capacity and trapping efficiency (Tabler 1986).

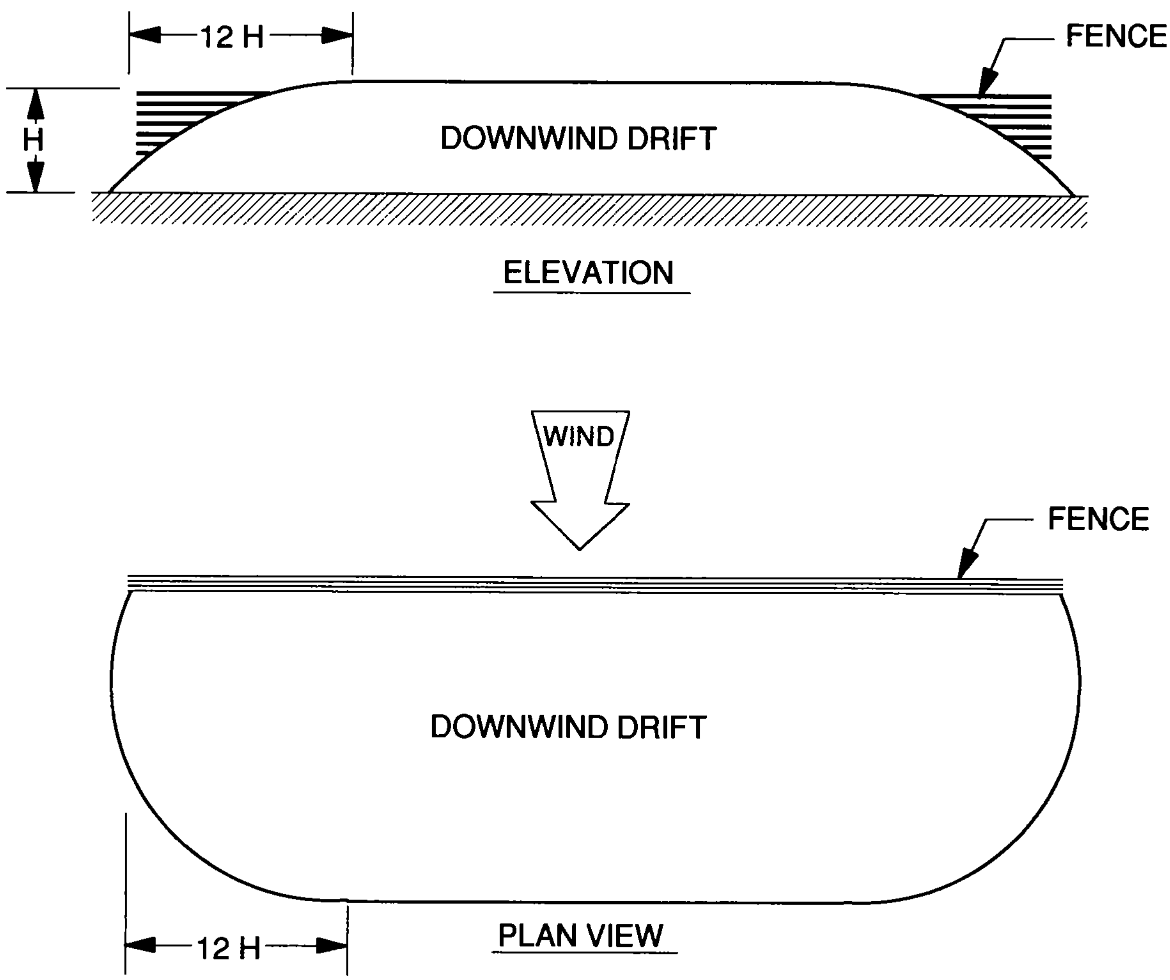


Figure 3.43. The three-dimensional rounding of drift ends that constitutes the end effect (Tabler 1986).

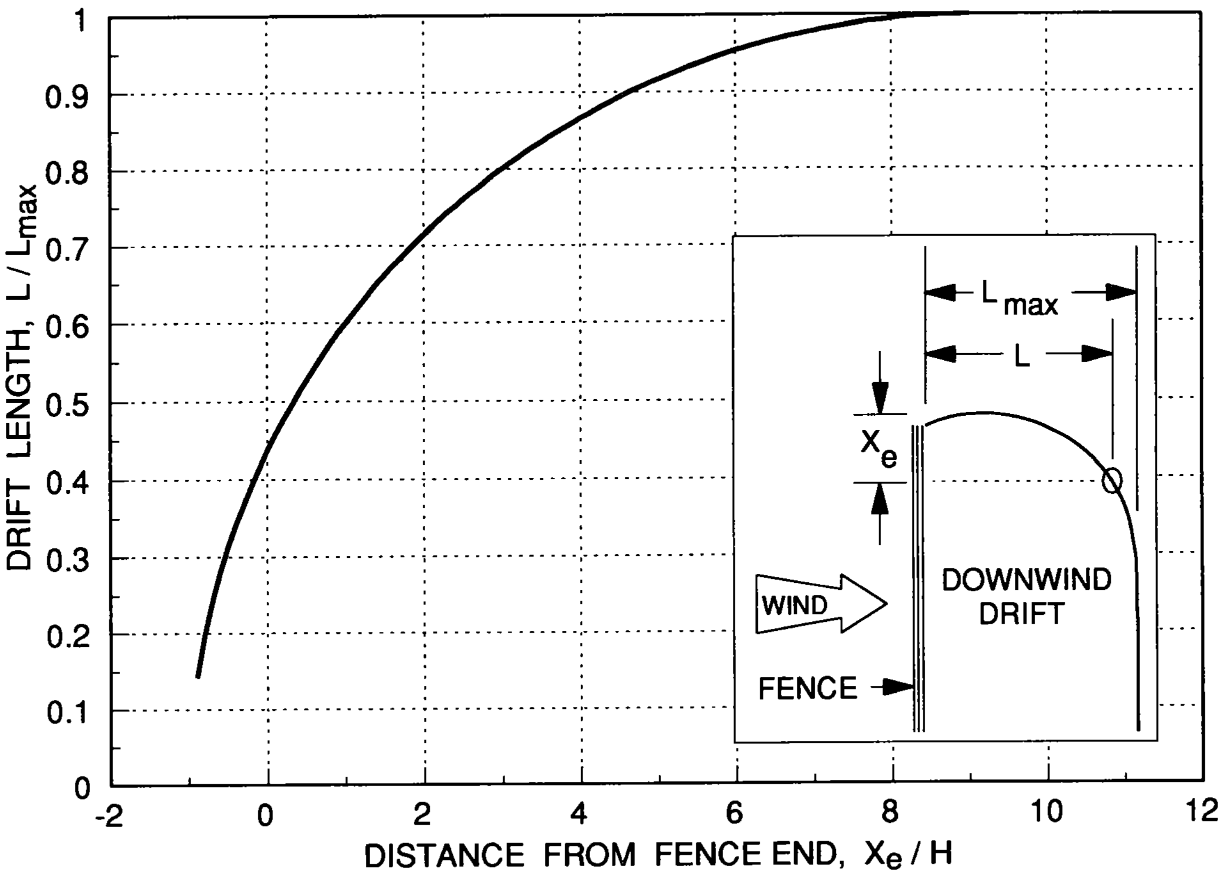


Figure 3.44. Length of an equilibrium downwind drift as a function of distance from the end of a 50%-porous fence on flat ground (Tabler 1980a).

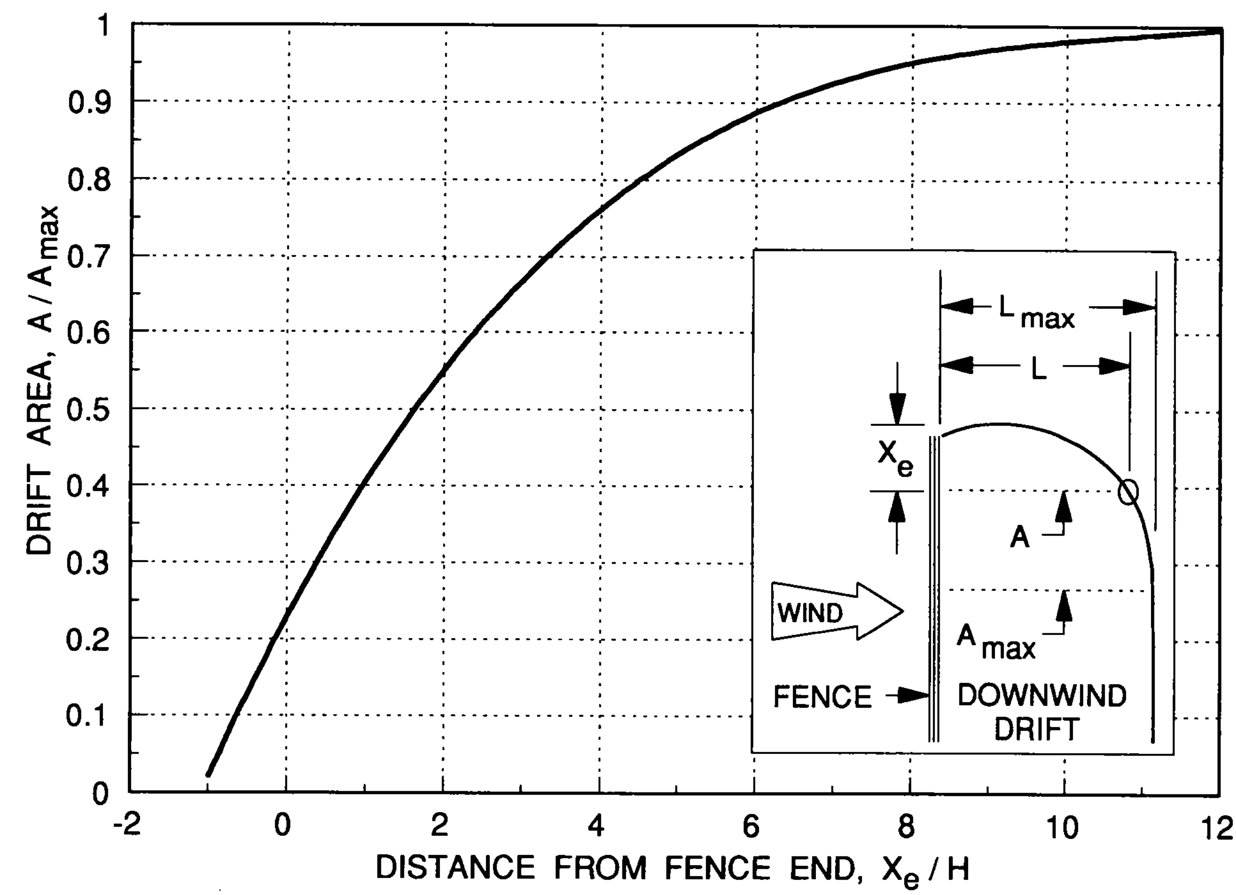


Figure 3.45. Cross-sectional area of equilibrium lee drifts as a function of distance from the end of a 50%-porous fence on flat ground (Tabler 1980a).

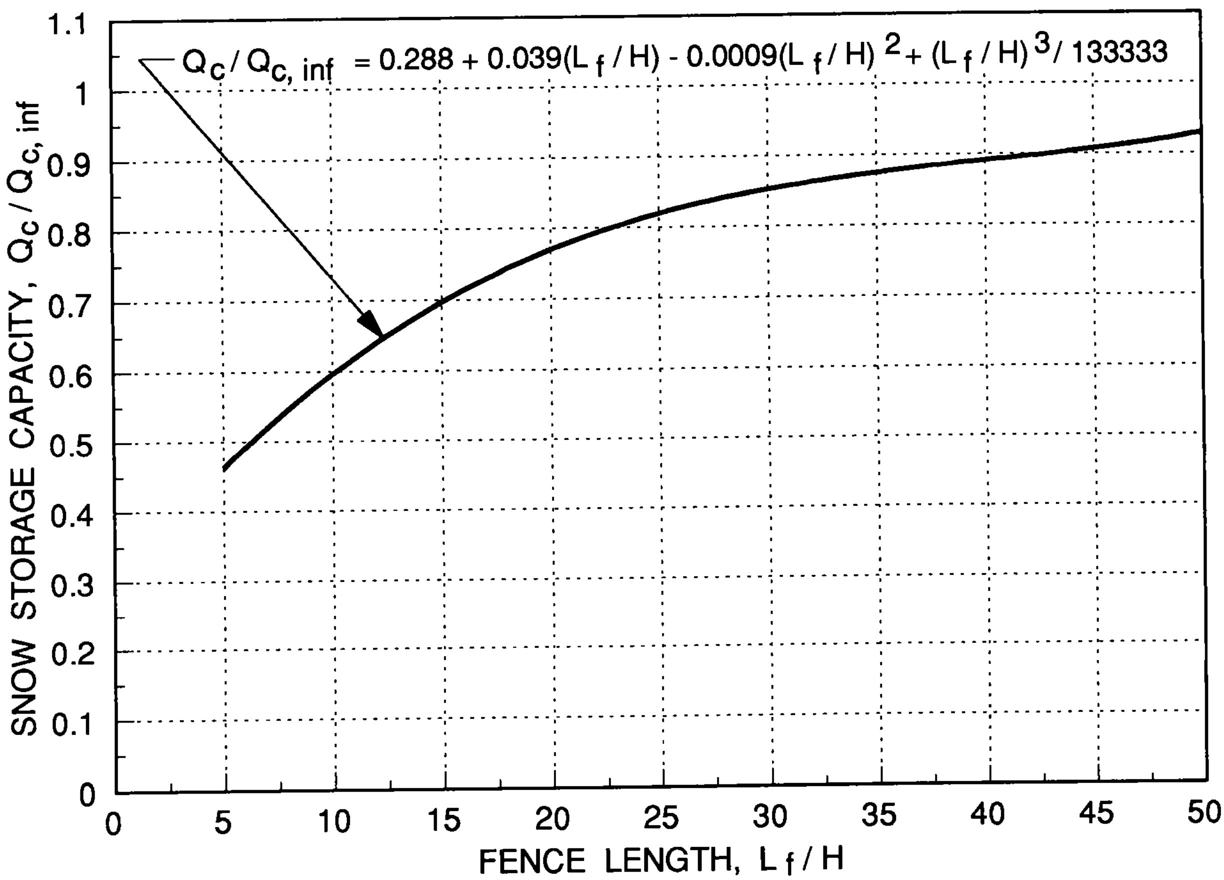


Figure 3.46. Total snow storage capacity as a function of fence length.

3.8.5.2.3 Bottom Gap

A space between the ground and the bottom of the fence minimizes snow deposition close to the fence, and keeps the saltating particles near the ground where they can be more easily trapped. Fences that become partially or totally buried are not as effective in trapping blowing snow, are often damaged by snow settlement, and can develop abnormally long drifts. The optimum bottom gap is equal to 10-15% of the total fence height. If the bottom gap is increased beyond these limits, the nose of the downwind drift is displaced farther downwind, drift depth decreases, drift length remains unchanged, and storage capacity is reduced (Figures 3.47 and 3.48). The depth of the upwind drift also decreases as the bottom gap increases.

The effect of bottom gap varies with wind speed. In a location with strong winds, a fence with a gap equal to about 25% of the height caught about 30% less snow than a fence with a gap equal to 10% of the height. At a location where wind speeds averaged 8 to 16 km/h (5 to 10 miles/h) less, the difference was only about 10%.

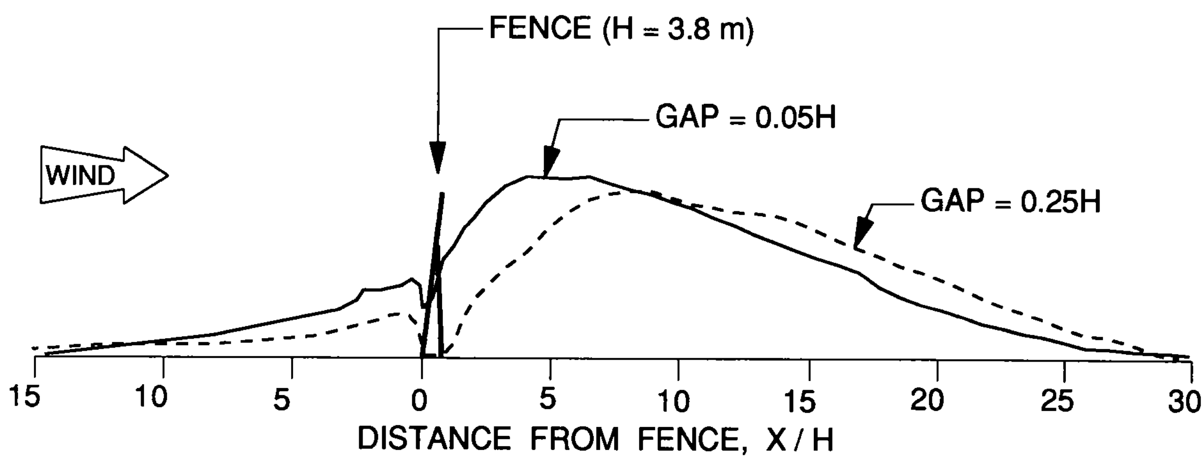


Figure 3.47. Comparison of drifts formed by two 3.8-m (12.4-ft) Wyoming fences that have 30- and 90-cm (12- and 36-in.) bottom gaps, respectively (Tabler 1986).

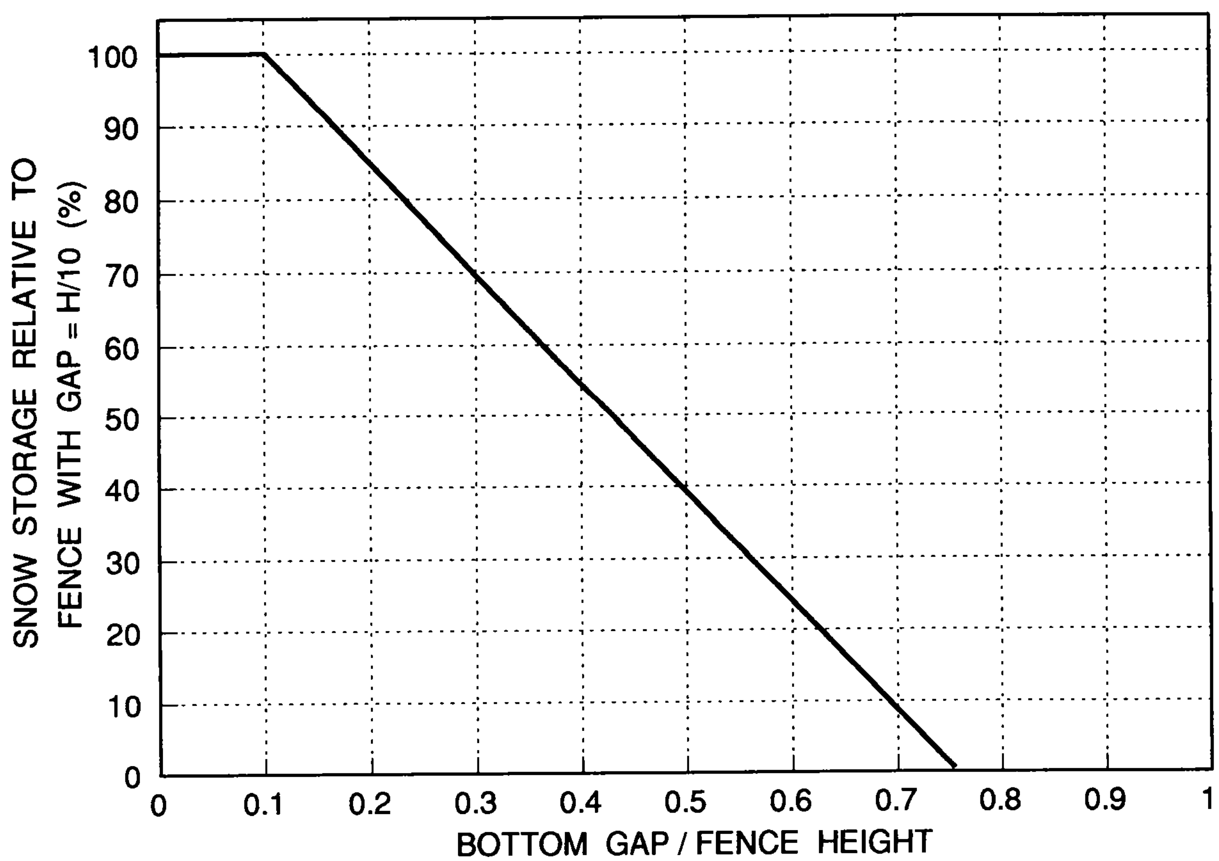


Figure 3.48. Effect of bottom gap on snow storage, as determined from field studies.

3.8.5.2.4 Fence Porosity

Fences that have a porosity of 0.4 to 0.5 form the largest drifts. Solid fences ($P = 0$) form larger drifts on their upwind sides, but smaller drifts on the downwind sides. Solid fences have significantly lower storage capacities than 50%-porous fences (Figure 3.49). As shown in Figures 3.50 and 3.51, snow storage capacity and the length of the downwind drift vary with porosity according to

$$L/H = 12 + 49P + 7P^2 - 37P^3 \tag{3.24}$$

$$Q_c = (3 + 4P + 44P^2 - 60P^3)H^{2.2} \tag{3.25}$$

A barrier's effect on the wind, and therefore its effect on snow deposition, is determined by its resistance to airflow. Porosity is thus important because it determines airflow resistance. Air flowing through an opening forms a jet with a cross-sectional area smaller than the opening itself. As a result, wind resistance increases as the size of the openings decreases, even if porosity remains constant. The resistance of a plastic fence with 5 cm (2-in.) circular openings and $P = 0.5$, for example, is greater than that of a wooden slat fence with rails 15 cm wide (6 in.) separated by spaces of the same width.

Over the range of opening sizes typical of snow fence materials, there appears to be little difference in the equilibrium drifts formed by fences with the same porosity but different shapes and sizes of openings, provided that the bottom gap remains free of snow (Tabler 1986, 1988b). The tendency for snow to deposit close to the fence and block the bottom gap, however, is affected by the size, shape, and orientation of the openings. The small openings typical of most plastic fencing materials favor deposition close to the fence, which can eventually block the bottom gap and bury the fence. The tendency for snow to deposit close to the fence is much lower with horizontal rails (Figure 3.52), and even if the bottom gap is buried, the spaces between the rails serve as bottom gaps to retard the rate of burial.

Although the optimum width of vertical slats or horizontal rails is uncertain, there is some evidence that rails as wide as 30 cm (12 in.) are less effective than those half that width. This may be due to the relationship between the width of the slats and the scale of turbulence they generate. Vortices form on the downwind side of solid members, and these eddies are periodically shed and carried downstream. Because the size of these vortices is proportional to the width of the member, the wider boards may promote suspension of the snow particles and increase surface shear stress downwind of the barrier.

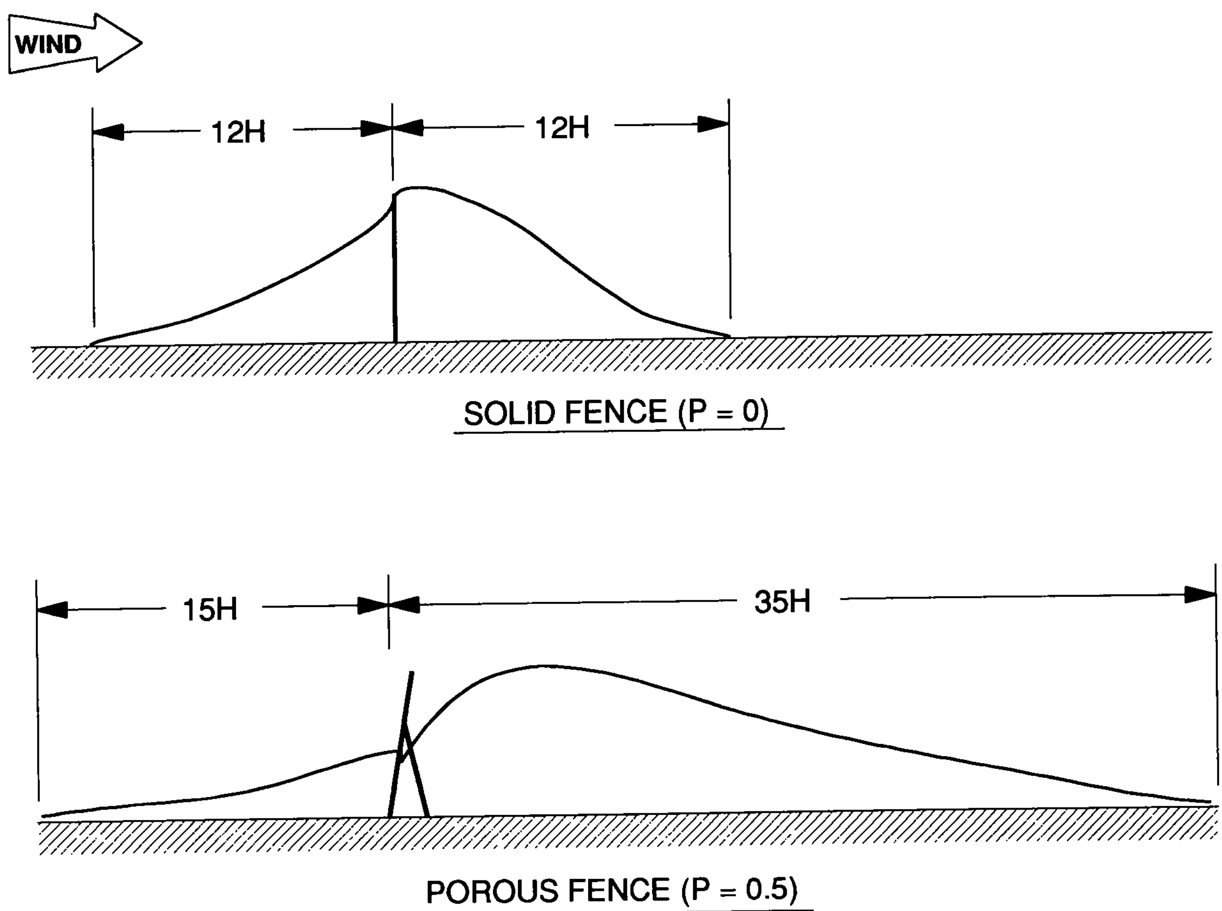


Figure 3.49. Comparison of drifts formed by 50%-porous and solid fences.

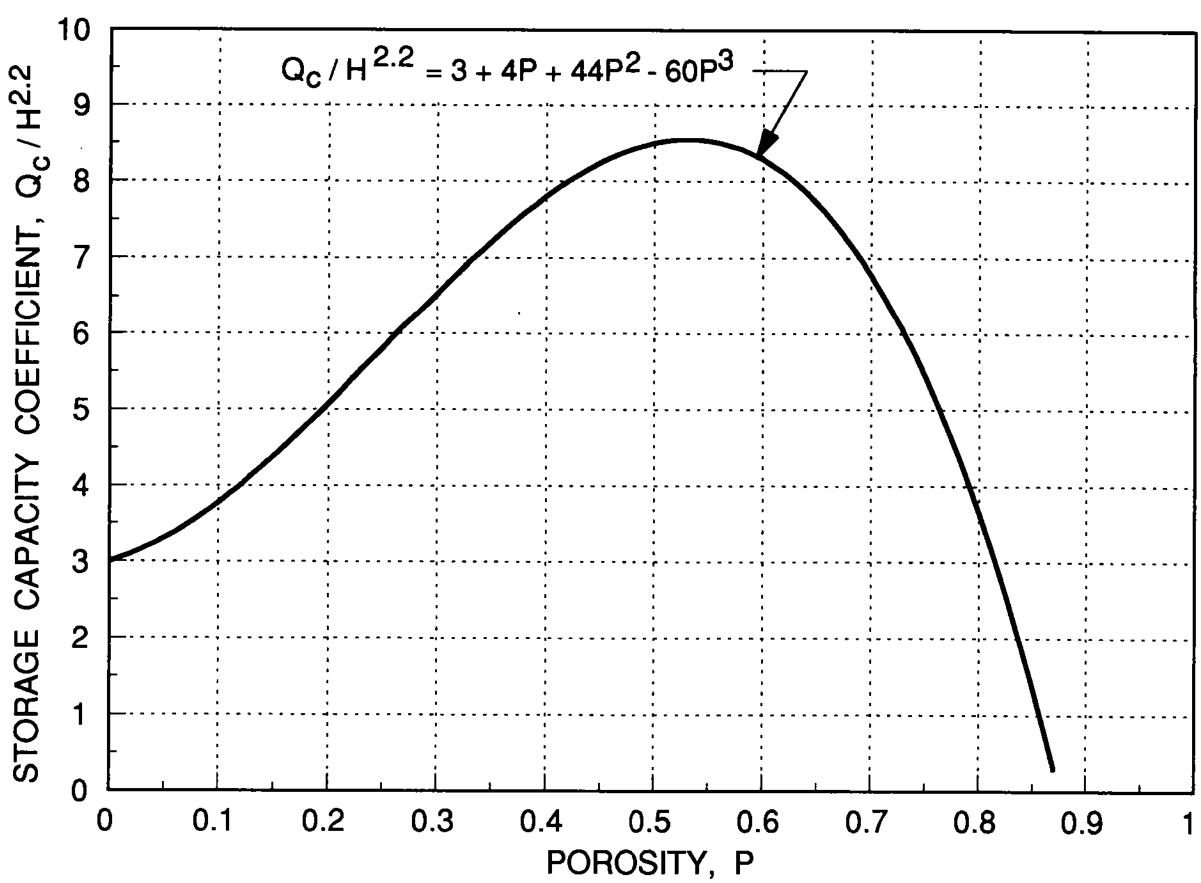


Figure 3.50. Snow storage capacity of the downwind drift as a function of fence porosity.

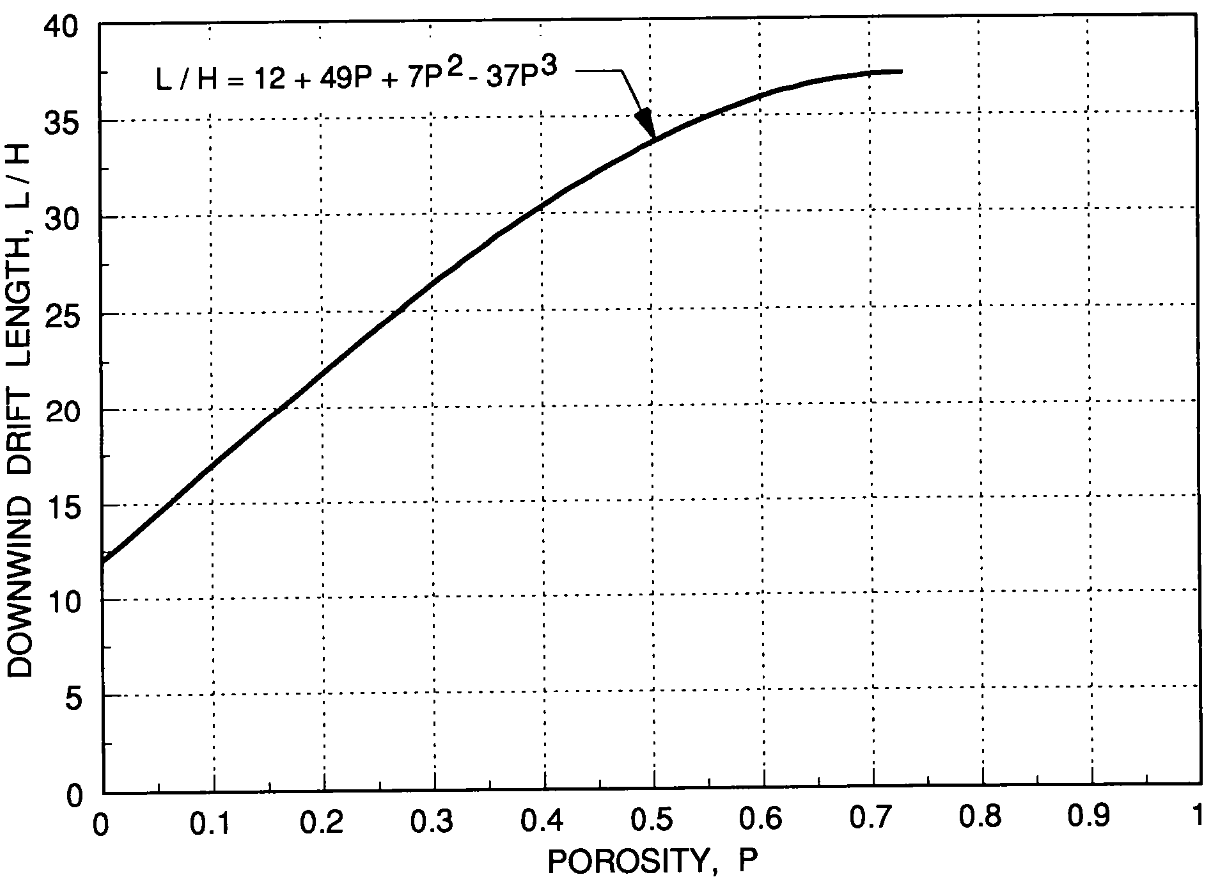


Figure 3.51. Length of the downwind drift as a function of fence porosity.

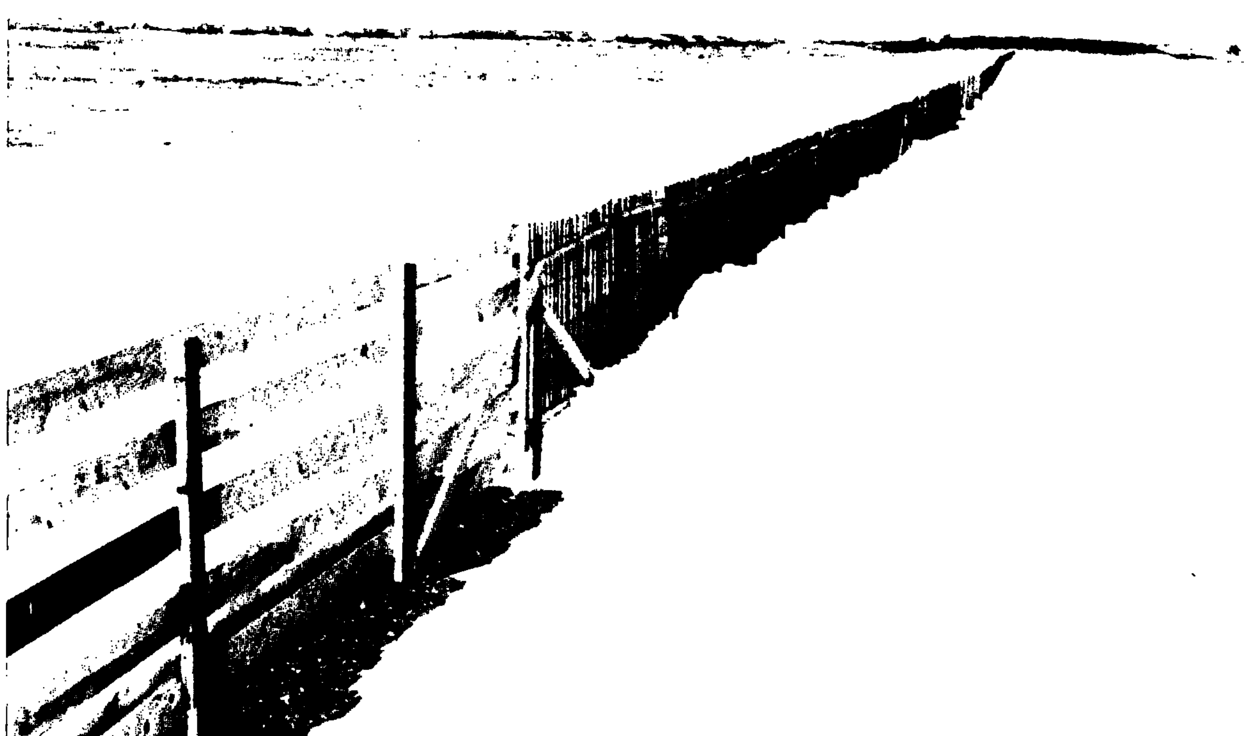


Figure 3.52. Horizontal slats reduce the tendency for snow deposition near the fence (Tabler 1986).

3.8.5.2.5 Inclination Angle

Inclining the top of a fence into the wind forces more wind through the bottom gap, displacing the nose of the leeward drift downwind, and reducing drift depth and storage capacity. Inclining the top of the fence downwind reduces the flow under the fence, with opposite effects. As a result, the loss in vertical height of inclined fences is compensated by a larger drift. For a fence with a porosity of 0.5, a downwind inclination angle up to 15° has little net effect on trapping efficiency or snow storage capacity (Tabler 1986). The 15° layback used for the standard Wyoming snow fence provides stability during construction, and allows maintenance workers to climb the fence easily if necessary.

3.8.5.2.6 Wind Direction

The angle of the wind on the fence is the *attack angle*. 90° is perpendicular to the fence, and 0° is parallel. The effects of the attack angle on drift geometry depend in part on the geometry of the fence. For a structure with braces, such as the Wyoming fence, the wind resistance increases as the attack angle decreases because a greater area of the braces is exposed to the wind. In the same way, the aerodynamic porosity of a vertical-slat fence decreases as the wind becomes more oblique to the fence. Empirical studies have shown, however, that for attack angles between 90° and 45°, the profile of a drift, *as measured parallel to the wind*, is independent of the attack angle (Figure 3.53) (Tabler 1980a). This means that the length and cross-sectional area of the downwind drift, *as measured perpendicular to the fence*, would decrease in proportion to the sine of the attack angle, α:

$$L = L_{90}(\sin \alpha) \tag{3.26}$$

$$A = A_{90}(\sin \alpha) \tag{3.27}$$

where the subscript $_{90}$ refers to dimensions of drifts formed when fences are perpendicular to the wind.

The airflow deflects laterally when it encounters a barrier aligned obliquely to the prevailing flow direction. This causes the wind to follow a sinuous course as it passes through such a barrier. This results in a cross-flow velocity component, which is manifested as an axial component of the recirculation vortex present during the second and third stages of drift growth. The result is an augerlike action that transports snow downwind. It eventually empties the snow into the slipstream around the downwind end of the fence, which reduces trapping efficiency. Although this effect has not been measured, it is probably insignificant for long fences with attack angles greater than 45°.

Because the equilibrium shape of a drift, *as measured perpendicular to the fence*, varies with wind direction, any change in wind direction will tend to change the shape of the drift. An increase in the attack angle, for example, might erode the nose of the downwind drift, deposit snow on the tail, and displace the maximum drift depth downwind. Because not all of the eroded snow is deposited, changes in wind direction reduce trapping efficiency and can cause episodes when snow can be seen blowing out of fences.

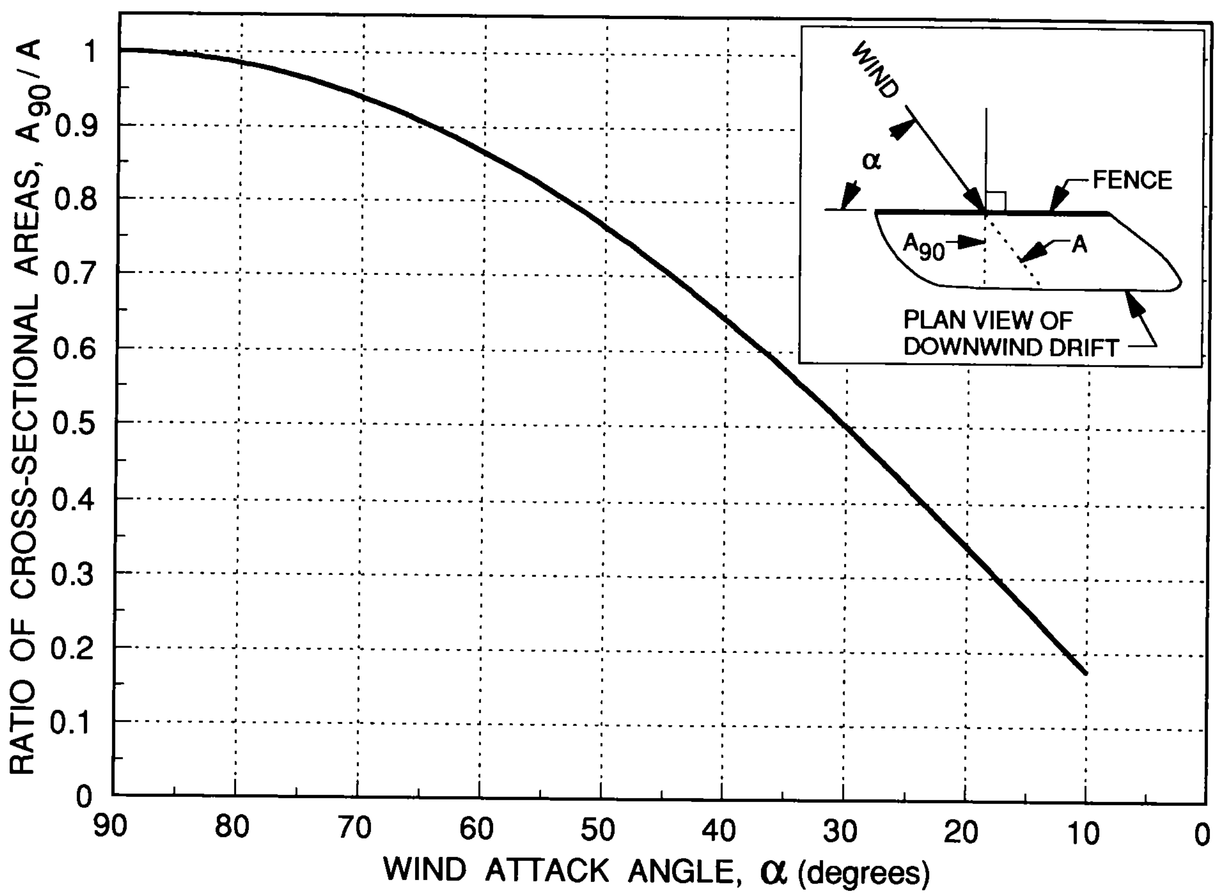


Figure 3.53. Cross-sectional area of drift versus wind attack angle (Tabler 1986).

3.8.5.2.7 Wind Speed

Although it seems reasonable to expect that the shape of equilibrium drifts would vary with wind speed, the differences must be subtle because equilibrium drifts are similar from year to year, and in different locations. One reason for this is that the range of natural wind speeds is not very great. The threshold for blowing snow is about 20 km/h (12 miles/h), and sustained winds above 100 km/h (62 miles/h) are uncommon. Another explanation for the apparent insensitivity of drift shape to wind speed is the interparticle bonding described in section 3.5.3. The equilibrium drift shape attained over a winter therefore tends to reflect the maximum attainable profile.

Although quantitative data are lacking, it seems likely that equilibrium drifts formed under strong winds would not be as deep as those formed by lighter winds. An increase in wind speed could therefore cause erosion of a previously deposited drift if the interparticle bonds had not had time to strengthen sufficiently.

3.8.5.2.8 Effect of Topography

The topography surrounding a fence can influence drift shape more than any factor described above. Although the problem is three dimensional, for simplification the discussion here is limited to the effects of upwind and downwind terrain, and therefore assumes uniform conditions in the direction across the wind.

Topography both upwind and downwind of a fence influences drift shape. Although terrain far upwind can influence the snow transport at a site, nearby terrain features affect the airflow at the fence and influence the shape of equilibrium drifts.

In general, the influence exerted by a topographic feature varies with its proximity to the fence relative to the scale of the feature, and the height of the fence. Because the possible combinations are essentially limitless, the discussion here is limited to generalizations that can be readily interpreted for practical application. The following outline describes the relationships illustrated in Figures 3.54 and 3.55. Slope direction is given in reference to the wind direction; upward slope means that the wind is blowing up the slope.

Upward slopes:

- On long, uniform slopes of about 15% or less, drift shape is the same as on level ground.

- On steeper or shorter slopes, such as fills and embankments, the drift is shaped as though the wind were horizontal rather than parallel to the slope. The drift is shorter and shallower than on level ground. In addition, the drift on the upwind side of the fence is very short and shallow, if it exists at all.

Downward slopes:

- On long, uniform slopes of about 15% or less, the shape of the drift is the same as on level ground.

- Fences located where snow tends to accumulate naturally will become buried.

- Long, uniform slopes steeper than about 18% favor deposition on the upwind side of the fence, which buries the fence. The drift on the downwind side of the fence is also longer.

Ridge crests:

- A fence on a ridge crest has a poorly developed or nonexistent drift on the upwind side, whereas the drift on the downwind side is much deeper and longer than on level ground. The surface of the equilibrium drift represents the maximum rate at which the wind can adjust to follow the change in topography. As a result, a fence on a ridge forms a much larger downwind drift than a fence of identical height on level terrain. As a rough guide, effective fence height increases about 0.15 m (0.5 ft) for each degree of upward approach slope.

Upward slope on the downwind side of the fence:

- Snow storage capacity is reduced by upward slopes and hills on the downwind side of a fence because they truncate the downwind drift. The closer a fence is to the toe of a slope, the deeper the upwind drift becomes.

Irregularities under drift:

- The surface of a drift is not affected by topographic irregularities underneath the drift. Depressions, such as stream channels, can greatly augment snow storage capacity, while mounds or hills reduce storage capacity.

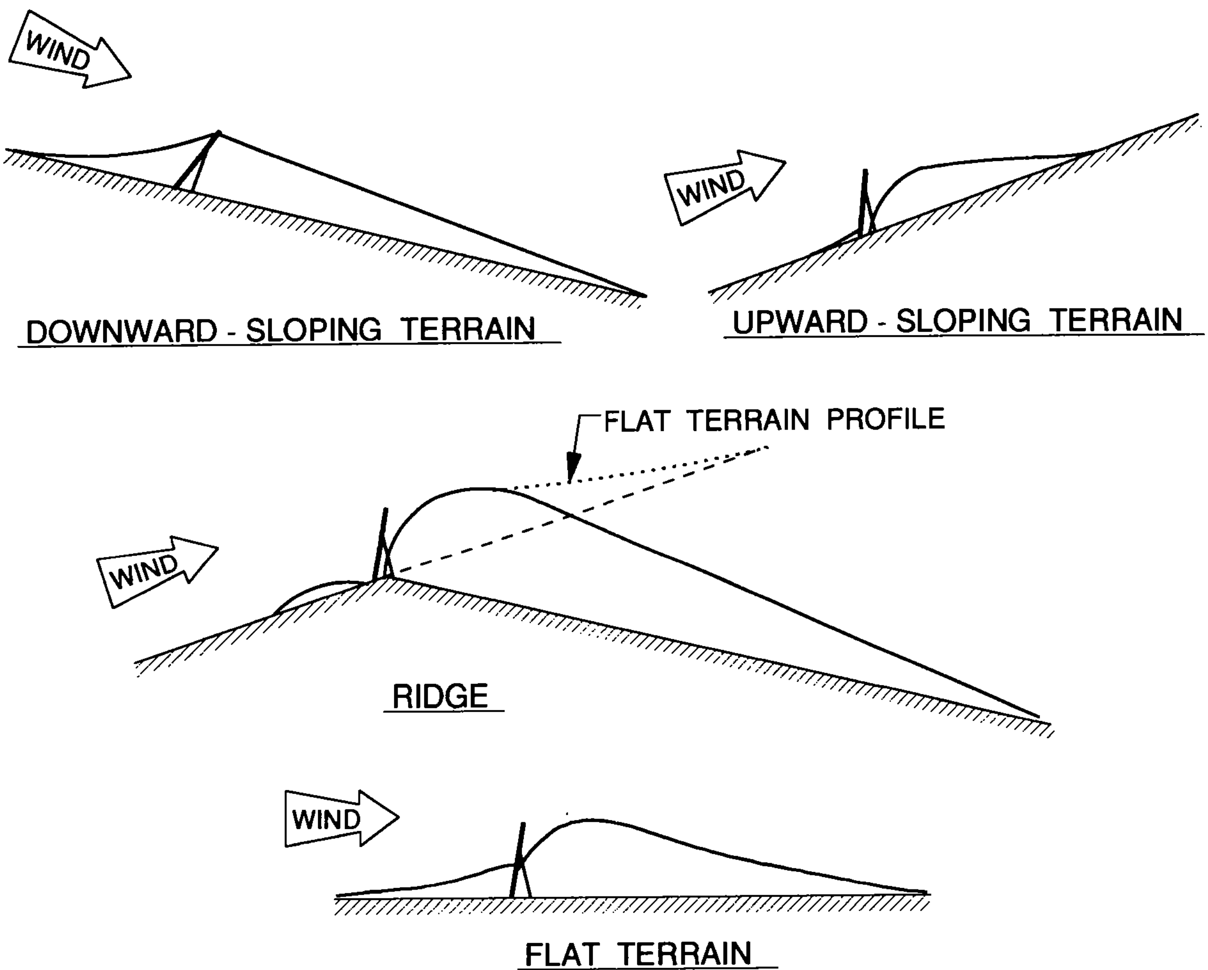


Figure 3.54. Effects of ground slope on the shape of equilibrium drifts (Tabler 1986).

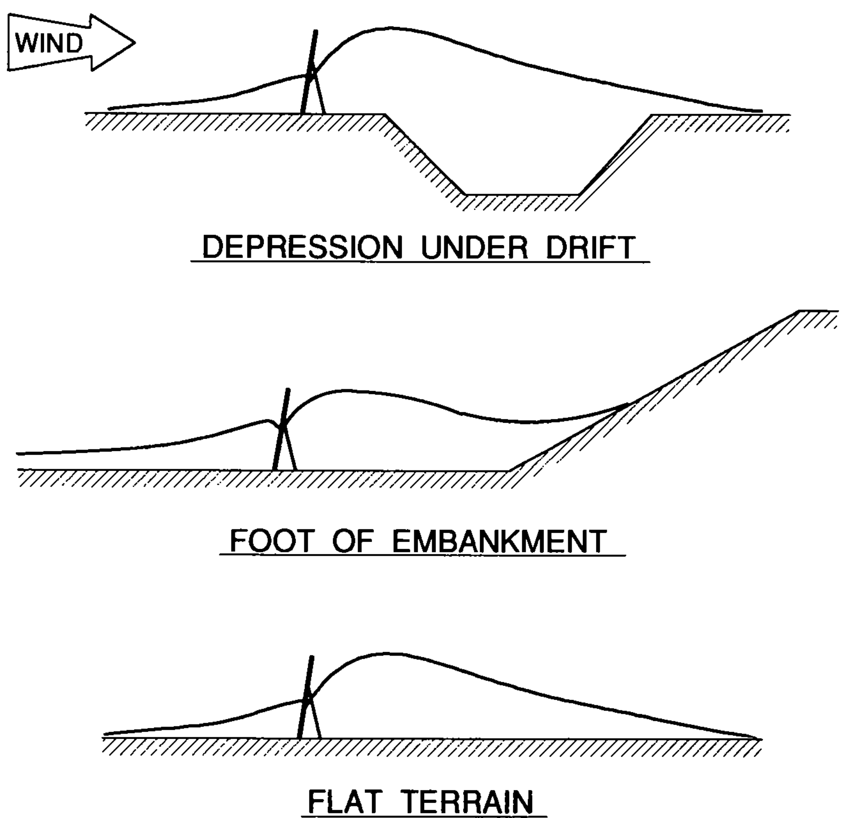


Figure 3.55. Effects of topographic irregularities on the shape of equilibrium drifts (Tabler 1986).

3.8.5.3 Equilibrium Drifts Formed by Various Fence Types

As indicated by the description of drift growth stages, not all streamlined drifts are at equilibrium. Equilibrium drifts are therefore difficult to identify without the benefit of repeated measurements to verify that growth has stopped. This difficulty in identifying drifts that are truly at equilibrium has undoubtedly contributed to the diversity of opinions in the literature about drift dimensions. The characteristics described here are the best available estimates, and are based on more than 30 years of field measurements of many different kinds of fences from 0.6 to 4.9 m (2 to 16 ft) tall (Tabler 1980a, 1986, 1989).

Coefficients for the polynomial equation that describes equilibrium drift shapes for the Wyoming fence are listed in Table 3.4. Dimensions, cross-sectional areas, and snow storage capacities for selected fence types are presented in Table 3.5. The dimensions and shapes presented here are representative of cross-sections not influenced by the end effect, located $12H$ or more from the ends of a fence.

Drift shapes for the various fence types can be summarized as follows:

Solid fences: The dimensions of the upwind and downwind drifts are similar. Both drifts have a length of $12\text{-}15H$, and a maximum depth equal to H. Total storage capacity is about 35% that of a 50% porous Wyoming fence (Figure 3.49).

Vertical slat-and-wire (H < 2 m): The upwind drift is triangular in cross-section, has a length of about $18H$, a maximum depth of about $0.6H$ at the fence, and a cross-sectional area of about $5.1H^2$. The downwind drift has a length of about $34H$, a maximum depth of about $1.03H$ at a distance $4.6H$ from the fence, and a cross-sectional area of $18.3H^2$. Total snow storage capacity is

$$Q_c = 7.9H^{2.2}, \quad H \geq 2 \text{ m} \tag{3.28}$$

where H is in meters, and Q_c is in tons per meter.

Synthetic fencing: Tests of many different kinds of snow fence materials indicate little difference in snow storage or drift length for fences of the same height and porosity ratio, *provided that the bottom gap remains open*. However, the small openings typical of most synthetic fencing materials usually result in deposition and blockage of the bottom gap early in the winter. This leads to a rapid increase in snow depth at the fence, and eventually to burial. The equilibrium drift shape in this case is less predictable, and snow storage may be more or less than, the capacity of the unburied fence.

For engineering purposes, it is reasonable to assume the same snow storage capacity and drift length for all fences of the same height and porosity ratio.

Wyoming Fence: The upwind drift is roughly triangular in cross-section, with a length of about $16H$, a maximum depth of about $0.5H$ at the fence, and a cross-sectional area of about

$3.6H^2$ (Figure 3.32). The downwind drift has a length of about $34H$, a maximum depth of about $1.2H$ at a distance $6.1H$ from the fence, and a cross-sectional area of $21.5H^2$. Total snow storage capacity, Q_c is given by

$$Q_c = 8.5H^{2.2} \tag{3.29}$$

where H is in meters, and Q_c is in t/m (Tabler 1989).

For engineering purposes, the drift characteristics for the Wyoming fence can be considered applicable for all fences with a 0.50 porosity ratio, height ≥ 1.8 m, and situated on flat terrain. Drift depths at various distances from the fence are given in Table 3.4, as calculated from the polynomial equation (3.17) using the coefficients in Table 3.3.

Snow storage capacities and drift lengths for various types of fences are presented in Table 3.5.

Table 3.3. Coefficients for polynomial equations describing equilibrium drifts formed by Wyoming snow fences 1.8 m (6 ft) tall or more. Letters correspond to terms in Equation (3.17).

Drift	Upwind	Downwind
A'	+0.52	+0.43
B'	-1/333.33	+1/3.3
C'	-1/46.08	-1/24.27
D'	+1/281.5	+1/456
E'	-1/4514	-1/18447
F'	+1/205930	+1/1958863
X/H Limit	<16	<34

Table 3.4. Snowdrift depth versus distance from a snow fence, for an equilibrium drift formed by a snow fence that is 50% porous and 1.8 m (6 ft) tall or more, on flat ground, as given by Equation (3.17) and coefficients in Table 3.3. All values are multiples of the effective fence height, H^*.

--Upwind Drift---		-------------------Downwind Draft-------------------			
Distance	Depth	Distance	Depth	Distance	Depth
at fence	0.52	at fence	0.43	18	0.60
1	0.50	1	0.69	19	0.55
2	0.45	2	0.89	20	0.51
3	0.39	3	1.02	21	0.47
4	0.34	4	1.11	22	0.44
5	0.28	5	1.16	23	0.40
6	0.24	6	1.17	24	0.37
7	0.20	7	1.16	25	0.33
8	0.18	8	1.13	26	0.29
9	0.16	9	1.09	27	0.26
10	0.14	10	1.04	28	0.22
11	0.13	11	0.99	29	0.18
12	0.11	12	0.93	30	0.14
13	0.09	13	0.87	31	0.11
14	0.07	14	0.81	32	0.08
15	0.05	15	0.75	33	0.06
		16	0.70	34	0.05
		17	0.65		

* Example for a fence 2 m (6.6 ft) tall: at a distance of $7H$ (14 m, or 46 ft) downwind of the fence, the drift depth would be $1.16H$ (2.32 m, or 7.6 ft).

Table 3.5. Dimensions of equilibrium snowdrifts formed by different types of fences.

	Upwind drift			Downwind drift			Total drift		
Fence type	A/H^2	$Q_c/H^{2.2}$	L/H	A/H^2	$Q_c/H^{2.2}$	L/H	A/H^2	$Q_c/H^{2.2}$	L/H
Wyoming	3.6	1.0	16	21.5	7.5	34	25.1	8.5	50
Slat-and-wire	5.1	1.5	18	18.3	6.2	34	23.4	7.7	52
Solid	5.0	1.4	15	5.0	1.6	12	10.0	2.9	27

A = cross-sectional area (m^2), Q_c = snow storage capacity (t/m), L = drift length (m), H = effective fence height (m).

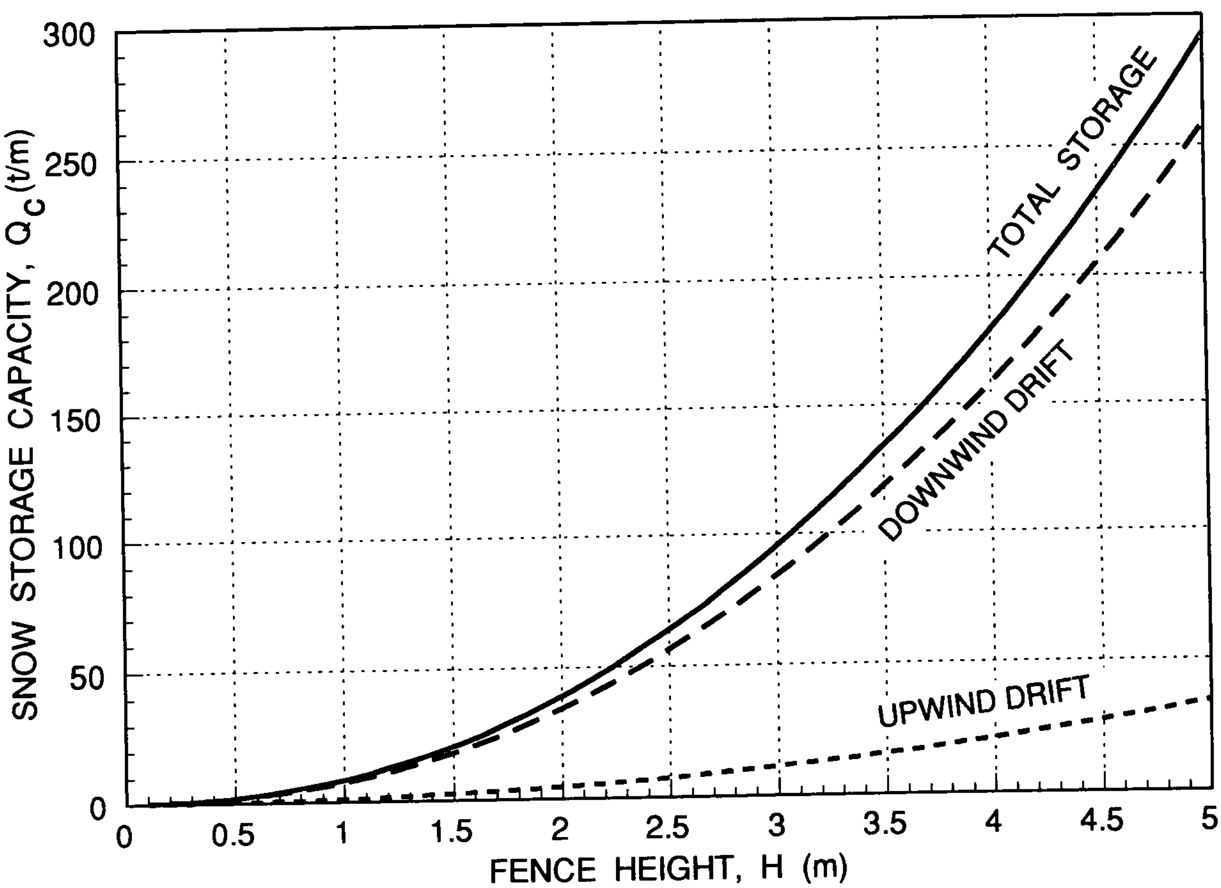


Figure 3.56. Snow storage in upwind and downwind drifts formed by Wyoming snow fences as a function of fence height.

3.8.6 *Trapping Efficiency of Porous Fences*

The following discussion of snow trapping efficiency is from the references by Tabler (1974, 1986) and Tabler and Jairell (1993).

3.8.6.1 Definitions

Trapping efficiency, E, of a snow fence is the proportion of incoming wind-transported snow, moving at or below the height of the barrier, that is permanently retained by the fence. *Absolute trapping efficiency* is the proportion of incoming wind-transported snow to 5 m (16 ft) height that is permanently retained by a barrier. The *initial trapping efficiency*, E_o, is the efficiency at the time of the first drifting event when there is no appreciable accumulation of snow in the fence.

3.8.6.2 Trapping Efficiency in Relation to Fence Height and Wind Speed

By using the vertical size distribution and fall velocity of snow particles, and the general characteristics of the airflow field behind a fence, it is possible to trace the trajectories of particles to determine how far they travel before they reach the ground. If this distance exceeds the region of decreasing surface shear stress behind the barrier, the particles are not trapped. Although quantitative data are lacking on the airflow field behind developing drifts, the distribution of wind speeds behind fences as shown in Figure 3.29 provides the basis for evaluating how initial trapping efficiency varies with wind speed and fence height. The relationship in Figure 3.57, derived from simulation modeling, shows that initial trapping efficiency decreases somewhat as fence height increases. This is attributable to the decrease in particle size (and hence fall velocity) with increase in height. The 10-m ambient wind speed has a much more pronounced effect on efficiency, however. For a 2-m-tall fence, for example, E_o varies from 99% at U_{10} = 35 km/h (22 miles/h), to 68% at U_{10} = 108 km/h (67 miles/h).

Absolute trapping efficiency increases with fence height as shown in Figure 3.58, demonstrating an advantage of tall fences.

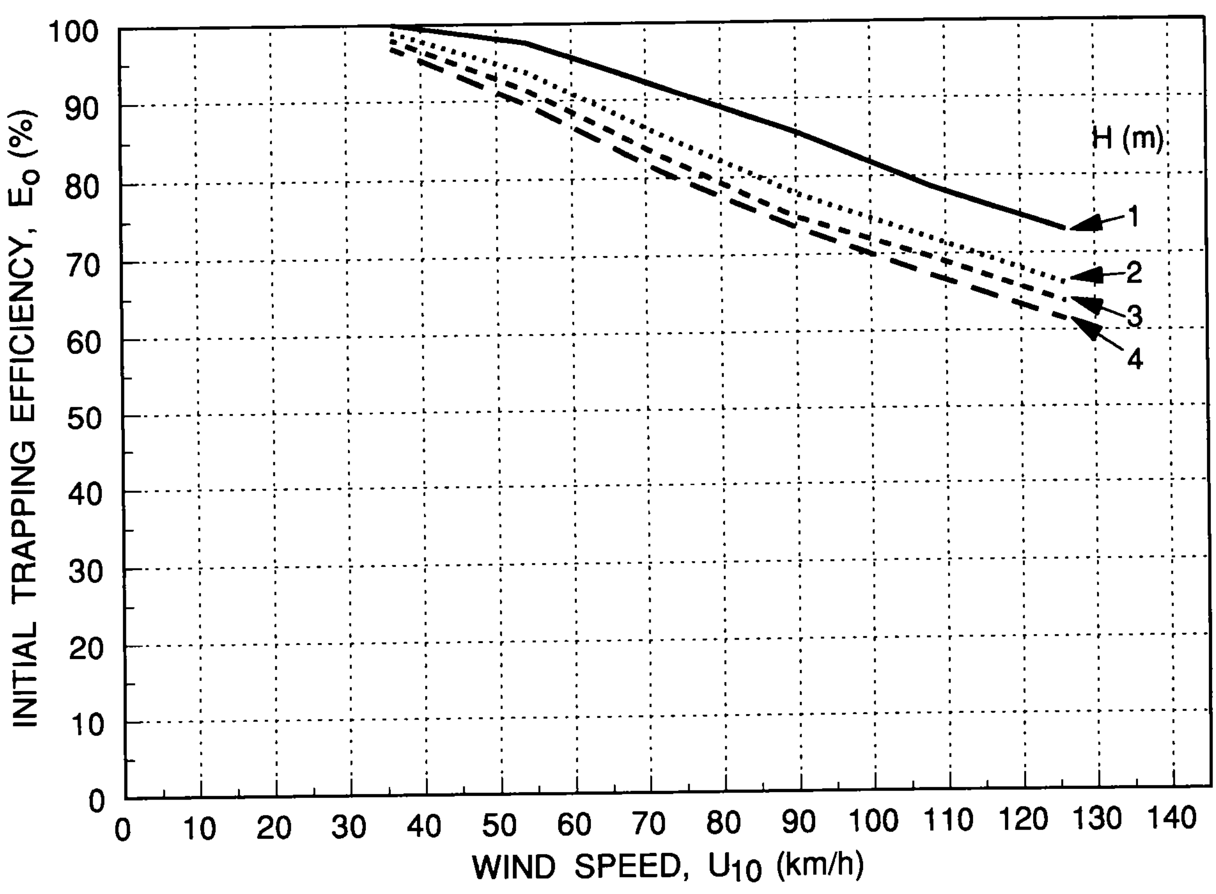


Figure 3.57. How initial trapping efficiency varies with fence height and wind speed (Tabler and Jairell 1993).

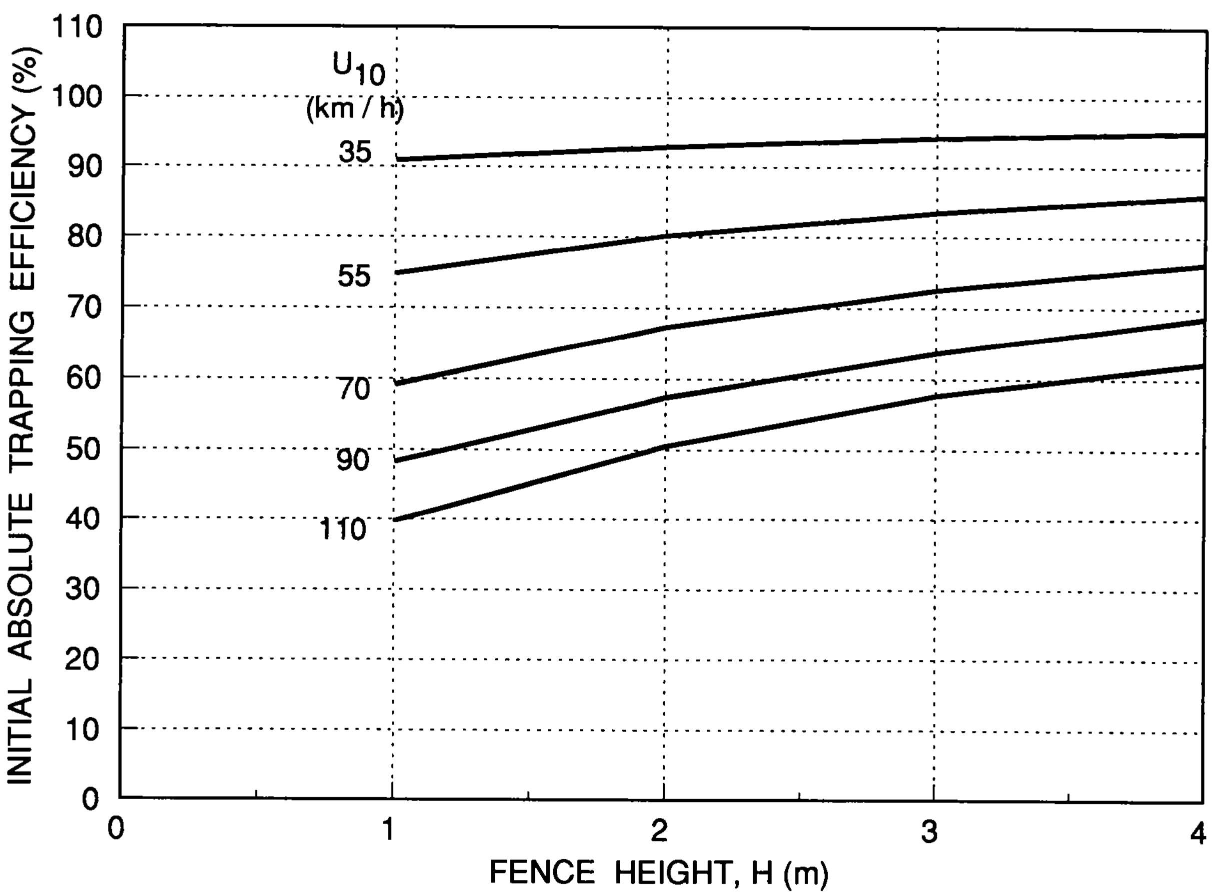


Figure 3.58. How initial absolute trapping efficiency varies with effective fence height.

3.8.6.3 Other Factors that Affect Trapping Efficiency

In addition to the effect of wind speed previously described, trapping efficiency also varies with wind direction relative to fence orientation, stage of drift growth, and the chronology of changes in wind speed or direction as this affects the erodibility of previously deposited snow.

Fence characteristics that affect trapping efficiency are length, height, bottom gap, and porosity. As a first approximation, it can be assumed that trapping efficiency is proportional to snow storage capacity; that is, trapping efficiency varies with fence length, bottom gap, and porosity as shown in Figures 3.46, 3.48, and 3.50. Solid fences are an exception to this rule, however, because they are relatively efficient in trapping snow during the early stages of growth before the upwind drift reaches equilibrium. Efficiency drops rapidly thereafter, which reflects the entrainment of snow particles in the accelerated flow over the top of the fence (Figure 3.59).

Figure 3.59. Snow particles jetting over the top of a solid barrier 1.2 m (4 ft) tall illustrate why the trapping efficiency declines after the upwind drift reaches the top of the fence.

3.8.6.4 How Trapping Efficiency Changes with Time

The effects of a snowdrift on trapping efficiency can be surmised from the discussion of snow deposition in topographic depressions (section 3.7.3). From the description of how snow is deposited behind a fence it is apparent that the angle of approach to the crest of the slip face changes as the drift grows, being positive (uphill) as the drift deepens during the second stage, and negative (downhill) as the drift lengthens during the third stage (Figure 3.32). Through much of the third stage, the approach angle remains relatively constant, averaging about 3°, consistent with a relatively high efficiency of 70% or so (Figure 3.26). Trapping efficiency changes in a complex way as a drift grows, and there may be intervals — especially during stage 2 — when trapping efficiency increases with time.

An engineering approximation for how trapping efficiency changes with time, based on field measurements, is

$$E \approx E_o[1 - (A/A_e)^2]^{0.5} \tag{3.30}$$

where E is trapping efficiency expressed as a fraction, E_o is initial trapping efficiency when the fence is empty, A is the cross-sectional area of the drift, and A_e is the cross-sectional area of the equilibrium drift when the fence is filled to capacity (Figure 3.60). Field measurements, and the results from the computer-based modeling presented in Figure 3.57, indicate that an appropriate value for E_o is 0.95. This also seems reasonable considering the simplistic view that snow transport is proportional to the 3.8 power of wind speed. A 50% reduction in wind speed would therefore reduce transport potential by 93% ($0.5^{3.8} = 0.07$).

The average efficiency, E_{ave}, over a winter having snow transport, Q_t, equal to or less than the capacity of the fence, Q_c, is estimated by integrating the area under the curve represented by Equation (3.30) from $A = 0$ to A_f, the value at the end of the season:

$$E_{ave} = [1/(A_f/A_e)](E_o)\{0.5(A_f/A_e)[1-(A_f/A_e)^2]^{0.5} + 0.5\sin^{-1}(A_f/A_e)\}, \quad Q_t \leq Q_c \tag{3.31}$$

Instantaneous and average trapping efficiencies of porous fences ($P = 0.5$) are presented in Table 3.6.

For the case where transport was just sufficient to fill the fence, the average trapping efficiency given by Equation 3.30 is $0.79E_o$. For years when snow transport is greater than the capacity of the fence,

$$E_{ave} = E_o(0.79)(Q_c/Q_t), \qquad Q_t > Q_c \tag{3.32}$$

The plot of average efficiency as given by Equations (3.31) and (3.32), and Figure 3.61, indicates that fences provide considerable benefits even in years when snow transport exceeds the design storage capacity of the fence.

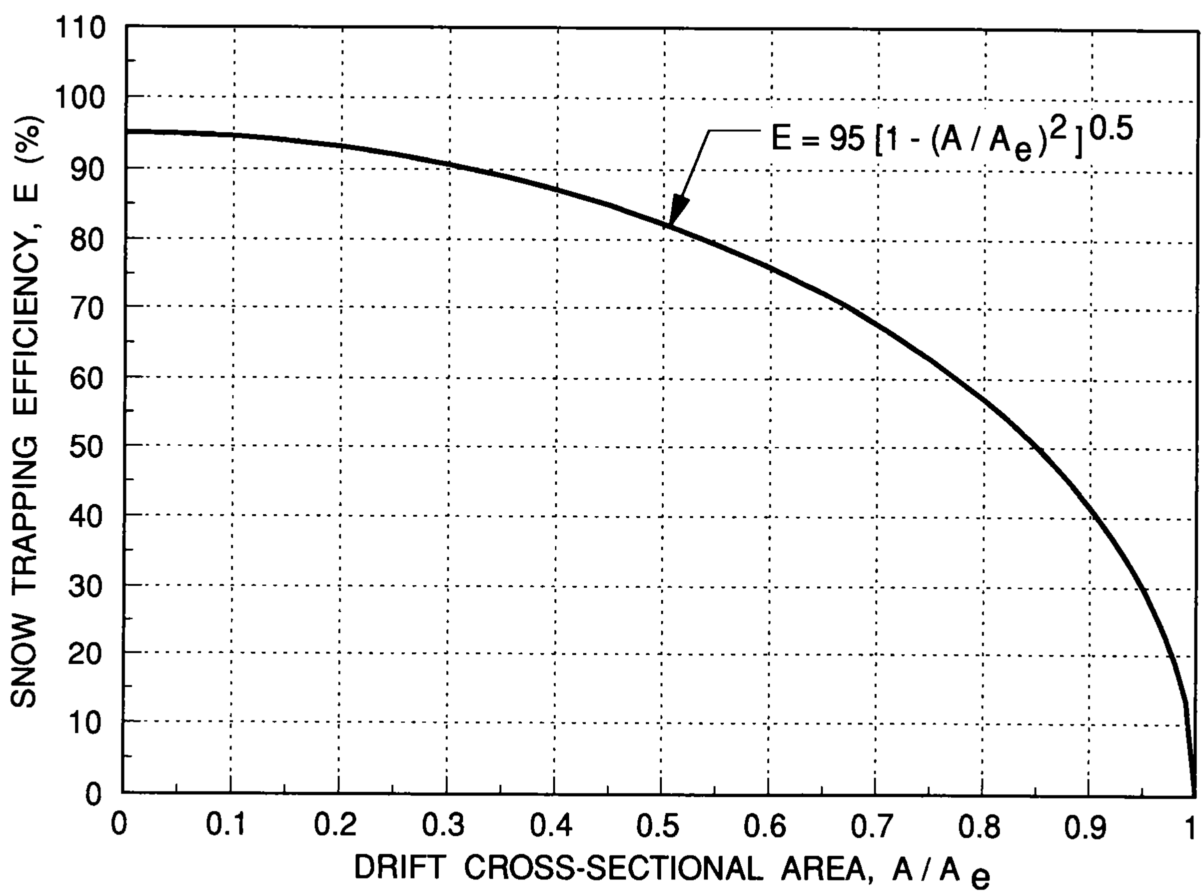


Figure 3.60. Decline in trapping efficiency as a 50%-porous snow fence fills with snow, assuming E_o = 0.95 (Tabler and Jairell 1993).

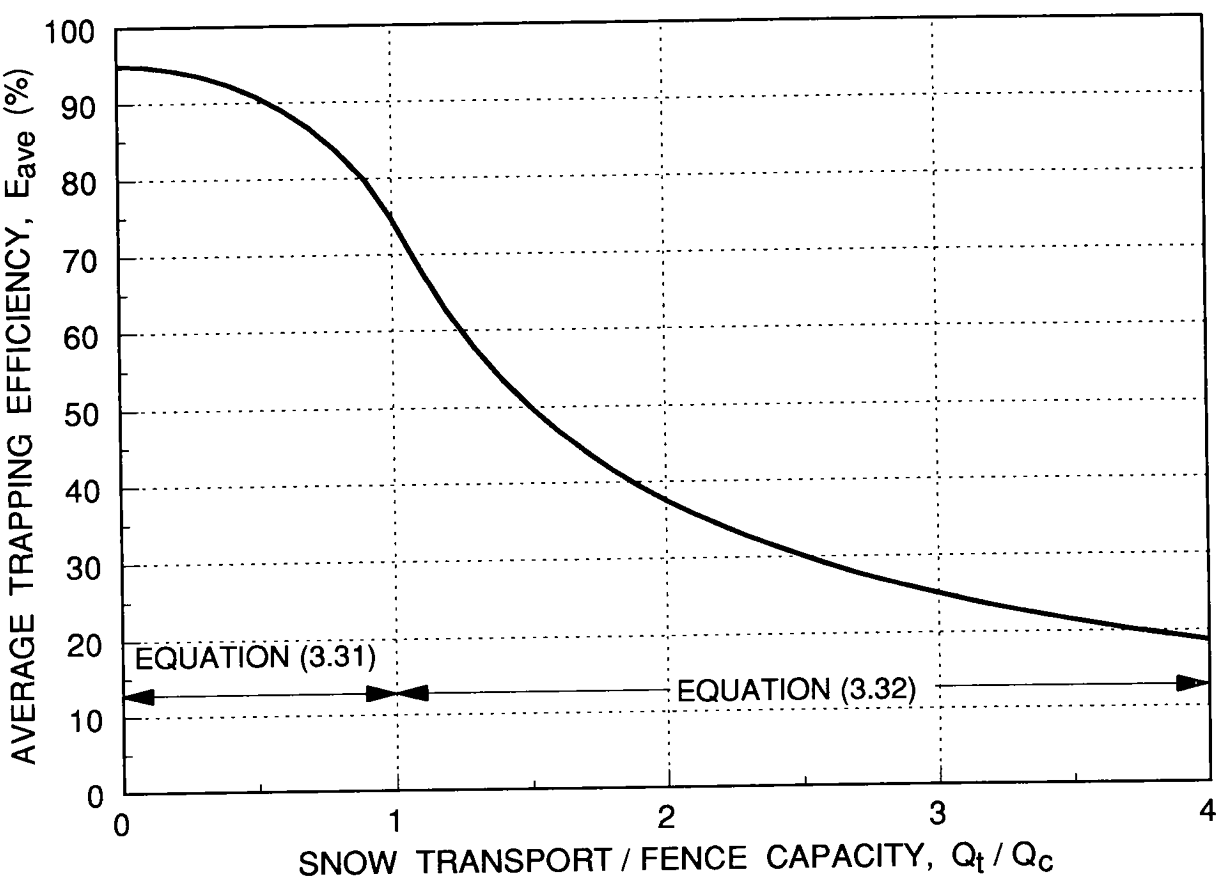


Figure 3.61. Average trapping efficiency as a function of snow transport relative to capacity (Tabler and Jairell 1993).

Table 3.6. Instantaneous (E) and average (E_{ave}) snow trapping efficiency of 50% porous snow fences, as a function of the relative cross-sectional area of the drift (A/A_e), as given by Equations (3.30) and (3.31) with initial trapping efficiency E_o equal to 0.95.

A/A_e	E	E_{ave}	A/A_e	E	E_{ave}
0.00	0.95	----	0.55	0.79	0.90
0.05	0.95	0.95	0.60	0.76	0.89
0.10	0.95	0.95	0.65	0.72	0.88
0.15	0.94	0.95	0.70	0.68	0.87
0.20	0.93	0.94	0.75	0.63	0.85
0.25	0.92	0.94	0.80	0.57	0.84
0.30	0.91	0.94	0.85	0.50	0.82
0.35	0.89	0.93	0.90	0.41	0.80
0.40	0.87	0.92	0.95	0.30	0.77
0.45	0.85	0.92	1.00	0.00	0.75
0.50	0.82	0.91			

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4. Quantifying the Blowing Snow Problem

4.1 Scope

This chapter recommends a procedure for analyzing snow drifting problems, and describes the information, data, and analyses required for quantifying wind-transported snow at a site.

The steps required before specific snow control measures can be designed are:

1. identify the problem
2. analyze the problem
3. identify the possible solutions
4. assemble the data
5. estimate the mean annual snow transport and direction
6. determine the snow storage capacity required for control measures

4.2 Highlights

- Identify the problem: Drift encroachment on the road? Poor visibility for drivers? Slush and ice formation?

- Determine the source of the problem. Evaluate factors such as cross-section geometry, alignment, safety barriers, roadside structures and vegetation, development of snow berms.

- Identify possible solutions to determine required data, information, and analyses.

- Data and information to be collected include:
  * Winter field measurements of wind direction and snow accumulation;
  * Wintertime aerial photos, especially for large projects;
  * Climatological data (snowfall, temperature, and wind);
  * Topographic maps;
  * Plans that show road geometry.

- Quantification of the blowing snow problem at a site involves a series of step-by-step calculations to estimate:
  * Snow accumulation season;
  * Potential snow transport, Q_{upot}, based on wind records;
  * Potential snow transport, Q_{spot}, based on snowfall and evaporation;
  * Prevailing transport direction(s);

* Fetch distance (F);
* Mean annual transport, $Q_{t,ave}$, for site;
* Design transport, Q_{des}, for snow control measures.

- The snow storage capacity for which control measures must be designed, Q_{des}, is determined by the desired exceedance probability or benefit-to-cost ratio.

- When benefits are equal to the reduction in snow removal costs, designing the capacity of snow fences and other control measures for the mean annual snow transport provides the maximum benefit-to-cost ratio.

4.3 Identifying the Problem

Although maintenance crews and law enforcement officers are most familiar with drifting problems within their jurisdiction, they are usually unaware of the potential for solving the problems. Managers and engineers who have maintenance responsibilities must take the lead in identifying and prioritizing drifting problems.

Drift problems can best be identified by meeting with maintenance personnel. Other means include questionnaires sent to maintenance foremen and review of winter accident data.

4.4 Analyzing the Problem

Although drift encroachment on a traffic lane might be identified as a problem, the drift's effects on highway safety and snow removal operations can be important considerations in the design of control measures. This section describes the preliminary information that should be collected before designing control measures. The information should be as specific and detailed as possible, but collection of detailed weather and site data should not be initiated until the problem analysis has been completed.

Upon completion of the problem analysis, the snow control specialist should be able to specify appropriate solutions.

To avoid compromising control measures before the design begins, existing right-of-way should not be considered as a constraint during the data collection and analysis stages.

4.4.1 Problem Components

Every snow drifting problem has four aspects:

1. Type of Problem (drift, poor visibility, slush or ice)

2. Effect (accidents, excessive snow removal costs, pavement repair costs)

3. Source of blowing snow (open field, frozen lake, corridor aligned with wind)

4. Cause of Problem (cross-section geometry, horizontal or vertical alignment, delineation, safety barrier, roadside vegetation or structure, snow removal practices, traffic)

4.4.2 Specifying the Problem and Effects

The following questions should be answered as part of every problem analysis.

- Is the problem caused by snow deposition, poor visibility, slush and ice formation, or a combination?

- If the problem is related to snow deposition, what is the safety hazard? (restricted site distance, poor visibility caused by snow blowing off the drift at windshield level, loss of vehicle control)

- What is the accident history at this location?

- Does the drift block roadside drainage or otherwise contribute to water infiltration? If so, what pavement damage is evident?

- What impact does the drift have on crew requirements, plowing schedules, and overtime?

- What is the year to year variability in problem occurrence and severity?

- What specific benefits would be derived from solving this problem? Would it improve safety for public or maintenance workers? reduce overtime? free equipment for use at other locations?

These questions help justify and prioritize the problem, and help to identify appropriate mitigation measures. The answers to many of these questions must come from on-site meetings with the field maintenance personnel who are most familiar with the problem, and from wintertime field reviews by the snow control specialist. In particular, maintenance employees who have long-term experience with the problem location should be consulted. Other useful information sources are law enforcement personnel, local residents, and accident records.

4.4.3 Source of Blowing Snow

The initial problem analysis should identify the source of blowing snow, and hence the approximate direction of the problem-causing winds. Only relative quantification is required at this preliminary stage: Is the snow transport high, medium, or low?

4.4.4 *Problem Causes*

The causes of a problem can be difficult to determine, but are important for specifying a solution or designing control measures. From the outset, it is important for the snow control specialist to be objective in order to avoid overlooking options. A preoccupation with designing drift-free cross-sections, for example, can preclude the option of improving visibility by using snow fences.

The following factors can be contributing causes to a snowdrifting problem.

- Cross-section geometry: Drifts that form in cuts can encroach on the road surface; insufficient fill height above grade can make the road surface lower than the snow cover or plow berm; high embankments with steep sides promote the deposition of snow along the shoulder (which can be exacerbated by a safety barrier); the ditch cross-section may be insufficient to hold plowed snow.

- Horizontal alignment: Alignment parallel to wind allows the road corridor to serve as a source of blowing snow, and limits the use of snow fences.

- Vertical alignment: Because plow cast distance varies with truck speed, plow berms are higher and closer to the road where uphill grades cause trucks to lose speed.

- Roadside structures: Board fences (Figure 4.1), signs (Figure 4.2), buildings, bridge abutments, and improperly placed snow fences can form drifts encroaching on the road.

- Roadside vegetation: Trees, shrubs, and unmowed vegetation can cause drifts.

- Safety barriers: W-beam guardrails and concrete safety barriers cause deposition of blowing snow. Equally important, they exacerbate the accumulation of a plow berm by interfering with snowplow cast.

- Snow removal operations: Snow removal procedures that promote the growth of plow berms include casting snow into the wind and driving too slowly while plowing. Rotary plows minimize plow berm formation and should be used in place of displacement plows for some operations.

- Inadequate delineation contributes to accidents in blowing snow conditions. Delineator posts should be spaced no further apart than 60 m (200 ft), and should extend at least 1.5 m (5 ft) above the snow cover or plow berm.

- Traffic volume contributes to the hazards associated with limited visual range.

- Maintenance standards contribute directly to blowing snow problems. Light blowing snow conditions can create significant maintenance problems in areas having a "bare pavement" policy, whereas the same conditions would require no maintenance action if standards were less rigorous.

Figure 4.1. A board fence, 2.4-m (8 ft) tall, that caused a drift on the road. Wind was from left. Structures and vegetation on the downwind side of the road are sometimes overlooked during summertime field reviews.

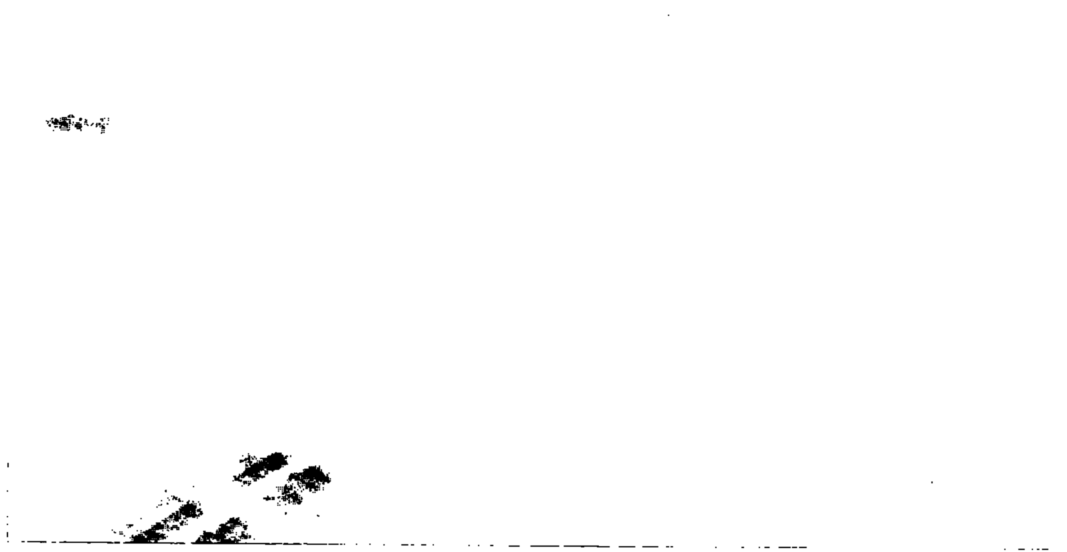

Figure 4.2. This tall billboard caused a snowdrift on the road even though it is 30 m (100 ft) from the shoulder. Plow drivers had not realized that the sign caused this drift.

4.5 Identifying Possible Solutions

The information collected for the problem analysis allows the snow control specialist to identify possible solutions. This preliminary selection will suggest priorities for data and analyses. Not all drifting problems can be solved. Solving a problem at one location, however, indirectly benefits other locations as well because the savings in time and other expenditures can then be shifted to locations where drift control measures are not feasible. This concept of indirect benefits applies on a district- or statewide basis, as well as for a particular route.

All possible solutions should be considered at the outset.

- Structural snow fences
- "Living" snow fences
- Cross-section modification
- Changes in snow removal operations
- Safety barrier modification
- Management of roadside vegetation
- Delineation improvement
- Warning signs

Although measures that are obviously inapplicable or inappropriate should be rejected early in the review process, care should be exercised to avoid preconceptions about right-of-way constraints, cost, or the "best" solution among remaining options. Specific measures should not be recommended until after the data have been analyzed, as described in section 4.7.

4.6 Assembling Data and Information

This section describes the information required for the problem analysis, and procedures for obtaining the data.

4.6.1 Winter Field Measurements and Observations

This section describes the most important information to be collected during an on-site review of a particular problem. Suggested forms for a *Problem Evaluation Checklist* are presented in the Appendix.

4.6.1.1 Determining Exact Location

The milepost or survey station that marks the beginning and end of each problem should be identified by winter field measurements. Although these observations should be made with the input of the local maintenance foreman or superintendent, the snow control specialist should make an independent assessment to interpret maintenance input based on the information contained in this guide.

Locations should be identified to within 10 m (33 ft) and marked on plan sheets at the time of observation. Aerial photos taken during the winter are useful for documenting problem boundaries, and also provide information on wind directions. Refer to section 4.6.2 for aerial photography guidelines.

4.6.1.2 Quantifying and Documenting the Drift Problem

The following measurements and observations should be obtained by the snow control specialist during the winter:

1. Record snow depth at shoulder at representative locations,
2. Measure snowdrift profile (if cut section) by level survey or probing, at representative locations,
3. Document typical visibility/road surface conditions with photos or video.

4.6.1.3 Measuring Prevailing Transport Direction

Plow drivers are an important source of information about the *general* wind direction associated with drifting problems, and particularly about "problem storm" directions. A more rigorous determination of the prevailing transport direction(s) is required for designing drift control measures, however. It is important to remember that the actual wind direction can differ appreciably from that perceived by maintenance personnel because: 1) the direction of the wind in cuts can be markedly different from that of the approaching wind, and 2) the driver's perception of wind direction is distorted by the relative motion of the truck, and the variability of the road alignment.

Wind direction can be determined in the field by using a compass to measure:

- Wind direction itself, facing into the wind;
- Alignment of drift features in the field;
- Alignment of wind-sculpted vegetation, such as flagged or bent trees;
- Orientation of snow-caused abrasion on wood poles or posts.

4.6.1.3.1 Field Wind Measurements

Wind direction can be measured with a hand-held compass while facing into the wind. Wind direction must be measured where it is not influenced by the road itself. Wind direction in a cut, for example, can differ from that of the approaching wind by as much as 45°. If wind measurements are to be meaningful, they must be taken during strong winds and repeated several times throughout the winter.

4.6.1.3.2 Field Snowdrift Measurements

Similar to the wind measurements described above, a hand-held compass can be used to measure the alignment of drifts behind shrubs, trees, or other objects. The streamlined shapes of drifts (Figure 4.3) provide readily identifiable indicators for wind direction. The alignment of large drifts, measured late in the winter, represents the average direction of drifting. If only small drifts are available, measurements must be repeated several times over a winter to obtain a meaningful average. Because road geometry can affect the wind, it is important *not* to use drifts in road cuts or other locations where the wind direction is not representative of that where the fences would be placed.

Figure 4.3. The orientation of streamlined drifts formed by bushes and trees can be used to determine the prevailing direction of the snow transport.

4.6.1.3.3 Other Indicators of Snow Transport Direction

Blowing snow can affect the shape of exposed plants. The primary mechanism by which blowing snow alters vegetative growth is by wearing away the protective layer of wax, resulting in desiccation of exposed plant tissue. Growing points that face downwind or that are otherwise protected are spared, resulting in the flagged and hedged appearance of trees and shrubs in exposed locations. The orientation of wind-sculpted vegetation, or the abrasion pattern on wood posts or poles, can provide a reasonable estimate of the prevailing wind direction in blowing snow conditions (Figure 4.4), even during summer months.

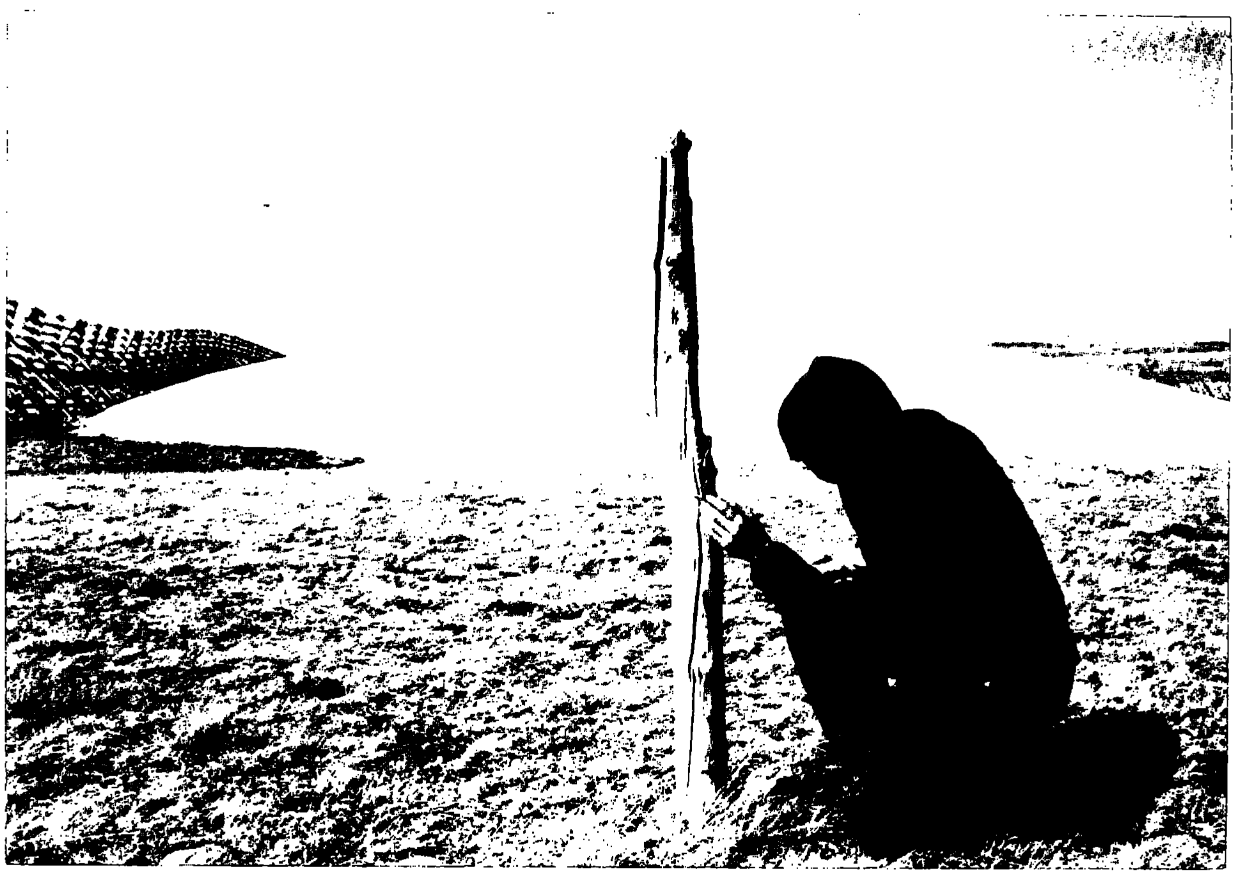

Figure 4.4. Abrasion pattern on posts indicates prevailing direction of snow transport (Tabler 1986).

4.6.1.4 Measuring Snow Depth over the Fetch

If possible, the depth of the snow that remains on the fetch at the end of the winter should be measured. The best date for such a measurement is a week or so before the end of the snow accumulation season, as described in section 4.7.2.

4.6.2 Obtaining Aerial Photographs

For larger projects, wintertime aerial photographs facilitate measurements of prevailing transport directions and locations of problem areas. As shown in Figure 4.5, the alignment of drifts formed by solitary objects is readily discernible at scales up to 1:12,000 if the following requirements are met: 1) black-and-white film must be used (color film usually does not provide sufficient contrast); 2) photographs must be taken on bright, sunny days at low sun angles; 3) flights should be scheduled after major drifting events with typical winds, but not after a recent snowfall that can cover up drift features; 4) photographs must be taken before significant melting takes place, and preferably near the time of peak snow accumulation; and 5) there must be objects protruding above the snow cover that form drifts.

Aerial photographs can also be used to identify and delineate problem locations, measure fetch distance, and provide an expedient medium for laying out fence locations. The cost of aerial photographs is easily repaid by the time saved in field measurements, design, and preparation of location maps. For major projects, two or even three photography flights during a winter would be justifiable to ensure reliable estimates.

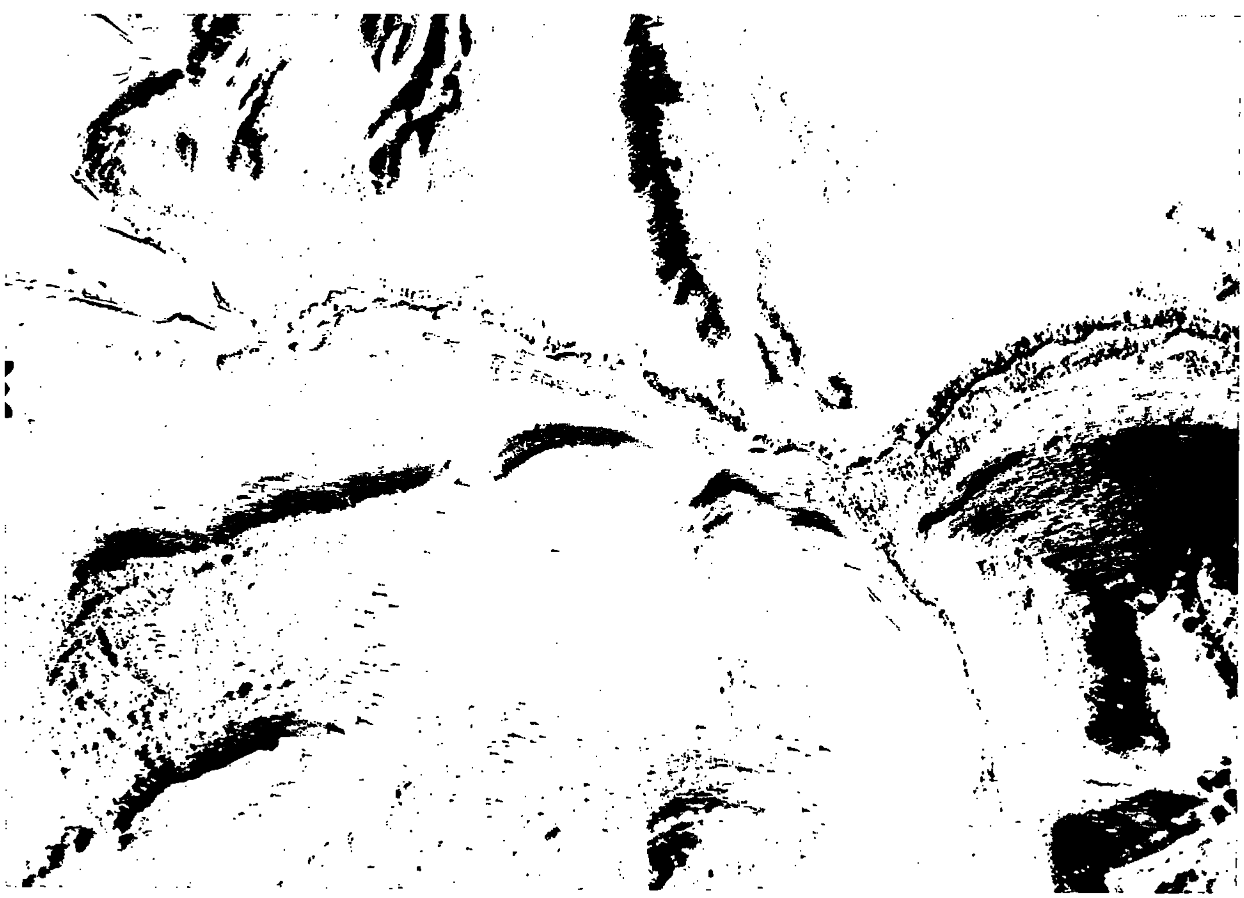

Figure 4.5. An aerial photo at a scale of 1:12,000 shows drift alignment (Tabler 1986).

4.6.3 Assembling Climatological Data

This section describes data sources and specific variables to be determined.

4.6.3.1 Sources of Climatological Data

The following publications are available from the National Climatic Data Center, Federal Building, Asheville, North Carolina 28801-2733; telephone 704-259-0682. The letters in brackets indicate sources of precipitation and snowfall [P], temperature [T], and wind [W] data.

Local Climatological Data (Annual Summary) (specify city) [P,T]

Climatological Data (Annual Issue) (specify state) [P,T]

Climatological Summaries, No. 20 (specify city) [P,T]

Climates of the States, No. 60 (specify state) [P,T]

Monthly Normals, 1961-90, No. 81 (specify state) [P,T]

Summary of Hourly Observations, 1951-60, No. 82 (specify city) [W]

Climatological Summary of States, 1951-60, No. 86 (specify state) [P,T]

Airport Climatic Data, 1965-74, No. 90 (specify city) [P,T,W]

Wind Energy Resource Information System, monthly and annual

Comparable publications are available for Canada, in addition to the *Climatological Atlas for Canada*, published by the Department of Transport and the Division of Building Research.

Climatological data summaries are also available from federally funded regional climate centers established as part of the U.S. National Climate Program:

Northeast Regional Climate Center
1123 Bradfield Hall
Cornell University
Ithaca, NY 14853-1901
(607) 255-1751

Midwest Climate Center
Illinois State Water Survey
2204 Griffith Drive
Champaign, IL 61820
(217) 244-1488

High Plains Climate Center
239 L.W. Chase Hall
University of Nebraska
Lincoln, NE 68583-0728
(402) 472-6709

Western Regional Climate Center
Desert Research Institute
Box 60220
Reno, NV 89506
(702) 677-3100

Snowfall and snow depth probabilities for the northeastern United States and southeastern Canada have been compiled in an atlas by Cember and Wilks (1993). Digital data are also available (Cember, Eggleston and Wilks 1993).

Snow Surveys and Basin Outlook Reports (for specific states, months, and years), issued by the Soil Conservation Service, U.S. Department of Agriculture, are a useful source of data for estimating snowfall water-equivalent (winter precipitation). In Canada, similar reports are issued by the Water Resources Division, Indian and Northern Affairs Canada.

4.6.3.2 Historical Wind Records

Historical wind records can be used to estimate snow transport and to determine its directional distribution. The form of data required for such an analysis is a tabular presentation for each month showing the frequency of observations by wind speed and direction classes, as shown in Table 4.2. Tabulation should be by 16 direction classes (N, NNE, NE, ENE, etc.), in the narrowest wind speed classes available. Three-knot (or 6 km/h) class widths are optimum, but the standard classes used in *Airport Climatological Summaries* will suffice (in knots, 0-3, 4-6, 7-10, 11-16, 17-21, ..., >40). Ideally, "percent frequency of observations" should be calculated to 0.01 resolution; a 0.1 resolution will provide usable but less accurate approximations of total snow transport.

Finally, the height of the anemometer must be determined so that the wind speeds can be adjusted to those at 10-m height (U_{10}). This information is provided in the *Local Climatological Data* publications described in section 4.6.3.1.

4.6.3.3 Mean Monthly Temperatures

Mean monthly air temperatures are used to calculate the snow accumulation season, and can be obtained for nearby weather stations from National Weather Service publications listed in section 4.6.3.1, climatic atlases, or other sources.

If the elevation at the weather station is much different from the problem location, reported temperatures can be adjusted using the normal or standard lapse rate of temperature in the atmosphere:

$$\text{Temperature decrease with increase in elevation} = 0.65\ ^\circ\text{C}/100\ \text{m} \quad (3.5\ ^\circ\text{F}/1000\ \text{ft}) \tag{4.1}$$

4.6.3.4 Snowfall and Winter Precipitation

Winter snowfall water-equivalent, S_{we}, is used to estimate snow transport. Mean monthly snowfall water-equivalent should be estimated for the problem location from records for nearby reporting stations. A reasonable estimate for water-equivalent is (Tabler, Berg et al. 1990)

$$S_{we} = (\text{snowfall depth}) / 10 \tag{4.2}$$

If essentially all of the winter precipitation is in the form of snow, snowfall water-equivalent can also be assumed equal to the precipitation received during the snow accumulation season.

All precipitation gages and exposed snow boards (boards used to provide a reference surface for snow depth measurements) underestimate the actual precipitation when wind is blowing. At windy sites where the gage is not equipped with a wind shield, true precipitation can be as much as twice that caught in the gage. Most precipitation gages operated by the National Weather Service are in exposed locations (such as airports), and not all are equipped with wind shields. When using precipitation data, it is wise to visit the weather stations involved to determine whether some allowance should be made for gage-catch error (Tabler, Berg et al. 1990).

The best estimate for winter precipitation is provided by peak snowpack water-equivalent as measured on snow courses operated by the U.S. Soil Conservation Service. Because these snow courses are usually located in sheltered forest openings, the snowpack water-equivalent provides a very good measure of precipitation. Snow courses are mainly used for streamflow and flood forecasting, and are most readily available for areas in the western U.S. and Canada. It is possible to use regional snow course data from the mountains to develop a precipitation/elevation relationship that can be extrapolated to lower elevations as an alternative to using precipitation or snowfall data reported by the National Climatic Data Center.

Where data are not available for a problem location, various regression techniques can be used to estimate precipitation using data from other stations. In locations where precipitation is known to increase with elevation, for example, precipitation can be plotted against elevation for the nearest stations. This relationship can be used for estimates at the problem location.

4.6.4 Topographic Information

Topographic maps are used to a) determine the fetch, b) identify topographic or man-made features that affect snow fence placement, and c) determine magnetic declination needed to correct compass readings to true north. The most recent editions of 7.5-minute quadrangles (scale 1:24,000) that show trees and brush should be used. Topographic maps enlarged to a scale of 1:6,000 or larger (1 cm = 60 m; 1 in. = 500 ft) also provide excellent field maps for snow fence layout.

Topographic maps are available from the U.S. Geological Survey, Map Sales, Federal Center, Box 25286, Denver, Colorado 80225, or telephone (303)-236-7477. Maps are also available from state cartographic divisions.

4.6.5 Road Geometry

4.6.5.1 Plan and Profile for Road

The following information can be obtained from plan and profile sheets or from a field survey, if required:

- Exact stationing of problem limits
- Elevation
- True bearing of the road
- Right-of-way widths
- Land ownership adjacent to right-of-way
- Vertical gradient

4.6.5.2 Typical Road Cross-Sections at Site

Typical as-built cross-sections are used to determine the cause of snowdrifting problems, estimate the snow storage capacity in the existing section, and to determine what earthwork would be required to eliminate drift encroachment. Cross-sections are also used to determine fence placement (chapter 5).

Because the topography both upwind and downwind of the road section influences the equilibrium snow deposit at the road section, cross-section data should begin at least 60 m (200 ft) upwind of the right-of-way and extend for at least 60 m beyond the downwind shoulder. Elevations and distances should be measured to the nearest 0.1 m (0.3 ft). Along each cross-section, elevations should be measured at 3-m (10 ft) intervals, with intermediate stations at slope breaks.

4.6.6 Other Information

4.6.6.1 Vegetation over the Fetch Distance

Vegetation influences how much snow is retained on the fetch. The average plant height can provide a basis for estimating snow retention in areas where total snowfall is the primary factor that limits snow transport (that is, locations periodically swept bare by the wind).

4.6.6.2 Land Use

Land use can also be a consideration in determining the type of control measure appropriate for a site. It may be preferable to use tree plantings instead of structural snow fences in areas where appearances are important, and temporary fences may be necessary on cultivated farmland.

4.6.6.3 Soils

Soils information is necessary for specifying supports for structural snow fences, and for determining the feasibility of, and species required for, living snow fences. Specific information should include:

- Geologic parent material;
- Depth to bedrock;
- Texture (e.g., sandy clay loam);
- Drainage (e.g., wet, well-drained);
- Salinity problem, if any;
- Qualitative bearing strength (poor, average, good).

4.7 Estimating the Mean Annual Snow Transport

4.7.1 Outline of Procedure

As described in chapter 3, snow transport is the mass of blowing snow in the first 5 m (16 ft) above the ground, per meter of width across the wind, over a specified time. This information is needed to specify the snow storage capacity of fences, vegetative plantings, or cut sections. This section describes the procedure for estimating mean annual snow transport from climatological data.

Potential snow transport is the maximum quantity of blowing snow expected at a site, disregarding fetch, and is represented by Q_{inf}, the subscript indicating an infinite fetch. Q_{spot} is the potential snow transport calculated from the standard snow transport equation (Equation (3.9)). For snowfall water-equivalent, S_{we}, in millimeters, and F and T in meters,

$$Q_t = 0.5\ T\ S_{rwe}(1 - 0.14^{F/T}) \tag{4.3}$$

where mean annual snow transport, $Q_{t,ave}$, is in kg/m.

Q_{spot} is the transport that would result if all winter snowfall were relocated ($S_{rwe} = S_{we}$) over an unlimited fetch, so that Equation (4.3) becomes

$$Q_{spot} = 0.5\ T\ S_{we} \tag{4.4}$$

If wind is the factor that limits snow transport, as would be the case if an erodible snow cover persisted throughout the winter, then snow transport would be determined by the wind, and potential transport would be calculated from wind records using Equation (3.4):

$$Q_{0\text{-}5} = U_{10}^{3.8} /233847 \tag{4.5}$$

where $Q_{0\text{-}5}$ is in kg/s per meter of width across the wind, and U_{10} is in m/s. Potential transport calculated in this manner is designated Q_{upot} and is calculated as

$$Q_{upot} = \Sigma q \tag{4.6}$$

where q is the contribution of each wind speed/direction cell in a tabulation of the frequency distribution of wind speed and direction, over the range of wind directions relevant to designing snow control measures at a particular site.

If Q_{upot} is less than Q_{spot}, then wind is the factor limiting transport, and Q_{inf} is taken as being equal to Q_{upot}. If Q_{spot} is less than Q_{upot}, then snowfall controls snow transport, and Q_{inf} is calculated as $0.5TS_{rwe}$ (Equation (4.4)).

Finally, the mean annual snow transport is calculated by correcting Q_{inf} for the actual fetch at the site, using Equation (3.10):

$$Q_{t,ave} = Q_{inf} (1 - 0.14^{F/T}) \tag{4.7}$$

Estimating snow transport therefore requires a step-by-step procedure as shown in Figure 4.6. The remainder of section 4.7 describes this procedure in detail.

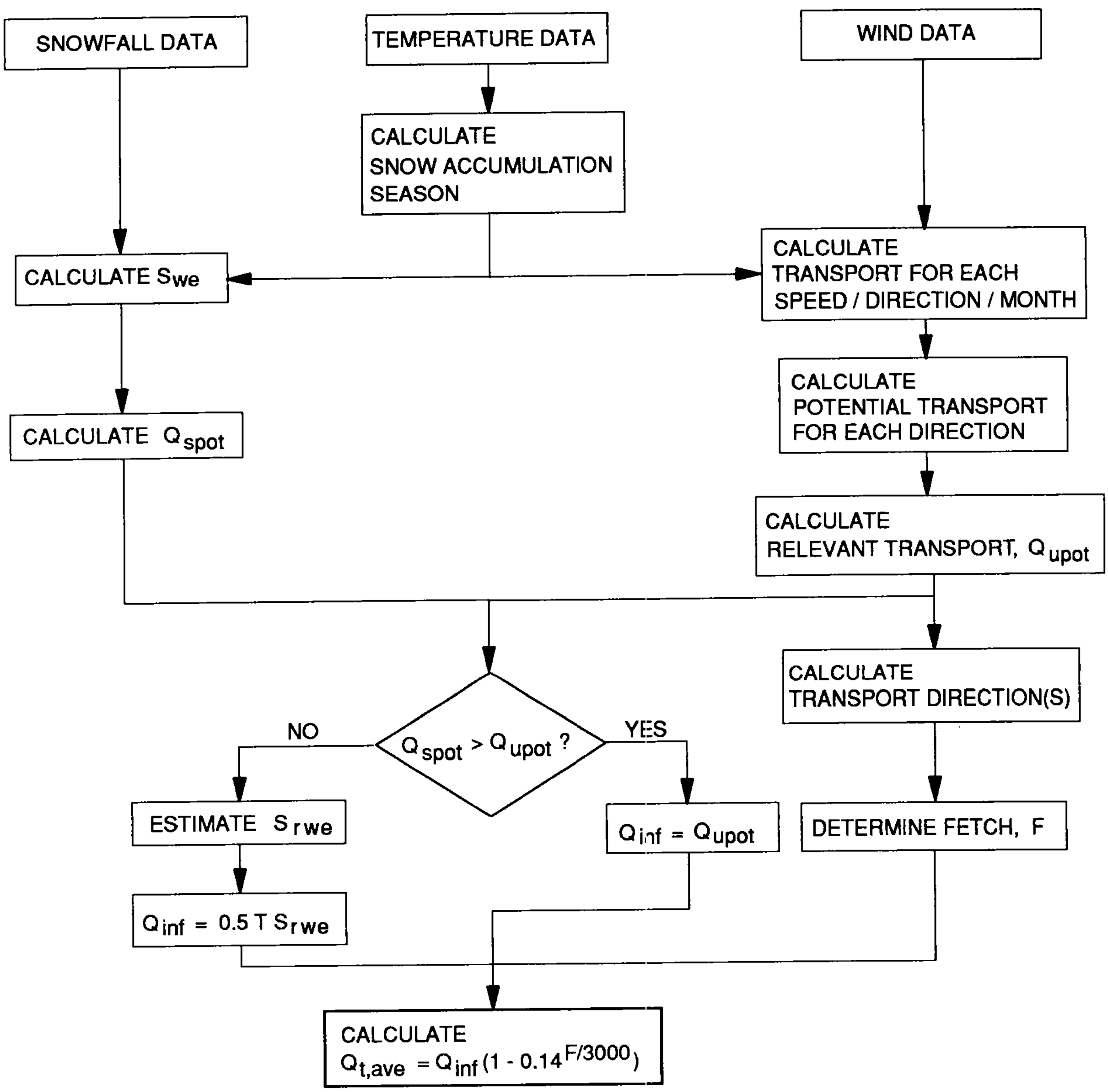

Figure 4.6. Flow chart of the procedure for estimating mean annual snow transport, $Q_{t,ave}$ (Tabler 1993).

4.7.2 *Determining the Dates of Snow Accumulation Season*

The snow accumulation season is the period of drift growth that begins with the first blowing snow event that causes drifts persisting through the winter, and ends when snowdrifts reach maximum volume for the winter (Tabler 1988). Calendar dates of the *average* snow accumulation season must be estimated as the first step in estimating snow transport.

Although the National Climatic Data Center publications listed in section 4.6.3.1 report "snow on ground" for some stations, it is usually not possible to use this information to determine the snow accumulation season. "Snow on ground" is typically measured in locations exposed to the wind. Even at sheltered locations, it is difficult to determine the date of peak water-equivalent from snow depth data because water-equivalent can increase while snow depth decreases due to densification.

Snow survey data, such as reported by the Soil Conservation Service (U.S. Department of Agriculture), can be used to estimate snow accumulation dates at locations equipped with recording equipment. Most historical data consist of manual measurements that commence in mid-winter and are repeated at monthly or biweekly intervals. The result is that the fall date cannot be estimated, and the resolution of the spring date is poor.

The snow accumulation season is delimited by the dates when average air temperature reaches 0°C, *as computed from mean monthly temperatures* (Tabler 1988). This latter qualification, imposed because monthly mean values are readily available and convenient to use, assumes that the monthly mean applies to the middle of the month. 0°C dates are therefore computed by interpolation between consecutive months that have mean temperatures above and below 0°C. If temperatures are in °C, this interpolation procedure is represented by equation,

$$n = 30(T_+)/(T_+ - T_-) \tag{4.8}$$

where n is the number of days from the middle of the warmer month to the 0°C date (n is added to the mid-date of the warmer month in the fall, and subtracted from the mid-date of the warmer month in the spring). T_+ and T_- are the mean temperatures (°C) of the warmer and colder months, respectively.

For locations where representative climatological data are available, 0°C dates are computed directly from Equation 4.8, as shown by the following example.

4.7.2 Determining the Dates of Snow Accumulation Season

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For locations where representative climatological data are available, 0°C dates are computed directly from Equation 4.8, as shown by the following example.

Example (Buffalo, New York):

Given:

Mean monthly temperatures

	Nov	Dec	Jan	Feb	Mar	Apr
°F	40.0	29.6	24.7	24.6	32.5	43.6
°C	4.4	-1.3	-4.1	-4.1	0.3	6.4

Required: Calculate dates of snow accumulation season:

Solution: Equation (4.8):

Fall date: $n = 30(4.4)/(4.4 + 1.3) = 23$; Nov 15 + 23 days = Dec 8

Spring Date: $n = 30(0.3)/(0.3 + 4.1) = 2$; Mar 15.5 - 2 days = Mar 14

Examples of 0°C dates calculated from 10- to 30-year mean temperatures are:

Ames, Iowa:	November 27 - March 10
Barrow, Alaska:	September 8 - June 13
Boise, Idaho:	December 16 - January 29
Buffalo, New York:	December 8 - March 14
Denver, Colorado:	December 22 - February 6
Flagstaff, Arizona:	December 5 - February 26
Kalispell, Montana:	November 12 - March 19
Laramie, Wyoming:	November 11 - March 29
Lincoln, Nebraska:	December 3 - February 28
Madison, Wisconsin:	November 21 - March 19
Mansfield, Ohio:	December 12 - February 22
Salt Lake City, Utah:	December 10 - February 6
Charlottetown, Prince Edward Island:	November 28 - April 2

At locations where temperature data are not available, 0°C dates can be estimated from regression equations that relate 0°C dates at other stations to elevation, latitude, and longitude, because the geographic variation of air temperature is reasonably well described by these three variables:

$$\text{Date} = A'' + B''(\text{Elevation}) + C''(\text{Latitude}) + D''(\text{Longitude}) \qquad (4.9)$$

where *Date* is day of the year, elevation is in meters, and latitude and longitude are in degrees. Values for A'', B'', C'', and D'' can be determined for a particular area by statistical regression analysis of data from surrounding stations. Once the coefficients in Equation (4.9) are determined, dates can be estimated for locations that lack data. Areas with relatively few climatological stations may require utilization of regional or statewide data. Table 4.1 presents values for A'', B'', C'', and D'', for selected states, as determined from regression analyses of 10- to 30-year means for monthly temperatures reported in the publications described in section 4.6.3.1, and by Wernstedt (1972).

Although the statewide equations only approximate snow accumulation dates at a particular location, the coefficients in Table 4.1 illustrate how dates vary with elevation, latitude, and longitude within a particular state. As an example, values for the elevation coefficient *B* were used to develop the diagram of snow accumulation season versus elevation in Wyoming (Figure 4.7).

On average for the United States, dates of the snow accumulation season vary at the average rate of 2.5 days per 100 m (328 ft) of altitude, 5.5 days per degree of latitude, and 1 day per degree of longitude, earlier northward, eastward, and upward in the fall, and the reverse in the spring (Tabler 1988).

Example (Buffalo, New York):

Given: Table 4.1
Latitude = 42°56'N,
Longitude = 78°44'W,
Elevation = 215 m (705 ft)

Required: Calculate dates of the snow accumulation season for Buffalo, New York.

Solution: Equation (4.9):

Fall Date: $519 - 0.0329(215) - 5.80(42.93) + 0.99(78.73) = 341$ = Dec 7
Spring Date: $-204 + 0.0329(215) + 7.00(42.93) - 0.41(78.73) = 71$ = Mar 12

Table 4.1. Values of coefficients in the equation 0 °C Date = A" + B"(Elev) + C"(Lat) + D"(Long), where elevation is in meters, for selected states. Number of stations used in analysis is shown in parentheses after state name. R^2 is the coefficient of multiple determination (Tabler 1988).

	Fall Date					Spring Date				
State	*A"*	*B"*	*C"*	*D"*	R^2	*A"*	*B"*	*C"*	*D"*	R^2
Alaska (64)	+ 784	- 0.0419	- 5.35	- 1.02	0.90	- 391	+ 0.0189	+ 4.63	+ 1.38	0.91
Arizona (19)	+ 255	- 0.0339	- 4.74	+ 3.01	0.40	- 46	+ 0.0505	+ 3.86	- 1.41	0.65
California (13)	+ 652	- 0.0308	- 6.36	0.00	0.37	- 2	+ 0.0484	- 0.57	0.00	0.85
Colorado (80)	+ 713	- 0.0236	- 5.05	- 1.32	0.70	- 270	+ 0.0389	+ 7.54	- 0.34	0.85
Idaho (85)	+ 521	- 0.0333	- 3.37	0.00	0.82	- 217	+ 0.0487	+ 4.95	0.00	0.88
Illinois (51)	+ 661	- 0.0536	- 7.50	0.00	0.81	- 341	+ 0.0604	+ 9.39	0.00	0.85
Indiana (49)	+ 738	- 0.0607	- 9.29	0.00	0.77	- 440	+ 0.0736	+ 11.68	0.00	0.84
Iowa (86)	+ 600	- 0.0144	- 6.25	0.00	0.94	- 242	+ 0.0119	+ 7.28	0.00	0.94
Kansas (54)	+ 895	- 0.0138	- 13.64	0.00	0.83	- 466	+ 0.0042	+ 12.81	0.00	0.79
Maine (20)	+ 508	- 0.0345	- 3.93	0.00	0.86	- 114	+ 0.0331	+ 4.31	0.00	0.92
Maryland (5)	+ 589	- 0.0541	- 10.05	+ 2.42	0.80	- 383	+ 0.0579	+ 14.67	- 2.31	0.70
Michigan (72)	+ 494	- 0.0469	- 4.04	+ 0.33	0.92	- 104	+ 0.0214	+ 6.55	- 1.31	0.94
Minnesota (80)	+ 452	- 0.0166	- 2.86	0.00	0.90	- 78	+ 0.0148	+ 3.44	0.00	0.93
Missouri (38)	+ 881	- 0.0012	- 13.36	0.00	0.80	- 501	+ 0.0015	+ 13.79	0.00	0.73
Montana (106)	+ 431	- 0.0200	- 5.26	+ 1.45	0.40	+ 2	+ 0.0318	+ 7.14	- 2.68	0.75
Nebraska (53)	+ 552	+ 0.0004	- 5.21	0.00	0.77	- 290	- 0.0036	+ 8.56	0.00	0.80
Nevada (34)	+ 222	- 0.0057	- 6.65	+ 3.41	0.59	- 4	+ 0.0360	+ 8.24	- 2.91	0.82
New England* (67)	+ 690	- 0.0292	- 8.07	0.00	0.76	- 285	+ 0.0313	+ 8.15	0.00	0.86
New Jersey[1] (20)										
New Mexico (33)	+ 1073	- 0.0413	- 7.43	- 3.55	0.59	- 615	+ 0.0606	+ 9.60	+ 1.77	0.78
New York (61)	+ 519	- 0.0329	- 5.80	+ 0.99	0.89	- 204	+ 0.0329	+ 7.00	- 0.41	0.88
North Dakota (71)	+ 373	- 0.0115	- 3.35	+ 1.03	0.86	+ 36	+ 0.0171	+ 3.81	- 1.37	0.88
Ohio (52)	+ 952	- 0.0572	- 9.65	- 2.36	0.75	- 693	+ 0.0511	+ 13.45	+ 2.22	0.83
Oregon (52)	+ 235	- 0.0400	- 3.62	+ 2.61	0.63	- 158	+ 0.0563	+ 7.67	- 1.63	0.75
Pennsylvania (60)	+ 631	- 0.0449	- 7.87	+ 0.65	0.71	- 249	+ 0.0454	+ 9.93	- 1.45	0.83
South Dakota (84)	+ 367	- 0.0131	- 5.65	+ 2.15	0.75	+ 10	+ 0.0153	+ 5.42	- 1.83	0.76
Utah (72)	+ 361	- 0.0252	- 4.03	+ 1.57	0.56	- 141	+ 0.0436	+ 7.38	- 1.53	0.75
Virginia[2] (2)										
Washington (57)	+ 1021	- 0.0252	- 11.73	- 0.94	0.80	- 772	+ 0.0408	+ 10.77	+ 2.41	0.89
West Virginia[3] (13)										
Wisconsin (88)	+ 571	- 0.0289	- 3.04	- 1.16	0.90	- 112	+ 0.0177	+ 4.52	- 0.15	0.91
Wyoming (76)	+ 667	- 0.0185	- 3.47	- 1.55	0.64	- 216	+ 0.0341	+ 5.70	- 0.06	0.76

* New England states: Vermont, New Hampshire, Massachusetts, Rhode Island, and Connecticut.

[1] Same as Pennsylvania

[2, 3] Same as Maryland

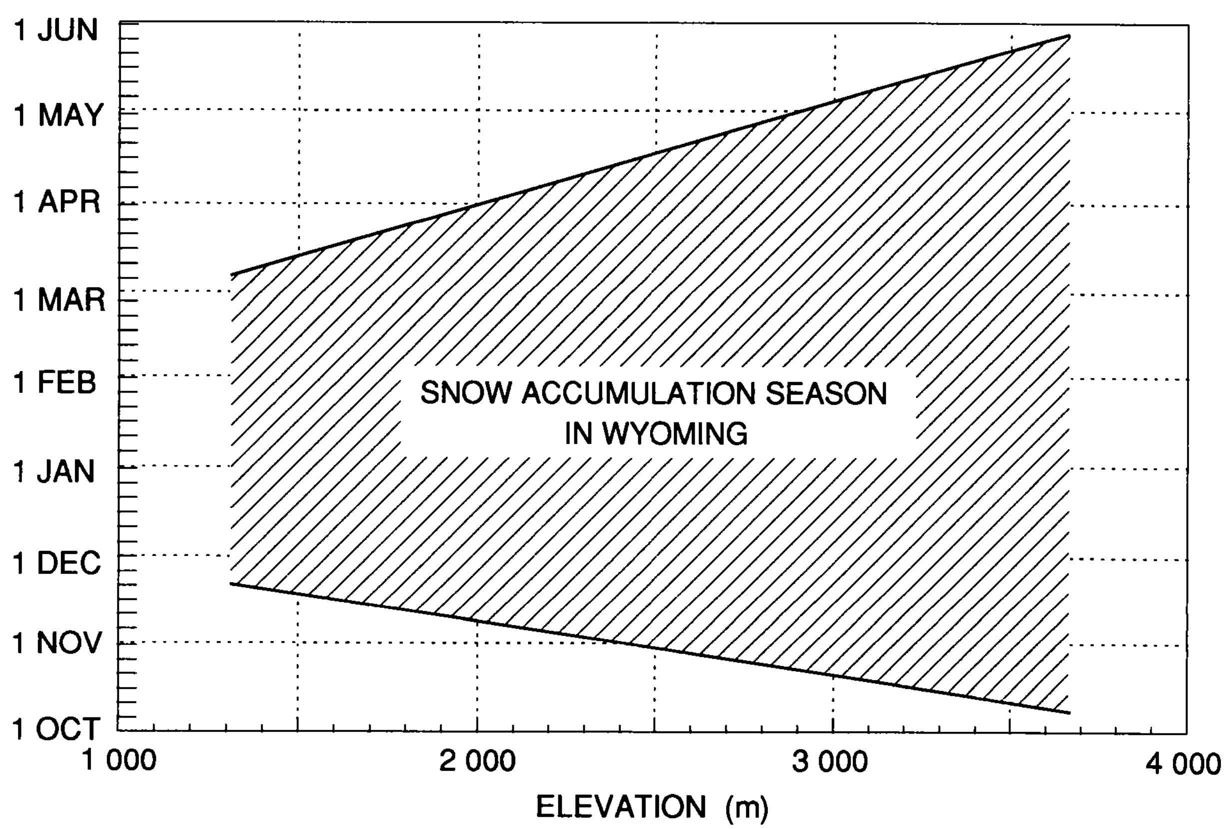

Figure 4.7. How the dates of the snow accumulation season vary with elevation in Wyoming, as derived by using the coefficients in Table 4.1 and latitude and longitude at the center of the state (Tabler 1988).

4.7.3 Calculating Potential Snow Transport from Wind Speed Records

4.7.3.1 Calculating Q_{upot} for Each Wind Direction

The following procedure is used to calculate potential transport for each month within the snow accumulation season, using the tabulation of wind direction/wind speed frequencies described in section 4.6.3.2.

Because anemometers are often installed at some height other than the standard 10 m (33 ft), the first step is to calculate a correction factor to adjust wind speed to 10-meter height using the wind profile described in section 3.3.3. From Equation (3.3), the ratio of U_{10} to U_z, the wind speed at height Z, is

$$U_{10}/U_z = (10/Z)^{1/7} = C_u \tag{4.10}$$

where C_u is the factor used to correct recorded wind speeds at anemometer height Z to 10-m (33-ft) height.

The threshold wind speed for blowing snow varies with snow conditions, elevation, and temperature. For estimating potential transport, however, the lowest threshold speed should be used — about 20 km/h (12 miles/h). For all wind speed classes equal to or greater than this value, total transport to 5 m (16 ft) for the *j*th direction class, $q_{i,j}$ (kg/m), is calculated as

$$q_{i,j} = (f_{i,j})(D)(86400)[(C_u U_{i,j})^{3.8}]/233847 \tag{4.11}$$

where $f_{i,j}$ is the frequency of observations in the *i*th speed class and *j*th direction class, D is the number of days in the month that fall within the snow accumulation season as calculated in section 4.7.2, and $U_{i,j}$ is the mid-class wind speed in m/s. Total monthly potential transport for each wind direction class, $(Q_{upot})_j$, can then be computed as the sum of q_i for each direction.

Snow transport estimated in this manner has been shown to approximate closely snow accumulation measured behind tall snow fences at Prudhoe Bay, Alaska. (Tabler, Benson, et al. 1990).

Example (Buffalo, New York):

Given:

a) Snow accumulation season = December 8 - March 13
b) Wind data for December as shown in Table 4.2
c) Anemometer height = 6.1 m (20 ft)

Required: Calculate potential snow transport from the north in December, 11-16-knot wind speed class, and total potential transport from the north for the snow accumulation season.

Solution:

a) Mean wind speed for this class = 0.5(10.5 + 16.5) = 13.5 knots
b) $C_u = (10/6.1)^{1/7} = 1.073$
c) Factor to convert knots to m/s = 0.5145
d) $D = 24$ (days in December in snow accumulation season)
e) Therefore, from Equation (4.11):

$$q_{N,11\text{-}16} = (0.011)(24)(86400)[(1.073)(0.5145)(13.5)]^{3.8}/233847 = 201 \text{ kg/m } (135 \text{ lbs/ft})$$

Total potential transport from north = sum of transport over all wind speed classes and all months = 336 + ... = 1400 kg/m (941 lbs/ft) (Table 4.3)

Table 4.2. Wind speed at 6.1 m (20 ft) versus direction at Buffalo, New York, December 1965-74.

Wind azimuth	Direction	Wind speed class (kts)									
		0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	>40	Total
(Degrees, true north)		Frequency of observation (%)									
348.75 - 011.25	N	0.40	1.30	1.90	1.10	0.20	0.00	0.00	0.00	0.00	4.90
011.25 - 033.75	NNE	0.10	0.50	0.80	0.60	0.00	0.00	0.00	0.00	0.00	2.00
033.75 - 056.25	NE	0.20	1.50	1.10	0.60	0.20	0.00	0.00	0.00	0.00	3.60
056.25 - 078.75	ENE	0.30	1.30	1.50	1.10	0.30	0.10	0.00	0.00	0.00	4.60
078.75 - 101.25	E	0.40	1.90	2.90	3.30	0.20	0.05	0.00	0.00	0.00	8.75
101.25 - 123.75	ESE	0.10	1.20	1.60	0.20	0.00	0.00	0.00	0.00	0.00	3.10
123.75 - 146.25	SE	0.40	0.80	1.50	0.20	0.00	0.00	0.00	0.00	0.00	2.90
146.25 - 168.75	SSE	0.40	1.00	2.10	0.50	0.05	0.00	0.00	0.00	0.00	4.05
168.75 - 191.25	S	0.40	2.60	2.70	2.00	0.40	0.00	0.05	0.00	0.00	8.15
191.25 - 213.75	SSW	0.30	1.30	1.80	2.80	1.00	0.20	0.00	0.00	0.00	7.40
213.75 - 236.25	SW	0.10	1.10	1.40	2.50	1.00	0.40	0.10	0.05	0.00	6.65
236.25 - 258.75	WSW	0.10	0.80	2.30	2.70	1.70	1.20	0.30	0.05	0.00	9.15
258.75 - 281.25	W	0.10	1.50	4.40	7.10	3.20	0.90	0.00	0.00	0.00	17.20
281.25 - 303.75	WNW	0.20	1.00	2.50	2.70	0.80	0.20	0.00	0.00	0.00	7.40
303.75 - 326.25	NW	0.00	0.60	1.50	1.20	0.30	0.00	0.00	0.00	0.00	3.60
326.25 - 348.75	NNW	0.10	0.80	1.40	1.60	0.60	0.05	0.00	0.00	0.00	4.55
000.00 - 360.00		3.60	19.20	31.40	30.20	9.95	3.10	0.45	0.10	0.00	98.00

Table 4.3. Potential snow transport versus direction at Buffalo, New York, December 8-31.

Wind azimuth	Direction	Wind speed class (kts)									
		0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	>40	Total
(Degrees, true north)		Kilograms per meter									
348.75 - 011.25	N	0	0	0	201	134	0	0	0	0	336
011.25 - 033.75	NNE	0	0	0	110	0	0	0	0	0	110
033.75 - 056.25	NE	0	0	0	110	134	0	0	0	0	244
056.25 - 078.75	ENE	0	0	0	201	201	176	0	0	0	579
078.75 - 101.25	E	0	0	0	604	134	88	0	0	0	827
101.25 - 123.75	ESE	0	0	0	37	0	0	0	0	0	37
123.75 - 146.25	SE	0	0	0	37	0	0	0	0	0	37
146.25 - 168.75	SSE	0	0	0	92	34	0	0	0	0	125
168.75 - 191.25	S	0	0	0	366	268	0	203	0	0	838
191.25 - 213.75	SSW	0	0	0	513	671	353	0	0	0	1537
213.75 - 236.25	SW	0	0	0	458	671	705	405	422	0	2662
236.25 - 258.75	WSW	0	0	0	495	1141	2116	1216	422	0	5391
258.75 - 281.25	W	0	0	0	1300	2148	1587	0	0	0	5036
281.25 - 303.75	WNW	0	0	0	495	537	353	0	0	0	1384
303.75 - 326.25	NW	0	0	0	220	201	0	0	0	0	421
326.25 - 348.75	NNW	0	0	0	293	403	88	0	0	0	764
000.00 - 360.00		0	0	0	5532	6678	5467	1824	845	0	20347

Table 4.4. Potential snow transport versus direction at Buffalo, New York, December 8-March 14.

Wind azimuth	Direction	Wind speed class (kts)									
		0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	>40	Total
(Degrees, true north)		Kilograms per meter									
348.75 - 011.25	N	0	0	0	903	497	0	0	0	0	1400
011.25 - 033.75	NNE	0	0	0	616	39	0	0	0	0	635
033.75 - 056.25	NE	0	0	0	499	339	0	0	0	0	838
056.25 - 078.75	ENE	0	0	0	1027	571	496	0	0	0	2094
078.75 - 101.25	E	0	0	0	1626	913	316	0	0	0	2855
101.25 - 123.75	ESE	0	0	0	236	126	0	118	0	0	481
123.75 - 146.25	SE	0	0	0	170	20	0	0	0	0	189
146.25 - 168.75	SSE	0	0	0	382	93	0	0	0	0	474
168.75 - 191.25	S	0	0	0	990	1112	662	465	0	0	3229
191.25 - 213.75	SSW	0	0	0	1784	2106	1677	0	0	0	5567
213.75 - 236.25	SW	0	0	0	1996	4524	3768	1525	1514	960	14287
236.25 - 258.75	WSW	0	0	0	3344	8911	12287	6453	2011	1054	34061
258.75 - 281.25	W	0	0	0	5587	9944	10600	2762	1091	0	29985
281.25 - 303.75	WNW	0	0	0	2099	3508	1740	737	0	0	8083
303.75 - 326.25	NW	0	0	0	939	759	259	0	0	0	1957
326.25 - 348.75	NNW	0	0	0	768	864	410	0	0	0	2061
000.00 - 360.00		0	0	0	22965	34347	32215	12060	4616	2014	108217

4.7.3.2 Determining Relevant Snow Transport and Prevailing Direction

Knowing the orientation of the road at the problem site, the directions contributing significant transport are readily apparent from the tabulation of transport by direction, as given for the example in Table 4.4. The transport is then summed over the directions of interest, and a mean drifting direction is calculated, as illustrated in the following example.

Example (Buffalo, New York):

Given: a) Table 4.4
b) Road orientation north/south

Required: a) Relevant directions of snow transport,
b) Total transport for relevant directions,
c) Prevailing transport direction.

Solution: a) Directions of interest would be SSW through WNW.

b) Total transport for relevant directions =
Q_{upot} = 5567 + 14287 +...+ 2061 = 91 983 kg/m (61,817 lb/ft)

c) Prevailing transport direction:

[(202.5)(5567) + (225)(14287) +...+ (292.5)(8083)]/91983 = 253° azimuth.

Comparing Tables 4.2 and 4.3 demonstrates that the directional distribution of snow transport is often significantly different from the prevailing wind direction. The prevailing wind direction at Buffalo in December is seen to be approximately due west, but the transport direction is about 253°. Another example is shown by the wind records for Charlottetown, Prince Edward Island, where analysis of Q_{upot} indicates that about half of the total snow transport is associated with northerly winds, and half with westerlies (Figure 4.8). This nearly equal bimodal distribution is not readily apparent from the wind distribution itself. This example underscores the importance of analyzing wind data on the basis of potential snow transport, rather than using the wind distribution itself. It must also be recognized that in cases where the "problem storm" is always associated with snowfall, the direction may not be evident from the potential transport analysis. Results from the quantitative analysis recommended here should always be checked for consistency with the reports of field maintenance personnel.

For maximum effectiveness, drift control measures such as snow fences must provide protection for a *range* of wind directions. The directional distribution exemplified by Table 4.4 provides the quantitative information necessary to specify how far fences should overlap the protection limits.

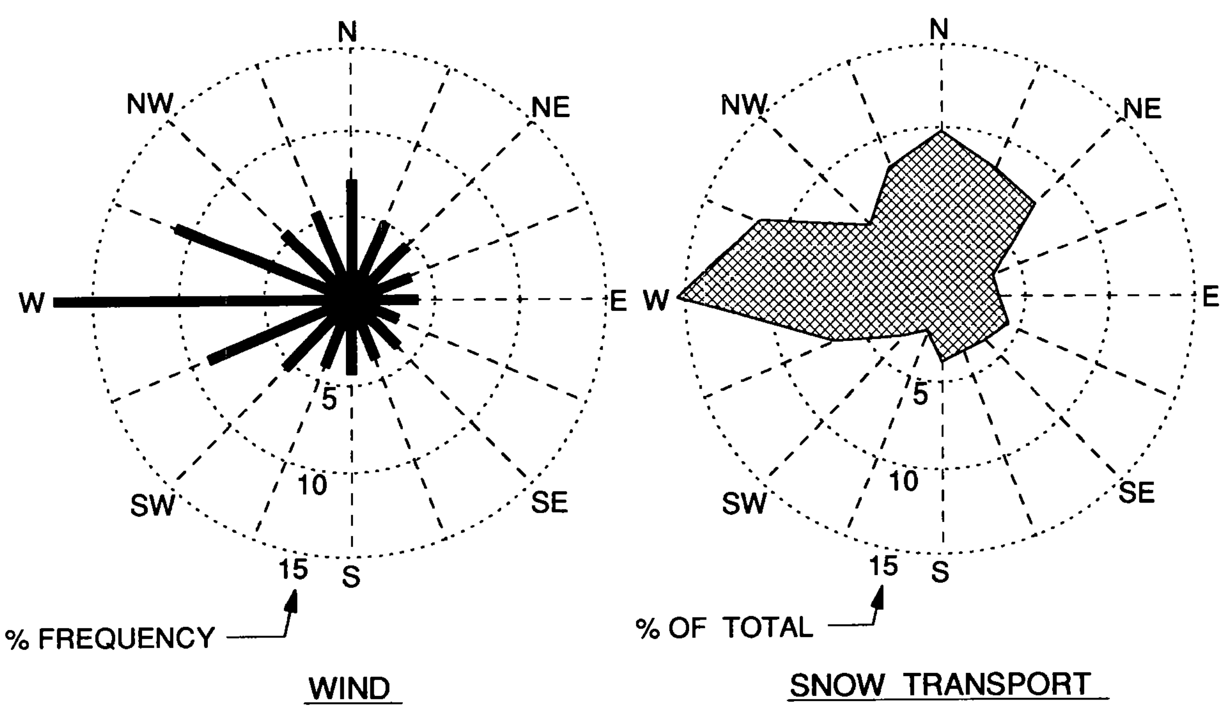

Figure 4.8 Directional distribution of wind and potential snow transport (Q_{upot}) at Charlottetown, Prince Edward Island.

4.7.4. Determining Potential Transport Based on Snowfall (Q_{spot})

In especially windy areas such as occur in Montana and Wyoming, potential transport calculated from wind records, Q_{upot}, is much greater than actual transport because there are frequent periods in the winter where no snow is available for relocation by the wind. One method to determine if snowfall, rather than wind, is the limiting factor, is to use Equation (4.4) to calculate the transport, assuming that all snowfall is relocated by the wind over an unlimited fetch.

4.7.4.1 Estimating Average Snowfall Water-Equivalent

The recommended method of estimating snowfall water-equivalent, S_{we}, is to calculate the total snowfall received during the snow accumulation season, and divide this value by 10 to obtain water-equivalent (Equation (4.2)). Snowfall over the accumulation season is estimated by assuming that the contributions of the first and last months are in proportion to the number of days in the month that fall in the snow accumulation season.

Snowfall water-equivalent can also be estimated from *precipitation* data for locations where all of the winter precipitation is in the form of snow; however, the following example illustrates that precipitation data should not be used to estimate S_{we} in locations where rain occurs during the snow accumulation season.

Example (Buffalo, New York):

Given: a) Snow accumulation season = December 8 to March 14 (section 4.7.2)
b) Climatological data:

	Mean monthly snowfall					Mean monthly precipitation			
	Dec	Jan	Feb	Mar		Dec	Jan	Feb	Mar
cm	58	63	45	29	mm	86	76	61	74
in.	23	25	18	11	in.	3.4	3.0	2.4	2.9

Required: Snowfall water-equivalent (S_{we}) over snow accumulation season from
a) Snowfall data
b) Precipitation data
c) Best estimate of S_{we} for designing control measures

Solution: a) From snowfall data and Equation (4.2):
Snowfall for season =
$$(24/31)(58) + 63 + 45 + (14/31)(29) = 166 \text{ cm (65 in.)}$$
S_{we} = 166/10 = 16.6 cm = 166 mm (6.5 in.)

b) From precipitation data:
S_{we} = (24/31)(86) + 76 + 61 + (14/31)(74) = 237 mm (9.3 in.)

c) Rain occurs during winter. Best estimate of S_{we} = 166 mm (6.5 in.)

The preceding example illustrates the importance of distinguishing between snowfall water-equivalent and precipitation.

Where data are not available for a problem location, various regression techniques can be used to estimate precipitation by using data from other stations. In locations where precipitation is known to increase with elevation, for example, precipitation can be plotted against the elevations of the nearest stations to generate estimates at the problem location.

Where available, winter precipitation can be estimated from peak snowpack water-equivalent for snow courses as reported by the U.S. Soil Conservation Service. As described in section 4.6.3.4, these data are preferable to snowfall data reported by the National Weather Service because snow course data are less subject to wind-caused measurement errors.

4.7.4.2 Calculating Potential Snow Transport Based on Snowfall

The potential transport based on snowfall data, Q_{spot}, is calculated from Equation (4.4) where S_{we} is in millimeters, T is in meters, and Q_{spot} is in kg/m

$$Q_{spot} = 0.5\ T\ S_{we}$$

Standard practice is to assume that the maximum transport distance, T, is equal to 3000 m (section 3.4.6). It is kept as a distinct variable throughout this guide, however, to allow other values to be used if indicated by future research.

Example (Buffalo, New York):

Given: a) Snowfall water-equivalent (S_{we}) = 166 mm (6.5 in.)
b) Assume T = 3000 m (10,000 ft)

Required: Potential snow transport from snowfall data (Q_{spot})

Solution: Equation (4.4):
$Q_{spot} = 0.5\ T\ S_{we} = (0.5)(3000)(166) = 249\ 000$ kg/m (167,340 lbs/ft)

4.7.5 *Determining Potential Snow Transport for Infinite Fetch*

If potential transport calculated from the snowfall data (Q_{spot}) is greater than that calculated from wind data (Q_{upot}), then wind is the primary factor limiting transport and

$$\text{If } Q_{spot} > Q_{upot}\text{:} \quad Q_{inf} = Q_{upot} \tag{4.12}$$

If $Q_{spot} < Q_{upot}$, then potential transport is given by Equation (3.11). For Q_{inf} in kg/m, T in meters, and S_{rwe} in millimeters,

$$\text{If } Q_{spot} < Q_{upot}\text{:} \quad Q_{inf} = 0.5\ T\ S_{rwe} \tag{4.13}$$

This calculation requires an estimate for the *relocated* snow water-equivalent, S_{rwe}. Studies have shown that even in the windiest areas, only 70% of the winter snowfall is relocated by the wind (section 3.4.6), and this proportion can be assumed if a conservative design is desirable or acceptable. The alternative is to estimate the water-equivalent of the snow cover at the end of the snow accumulation season by actual snow measurements over the fetch, or by assuming that the depth of the snow retention will equal the height of the vegetation on the fetch. As a rough approximation, it can be assumed that the density of the retained snow will average 250 kg/m^3 (15.6 lbs/ft^3).

Example (Buffalo, New York):

Given: a) Road oriented north/south
b) Relevant Q_{upot}=91 983 kg/m (61,817 lb/ft) (section 4.7.3.2)
c) Q_{spot}=249 000 kg/m (167,340 lb/ft) (section 4.7.4.2)
d) Snowfall water-equivalent (S_{we}) = 166 mm = 16.6 cm (6.5 in.) (section 4.7.4.1)
e) Average height of vegetation over fetch = 30 cm (12 in.)

Required: Potential snow transport for infinite fetch (Q_{inf})

Solution: Equation (4.12):
$Q_{spot} > Q_{upot}$; therefore, $Q_{inf} = Q_{upot}$ = 91 983 kg/m (61,817 lb/ft)

If Q_{spot} had *not* been greater than Q_{upot}, then
Assume snow density = 250 kg/m^3 (specific gravity = 0.25)
Then relocated snowfall S_{rwe} = 166 - 0.25(300) = 91 mm (3.6 in.)
From Equation (4.13):
Q_{inf} = (0.5)(3000)(91) = 136 500 kg/m (91,734 lb/ft)

4.7.6 Estimating Mean Annual Snow Transport

4.7.6.1 Transport Equation

The mean annual snow transport, $Q_{t,ave}$, at the problem location is estimated using Equation (4.7):

$$Q_{t,ave} = Q_{inf}\,(1 - 0.14^{F/T})$$

where the parenthetical term corrects for fetch, F. T is customarily taken as 3000 m (10,000 ft), and F is determined as described in the following section.

4.7.6.2 Determining the Fetch

The prevailing snow transport direction determined from the potential snow transport analysis may not be applicable to the problem location. This depends on the proximity of the weather station and how local topography may affect wind direction. The prevailing transport direction as calculated in section 4.7.3.2 should therefore be confirmed by field observations and aerial photographs, as described in section 4.6.1.3.

After the prevailing transport direction has been verified, the fetch can be measured from aerial photographs, topographic maps, or in the field. The fetch is measured from the location to be protected to the nearest upwind boundary that defines the limits of snow transport. As described in chapter 3, examples of boundaries include forest margins, stream channels or other depressions where large drifts form, tall brush, or shorelines of open bodies of water. Where the fetch is extensive and has no well-defined boundary, F is assumed to be infinite and the quantity $0.14^{F/3000}$ becomes zero.

Example (Buffalo, New York):

Given: a) Q_{inf}=91 983 kg/m (61,817 lbs/ft)(section 4.7.5)
b) Use standard assumption that T = 3000 m (10,000 ft)

Required: Calculate average annual transport $Q_{t,ave}$ for:
a) Fetch = 500 m (1640 ft)
b) Fetch = infinite

Solution: Equation(4.7): $Q_{t,ave} = Q_{inf}(1 - 0.14^{F/T})$

a) For F=500 m, $Q_{t,ave} = 91\ 983(1 - 0.14^{500/3000}) = 91\ 983(1 - 0.14^{0.1667})$
$= 91\ 983(1 - 0.7206) = 25\ 700$ kg/m (17,272 lb/ft)

b) For F = infinite, $Q_{t,ave} = 91\ 983(1-0) = 91\ 983$ kg/m (61,817 lb/ft)

4.7.6.3 Snow Transport Classification

Table 4.5 presents a severity classification for blowing snow, based on a logarithmic scale of snow transport. This classification places the blowing snow problem in perspective, and provides a framework for generalizing the control measure guidelines in subsequent chapters.

For the Buffalo, New York example, a site that has a 500-m fetch could be ranked in Class 3: light-to-moderate. The site with an unlimited fetch would be ranked in Class 5: moderately severe.

Table 4.5 Severity classification for mean annual snow transport.

Class	Snow transport (t/m)	Description
1	<10	Very light
2	10 - 20	Light
3	20 - 40	Light-to-moderate
4	40 - 80	Moderate
5	80 - 160	Moderately severe
6	160 - 320	Severe
7	>320	Extreme

1 t/m = 0.3357 tons/ft

4.8 Determining Design Transport

Having estimated the mean annual snow transport, $Q_{t,ave}$, the next question is "What is the optimum design year?" Should the storage capacity provide complete control during a winter that has an above-average transport? If so, what is the best design year — one that occurs 2 years out of 10? One year out of 10? This same question is addressed when designing culverts and other hydraulic structures. In the case of snow control measures, however, the problem is complicated by the fact that even though transport may exceed the design capacity in some years, irrevocable benefits still accrue up to the time the capacity is exceeded. In addition, exceeding the design year usually does not have catastrophic consequences — it simply means that more money is spent for mechanical snow removal.

The ratio of "design year" snow transport to the average snow transport is called the "design modulus," and is represented in this guide as K. Multiplying the average annual transport, $Q_{t,ave}$, by the design modulus gives the *design transport*, Q_{des}:

$$Q_{des} = K\ Q_{t,ave} \tag{4.14}$$

If $K = 1$, for example, the storage capacity of the system is exactly equal to the average annual snow transport. If $K = 0.5$, storage capacity would be half of the mean annual snow transport. The discussion here is intended to help the designer select an appropriate design modulus for snow control projects.

4.8.1 Probability Distribution for Annual Snow Transport

Until more information becomes available, the following working hypothesis is proposed (Tabler and Jairell 1993):

The modular coefficients of annual snow transport are normally distributed with mean 1.0 and variance 0.088.

This distribution has been shown to apply to a variety of hydrologic variables, including annual streamflow (Markovic 1965), peak annual snow accumulation throughout Wyoming (Tabler 1988), and snow transport for the easterly winds at Prudhoe Bay, Alaska (Tabler, Benson et al. 1990). The probability distribution for annual snow transport is therefore given by

$$F(K) = (s(2\pi)^{0.5})^{-1} \int_{-\infty}^{k} \exp\{-(K-1)^2/2s^2\}dK \tag{4.15}$$

where

K = design modulus ($Q_{des}/Q_{t,ave}$),
$F(K)$ = frequency (F not to be confused with fetch), and
s^2 = variance.

Exceedance probabilities calculated from Equation (4.15) are presented in Table 4.6. To illustrate interpretation of this table, snow transport 50% greater than the long-term average (K = 1.50) would be expected to occur about 5 years out of 100. The design coefficient, K, can be taken directly from this table for any desired return period. In the following section, the design coefficient will be related to the benefit-to-cost ratio.

Table 4.6 Probabilities of larger values for annual snow transport, expressed as design modulus *K*. Values are 1 - *F(K)*, where *F(K)* is given by Equation (4.15) with s^2 = 0.088 (Tabler 1982).

K	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	.9996	.9996	.9995	.9995	.9994	.9993	.9992	.9991	.9990	.9989
0.1	.9988	.9987	.9985	.9983	.9981	.9979	.9977	.9974	.9971	.9968
0.2	.9965	.9961	.9957	.9953	.9948	.9943	.9937	.9931	.9924	.9917
0.3	.9909	.9900	.9891	.9880	.9870	.9858	.9845	.9832	.9817	.9801
0.4	.9784	.9766	.9747	.9727	.9705	.9681	.9656	.9630	.9602	.9572
0.5	.9541	.9507	.9472	.9434	.9395	.9354	.9310	.9264	.9216	.9165
0.6	.9112	.9057	.8999	.8939	.8875	.8810	.8741	.8670	.8596	.8520
0.7	.8441	.8359	.8274	.8186	.8096	.8003	.7908	.7809	.7708	.7605
0.8	.7499	.7391	.7280	.7167	.7052	.6934	.6815	.6694	.6571	.6446
0.9	.6320	.6192	.6063	.5933	.5801	.5669	.5536	.5403	.5269	.5134
1.0	.5000	.4866	.4731	.4597	.4464	.4331	.4199	.4067	.3937	.3808
1.1	.3680	.3554	.3429	.3306	.3185	.3066	.2948	.2833	.2720	.2609
1.2	.2501	.2395	.2292	.2191	.2092	.1997	.1904	.1814	.1726	.1641
1.3	.1559	.1480	.1404	.1330	.1259	.1190	.1125	.1061	.1001	.0943
1.4	.0888	.0835	.0784	.0736	.0690	.0646	.0605	.0566	.0528	.0493
1.5	.0459	.0428	.0398	.0370	.0344	.0319	.0295	.0273	.0253	.0234
1.6	.0216	.0199	.0183	.0168	.0155	.0142	.0130	.0120	.0109	.0100
1.7	.0091	.0083	.0076	.0069	.0063	.0057	.0052	.0047	.0043	.0039
1.8	.0035	.0032	.0029	.0026	.0023	.0021	.0019	.0017	.0015	.0013
1.9	.0012	.0011	.0010	.0009	.0008	.0007	.0006	.0005	.0005	.0004
2.0	.0004	.0003	.0003	.0003	.0002	.0002	.0002	.0002	.0001	.0001

4.8.2 *How Snow Removal Cost Varies with the Design Modulus*

The probability distribution described in section 4.8.1 allows an economic analysis to determine how the benefit-to-cost ratio varies with design year. If benefits are derived solely from the savings in expenditures for mechanical snow removal, benefits will be proportional to the snow-trapping efficiency of the control measures.

Figure 4.9 shows the long-term reduction in snow removal costs in relation to design modulus and exceedance probability, obtained by computing the average trapping efficiency for all possible snow transport amounts weighted by their probability of occurrence using the frequency distribution in section 4.8.1. Because of the extremely small exceedance probabilities associated with $K > 2$, the only range of practical interest is $K \leq 2$. Over this range, the long-term reduction in snow removal costs, C_{red}, is approximated by

$$C_{red} = 142.9K - 76.28K^2 + 13.91K^3; \quad K \leq 2 \tag{4.16}$$

Using the average winter as the design year (capacity exceeded in 50 years out of 100) reduces snow removal costs by about 80%. Doubling the storage capacity reduces costs by only another 12% or so.

Figure 4.9 can be used to select a design coefficient yielding a specified reduction in costs.

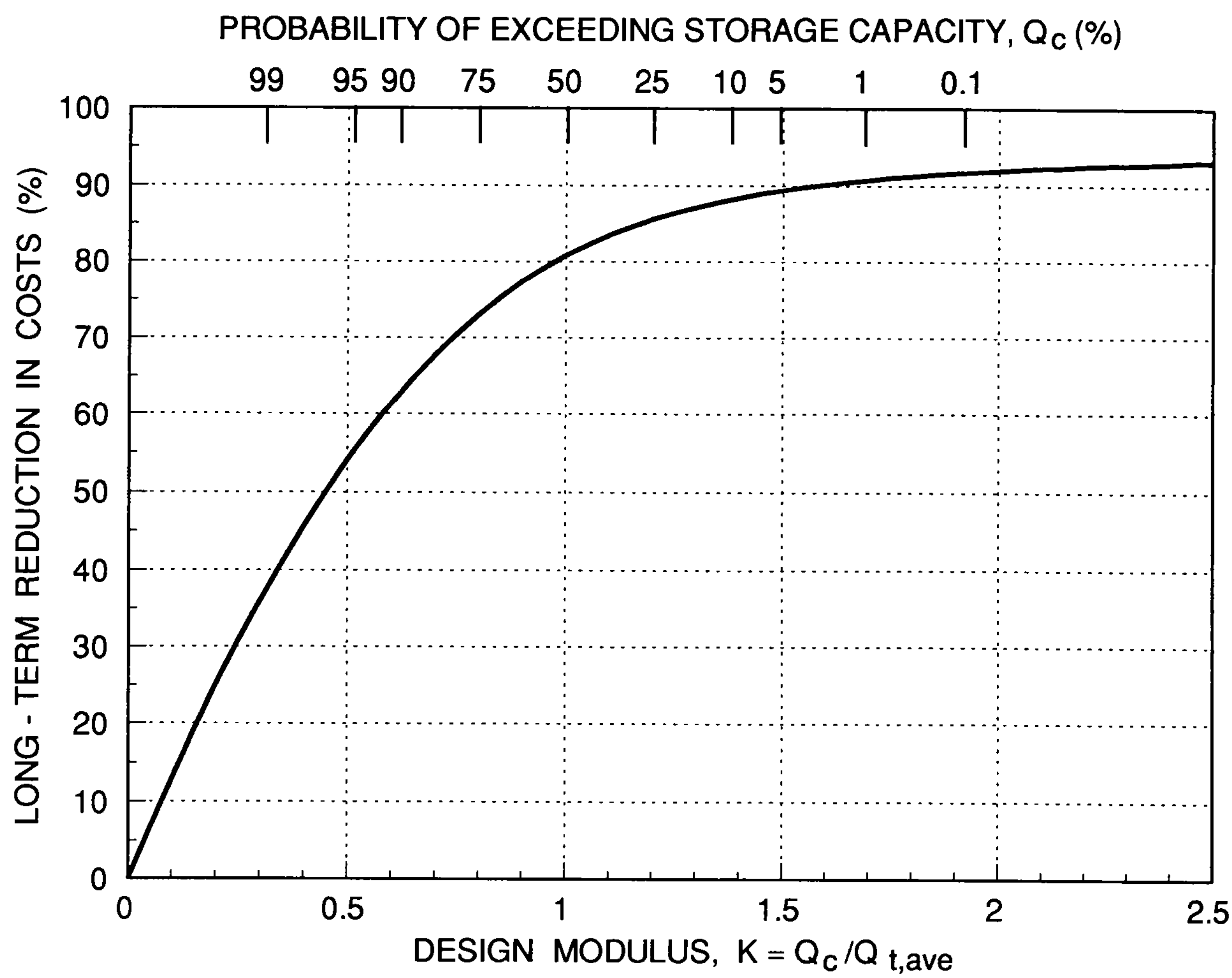

Figure 4.9 Long-term reduction in snow transport as a function of design year (Tabler and Jairell 1993).

Example: Buffalo, New York:

Given: a) Fetch F - 500 m (1640 ft)
b) Average annual snow transport $Q_{t,ave}$ =
25 700 kg/m = 25.7 t/m (8.6 tons/ft)

Required: a) Design transport Q_{des} for average year,
b) Design transport Q_{des} for exceedance in 1 year out of 10
c) Design transport Q_{des} required to reduce snow removal costs 90%.

Solution: Equation (4.14): $Q_{des} = KQ_{t,des}$
a) For average year, probability of exceedance = 0.5.
From Table 4.6, K = 1.0.
Therefore, $Q_{des} = (1.0)Q_{t,tave}$ = 25.7t/m (8.6 tons/ft)

b) For exceedance 1 year in 10, probability = 0.1000.
From Table 4.6, K = 1.38.
Therefore, $Q_{des} = (1.38)Q_{t,tave}$ = (1.38)(25.7) =
35.5t/m (11.9 tons/ft)

c) For 90% reduction in snow removal costs, K=1.6 (from Figure 4.9)
Therefore, $Q_{des} = (1.6)Q_{t,tave}$ = (1.6)(25.7) = 41.1t/m (13.8 tons/ft)

4.8.3 Benefit-to-Cost Criterion for Design Modulus

Considering only benefits from reduced snow removal expenditures, the expected annual snow removal benefit, B_{sr}, from a snow fence system is given by

$$B_{sr} = C_{sr}C_{red}KQ_{t,ave}/100 \quad (4.17)$$

where C_{sr} is the unit cost for mechanical snow removal, and C_{red} is the percent reduction in snow deposited on the road. If, without the snow fence, all of the blowing snow would be deposited on the road, then C_{red} is equal to the long-term trapping efficiency of the fence. Although hardly realistic, this simplifying assumption provides a valid basis for determining the optimum design modulus.

As described in chapter 3, the storage capacity of 50% porous snow fence varies with the effective fence height H (in meters), according to

$$Q_c = 8.5\ H^{2.2} \quad (4.18)$$

where Q_c is in metric tons per meter of fence length. As will be presented in section 5.3.2.1., the design transport is the required snow storage capacity of the snow fence, so that

$$Q_c = Q_{des} = KQ_{t,ave}$$

Because snow fence construction cost increases linearly with height, average annual cost of a snow fence system is therefore related to the design modulus and average annual snow transport according to

$$C_{sf} = O + a_{it}I = O + a_{it}P_fH_{req} = O + a_{it}P_f(KQ_{t,ave}/8.5)^{1/2.2} \qquad (4.19)$$

where

C_{sf} = average annual cost of snow fence system,
O = annual maintenance expense,
a_{it} = annual capital charge per dollar of fixed investment for interest i and amortization period t,
I = fixed capital investment for snow fence,
H_{req} = fence height required to store design transport,
P_f = capital investment cost per square meter of fence frontal area (cost per meter of length divided by height).

The annual capital charge per dollar of fixed investment, a_{it}, is given by

$$a_{it} = i/[1 - (1 + i)^{-t}] \qquad (4.20)$$

where i and t are interest rate and amortization period, respectively (Burington 1948).

Figure 4.10 shows how the benefit-to-cost ratio varies with average annual snow transport $Q_{t,ave}$ and cost of mechanical snow removal, for the following typical conditions:

i = 7%
t = 25 years
P_f = \$15 per square meter
Q_c = $Q_{t,ave}$
O = 5% of initial capital investment

Figure 4.11 shows how benefit/cost ratio varies with design modulus K, if:

i = 7%
t = 25 years
P_f = \$15 per meter of height
$Q_{t,ave}$ = 60 tons per meter
O = 5% of initial capital investment
C_{sr} = \$5 per ton

For all values of $Q_{t,ave}$, O, P_f, i, and t, the benefit-to-cost ratio reaches a maximum at approximately $K = 0.90$; that is, when storage capacity equals 90% of mean annual snow transport.

If the snow control objective is solely to reduce expenditures for mechanical snow removal, designing snow fence capacity equal to mean annual snow transport ($K = 1$) is economically reasonable, and a value of 1.0 should be used in the absence of other criteria. However, a more stringent criterion might be warranted for those projects where safety improvement was an objective.

Example: Buffalo, New York:

Given: a) Fetch $F=$ m (1640 ft)

b) Average annual snow transport $Q_{t,ave}$ = 25,700 kg/m = 25.7 t/m (8.6 tons/ft)

c) Design modulus K = 1.0; Q_{des} = 25.7 t/m (8.6t/ft)

d) Fence height required (H_{req}): 1.65 m (5.4 ft)

e) Cost for mechanical snow removal C_{sr} = \$2.50/t (\$2.75/ton)

f) Cost for snow fence and easement $P_f=$ \$21.50/m^2 (\$2.00/ft^2)

g) Annual maintenance cost O = 5% of investment = \$1.075/m^2 (\$0.10/ft^2)

h) Service life t = 25 years

i) Interest rate i = 6%

Required: a) Ratio of snow removal benefits to fence costs, assuming all blowing snow is deposited on road.

Solution: a) From Equation (4.20): a_{it} = 0.07823

b) Reduction in snow removal cost = C_{red} = 81% (from Figure 4.9)

c) Snow removal benefits B_{sr}, from Equation (4.17):

$B_{sr}=C_{sr}C_{red}Q_{des}/100=(2.50)(81)(25.8)/100$ = \$52.24/m

d) Snow fence costs C_{sf} from Equation (4.19):

$C_{sf}=O+A_{it}P_fH_{req}$ = (1.075)(1.65) + (0.07823)(21.50)(1.65) = 4.55\$/m

e) Snow removal benefits/fence costs = \$52.24/4.55 = 11.5 : 1

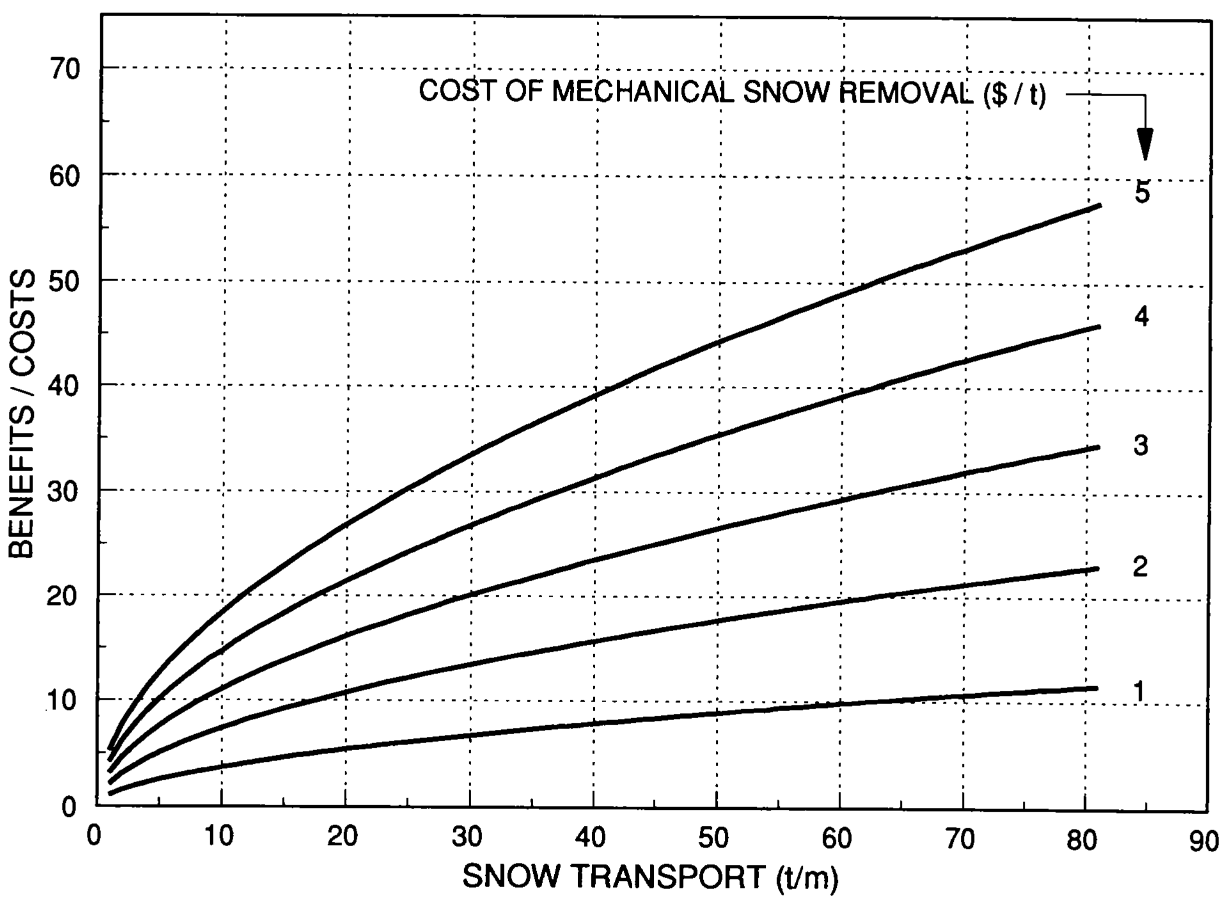

Figure 4.10. Benefit-to-cost ratio for snow fences, as a function of average annual snow transport, $Q_{t,ave}$, and cost of mechanical snow removal.

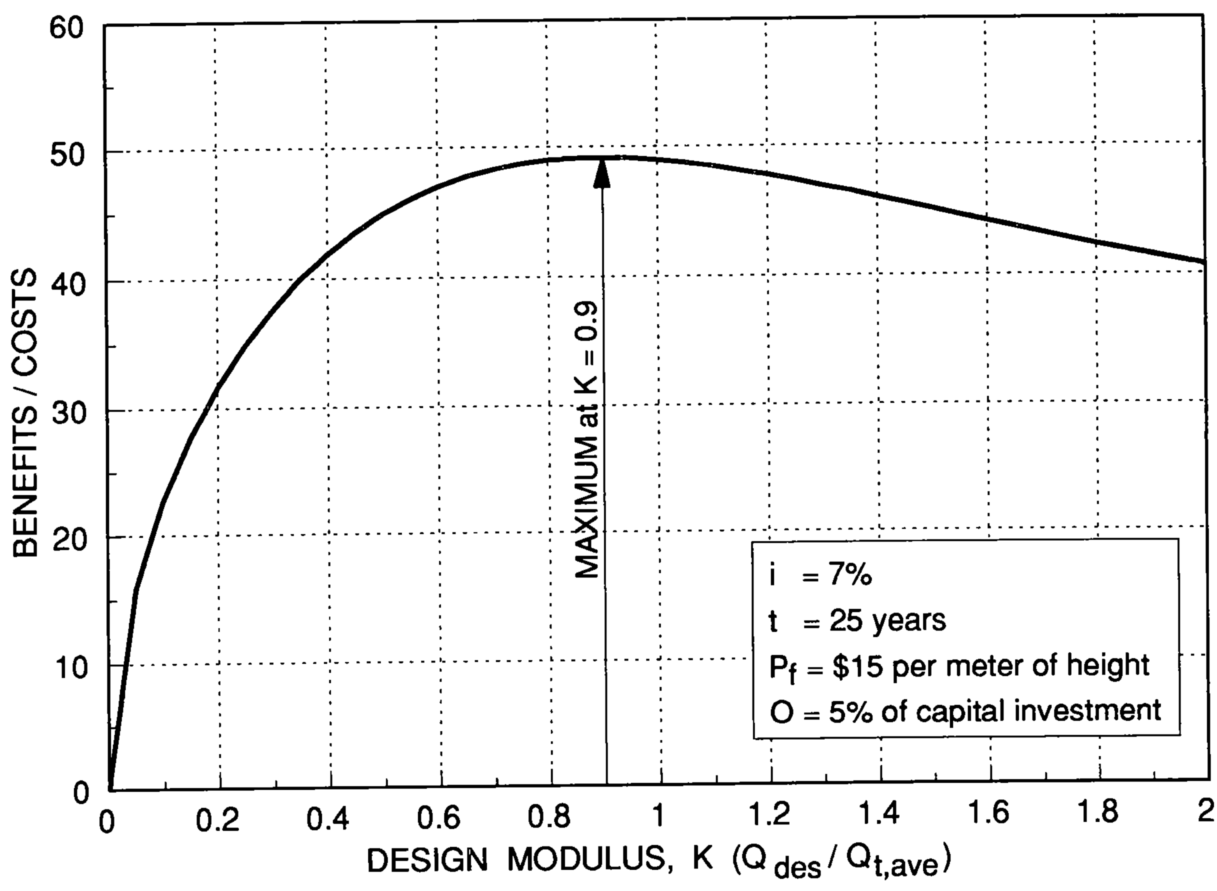

Figure 4.11. Benefit-to-cost ratio for snow fences, as a function of design modulus *K*, assuming \$5/t cost for mechanical snow removal and 60 t/m mean annual snow transport.

4.9 Design Data Summary Sheet

The following sheet provides a convenient format for summarizing the design parameters calculated in this chapter.

Drift Control Design Data

Site Name:____________________

Site I.D.:____________________

Snow Accumulation Season:____________________

Snowfall (S):____________________

Snowfall Water-Equivalent (S_{we}): ____________________

Seasonal Precipitation:____________________

Snow Relocation Coefficient (θ):____________________

Relocated Snowfall Water-Equivalent (S_{rwe}):____________________

Potential Snow Transport from Wind Records (Q_{upot}):____________________

Potential Snow Transport from Evaporation Equation (Q_{spot}):____________________

Relevant Potential Transport (Q_{inf}):____________________

Fetch (F):____________________

Mean Annual Snow Transport ($Q_{t,ave}$):____________________

Design Modulus (K):____________________

Design Snow Transport:____________________

Exceedance Probability:____________________

Relevant Transport Direction:____________________

Mean Drifting Direction (s):____________________

"Problem Storm" Direction (if any):____________________

Wind Speed Used for Structural Design:____________________

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5 Design and Placement of Structural Snow Fences

5.1 Scope

This chapter provides specific guidelines for designing and placing snow fences, based on the characteristics of snow transport and deposition described in chapter 3. The presentation assumes that the designer is familiar with the information in chapter 3, and has completed the basic calculations described in chapter 4.

There are two types of snow fences — those that trap snow upwind of the area to be protected (collectors), and those that change the velocity of the airflow so as to deflect snow around the protected area (deflectors). Collector-type fences are emphasized here, although some of the applications and design criteria for deflector-types are described in section 5.4.

5.2 Highlights

- Snow storage capacity of collector fences should be equal to the design transport, Q_{des}. This is the most important requirement for successful fences.

- The trapping efficiency of a snow fence, and thus its effectiveness, increases with its height.

- A single row of tall fence is more economical than multiple rows of shorter fence with the same total capacity. Required fence height is a function of fence porosity and the desired storage capacity.

- Fences that have a porosity ratio of 0.5 are the most efficient and hold the most snow, but less porous fences can reduce the required setback distance.

- A gap equal to about $H/10$ should be left under the fence to improve snow-trapping efficiency and prevent damage from snow settlement.

- Fences can be either surface mounted, like the Wyoming fence, or pole supported. Surface-mounted fences are usually the least expensive to build, but pole-supported fences are better able to resist snow creep on slopes. Less land area is occupied by pole-supported fences, and this type of construction is suitable for permafrost soils.

- The Wyoming fence is constructed of 15-cm wide horizontal boards that are spaced 10 to 15 cm apart and fastened to wooden trusses. It ranges in height from 1.8 to

4.3 m (6 to 14 ft). The top of the fence is inclined 15° downwind, and the bottom gap is equal to about *H*/8. Individual panels are 5 m (16 ft) long and are anchored with a system of reinforcing bar and U-shaped clips.

- Synthetic fencing materials will provide economical service if they are properly installed. Most plastic fencing materials are susceptible to abrasion and shear, so they must be properly tensioned and immobilized at vertical supports. Black plastics are most resistant to degradation by ultraviolet light because carbon black is an effective UV inhibitor.

- A rail 125 mm (5 in.) wide made from a polyolefin polymer with wires embedded in it can be used to build snow fences of any desired height and porosity. Important advantages include ease of construction, conformability to terrain irregularities, and resistance to damage caused by snow settlement.

- Transverse guys and braces should not be used to support snows fences because snow settlement and creep can impose damaging loads. Vertical supports should therefore be free-standing. Construction cost often increases as spacing between vertical supports increases.

- Wind loads on snow fences tabulated according to fence height and wind speed can be adjusted for fence porosity and environmental conditions using a simplified system of correction factors.

- Fences 2 m (6.6 ft) or taller should be used where summer land use requires temporary (seasonal) snow fences. A new panelized fence system has been developed by the Tensar Corporation.[1] This patented design consists of panels 2.4 m (8 ft) long made by tensioning plastic fencing across a wood frame. Individual panels are connected together with a system of U-clips and reinforcement bar pins. The Tensar Corporation will soon have available prefabricated panels 1.2 m × 1.8 m (4 ft × 6 ft) and weighing less than 4 kg (8.8 lb), that consist of heavy duty plastic fencing molded into a structural foam frame. These panels can be stacked to make a 2.4-m (8-ft) tall fence.

- Deflector fences such as the jet roof and *Kolktafeln* can be used to accelerate wind and prevent cornices from forming at the top of cut slopes.

- Blower fences are used in Japan to reduce snow deposition and improve visibility. These structures, which consist of multiple vanes to deflect the wind downward, must be placed close to the road because their effectiveness is limited to within 1.5 times their height.

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[1] The use of trade names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the National Research Council to the exclusion of others that may be suitable.

- A lateral deflector, such as a solid V-shaped fence pointing into the wind, creates a long, narrow, snow-free area downwind, with snowdrifts along the sides. Although useful for livestock shelters and to protect isolated structures, lateral deflectors have few applications for drift control on roads.

- Fences should be oriented parallel to the road if the prevailing transport direction is within 25° of being perpendicular to the road. For more oblique winds, they should be aligned perpendicular to the prevailing snow transport direction.

- Fences should be far enough from the road that the downwind drift does not extend onto the road. This distance is normally about 35 times the fence height for a fence with a porosity ratio of 0.5, but less for a more dense fence.

- Setback distance can be reduced by using a taller fence than is required for snow storage. In general, the required setback for a fence with storage capacity equal to twice the mean annual snow transport is 18 times its height. With this guideline, the probability of drift encroachment is approximately 1 year out of 100.

- For fences aligned at an angle to the road, stepping down the height at the end of a fence allows closer placement to the road.

- Fences should extend far enough beyond the protected area to intercept blowing snow from 30° on either side of the prevailing transport direction.

- Avoid even small gaps between fence panels. A space as little as 30 cm (12 in.) between Wyoming fence panels causes significant drift erosion and loss of storage capacity.

- Care should be taken to avoid creating dangerous transitions from protected to unprotected conditions at the ends of a fence system. Mitigation measures include: 1) tying in fences with natural features that reduce blowing snow, such as trees and brush; 2) filling in gaps between fence systems; and 3) phasing out protection by stepping down fence height, or increasing fence porosity, near fence ends.

5.3 Design of Collector Fences

The type of fence used depends on many factors, including the required snow storage capacity, fence height and porosity, permanency, terrain, soil conditions, wind loads, available materials, and construction costs. This section is organized to help the designer select the best type of fence for a particular application.

Placement requirements described in section 5.5 must be considered as part of the design process, and several iterations may be required before a design can be finalized. Because both fence porosity and height determine snow storage capacity and minimum setback distance, alternative combinations may have to be compared before the optimum design can be specified.

5.3.1 *Snow Storage Capacity*

The snow storage capacity of a snow fence system is the maximum quantity of snow that a fence system is designed to retain, and should be equal to the design transport, Q_{des}, calculated as described in chapter 4. *Adequate storage capacity is the most important requirement for a snow fence system, just as it is for hydraulic structures.* Sizing a snow fence is similar to determining the required capacity for a culvert, detention pond, or storm drain. After estimating how much blowing snow arrives at the prospective fence site, it is possible to specify the height and number of rows of fencing required to store this quantity of snow. As will be shown in section 5.3.2, a single row of tall fence is more economical than multiple rows of shorter fence that have the same storage capacity. Therefore, the usual approach is to calculate the required height of a single row of fence.

5.3.2 *Specifying Fence Height*

5.3.2.1 Calculating Required Structural Fence Height, $H_{s,req}$

Because both fence height and porosity affect snow storage capacity, the determination of required fence height may be an iterative process if placement constraints demand a specific equilibrium drift length. The usual procedure, however, is to begin by determining the required height for a porosity ratio of 0.5. For maximum efficiency, porosity should be in the range of 0.45 to 0.5.

Snow storage capacity varies with fence height and porosity ratio as indicated by Equation (3.25):

$$Q_c = (3 + 4P + 44P^2 - 60P^3)H^{2.2} \tag{5.1}$$

where H is in meters and Q_c is in tons per meter. Substituting Q_{des} for Q_c and solving for required effective fence height, H_{req},

$$H_{req} = [Q_{des} / (3 + 4P + 44P^2 - 60P^3)]^{0.455} \tag{5.2}$$

For the usual case where $P = 0.5$,

$$H_{req} = (Q_{des}/8.5)^{0.455} \tag{5.3}$$

Maintaining the distinction between the structural and effective heights, the required structural fence height, $H_{s,req}$, is given by

$$H_{s,req} = H + \text{ambient snow depth} \tag{5.4}$$

Required fence heights for different snow transport severity classes are shown in Table 5.1.

Example:

Given: Design transport Q_{des} = 50 t/m
Porosity ratio P = 0.5

Required: Fence height required to store design transport

Solution: Equations (5.2), (5.3): $H_{req} = [(50)/8.5]^{0.455} = 2.24$ m (7.3 ft)

Table 5.1 Required fence heights for the snow transport severity classes.

Classification	Snow transport (t/m)	Fence height (m)
Very Light	< 10	1.1
Light	10 - 20	1.5
Light-to-Moderate	20 - 40	2.0
Moderate	40 - 80	2.8
Moderately Severe	80 - 160	3.8
Severe	160 - 320	5.2
Extreme	> 320	> 5.2

1 t/m = 0.3357 tons/ft
1 m = 3.281 ft

5.3.2.2 Advantages of Tall Fences

The effectiveness of a snow fence increases with height not only because storage capacity is proportional to $H^{2.2}$, but also because the mechanics of snow deposition are such that most of the snow passing over the top of a fence escapes downwind. As shown in chapter 3, there is appreciable blowing snow at heights above 1 m (3.3 ft). More than one-third of the transport is above this height when there are 88-km/h (55-mile/h) winds, for example. Consequently, the percentage of total transport intercepted by a fence increases with fence height.

In general, it is more economical to build a single row of tall fence than multiple rows of shorter fence with the same total storage capacity. This is because over the range of heights commonly used, the cost of building a fence is approximately proportional to fence height, whereas storage capacity increases as $H^{2.2}$. Past construction projects in Wyoming support this generalization. As shown in Figure 5.1, a 3.66-m (12-ft) fence costs less than one-third as much as an equivalent system consisting of 4 rows of 1.8-m (6-ft) fence, and one row of 1.2-m (4-ft) fence.

Costs for easements or land acquisition are usually less for a single tall fence than for multiple rows of shorter fence because less land area is occupied. For example, a single 3.66-m (12-ft) fence would typically be placed about 35*H*, or 128 m (420 ft), from the shoulder of the road. Because the recommended spacing between multiple rows of fence is 25*H* (section 5.5.3), if four rows of 1.8-m fence were used, the fence furthest upwind would have to be placed $(3 \times 1.8 \times 25) + (35 \times 1.8) = 198$ m (650 ft) from the shoulder.

Other advantages of using a single tall fence include a lower rate of snowmelt runoff (because of the differences in surface area/volume ratios), and reduced visual impact because of fewer fence lines and placement farther from the road.

On agricultural land, however, snowdrifts can delay planting in the spring. The time required for a drift to melt is directly proportional to its depth, and thus to fence height. The melt-out date for drifts can be estimated from climatological data using the relationship

$$\text{Melt rate of snowdrifts: } 1 \text{ cm depth} / {}^\circ\text{C-day} \tag{5.5}$$

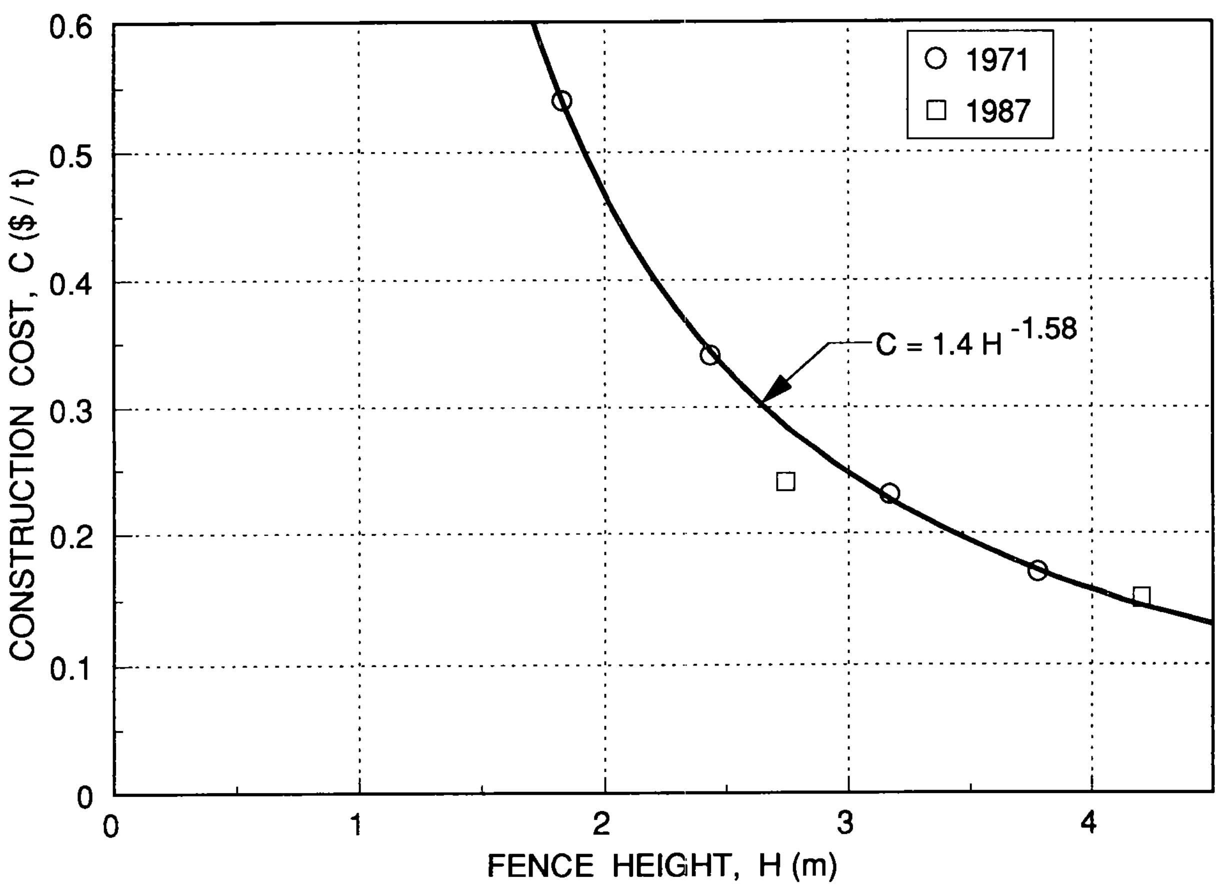


Figure 5.1. Fence construction cost per unit of snow storage, as a function of fence height, for two large projects in Wyoming (Tabler 1989).

5.3.3 Calculating Number of Rows

If it is necessary to use several rows of shorter fence rather than a single taller fence, the number of rows of fencing required to provide the required storage capacity can be calculated from

$$R = (H_{req} / H)^{2.2} \tag{5.6}$$

where H_{req} is required height of a single row of fence, as given by Equation (5.2), and H is the height of fence to be used.

Example:

Given: Design transport Q_{des} = 50 t/m
H_{req} = 2.24 m (7.3 ft)
Fence height to be used = 1.37 m (4.5 ft)

Required: Number of rows of fence 1.37-m (4.5-ft) required to store design transport

Solution: Equation (5.6): $R = (2.24/1.37)^{2.2} = 2.9 \rightarrow 3$ rows required

---

5.3.4 Selecting Porosity

5.3.4.1 Non-Porous Fences ($P = 0$)

Although the snow storage capacity of a non-porous barrier is only one-third that of a 50% porous fence of equal height, solid fences have two advantages: 1) snow is initially deposited on the upwind side (until the upwind drift approaches equilibrium); and 2) much of the blowing snow passing over the top of a solid barrier is injected into the high speed airstream (Figure 3.59) where it is diffused by turbulence and transported for long distances downwind.

Solid barriers can therefore be used to eliminate blowing snow problems on steep embankments where porous collector fences would be relatively inefficient. The solid structure shown in Figures 5.2 and 5.3 protects highway 230 near Nakayama Pass southwest of Sapporo, Japan. Most of the blowing snow is deposited on the slope below the fence, and the remaining particles are diffused vertically by the turbulent airflow over the top of the barrier. The structure is sufficiently strong to support snow removal equipment. According to the designer, Tetsuya Uchiya of the Hokkaido Development Bureau, solid barriers such as this should be installed perpendicular to the slope; the fence at Nakayama pass was inclined to avoid blocking the scenic view.

Embankments are another type of solid barrier used for snow control. Figure 5.4 shows a typical dust levee built to protect railroads from blowing topsoil on the eastern plains of Colorado. These structures also provide protection against blowing snow. However, the cost of constructing an earthen embankment far exceeds that for a porous snow fence. The structure illustrated in Figure 5.4, for example, would store as much snow as a 2.2-m-tall (7.2 ft) snow fence that had a porosity ratio of 0.5.

Snow embankments are sometimes constructed to protect villages and facilities in the Arctic from blowing snow, with one notable example being Baker Lake in Canada's Northwest Territories. An effective method for temporary fences is to install a 1.2-m (4-ft) tall fence on a snow embankment of sufficient height to provide the required snow storage capacity.

As will be described in chapter 6, dense tree barriers can also function as solid barriers.

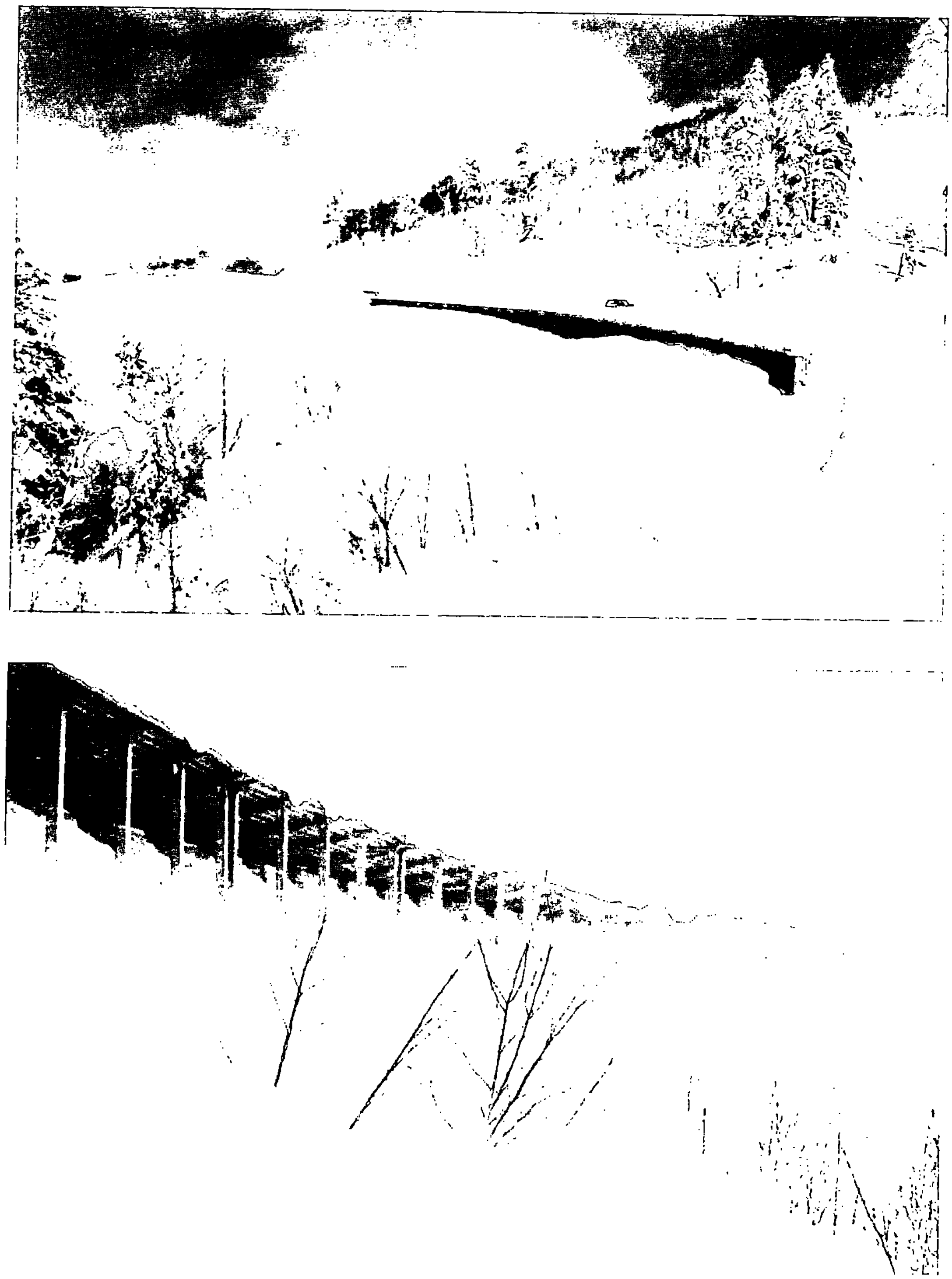


Figure 5.2. Solid barrier near Nakayama Pass, Hokkaido, Japan, causes snow to be deposited on the slope below the road, diffuses snow vertically, and retards deposition on the road (the prevailing wind blows uphill). Upper photo courtesy of Tetsuya Uchiya, Hokkaido Development Bureau.

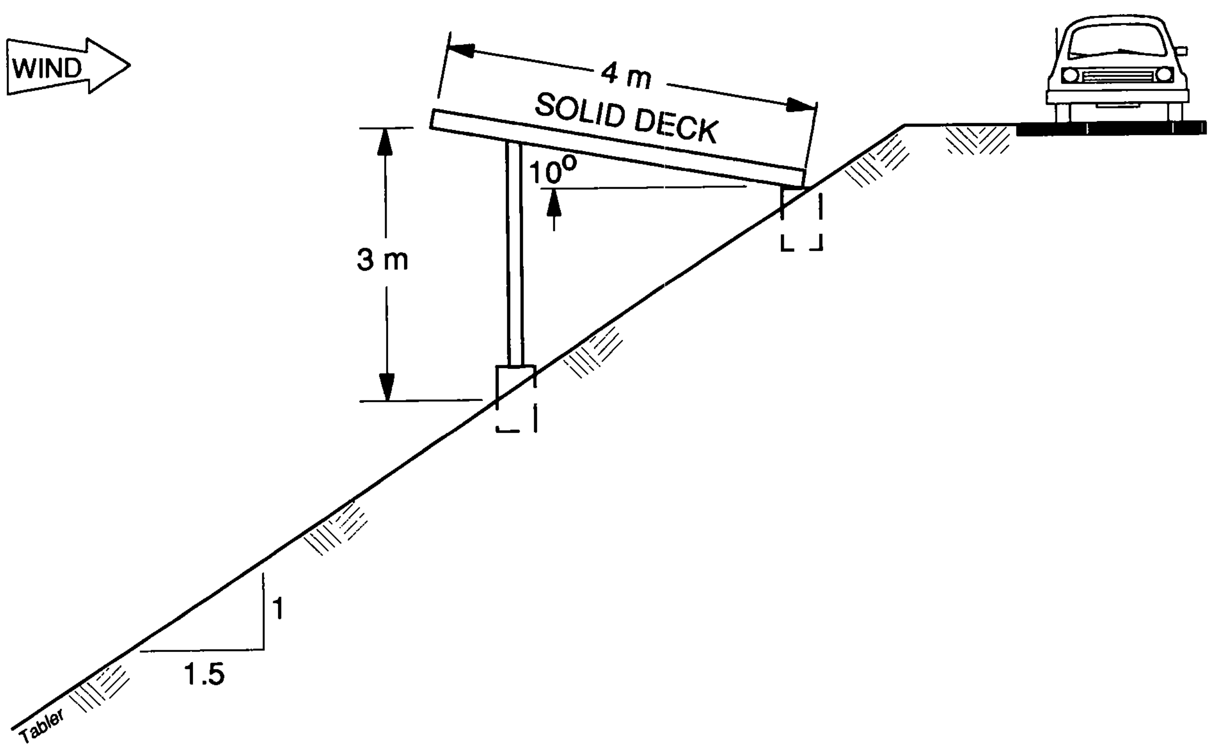


Figure 5.3. Design of the solid barrier on Nakayama Pass shown in Figure 5.2.

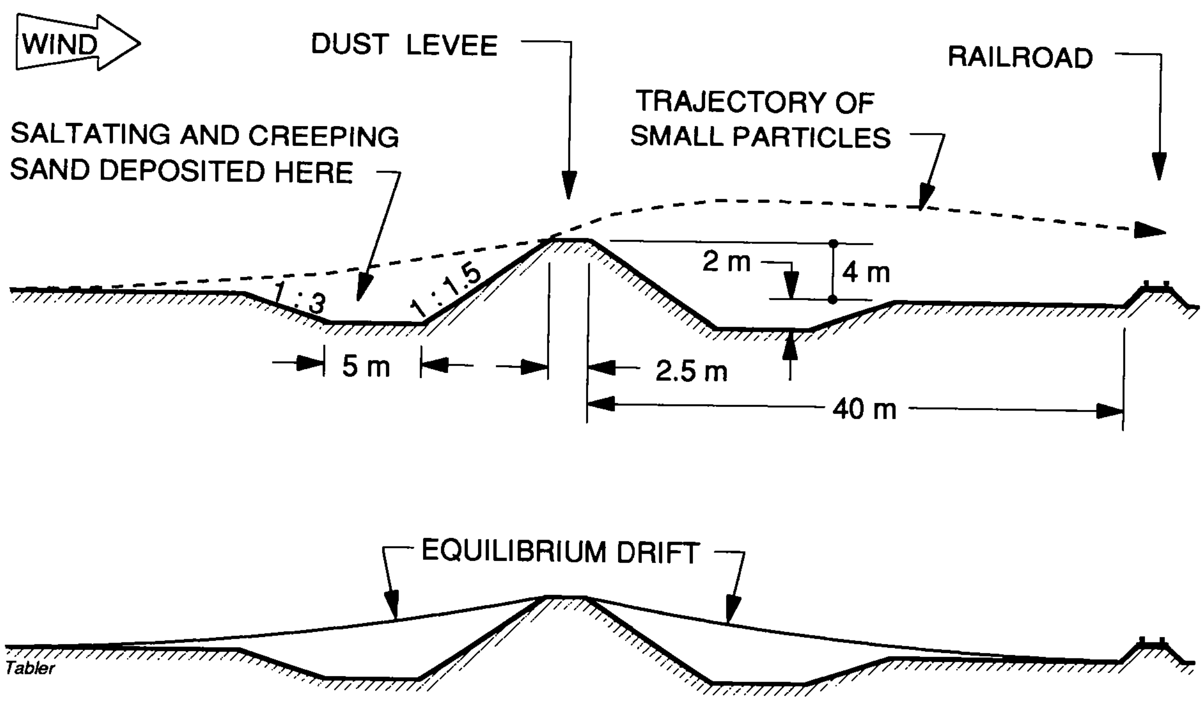


Figure 5.4. ***Dust levee*** **constructed to protect railways in eastern Colorado, induces deposition of saltating particles on upwind side, and entrains smaller particles in the higher speed airstream over the crest.**

5.3.4.2 Porous Fences

Generally, fences that have a porosity ratio of 0.4 to 0.5 have the greatest snow storage capacity. Because the length of the downwind drift decreases as porosity decreases (section 3.8.5.2.4), however, porosities below this optimum range may be selected to reduce setback distance. Equation 3.24 can be used to calculate the required porosity, keeping in mind that the required fence height also changes with porosity (Equation 5.2).

$$L/H = 12 + 49P + 7P^2 - 37P^3 \tag{5.7}$$

The bottom gap should be excluded in porosity calculations.

5.3.5 Specifying a Bottom Gap

The primary purpose of leaving a gap between the ground and the bottom of the fence is to reduce snow deposition in the immediate vicinity of the fence, thereby maintaining maximum effective height and preventing damage that might otherwise occur from settlement or creep of the deposited snow.

The gap between the soil surface and the bottom of a porous fence should not be less than $H_s/10$, regardless of topography or vegetation. The optimum gap is approximately $H_s/10$ *above the average vegetation height.* Larger gaps may be warranted on downward slopes facing downwind, or other locations prone to snow deposition. Bottom gaps up to $H_s/7$ can be used for the Wyoming-type fence.

5.3.6 Permanent Surface-Mounted Fences

5.3.6.1 Wyoming Snow Fence

The Wyoming fence is a horizontal board snow fence that has been used since 1971 by the Wyoming Department of Transportation. As shown in Figure 5.5, this fence consists of panels 4.9 m (16 ft) long comprised of 2.5 × 15-cm (1 × 6-in.) boards. The boards are spaced about 13 cm (11 in.) apart, and are fastened to wooden truss frames. Each panel is anchored with reinforcing bars (rebar) that are driven into the ground. Fence height ranges from 1.8 to 4.3 m (6 to 14 ft), including a bottom gap equal to approximately 12% of total height. The top of the fence is inclined 15° downwind to provide stability during construction, and to facilitate repairs by providing a more convenient platform for workers. Although there is some evidence that inclination up to 15° can increase snow storage capacity, the author's studies indicate that such an increase is less than 10%.

This fence design has undergone numerous revisions since it was first described (Tabler 1974), in a continuing effort to maximize effectiveness, and to minimize construction and maintenance costs. The designs presented here are able to withstand winds in excess of 160 km/h (100 miles/h), snow settlement pressures associated with complete burial, and forces imposed by livestock. Over the last 5 years, low bids on large contracts in Wyoming have averaged less than \$11.00/m^2 (\$1.00/ft^2) of frontal area.

Since 1971, more than 100 km (60 miles) of this fence have been installed along highways in Wyoming, and significant lengths are also in place in Montana, Arizona, and Alaska. When built according to specifications and properly anchored, the Wyoming fence has proved durable and relatively maintenance-free for at least 20 years.

Steel and aluminum versions of this fence have also been produced.

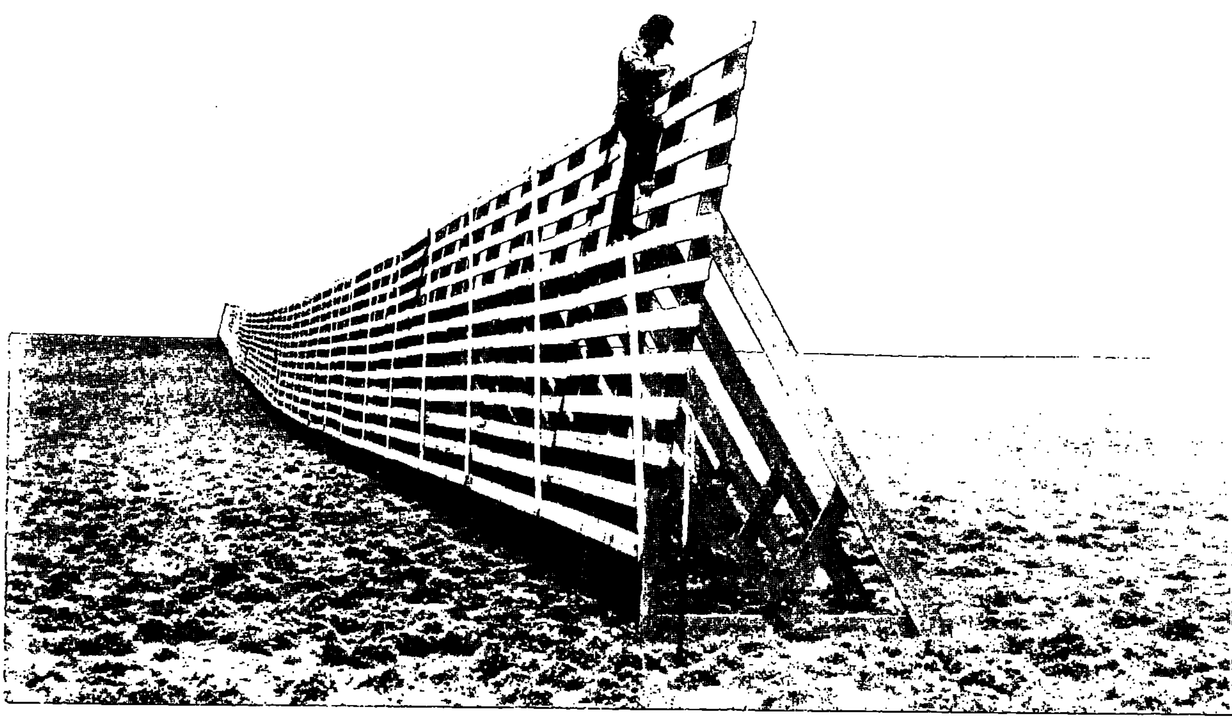


Figure 5.5. Wyoming snow fence 4.3 m (14 ft) tall.

5.3.6.1.1 Standard Plans

Dimensions of structural members shown in Figure 5.6 are listed in Table 5.2 for five fence heights. These plans assume full-dimension rough-sawn lumber. In 1988, lumber grading rules were changed to reflect the use of new precision planers. The new rules specify a minimum rough size 1/8" (3.175 mm) wider and thicker than the standard surfaced size (Western Wood Products Association 1988). The plans presented here are not necessarily suitable for rough size lumber with these new dimensions.

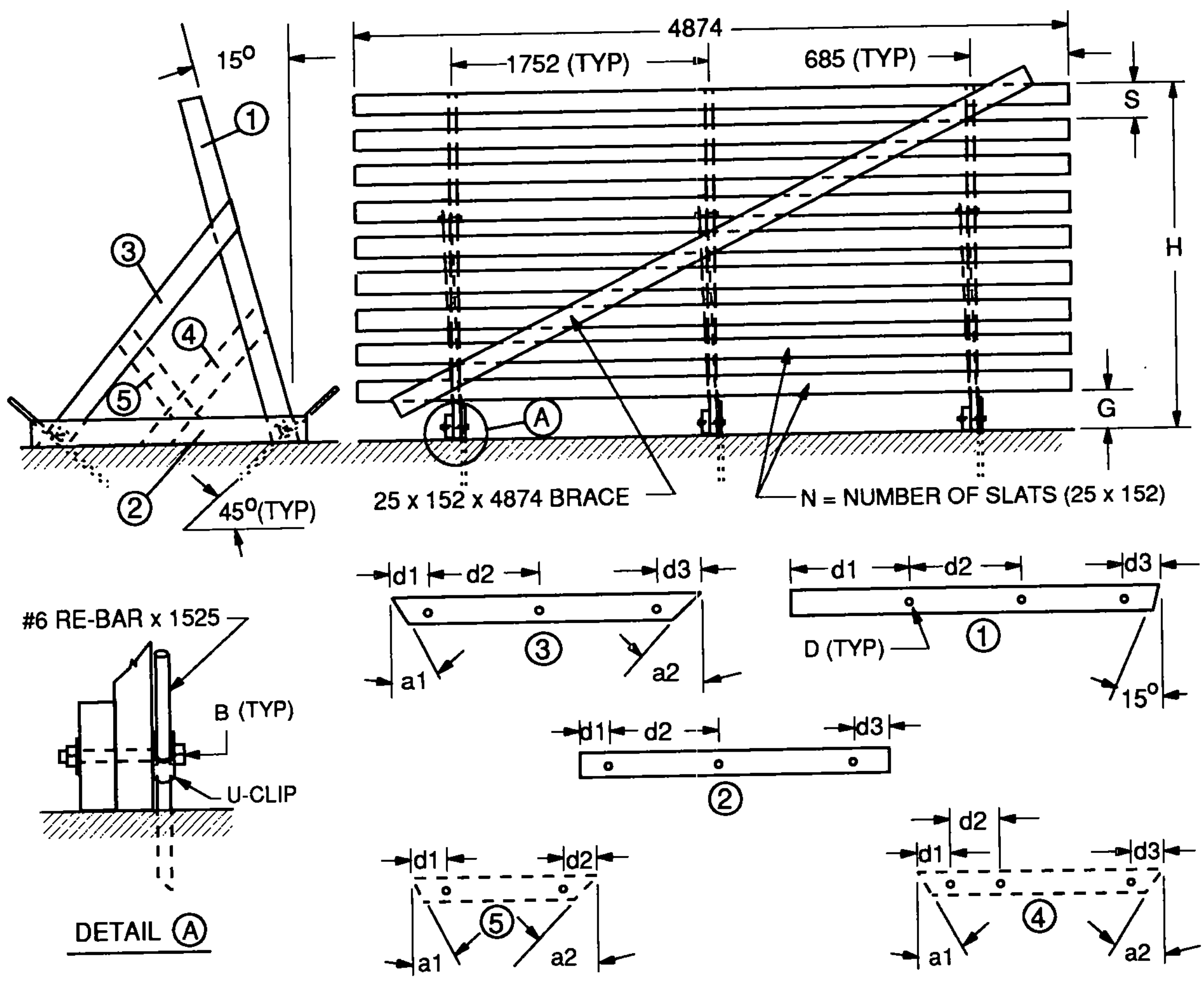


Figure 5.6. Generic plan for the Wyoming snow fence. Dimensions are given in Table 5.2

Table 5.2. Dimensions (mm) of structural members of the Wyoming snow fence shown in Figure 5.6. *S* and *G* dimensions are parallel to front vertical truss member. Lumber size for all truss members is 50 × 150 mm, except 50 × 200 mm is used for the long brace (Member Number 3) for the 4.3-m height.

Member I.D.	Description	Dimension I.D.	Dimension for Nominal Fence Height (m): 1.8	2.4	3.0	3.7	4.3
General	Vertical height	H	1766	2355	2944	3533	4122
	Slat spacing	S	279	279	279	279	279
	Number of slats	N	6	8	10	12	14
	Bottom gap	G	279	330	381	432	483
	Hole diameter	D	14	14	14	17	17
	Bolt diameter	B	13	13	13	16	16
1	Front vertical	Length	1829	2438	3048	3658	4267
		d1	610	819	819	792	1089
		d2	NA	NA	NA	1518	1832
		d3	76	95	95	95	95
2	Sill	Length	1372	1524	2134	2438	2438
		d1	152	152	152	152	152
		d2	NA	NA	NA	883	933
		d3	102	127	127	127	101
3	Long brace	Length	1676	2007	2743	3353	3658
		d1	152	140	140	137	133
		d2	NA	NA	NA	1340	1162
		d3	152	165	171	186	241
		a1	32°	32°	32°	29°	25°
		a2	43°	43°	43°	47°	50°
4	Short brace	Length	NR	NR	NR	1829	1829
		d1	NA	NA	NA	152	152
		d2	NA	NA	NA	152	203
		d3	NA	NA	NA	248	152
		a1	NA	NA	NA	38°	38°
		a2	NA	NA	NA	38°	38°
5	Knee brace	Length	NR	NR	NR	1372	1372
		d1	NA	NA	NR	152	152
		d2	NA	NA	NR	159	152
		a1	NA	NA	NR	39°	32°
		a2	NA	NA	NR	23°	32°

Bolt length at anchor attachments = 150 mm; all others = 125 mm. NR = not required, NA = not applicable

5.3.6.1.2 Economy Model

The sill member that rests on the ground (2) fixes the vertical inclination and provides rigidity to the frame. Because the sill must contact the ground over its entire length, however, it is usually necessary to smooth the ground under each sill. This seating process is often the most time-consuming construction operation on rocky or brush-covered sites, and adds significantly to construction cost. This sill member can be eliminated for fence heights up to 2.4 m (8 ft) or so without compromising structural strength. The angle cuts on the lower end of the frame members can also be eliminated. These modifications significantly reduce construction cost, and also provide flexibility in setting the inclination angle, and hence the vertical height. This latter advantage can turn into a disadvantage, however, if construction is not supervised adequately to ensure that the panels are installed at the correct angle.

5.3.6.1.3 Anchors

Reinforcing bar (rebar) provides an inexpensive anchor with excellent extraction resistance in most soils. Number 6 bar, with a diameter of 19 mm (3/4 in.), is best suited for this application. This diameter provides adequate extraction resistance, has adequate rigidity for driving, and is sufficiently flexible to allow deflection around stones in the soil. Fence panels are attached to the rebar using U-shaped clips (Figure 5.7) at both ends of each sill. These U-clips are efficient and inexpensive, and are available from sources that can be supplied by the author.

On dry mineral soils, 60-cm (24-in.) penetration is adequate to anchor fences 2.4 m (8 ft) tall, and 120-cm (4 ft) embedment is sufficient for the 4.2-m (14-ft) height. Longer rebar, or a different type of anchor, must be used on wet or boggy soils. Rebar must be driven at an angle from vertical of $45 \pm 5°$ (Figure 5.6) to achieve adequate extraction resistance. On permafrost soils, a pipe sleeve in the U-clip allows the fence to move vertically in response to the thawing and freezing of the active layer (Figure 5.8).

Steel angle can also be used as an anchor attachment, but the rebar must be welded to the angle to avoid failure after drying and shrinking of the wood loosens the connection (Figure 5.9). Most failures of driven anchors are caused by improper attachment of sills to the rebar. Crossed-and-wired rebar should not be used (Figure 5.10).

DIMENSION TABLE		
DIMENSION	BOLT SIZE	
	13 mm (1/2")	16 mm (5/8")
D	27	25
Ø	14	17

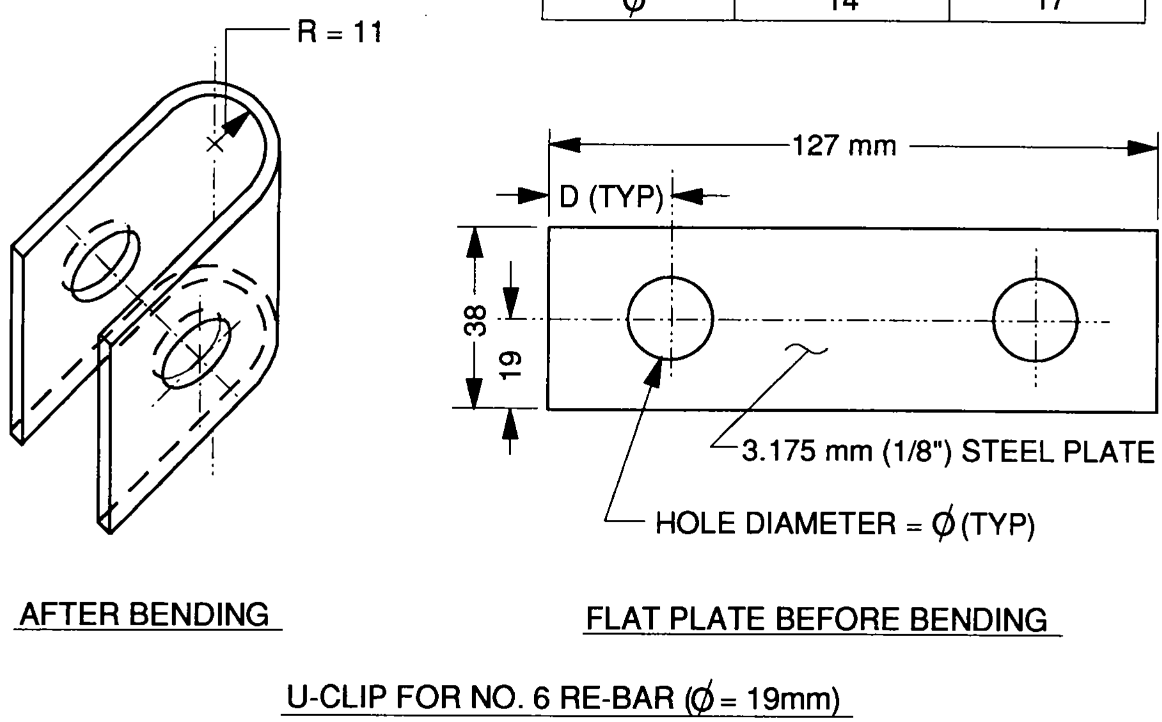
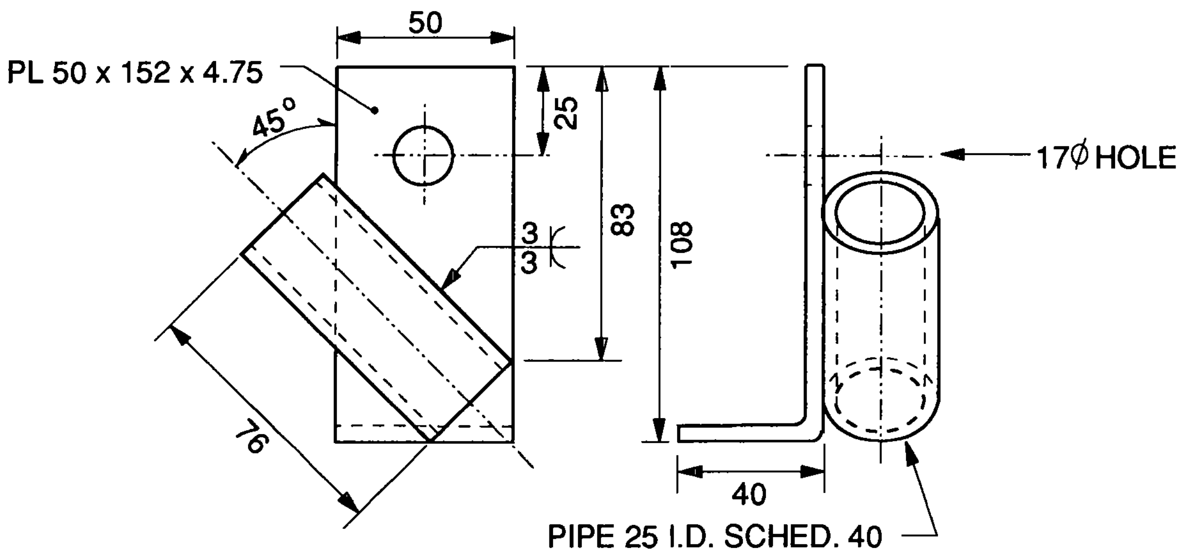
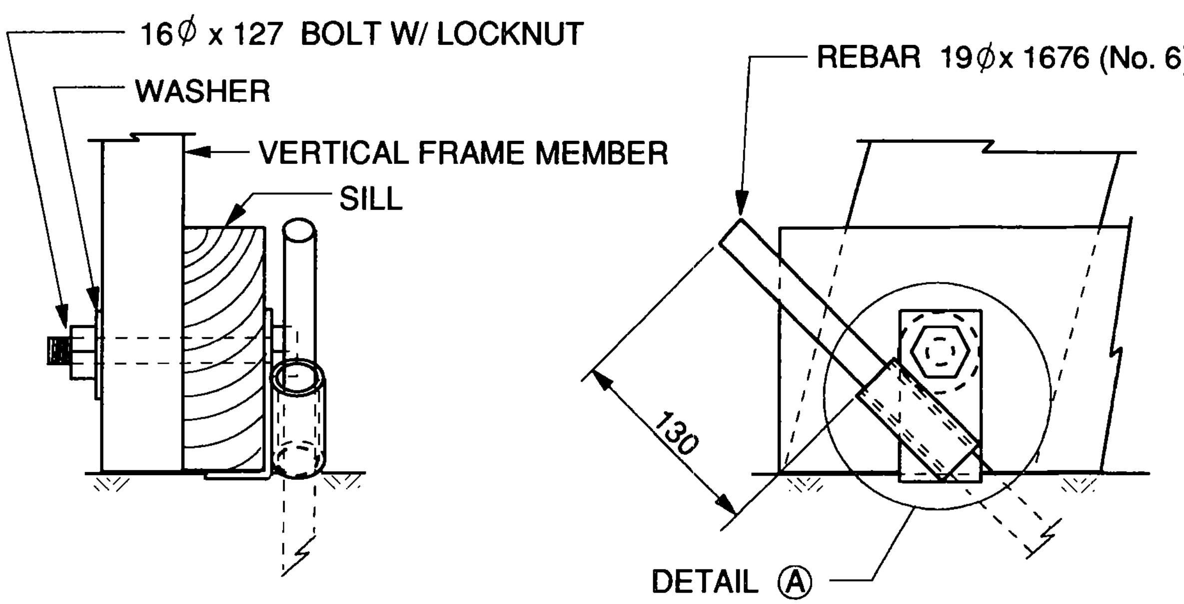


Figure 5.7. U-clip used to attach Wyoming fence to rebar anchor. All dimensions are in millimeters.



DETAIL Ⓐ : ANCHOR ATTACHMENT ASSEMBLY



ANCHOR ATTACHMENT: WINDWARD END OF SILL

Figure 5.8. Anchor attachment for permafrost soils allows fence to move vertically in response to thawing and freezing of active layer. Dimensions are in millimeters.

Figure 5.9. Steel angle can be used for anchor attachment, but rebar must be welded to angle to avoid failure after wood dries and shrinks.

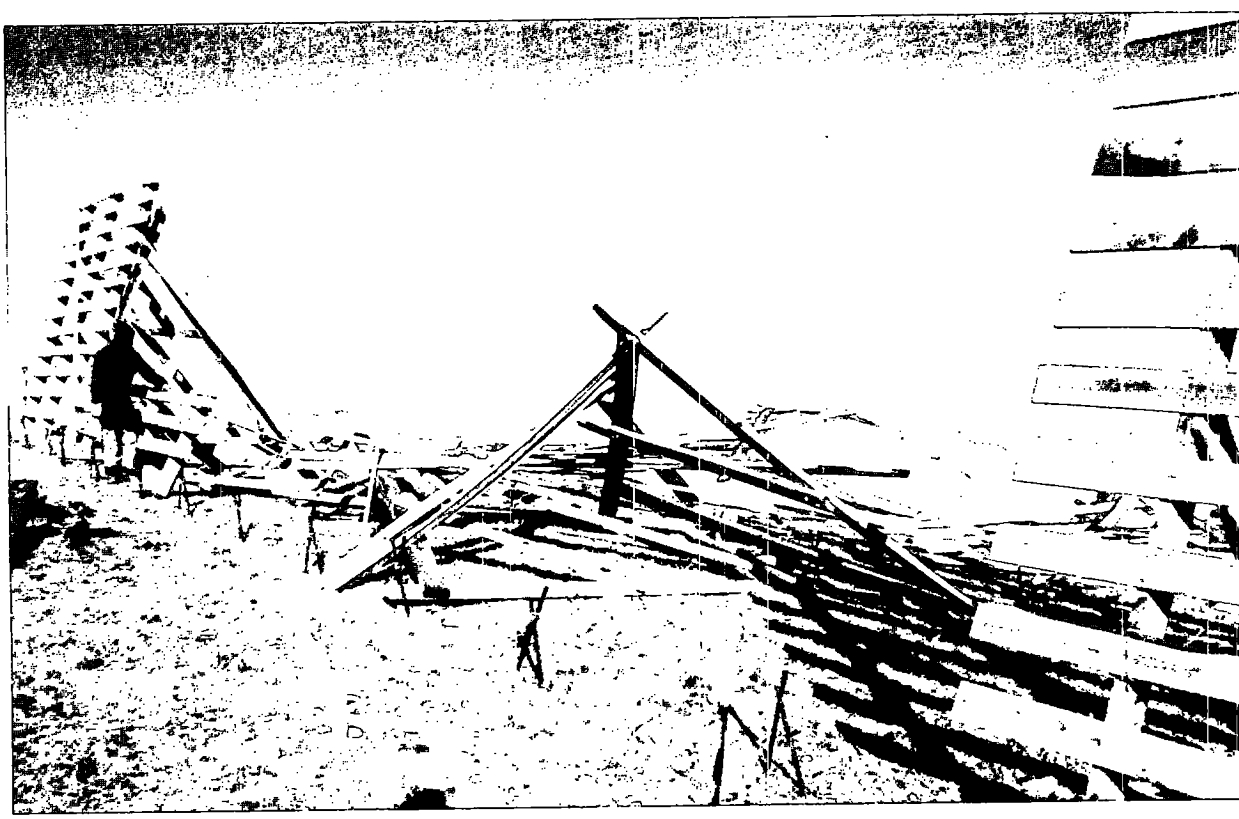


Figure 5.10. Crossed and wired rebar should *not* be used to anchor Wyoming fences.

5.3.6.1.4 Specifications

The following specifications for the Wyoming fence materials and construction indicate some of the provisions that experience has shown to be important. Modifications may be necessary to conform to a particular agency's standards.

5.3.6.1.4.1 Lumber Grades and Specifications

Lumber should be lodgepole pine, ponderosa pine, Engelmann spruce, Douglas fir, hemlock, western larch, or other pre-approved species. All lumber is to be rough sawn to within 3.175 mm (1/8 in.) of the sizes specified. Boards 25 mm (1 in.) should be WWPA No. 3 or better. All 50-mm (2-in.) dimensional lumber should be WWPA No. 2 or better. Lumber 50 mm (2 in.) should be treated with wood preservative for all applications. Unless otherwise specified because of dry climatic conditions, 25-mm (1-in.) boards should also be preservative treated. Cutting and boring should be completed prior to pressure treatment. If cutting and boring is permitted and performed after treatment, such cuts and holes should be swabbed, sprayed, or brushed with two coats of the preservative initially used. Treatment should conform to the requirements of the American Wood Preservers Association (AWPA) Standard C1 and C14. Where regulations permit, chromated copper arsenate is the recommended preservative. Handling and care should conform to AWPA Standard M4.

5.3.6.1.4.2 Hardware

Unless otherwise specified, nails should be plated or coated in accordance with ASTM A615. Bolts, nuts, and washers should meet the requirements of ASTM A307, A563, and F436, respectively. All bolts should be supplied with one nylon-insert locknut. U-clips do not need to be plated or painted, unless otherwise specified. Holes in U-clips should have a diameter 1 mm (1/16 in.) larger than that of the specified bolt, and may be punched. All other U-clip dimensions should be within 3 mm (1/8 in.) of those specified in Figure 5.7. Ring shank or screw shank nails shall be used for extraction resistance.

Reinforcing steel (rebar) used for anchors should be size No. 6 (20-mm or 3/4-in. diameter) Grade 60, that meets the requirements of ASTM A615.

The basis for acceptance for all materials should be the manufacturer's certification that the requirements of the appropriate specifications have been met.

5.3.6.1.4.3 Construction

The location of all cuts and borings should be within 6 mm (1/4 in.) of the dimensions shown. Bolt holes should be drilled to a diameter 1 mm (1/16 in.) larger than that of the specified bolt.

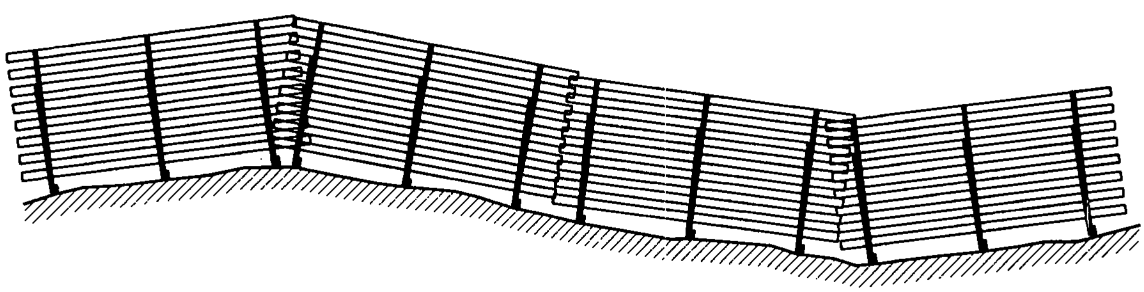
All defective, split, and broken lumber will be replaced after erection.

Panels should be placed within 25 mm (1 in.) of the marked fence line.

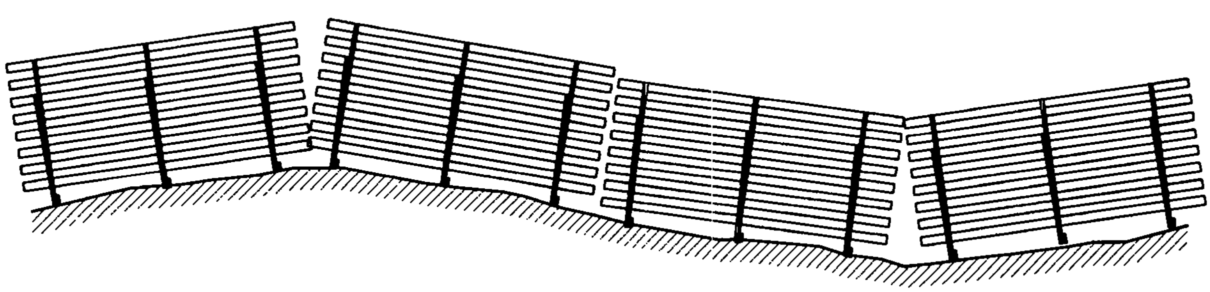
The panels should be placed so that the weight of each panel is equally distributed to the uprights, and so that all sills are in contact with the ground over 90% of their length. This will require grading the site prior to construction, or hand-shoveling under each sill. The contractor should perform such clearing and grubbing as may be necessary to construct the fence to the required grade and alignment, not to exceed 3 m (10 ft) from the fence line. If permitted, grading should be performed where necessary to provide a neat appearance and to maintain the specified bottom gap.

Panels should be placed so as to leave no more than 25 mm (1 in.) between panels at the widest point. In irregular terrain, this may require some overlapping of the ends of the panels (Figure 5.11). Overlapped panels should be installed with a maximum transverse displacement from the surveyed fence line of 50 mm (2 in.).

Driven rebar anchors should be placed as shown on the plans, and should be driven to full embedment depth at an angle of 45° ±5° from vertical in the direction perpendicular to the fence line. Where anchors cannot be driven due to bedrock, the rebar should be cemented with a bonding resin into a hole 22 mm (7/8 in.) in diameter drilled at least 15 cm (6 in.) into competent rock. The bolts at the ends of the sills shall be tightened so that the U-clips grip the rebar firmly, thereby immobilizing the fence with respect to the anchors.



THE RIGHT WAY



THE WRONG WAY

Figure 5.11. Panels should be overlapped to eliminate spaces between panels that greatly reduce trapping efficiency and snow storage capacity.

5.3.6.1.5 Service Life

Properly designed Wyoming fences are able to withstand winds of 160 km/h (100 miles/h), snow settlement pressures associated with complete burial on level terrain, and forces imposed by livestock. When built according to specifications and properly anchored, the Wyoming fence is durable and relatively maintenance-free for at least 25 years. Preventive maintenance is essential, however, if maximum benefits are to be realized from the initial capital investment. This is particularly true during the first two years after construction, when the drying of the lumber can loosen bolt connections.

5.3.6.2 Buck-and-Pole Fence

This fence consists of a buck-and-pole framework to which vertical slats are attached, often using log slabs discarded by sawmills (Figure 5.12). Various heights and porosities have been used.

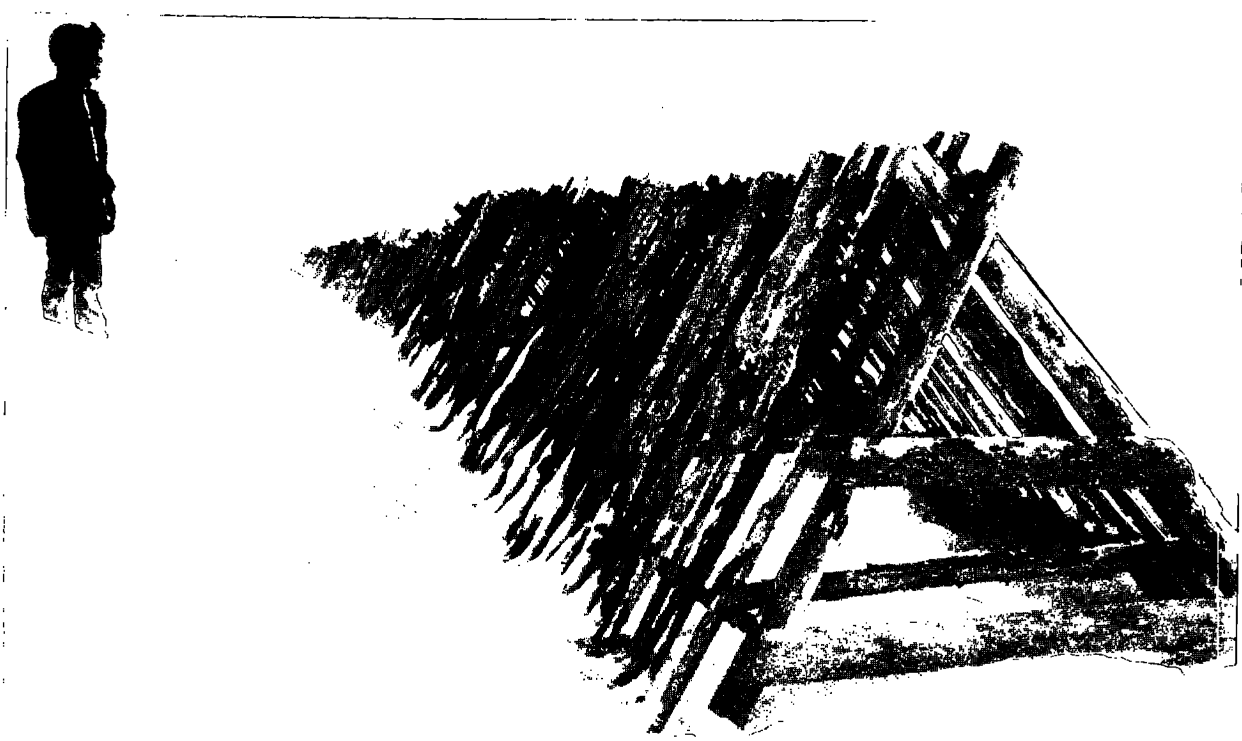


Figure 5.12. Vertical slats attached to buck-and-pole supports, with wind from right (Tabler 1986b). Slats are required on only the upwind side of the fence.

5.3.6.3 Swedish (or Norwegian) Fence

The Swedish or Norwegian fence is 2 m (6.5 ft) tall and is made from nine, 15-cm-wide (6-in.) horizontal boards separated by 6.4 cm (2.5 in.) spaces. The boards are fastened to trusses designed so that the top third of the fence slants into the wind (Figure 5.13). The reason for this reverse inclination is unknown. This type of fence has been used in the United States since at least 1885 with no substantial changes in design, and was the standard snow fence used by the Wyoming Department of Transportation until 1971. Many miles of this fence are still in service, particularly along railroads in Wyoming.

The snow storage capacity of the Swedish fence is approximately 70% that of the same height of Wyoming fence, and the length of the downwind drift is $24H$ (compared to $34H$ for the Wyoming fence).

Figure 5.13. A Swedish or Norwegian snow fence. This 2-m (6.5-ft)-tall fence was about 45 years old at the time this picture was taken (Tabler 1986b). The wind blows from the right.

5.3.6.4 Pole Crib Fences

Pole crib snow fences were built with round logs or poles stacked to form a barrier. The zig-zag design shown in Figure 5.14 offered a convenient way to construct free-standing fences from trees cleared during construction of roads or railways. Many such fences still in existence date back to the 1920s and 1930s. Pole crib fences were typically constructed with spaces between the horizontal members.

This type of fence may be useful where a rustic appearance is desired, but the design is not as efficient for trapping snow. The zig-zag plan reduces the snow-trapping efficiency, however, by causing the wind to accelerate as it is deflected by the Vs pointing upwind (Figure 5.15). Modern versions should strive for the widest acceptable angle.

Figure 5.14. Pole crib fence near La Veta Pass, Colorado (Tabler 1986b).

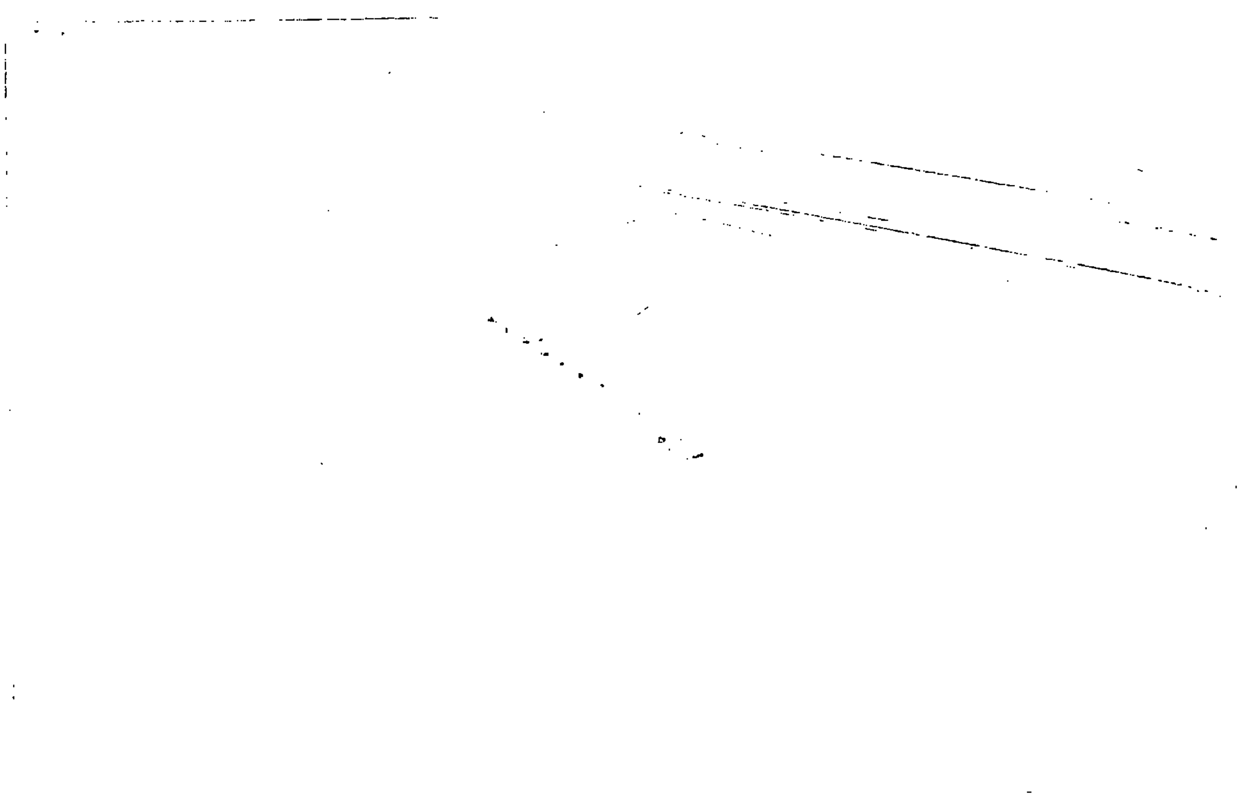


Figure 5.15. Aerial view shows zigzag design catches less snow than standard Wyoming fence (wind is from the left) (Tabler 1986b). Fence height is 3.8 m (12.5 ft). Photo by Robert L. Jairell.

5.3.7 *Materials for Pole-Supported Fences*

Horizontal rails greatly reduce the tendency for snow to be deposited close to the fence. Even if the bottom gap is plugged, the spaces between the rails serve as gaps to slow the rate of burial (Figure 3.52). The small openings typical of most plastic fencing materials favor deposition near the fence and make burial more likely. If the bottom gap remains open, however, there is little difference in snow storage capacity among materials having 40 to 55% porosity.

Wood, metal, plastic, and woven fabrics can be used. *If properly installed*, all these materials will provide economical service lives.

5.3.7.1 Wooden Slats and Rails

Boards, oriented either vertically (slats) or horizontally (rails), can be used as fencing material for pole-supported fences. If rails are used (Figure 5.16), the supports must be adequate to resist loads imposed by wind, snow settlement, and livestock contact. Maximum unsupported spans for horizontal boards are: 2.4 m for 25 × 150 mm, 3.7 m for 50 × 150 mm, and 4.3 m for 50 × 200 mm (8 ft for 1 × 6 in., 12 ft for 2 × 6 in., and 14 ft for 2 × 8 in.). Spaces between boards should be specified to provide the desired porosity. Rails wider than about 25 cm (10 in.) are not as effective as narrower ones.

There is a tendency for nails to loosen as a result of changes in the moisture content of the wood, alternating wind directions, and repetitious deflection. Extraction-resistant fasteners should therefore be used, such as ring-shank nails or screws. Rails can also be held in place with 50 × 100-mm (2 × 4-in.) battens fastened to each support with bolts or steel banding.

Slats can be oriented vertically by attaching them to horizontal stringers between vertical supports (Figure 5.17). Because it allows for greater spacing between posts, this design can be less costly for some applications.

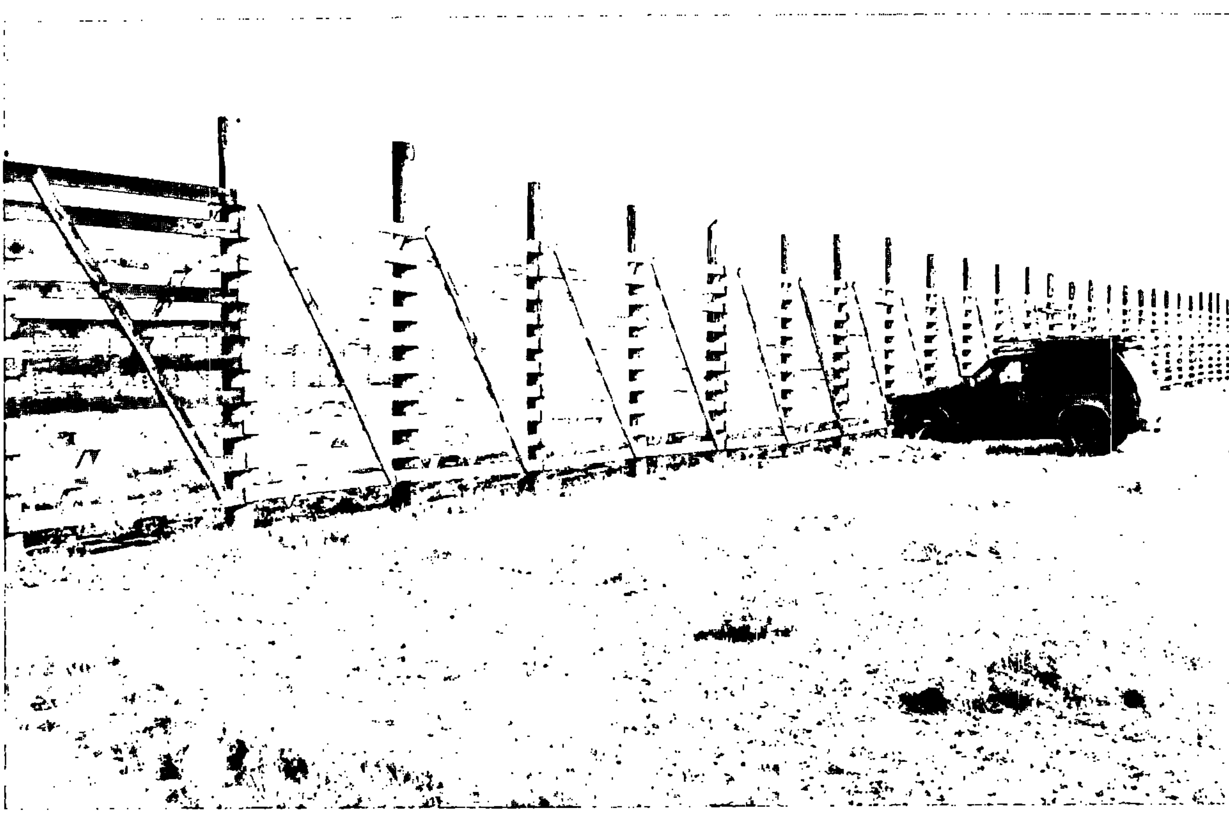


Figure 5.16. Rails between pole supports used for a fence 3.3 m (10 ft) tall.

Figure 5.17. Vertical slats supported by horizontal stringers between vertical supports were used for this 4.6-m-tall (15 ft) fence at Wainwright, Alaska. Photo by George Clagett, U.S. Soil Conservation Service.

5.3.7.2 Lath Fencing

The familiar lath snow fence, also referred to as cribbing or picket fencing, consists of slats 40 mm (1.5 in.) wide and 13 mm (0.5 in.) thick, held together with twisted wires. Although the most common height is 1.2 m (4.0 ft), some 1.8-m (6-ft)-tall material is manufactured. This material, available in 25- or 50-ft lengths, has a 10% lower snow storage capacity than horizontal rail fences of the same height, apparently because the slats are spaced farther apart than is optimum. Although slat spacing varies from roll to roll and increases with repeated stretchings, the porosity ratio is typically about 0.6.

If a bottom gap is provided under this type of material for a permanent installation, the top of the fencing should be wired to a horizontal wood stringer 50 × 100 mm (2 × 4 in.) in size. Even then, the individual slats gradually slip downward through the wire loops under the influence of gravity. For this same reason, lath fencing is not recommended when several tiers of material are required for taller fences (Figure 5.18).

For temporary installations, lath fencing can be installed easily with a minimum of support if the bottom gap is eliminated. The weight and bulk of the material, however, are disadvantages for transporting, handling and storage.

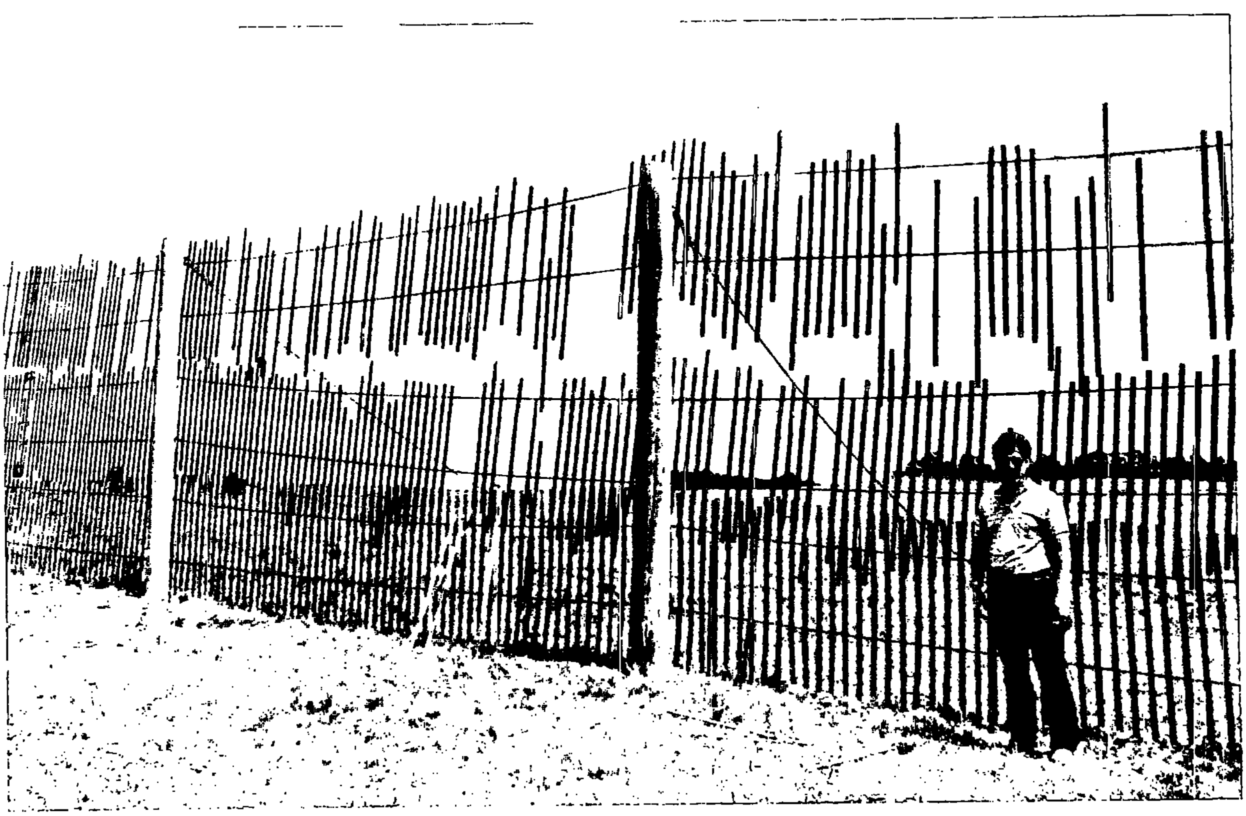


Figure 5.18. Lath fencing is unsuited for tall permanent fences because the slats fall out of the wire loops after several years of service.

5.3.7.3 Synthetic Fencing Materials

Numerous types of synthetic fencing materials are available, ranging from woven fabrics to extruded plastic nets, punched sheet drawn grids, and polymer rails. Advantages of synthetic materials include:

- Horizontal supports are not required;
- No slats to fall out;
- Compact, facilitating storage and handling;
- Lighter than lumber, so easier to handle and install;
- Rot resistant;
- In some cases, lower cost per unit area than lumber.

Woven or knitted material is easily damaged by abrasion if not firmly attached to vertical supports, sags significantly when partially buried, and is damaged by snow settlement. These disadvantages suggest that this material should only be used for temporary fences.

5.3.7.3.1 Properties and Specifications

There are two basic types of plastic fencing: those that are extruded into their final configuration (*extruded plastic nets*; Figure 5.19), and those that are formed by punching holes in sheets of plastic and then stretched to their final shape (*punched sheet drawn grids*; Figure 5.20). This latter process induces molecular orientation that results in high tensile strength (up to 379 MPa) (Wrigley 1987). Most plastic fencing materials currently available are made from polyethylene or co-polymers.

Although ultraviolet light from solar radiation can cause rapid deterioration of plastics, fencing products are made resistant to ultraviolet degradation by chemical additives and by optimization of the thickness of the material. Carbon black is an effective additive for this purpose, and black fencing materials have the greatest ultraviolet resistance. Laboratory tests indicate life expectancies in excess of 10 to 15 years. Field installations show no apparent change in the properties of the premium materials after 8 years of exposure at 2400 m (7875 ft) elevation.

According to Coker (1986), most plastic fencing materials are unaffected by temperatures from -50° to +95°C (-58° to 203°F). Plastic materials have been used for snow fences 4 to 5 m (13 to 16 ft) tall at Prudhoe Bay, Alaska, since 1988, and have been installed at temperatures as low as -40°C (-40°F) with no significant changes in handling characteristics (Figure 5.21).

Desirable specifications for snow fence materials include:

- Fully ultraviolet stabilized, including 2% carbon-black, well-dispersed;
- High tensile strength in both the longitudinal and transverse directions (strength in the vertical direction is important to prevent damage caused by snow settlement);
- Aperture size no less than 25 mm (1 in.) in any direction (to reduce snow deposition at the fence);
- Elongation less than 200 mm (7.9 in.) at 2.2-kN (500-lb.) tension on a width of 1.2 m (4 ft).

Premium grade materials should always be specified for fences taller than 2 m (6.5 ft).

Figure 5.19. Extruded high-density polyethylene "L-300 Sand and Snow Fence" manufactured by DuPont Canada Inc.

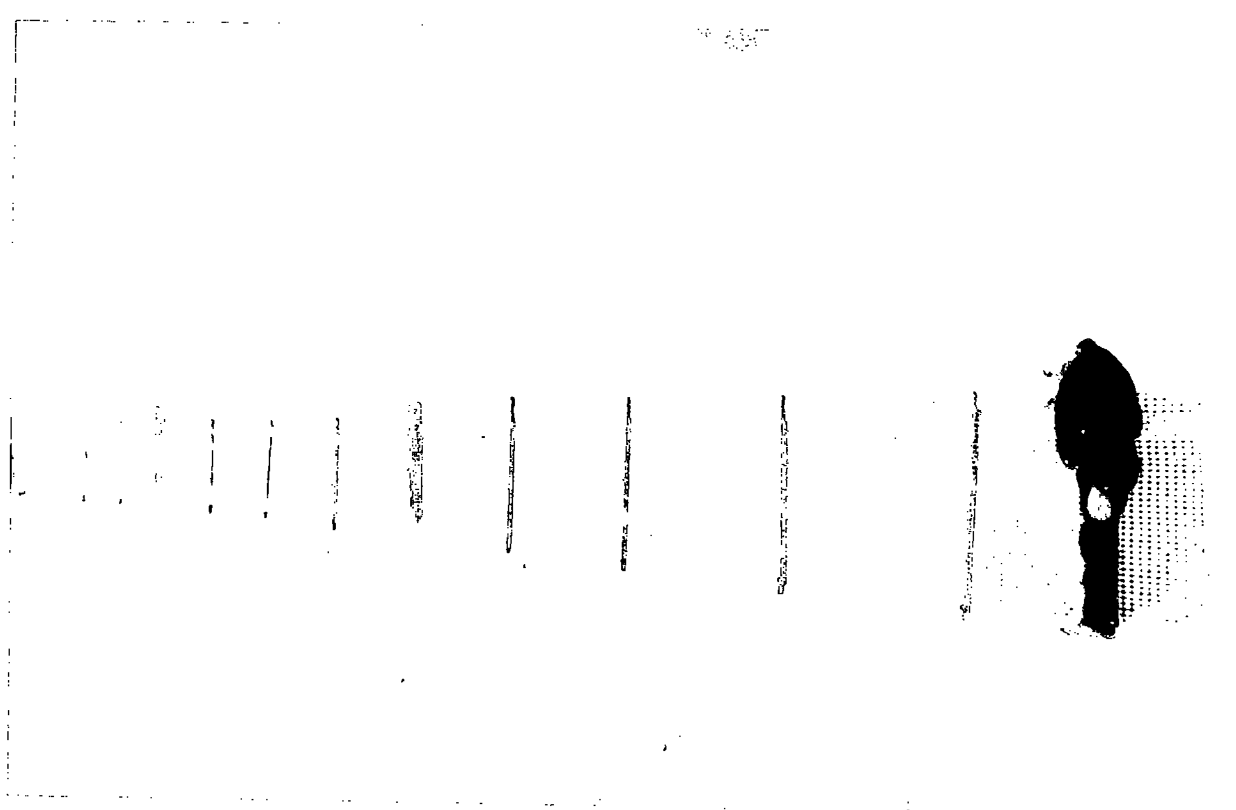


Figure 5.20. Punched and stretched high-density polyethylene "All Purpose Fence" manufactured by Conwed Plastics, Inc.

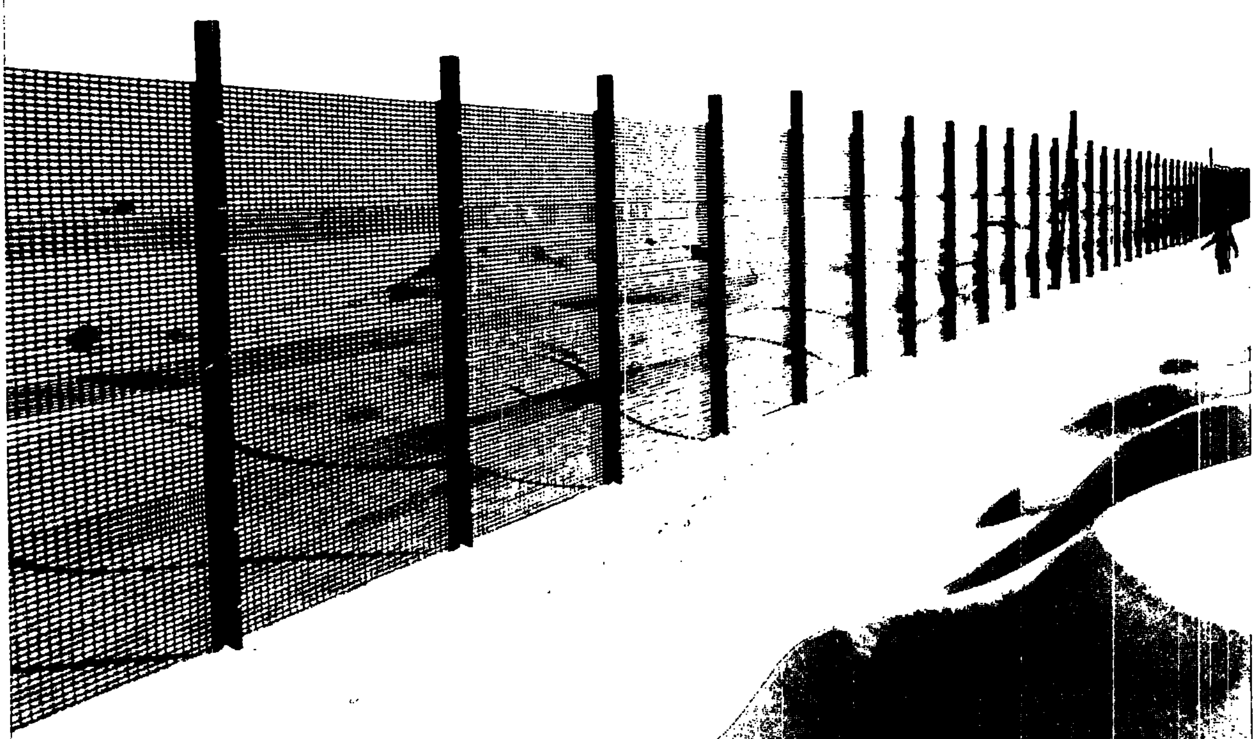


Figure 5.21. Snow fences 4.6 m (15 ft) tall at Prudhoe Bay, Alaska, utilize UX3100 high-density polyethylene snow fencing manufactured by the Tensar Corporation.

5.3.7.3.2 Design Requirements

Although many synthetic fencing materials have high tensile strength, most are easily cut and susceptible to abrasion. All fencing materials must therefore be immobilized at vertical supports. For tall, permanent fences, strips of elastomeric roofing membrane (EPDM) should be placed between the vertical support and the fencing, and between the fencing and the batten (Figure 5.22). Battens should be rigid, and secured tightly to vertical supports using bolts or steel banding.

End supports must be adequately braced to allow tensioning, and this is typically accomplished with a brace extending from the top of the end pole to the ground line of the adjacent line pole (Figure 5.23).

When plastic snow fencing 1.2 m (4 ft) wide is stretched to a specified tension, it cannot be made to conform to appreciable terrain irregularities without changing the distribution of tension across the width. This in turn leads to wrinkles or slack on the inside of the curvature. As a result, the vertical supports must use a method to account for slope changes such as one of those illustrated in Figure 5.24.

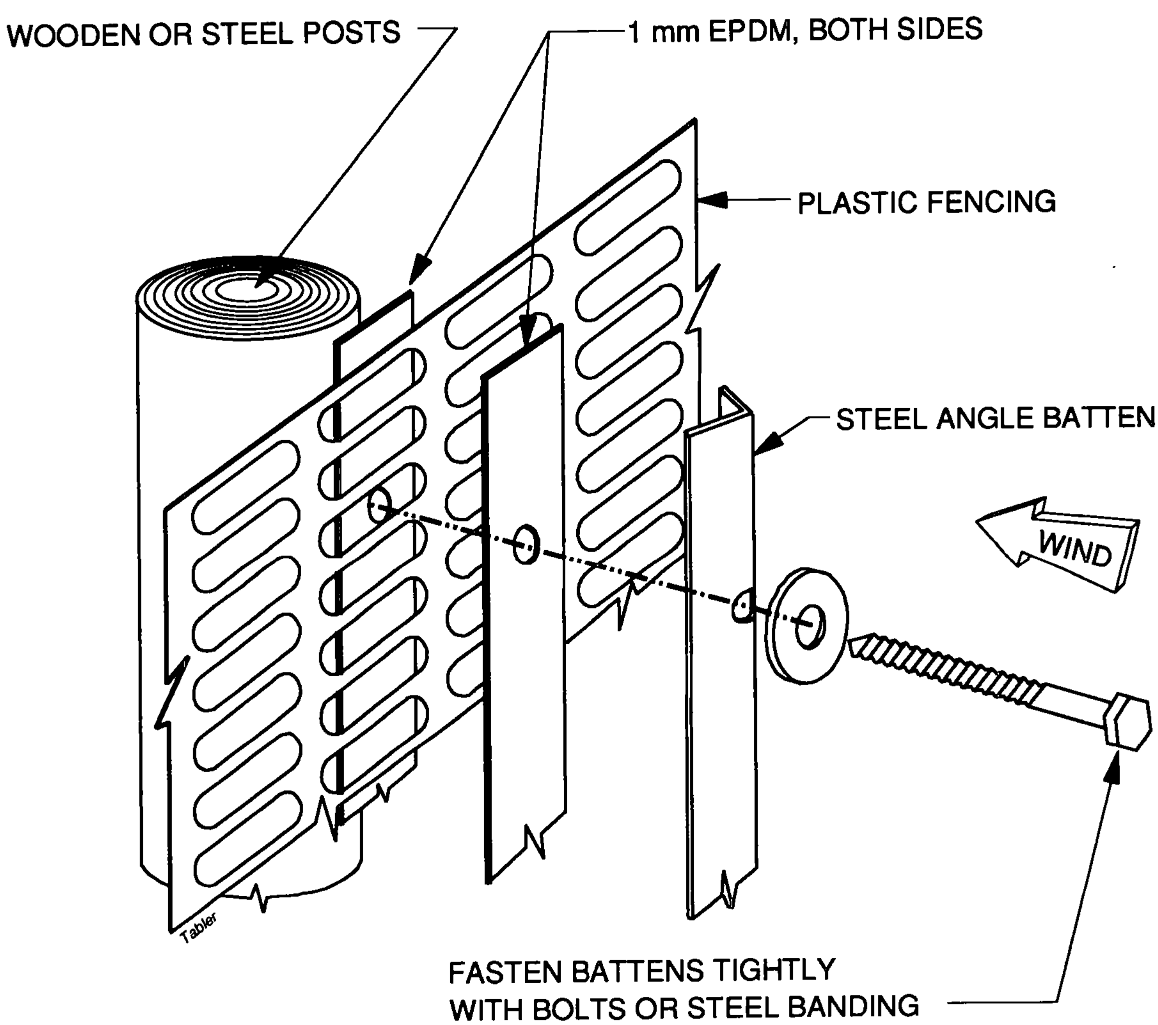


Figure 5.22. Strips of elastomeric roofing membrane (EPDM) on both sides of the plastic help to immobilize the plastic, and compensate for expansion and contraction of attachment materials.

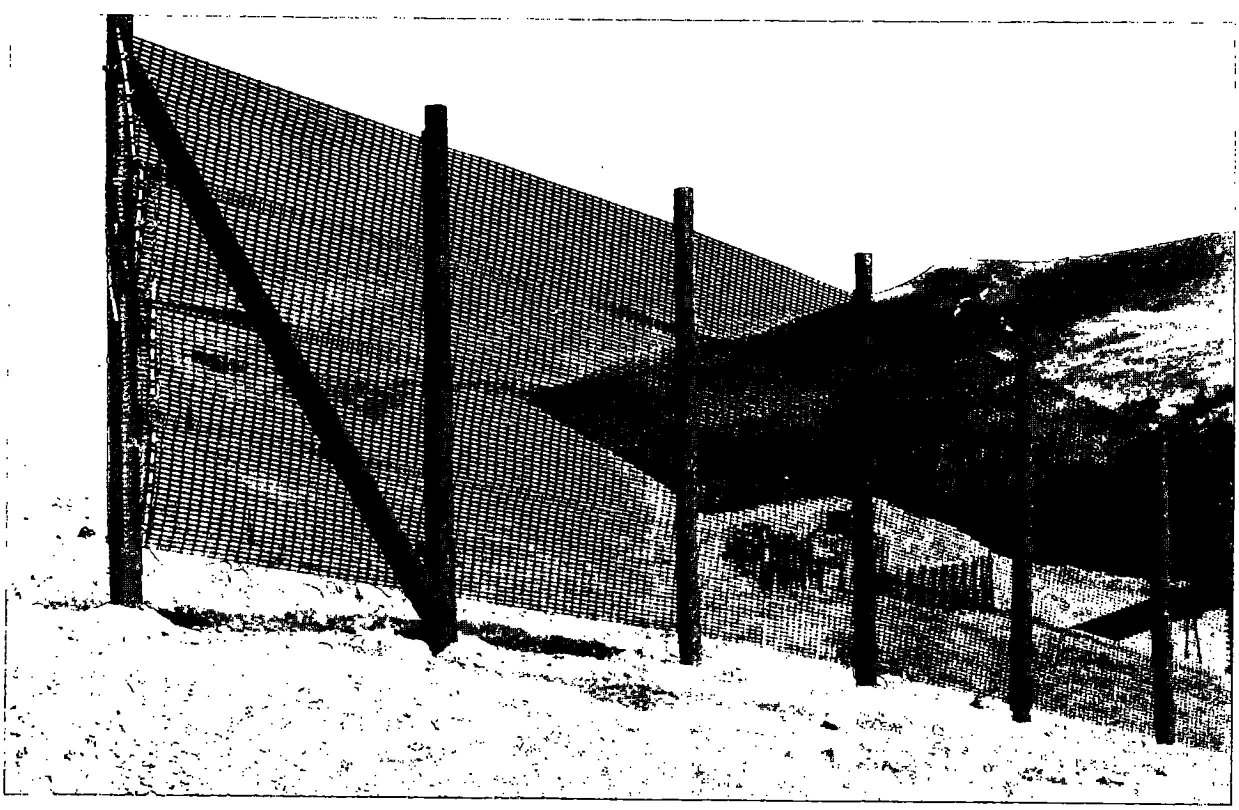


Figure 5.23. End supports must be braced longitudinally for tensioning synthetic materials. Tensar UX3100 material was used for this 5-m (16-ft) tall snow fence at Summitville, Colorado.

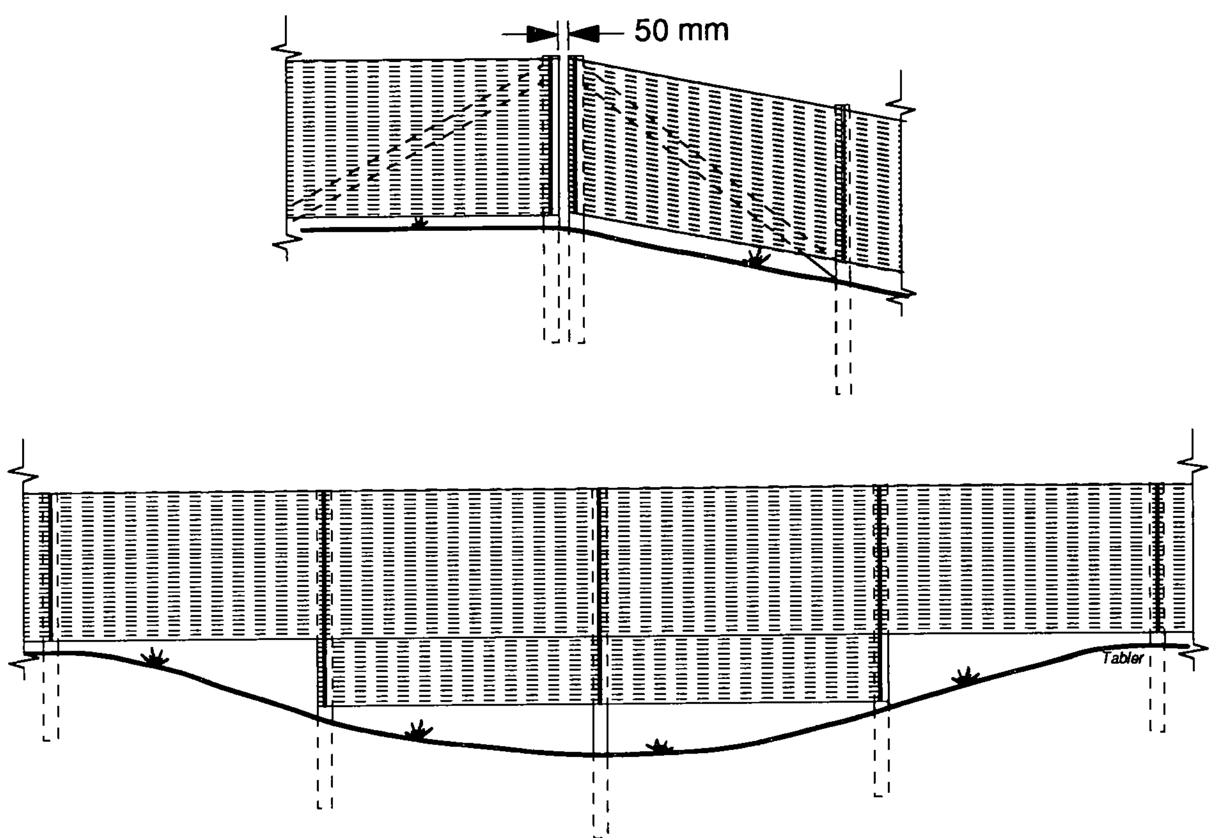


Figure 5.24. Methods for accommodating slope changes when using synthetic fencing materials.

5.3.7.3.3 Installation Requirements

To avoid excessive sagging from snow settlement (Figure 5.25), and to prevent excessive vibration that can lead to shear failure at points of attachment, all fencing materials should be stretched taut before fastening to supports. In all cases tensioning should be performed to the manufacturer's specification. Proper tension can be determined by observing elongation. The fencing material shown in Figures 5.21 and 5.23, for example, is properly tensioned to 4.4 kN (1000 lbf) with 1% elongation. The best procedure is to weave a 25-mm-diameter (1-in.) pipe through the openings on the slack end, and attach a chain at both ends of the pipe. Tension is applied in the center of the chain using a hand winch attached to a truck to hold position (Figure 5.26).

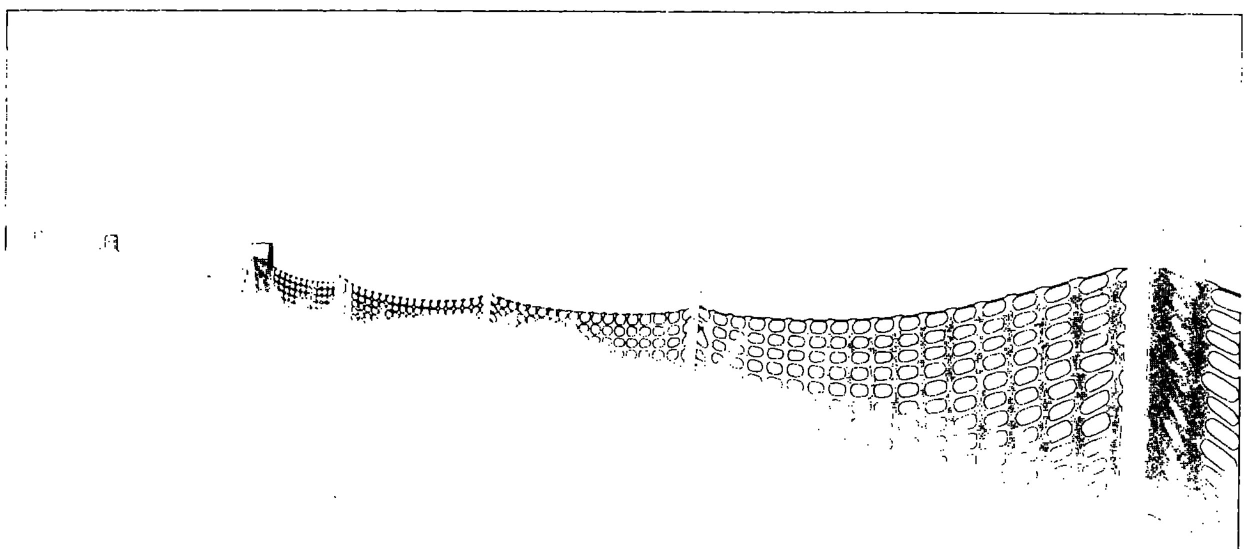


Figure 5.25. Synthetic fencing materials must be tensioned sufficiently to minimize sagging and damage caused by snow settlement and vibration (Tenax Gigan snow fence).

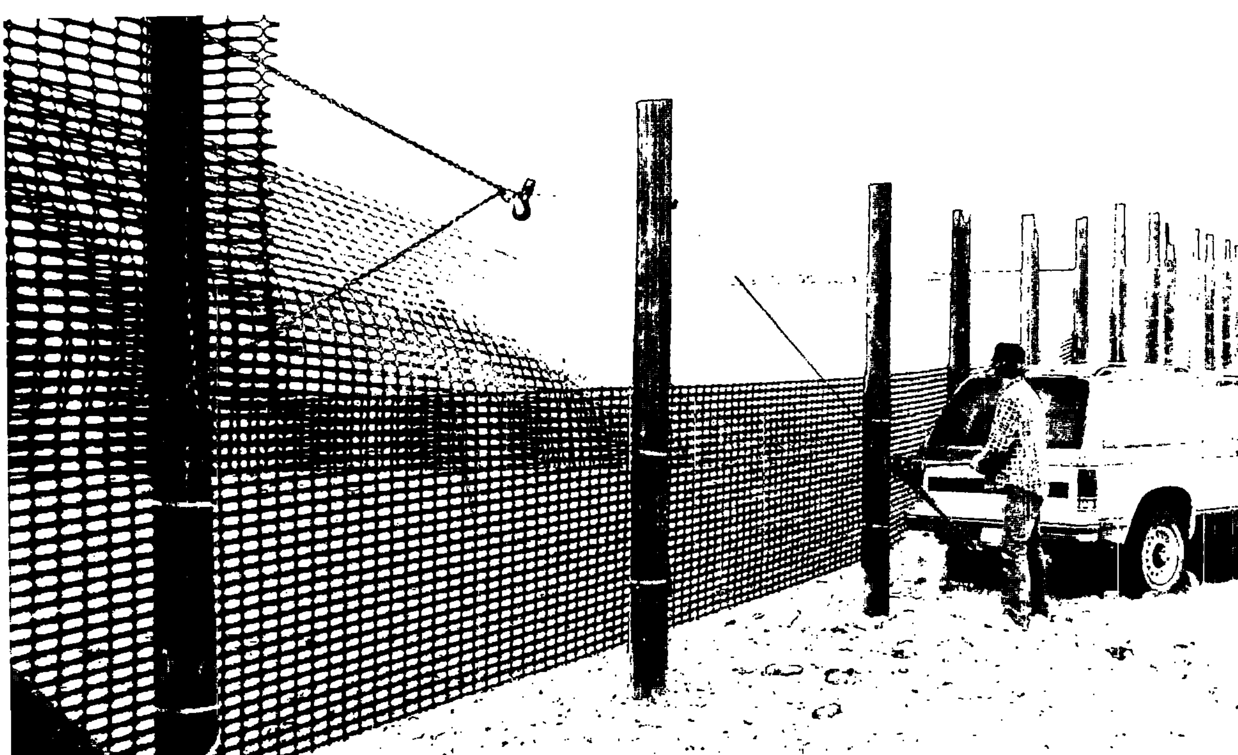


Figure 5.26. A tensioning method (Tensar UX3100 snow fence).

5.3.7.3.4 Composite Polymer/Cable Rail

A flexible polymer rail sold for livestock fencing can also be used to build snow fences of any desired height or porosity (Figure 5.27). Manufactured by Centaur HTP Fencing Systems, Inc., this product consists of a polymer strap 125 mm (5 in.) wide, in which three steel cables or wires, 2.5 mm (0.099 in.) in diameter are embedded (Figure 5.28). Cables are used in place of wires for snow fence applications to reduce breakage caused by vibration-induced flexing. Breaking strength is approximately 18 kN (4000 lbf). Standard roll lengths are approximately 200 m (660 ft). Tests in Wyoming as well as in the Arctic have shown this material to be suitable for use at low temperatures, with no increase in brittleness that might limit its use for snow fences. Advantages include:

- Can be installed while winds are blowing at 70 km/h (45 miles/h) or more, and with winds from any direction;
- Easily attached to vertical supports using the brackets supplied by manufacturer;
- Durable and resistant to vandalism because the wires are difficult to cut;
- Can be installed with vertical curvature to follow rolling terrain;
- Vertically straight runs can be easily tensioned with ratchet strap tensioners;
- Permanent tensioners facilitate repairs and preventive maintenance;
- Can be used for multipurpose fence to control both access and snow;
- Allows construction of fences of any desired porosity or height;
- Resistant to damage by snow settlement and creep;
- Attractive appearance.

The brackets used to attach the rail to vertical supports (Figure 5.29) allow the strap to move freely, so that tensioning can be accomplished after the brackets are installed. According to the manufacturer, each rail should be tensioned to 3.3 kN (750 lbf) to minimize wind-induced vibration. For lengths of fence that are vertical tangents, tensioning is facilitated by permanently installed ratchet strap winches. Because poles are set vertically plumb but the rails are usually not horizontal, the winches and terminations should be attached to the end supports with single bolts. This attachment allows the winches and terminations to rotate so that the rails are perpendicular to the take-up spools (Figure 5.30). Where rails follow the vertical curvature of the terrain, tensioning must be done using "strainers" on each individual cable (Figure 5.31). According to the manufacturer, tensioners can be spaced up to up to 300 m (1000 ft) apart.

Because the cables can break if subjected to excessive flexing, it is important to minimize wind-induced vibration by maintaining the prescribed tension, and by limiting the spacing between vertical supports to 2.4 m (8 ft). If wider spans are used, wooden stays 50 × 100 mm (2 × 4 in.) should be woven through the straps to limit unsupported lengths to 2.4 m (8 ft) or less.

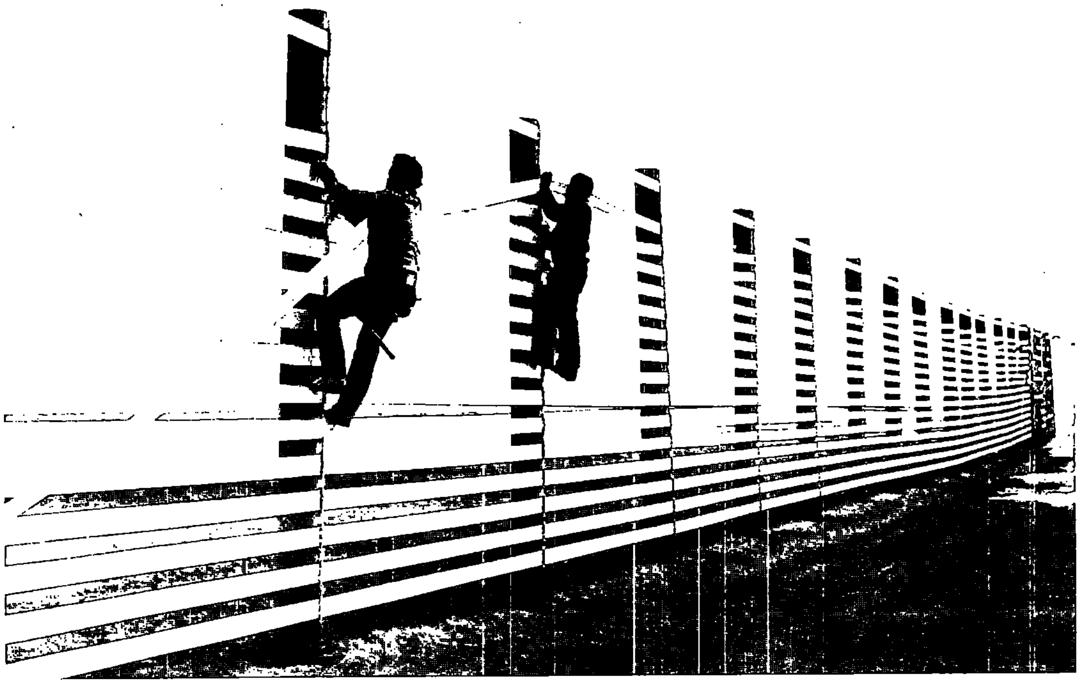


Figure 5.27. Composite polymer/cable rail manufactured by Centaur HTP Fencing Systems, Inc., was used for this 4-m (13-ft) fence.

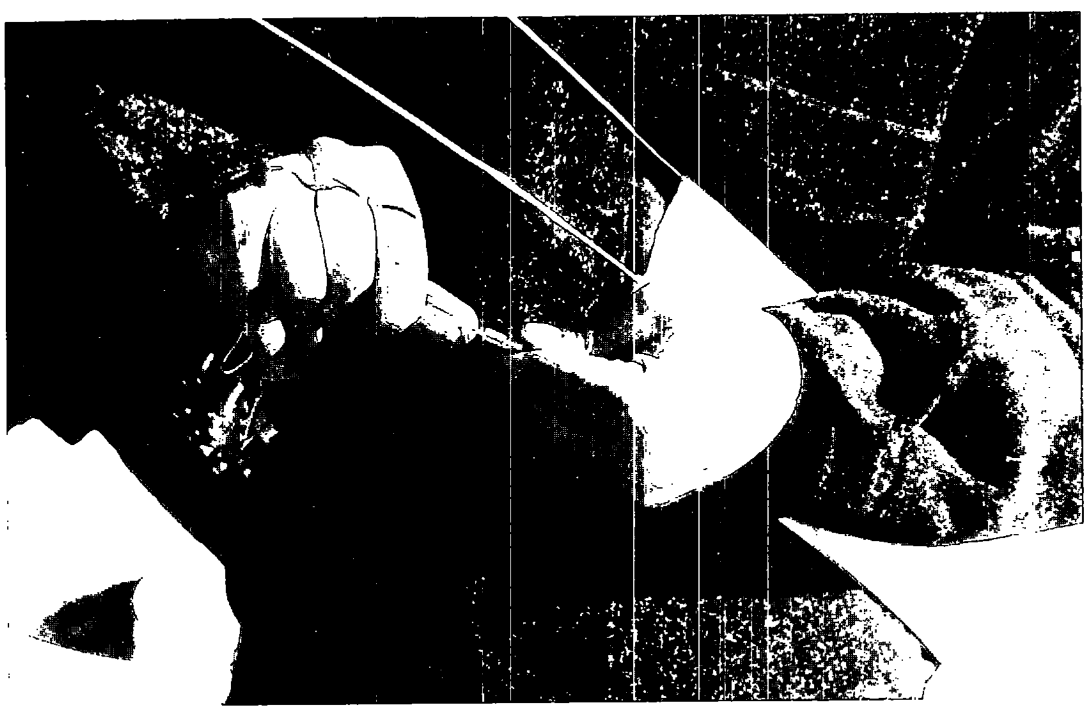


Figure 5.28. The Centaur rail consists of three steel cables or wires embedded in polyolefin polymer.

Figure 5.29. Brackets used to attach rail to vertical supports.

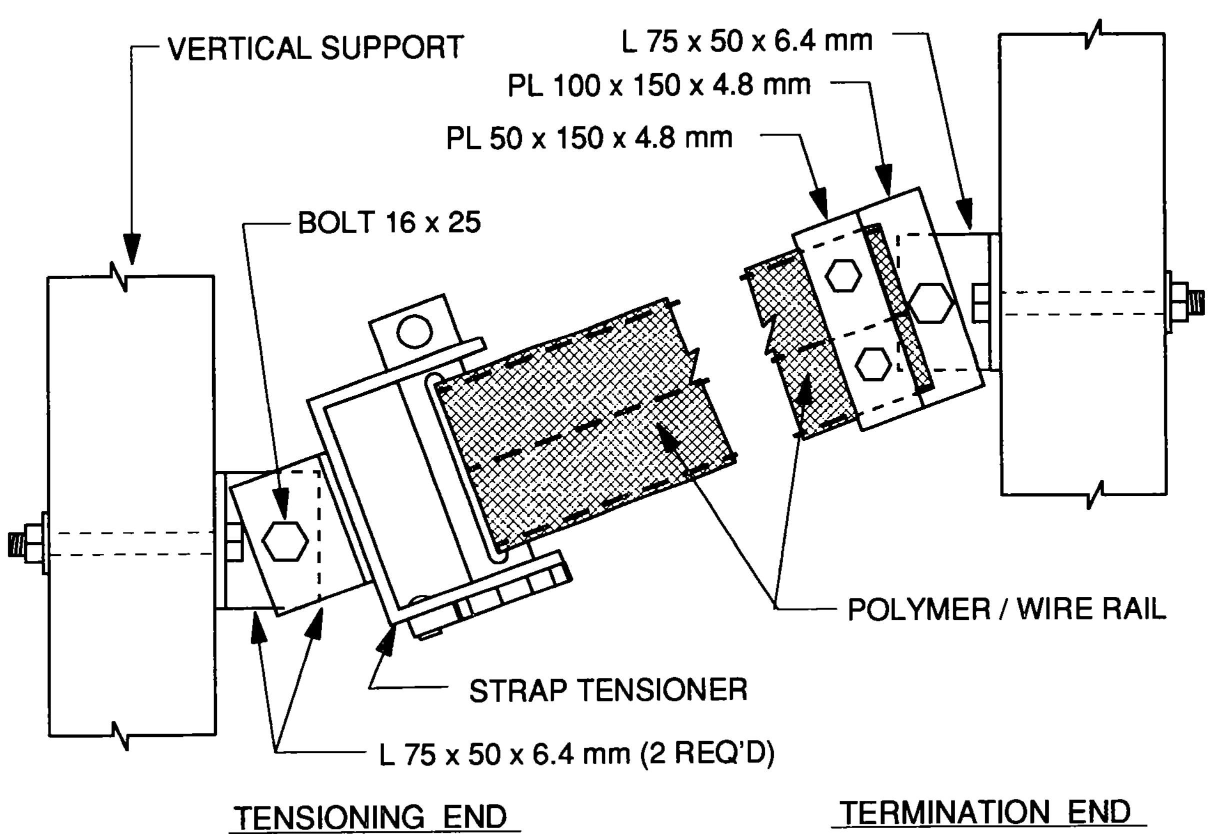


Figure 5.30. Attaching tensioning winches and terminations to vertical supports in this manner allows the take-up spool to be perpendicular to the rail.

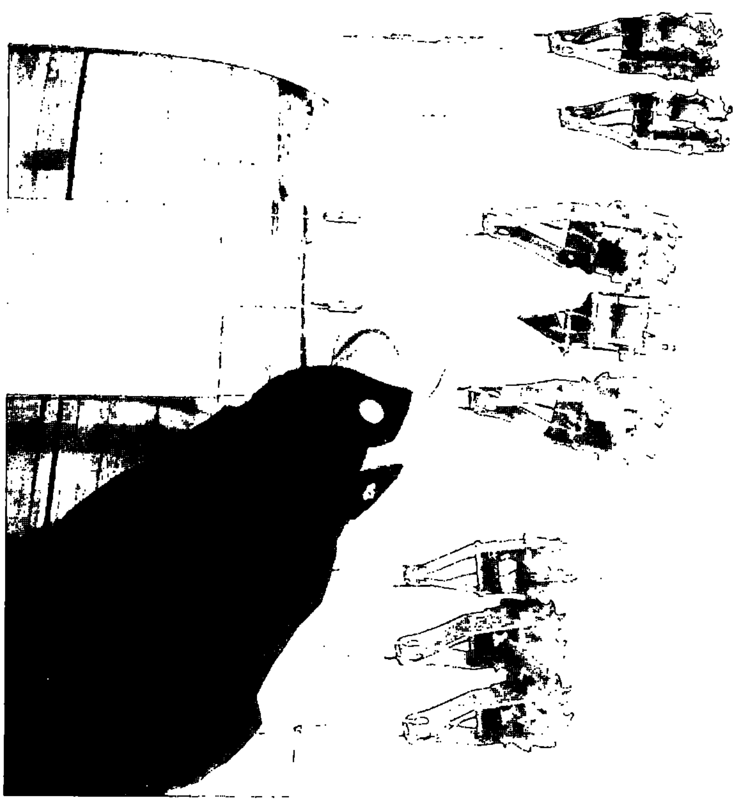


Figure 5.31. Strainers must be used for tensioning each cable separately if the rail curves vertically to follow terrain.

5.3.8 Pole Supports

Pole supports must be designed to withstand wind loads and to allow proper tensioning of fencing materials. Because plastic fencing requires tensions as high as 3.65 kN per meter of height (250 lbf/ft), posts at ends or corners must be braced longitudinally, and curved fence lines are generally undesirable.

As described in section 5.3.11, the force that the wind exerts on a fence depends on the wind speed, density of the air, upwind topography and ground cover, and the height and porosity of the fence. Although the wind speed to be used for the design of a structure varies with geographic location, applicable building codes, and standards set by the owner of the structure, snow fences are typically designed for 160 km/h (100 miles/h) winds.

Steel T-posts that support 1.2-m (4-ft) fences should be spaced 2.4 m (8 ft) apart to avoid bending in strong winds. The bending moment exerted by the wind on a fence 1.8 m (6 ft) tall is about 65% greater than on a 4-ft (1.2-m) fence, so steel posts must be spaced about 1.4 m (4.5 ft) apart to avoid the need for braces or guys. Steel T-post supports are therefore impractical for temporary fences taller than 1.8 m (6 ft).

Transverse braces and guys are to be avoided for post-supported fences. When these supports become buried in the drift, they sustain large loads that can damage the fence. This is particularly true on sloping ground where snow creep occurs. The vertical supports therefore must be sufficiently strong to resist bending or breaking under the design wind load, and embedment must be sufficient to keep the structure from overturning. The choice of materials for vertical supports depends primarily on cost and availability. Discarded steel well casing is used at Prudhoe Bay, for example, and some railroad fences have utilized scrap rail. The optimum spacing between supports is usually that which minimizes total cost, balancing the cost of materials with the cost of excavation and backfill.

The approach to designing pole fences is to determine, by iteration, a pole spacing that requires reasonable pole sizes and embedment depths. A reference for pole design is the *Timber Construction Manual*, published by the American Institute of Timber Construction (1974). Structural engineering handbooks (Gaylord and Gaylord 1979) also provide procedures for designing pole supports.

Table 5.3 provides an example of the size and embedment of wooden poles required to support various heights of snow fence in 160-km/h (100-mile/h) winds for several pole spacings. If it is assumed that the total cost for materials and installation varies in direct proportion to embedment depth and the cross-sectional area of the vertical supports, and inversely with support spacing, then the cost per unit length of fences increases as pole spacing increases. In other words, the 2.5-m (8-ft) spacing would be more economical than wider spacings.

Embedment depth is frequently limited by soil conditions, particularly depth to bedrock. Setting the supports in concrete significantly reduces the required embedment, but cost of this type of construction is often prohibitive. A less expensive way to increase lateral resistance is to backfill the hole halfway to the top with compacted excavated material, pour a 20-cm-thick (8-in.) collar of concrete around the pole, and complete the backfill with compacted material. To anchor the pole to the concrete, lag bolts are installed in the pole at the center of the collar.

Poles should be set vertically plumb with a maximum lean of 13 mm (0.5 in.) in any direction, and the windward face of all poles should be within 25 mm (1 in.) of the indicated fence line. Care should be taken to compact backfill in lifts 30 cm (12 in.) or less.

For permafrost installations, vertical supports should extend to a depth of 4 m (13 ft) below the active layer to prevent frost jacking.

Table 5.3. Butt circumference (Circ) and embedment depth (Embed) required to support indicated heights of 50% porosity snow fence in 160 km (100 miles/h) winds, for pole spacing S_p. Values are for Douglas fir poles, soil with average bearing strength (120 kPa = 2500 lbf/ft^2), compacted backfill, air temperature -20°C (-4°F), at sea level (Tabler 1986b).

Fence height	S_p = 2.5 m		S_p = 3.0 m		S_p = 3.5 m		S_p = 4.0 m	
	Circ	Embed	Circ	Embed	Circ	Embed	Circ	Embed
-m-	--- cm ---		--- cm ---		--- cm ---		--- cm ---	
1.0	27	76	31	88	35	101	39	113
1.5	37	101	41	113	46	131	51	146
2.0	45	122	51	137	57	159	63	177
2.5	53	140	59	162	67	183	74	207
3.0	60	159	68	180	76	207	84	232
3.5	67	177	76	201	85	229	94	259
4.0	74	192	83	219	93	250	103	280

1 m = 3.28 ft
1 cm = 0.39 in.

5.3.9 Temporary Fences

Temporary fences are necessary in locations where snow fences are incompatible with summer land use, such as cultivated land. Past practice has relied primarily on 1.2-m (4-ft) fencing installed on steel posts, but it is now clear that taller fences are much more effective.

5.3.9.1 Conventional T-Post-Supported Fences

The guidelines in Table 5.4 should be used for T-post-supported fences.

Table 5.4. Guidelines for fences supported by T-posts.

Factor	Fencing height (m) 1.2	1.8
T-post length (m)	2.0	2.6
T-post spacing (m)	2.4	1.4
Bottom gap (cm)	15	15

1 m = 3.28 ft
1 cm = 0.39 in.

Each end post should be braced with a steel post driven into the ground at an angle so as to extend from near the top of the end post to the ground line of the adjacent post, and wired in place (Figure 5.32).

If picket fencing is used, it should be pulled taut (at least 1.1 kN (250 lbf) for a 1.2-m (4-ft) width). Synthetic fencing material should also be pulled taut, as specified by the manufacturer.

Plastic fencing material should be sandwiched between a wooden lath against the post, and an outer wooden batten 50 × 50 mm (2 × 2 in.), wired tightly to the steel post at the center and at 15 cm (6 in.) in from each edge (Figure 5.32, detail B). A better method is to slip a piece of foam insulation for 25-mm (1-in.) pipe around the post instead of the wood member against the post (Figure 5.33).

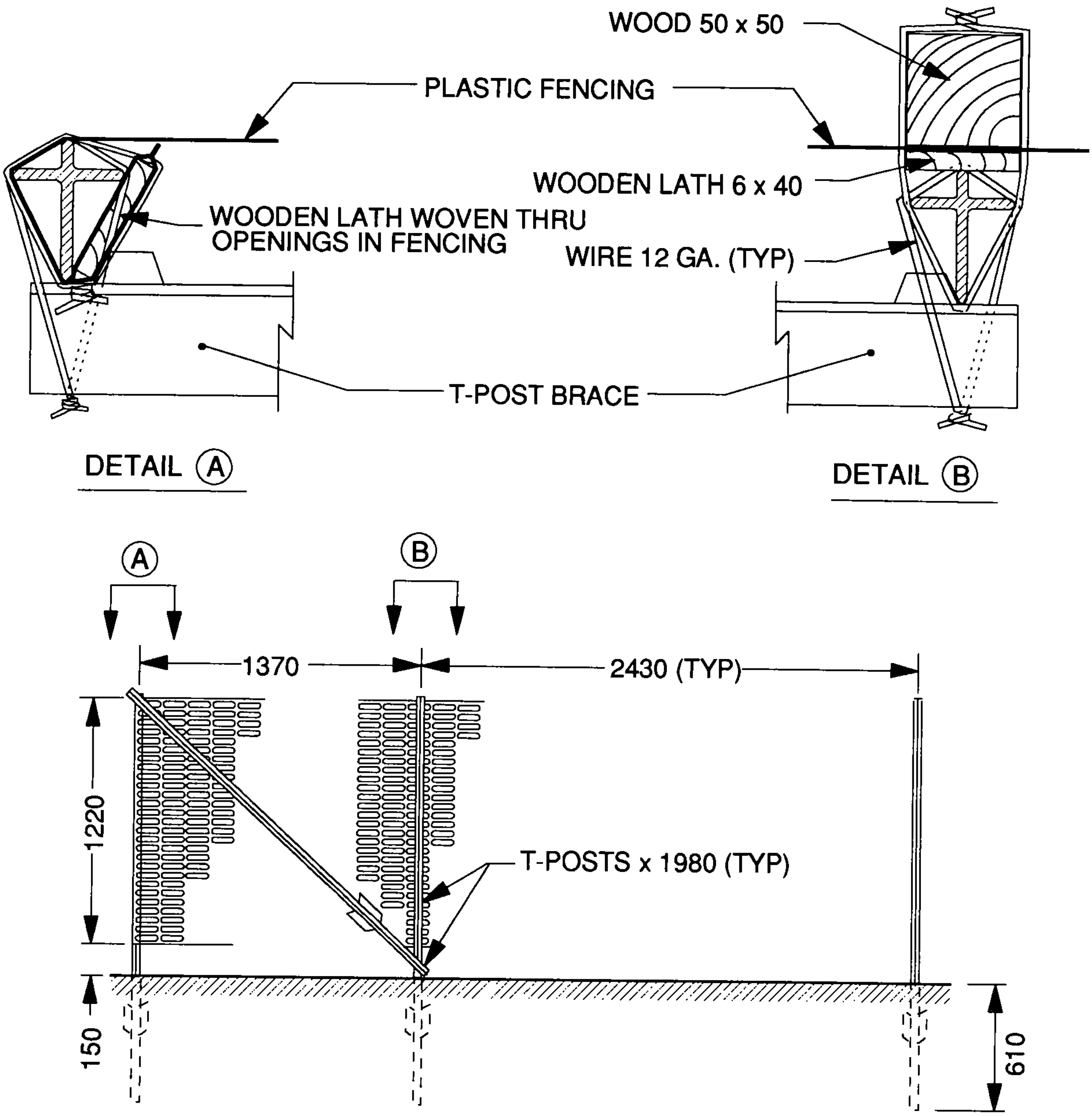


Figure 5.32. Guidelines for supporting 1.2-m (4-ft) synthetic fencing materials using steel T-posts. Lath woven through openings provides a secure attachment for the ends of the fencing material.

Figure 5.33. Foam pipe insulation slipped over a steel T-post provides a better grip on fencing than wooden lath.

5.3.9.2 The Tensar Portable Fence

The Tensar Corporation has a patented new design for portable fences 2 m (6.5 ft) and 2.4 m (8 ft) tall. A snow fence with an effective height of 2 m (6.5 ft) stores three times as much snow as a 1.2-m (4-ft) fence. A snow fence that is 2.4 m (8 ft) tall stores 4.6 times as much snow as the 1.2-m (4-ft) fence.

Each 2.4-m (8-ft)-long panel consists of a wooden frame comprised of 50 × 150-mm (2 × 6-in.) lumber, bolted together at the corners, with a 1.2-m (4-ft)-wide strip of plastic mesh snow fence (Tensar UX3100) pulled taut across the center (Figures 5.34 and 5.35). Tensioning is accomplished with threaded rods connected to a pipe woven through the plastic. The panels are connected to one another by rebar pins passing through the same type of U-clips used to anchor the Wyoming fences. U-clips also attach the fence to the rebar anchors that are driven into the ground. Adequate penetration for most soils is 50 cm (20 in.). The U-clip-and-pin connections (Figure 5.36) allow rapid setup and take-down. Panels can be overlapped at either the top or bottom as required to eliminate gaps between panels. The U-clips can be rotated as required to accommodate irregular terrain, and only a single U-clip needs to be tightened at each connection to prevent the pin from vibrating out. The U-clips can be made from either 3-mm (1/8-in.) steel plate or ultra-high-molecular-weight polyethylene.

Each pair of adjacent panels shares a single 50 × 150-mm (2 × 6-in.) brace member and a single upwind anchor, thereby minimizing the cost of materials and installation. The braces can be installed on either side of the fence.

The fence can be inclined at any desired angle. This is useful to control the pattern of snow deposition, and allows the effective height of the fence to be changed to fit available space. Inclining the 2-m (6.5-ft) snow fence at 45°, for example, makes a 1.4-m (4.5-ft) fence, and changes the maximum length of the downwind drift from 70 m (230 ft) to 49 m (161 ft).

Field installation of prefabricated panels requires approximately 3 person-hours per 30 m (100 ft) of fence, which is less than the time required to install a conventional 1.2-m (4-ft) lath or plastic snow fence. Field installation of the 2.4-m-tall (8-ft) fence requires only 10% as much time as is required to build a series of conventional 1.2-m (4-ft) fences with an equivalent storage capacity. Costs for materials and fabrication are comparable to costs for permanent fences. Time required for fabrication of either height is approximately 0.75 person-hours.

The wooden frame version will soon be replaced by an all-synthetic prefabricated panel being developed by the Tensar Corporation. Consisting of heavy duty fencing material molded into a structural foam frame, the panels are 1.2 × 1.8 m (4 × 6 ft) in size, weigh less than 4 kg (8.8 lb), and can be stacked vertically to make a 2.4-m (8-ft) tall fence.

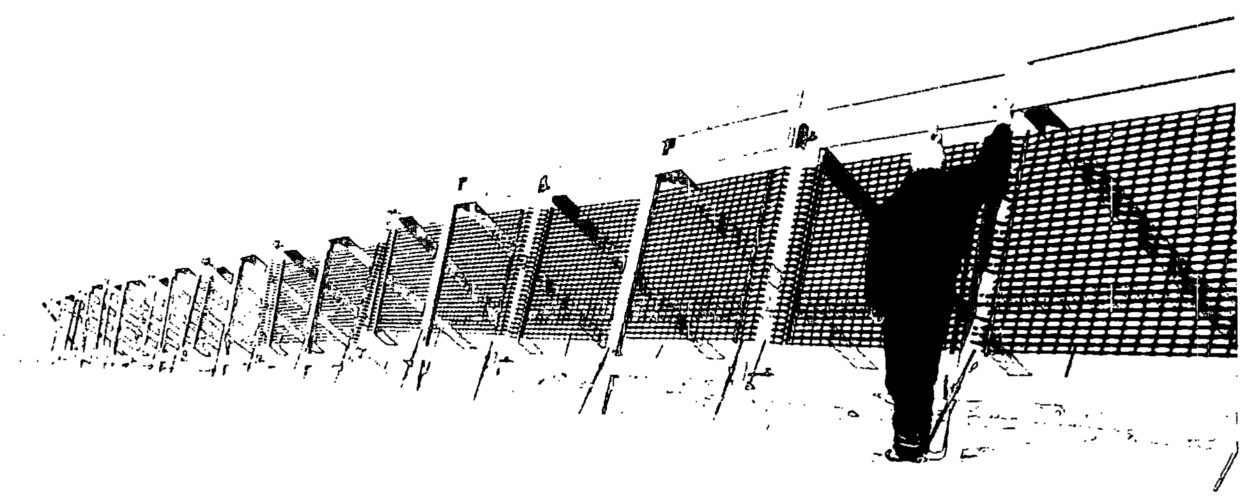


Figure 5.34. The Tensar 2- and 2.4-m-tall (6.5- and 8-ft) patented portable fence design uses a wooden framework to support the fencing material. Panels are connected using the U-clips shown in Figure 5.7, with rebar pins.

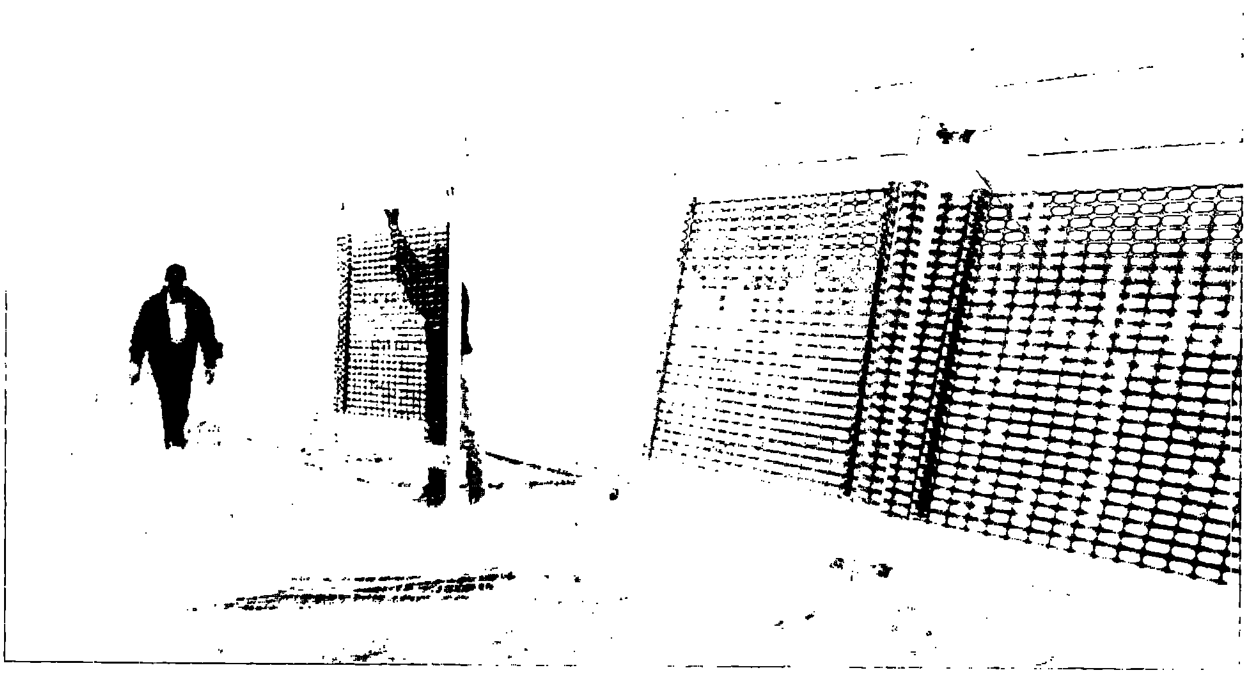


Figure 5.35. Installation of Tensar portable fence panels.

Figure 5.36. U-clip and pin connections used for the Tensar portable fence.

5.3.10 *Specifying Fence Type*

The type of fence selected for a particular application depends on relative cost, required height and porosity, appearance, fencing materials to be used, availability of materials, terrain, soil conditions, and use of the land where the fences are placed. Advantages and disadvantages of the Wyoming fence and pole-supported fences are summarized below.

Wyoming Fence

Advantages

Least expensive to build in most locations,
Relatively easy to remove or relocate,
Can be prefabricated to reduce field construction time,
Standard plans are available for most applications.

Disadvantages

Susceptible to damage by snow creep or glide on steep slopes,
Occupies significant land area,
Maximum practical height limited to about 4.3 m (14 ft).

Pole-Supported Fences

Advantages

Occupies least land area,
Suitable for any height of fencing,
Less susceptible to damage by snow creep on steep slopes,
Allows utilization of all types of fencing materials such as plastics,
Suitable for permafrost soils.

Disadvantages

Usually more expensive than the Wyoming fence,
Fences taller than 1.8 m (6 ft) are not easily relocated,
More time is required for field construction,
Supports must be custom-designed for each site.

5.3.11 Wind Loads on Snow Fences

5.3.11.1 Basic Equation

The force of the wind on a structure is given by

$$F_w = 0.5\rho_a C_d H_s S_p U^2 \tag{5.8}$$

where

F_w = wind force (N),
ρ_a = air density (kg/m^3),
C_d = drag coefficient,
H_s = structure height (m),
S_p = length or span (m),
U = wind speed (m/s)

Generalizations from Equation (5.8) are that the force of the wind increases as the square of the wind speed, in direct proportion to the area of the barrier, and in direct proportion to air density.

5.3.11.2 Air Density

Air density varies with temperature and atmospheric pressure. It is important to take this variation into account in computing wind loads. The following expression for air density as a function of elevation and temperature, was derived from relationships presented in List (1968):

$$\rho_a = \{353(1-.000022569E)^{5.255}\}/(t_a+273) \tag{5.9}$$

where

ρ_a = air density (kg/m^3)
E = elevation above sea level (m)
t_a = air temperature (°C)

5.3.11.3 Drag Coefficient

The drag coefficient C_d is the coefficient of proportionality between the force exerted on an object, and the dynamic pressure of the wind (defined as $0.5\rho_a U^2$). For purposes of structural design addressed here, drag coefficients are independent of wind speed above about 40 km/h (25 miles/h), the approximate speed at which natural winds become fully turbulent. Drag coefficients are experimentally determined from wind-tunnel or prototype measurements. Primary sources of published drag coefficients include Hoerner (1965) and Guyot (1978).

Because a drag coefficient can be computed that relates wind speed at any location to the force on an object, it is necessary to use a drag coefficient that is appropriate for the particular velocity used in Equation (5.8). It is possible, for example, to specify a drag coefficient that relates drag force on a 1-m (3.3-ft)-tall fence to the wind speed at 10 m (33 ft) above the ground. As used here, the drag coefficient corresponds to the mean square wind speed over the projected area of the object. This is a particularly important distinction for computing wind loads on objects attached to the ground.

A long, solid plate suspended high above the ground has a drag coefficient of 1.98. If this same plate is in contact with the ground, the drag coefficient is reduced to about 1.25, presumably due to the effect of the ground on vortex development. Three-dimensional objects do not show such large differences between free-stream and on-ground drag coefficients, and the same is true of porous screens.

The projected area of a porous object is that defined by its perimeter, and therefore includes any openings. Although drag coefficients are obviously related to the percent of solid area, this proportionality is generally not linear because the cross-section of the air flow is smaller than the opening itself. As a result, the aerodynamic porosity of a porous fence may be less than its physical porosity. For a given physical porosity, smaller openings result in a lower aerodynamic porosity (and therefore a larger drag coefficient) than larger openings.

Drag coefficients for various snow fences are listed in Table 5.5.

Table 5.5. Drag coefficients for snow fences.

Fence	Porosity, P	Source	C_d
Solid fence	0	Hoerner (1965)	1.25
Solid fence	0	Tabler (1978)	1.22 ± 0.03
Wyoming snow fence	0.5	Tabler (1978)	1.05 ± 0.01

± values indicate 95% confidence limits.

When experimentally determined drag coefficients for porous screens are unavailable, estimates can be made from empirical relationships, as described by Guyot (1978). As a working equation applicable to coarse materials, the author proposes a simple parabolic equation to approximate the relationship between drag coefficient and porosity shown in Figure 5.37 (Tabler 1986b):

$$C_d = 1.4 - 1.4P^2; \qquad P>0.3 \tag{5.10}$$

where P is the porosity ratio. This equation provides an outer envelope for the data that should be sufficiently conservative for engineering purposes. It has been fitted with the single constraint that $C_d = 1.05$ at $P = 0.5$, because this value is a reasonably close approximation for most snow fences. Equation (5.10) appears to overestimate the drag coefficient for barriers that have $P < 0.3$.

The preceding discussion applies to very long barriers. Although the drag coefficient is less for three-dimensional objects, correction is usually unwarranted for snow fence applications.

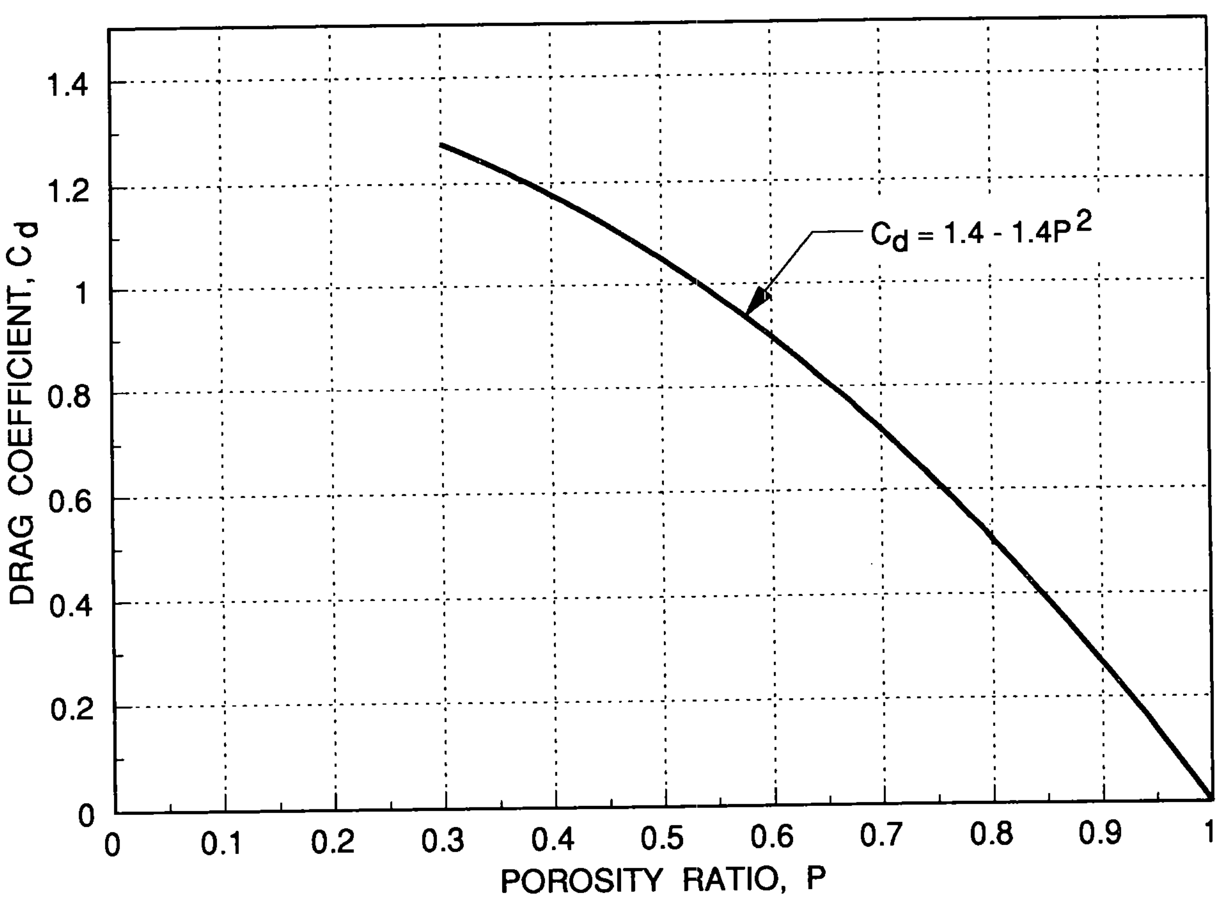


Figure 5.37. Independent drag coefficient as a function of barrier porosity (Tabler 1986b).

5.3.11.4 Wind speed

Assuming a wind profile as described in section 3.4.3, a close approximation to the mean squared velocity, U_m^2, over a fence of height H is

$$U_m^2 = 6.25\, U_*^2\{[\ln(H/Z_o)]^2 - 2\ln(H/Z_o)+2\} \qquad (5.11)$$

where other terms are as defined in section 3.4.3. The height above the ground, Z_f, at which the resultant of the drag force acts, is given by

$$Z_f = 0.5H\{[\ln(H/Z_o)]^2 - \ln(H/Z_o) + 0.5\}/\{[\ln(H/Z_o)]^2 - 2\ln(H/Z_o)+2\} \qquad (5.12)$$

For a snow-covered surface (where Z_o = 0.02 cm), Equation (5.12) indicates that to a reasonable approximation,

$$Z_f = 0.56H \qquad (5.13)$$

Wind pressures for 50%-porous snow fence are tabulated by fence height and wind speed in Table 5.6, for an assumed Z_o = 0.02 cm at sea level and a temperature of 20°C.

Table 5.6. Wind pressures, $P_{w,o}$, on snow fences that have porosity ratios of 0.5 (C_d = 1.05) at sea level and 20°C (68°F), as computed by numerical integration to determine the mean squared wind speed over fence height H, taking Z_o = 0.02 cm. Z_f is height of resultant force, or moment arm (Tabler 1986a).

		Wind speed at 10 m (km/h)										
H	Z_f	100	110	120	130	140	150	160	170	180	190	200
(m)	(m)	Wind pressure, $P_{w,o}$ (Pa)										
1.0	0.56	240	290	345	405	470	539	614	693	776	865	959
1.2	0.67	251	304	362	425	492	565	643	726	814	907	1005
1.4	0.79	261	316	376	441	512	588	669	755	846	943	1045
1.6	0.90	270	327	389	456	529	607	691	780	875	975	1080
1.8	1.01	278	336	400	470	545	625	711	803	900	1003	1111
2.0	1.12	285	345	410	482	559	641	730	824	923	1029	1140
2.2	1.23	292	353	420	493	571	656	746	843	945	1053	1166
2.4	1.34	298	360	429	503	583	670	762	860	964	1074	1190
2.6	1.45	303	367	437	512	594	682	776	876	982	1095	1213
2.8	1.56	308	373	444	521	605	694	790	891	999	1114	1234
3.0	1.67	313	379	451	530	614	705	802	906	1015	1131	1254
3.2	1.76	318	385	458	537	623	716	814	919	1030	1148	1272
3.4	1.87	322	390	464	545	632	725	825	932	1045	1164	1290
3.6	1.98	327	395	470	552	640	735	836	944	1058	1179	1306
3.8	2.09	331	400	476	559	648	744	846	955	1071	1193	1322
4.0	2.20	334	405	481	565	655	752	856	966	1083	1207	1337
4.2	2.31	338	409	487	571	662	760	865	977	1095	1220	1352
4.4	2.41	341	413	492	577	669	768	874	987	1106	1233	1366
4.6	2.52	345	417	496	583	676	776	883	996	1117	1245	1379
4.8	2.63	348	421	501	588	682	783	891	1006	1127	1256	1392
5.0	2.74	351	425	506	593	688	790	899	1015	1138	1267	1404

km/h = 1.606·miles/h
m = 0.305·ft
Pa = 47.85(lb/ft^2)

Table 5.7. Correction factors $C_{E,T}$ for adjusting wind pressures in Table 5.6 for different elevations and temperatures, using Equation (5.14). Example: To determine the wind load at 2200 m and -10°C, multiply value in Table 5.6 by 0.85 (Tabler 1986a).

Elevation (m)	Air temperature (°C) -40	-30	-20	-10	0	+10	+20
	Correction Factor, $C_{E,T}$						
0	1.26	1.21	1.16	1.11	1.07	1.04	1.00
200	1.23	1.18	1.13	1.09	1.05	1.01	0.98
400	1.20	1.15	1.10	1.06	1.02	0.99	0.95
600	1.17	1.12	1.08	1.04	1.00	0.96	0.93
800	1.14	1.10	1.05	1.01	0.98	0.94	0.91
1000	1.12	1.07	1.03	0.99	0.95	0.92	0.89
1200	1.09	1.04	1.00	0.96	0.93	0.90	0.87
1400	1.06	1.02	0.98	0.94	0.91	0.87	0.84
1600	1.04	0.99	0.95	0.92	0.88	0.85	0.82
1800	1.01	0.97	0.93	0.90	0.86	0.83	0.80
2000	0.99	0.95	0.91	0.87	0.84	0.81	0.78
2200	0.96	0.92	0.89	0.85	0.82	0.79	0.77
2400	0.94	0.90	0.86	0.83	0.80	0.77	0.75
2600	0.92	0.88	0.84	0.81	0.78	0.75	0.73
2800	0.89	0.86	0.82	0.79	0.76	0.73	0.71
3000	0.87	0.83	0.80	0.77	0.74	0.72	0.69

°C = 0.556(°F - 32)
m = 0.305·ft

Table 5.8. Correction factor C_P for adjusting wind loads in Table 5.6 for different fence porosities using Equation (5.10) to estimate the drag coefficient, C_d (Tabler 1986a).

Porosity ratio, P	C_d	Correction factor, C_P
0	1.40	1.33
0.05	1.40	1.33
0.10	1.39	1.32
0.15	1.37	1.30
0.20	1.34	1.28
0.25	1.31	1.25
0.30	1.27	1.21
0.35	1.23	1.17
0.40	1.18	1.12
0.45	1.12	1.06
0.50	1.05	1.00
0.55	0.98	0.93
0.60	0.90	0.85
0.65	0.81	0.77
0.70	0.71	0.68
0.75	0.61	0.58
0.80	0.50	0.48
0.85	0.39	0.37
0.90	0.27	0.25
0.95	0.14	0.13
1.00	0.00	0.00

5.3.11.5 Selecting a Design Wind Speed

Design wind speeds (or effective wind loads) are often specified in local building codes. *The Uniform Building Code* (ICBO 1982), or *UBC*, states:

> "The minimum basic wind speed for determining design wind pressure shall be taken from Figure No. 4 [map of the U.S. showing winds with 50-year recurrence interval]. Where terrain features and local records indicate that 50-year wind speeds at standard height are higher than those shown in Figure No. 4, these higher values shall be the minimum basic wind speeds."

These "basic" wind speeds are those for the "fastest mile," calculated from the shortest time required for a mile of wind to pass an anemometer. Some additional allowance should be made for higher-speed short duration gusts. Although a general rule for non-mountainous terrain is that gusts are 30-50% greater than the wind speed average over a period of 5-10 minutes, this gust factor does not apply to the "fastest mile" because of the shorter averaging time represented by the "fastest mile" (e.g., 58 seconds at 100 km/h = 62 miles/h). The *UBC* provides an adjustment for gusts based on exposure and height. The combined height, exposure and gust factor coefficient, C_e, is 1.2 for a structure less than 6.1 m (20 ft) tall and with an open exposure. Because dynamic pressure is proportional to the square of wind speed, a value of 1.2 essentially allows for a gust 10% higher than the "fastest mile." For structures 6-12 m (20-40 ft) tall, C_e = 1.3, which allows for gusts about 15% higher than the "fastest mile." Adding 15% to the 50-year "fastest-mile" is therefore adequate for designing snow fences.

5.3.11.6 Procedure for Calculating Wind Loads

The procedure for calculating wind pressures using Tables 5.6 to 5.8 follows.

1. Determine required fence height (H_s) and porosity (P).
2. Determine the design wind speed.
3. Determine the elevation of the site, and the lowest temperature expected to occur with the design wind speed.
4. From Table 5.6, read the wind pressure, $P_{w,o}$, for a fence with porosity 0.50 at sea-level and 20°C (68°F).
5. From Table 5.7, determine the correction factor ($C_{E,T}$) appropriate for the elevation and design temperature of the fence site.
6. From Table 5.8, determine the correction factor (C_p) for the porosity of the fence.
7. Multiply the value obtained in Step 4 by the correction factors obtained in Steps 5 and 6 to obtain the design wind pressure P_w

$$P_w = (C_{E,T})(C_p)(P_{w,o}) \tag{5.14}$$

The wind force, F_w, on support members spaced S_p apart is obtained by multiplying the design wind pressure (P_w) by the fence area between supports ($H_s \cdot S_p$). The bending moment of the applied force with respect to the ground surface is obtained by multiplying F_w by Z_f given in Table 5.6.

Example for Buffalo, New York:

Given: Fence height = 2.4 m (7.9 ft)
Fence porosity ratio = 0.4
Design wind speed = 140 km/h (87 miles/h)
Elevation = 215 m (705 ft)
Lowest temperature expected with design wind = -10°C (14°F)

Required: Calculate the design wind pressure and resultant bending moment on vertical supports spaced 3.0 m (9.8 ft) apart. Assume that point of fixity is at surface.

Solution:
From Table 5.6, $P_{w,o}$ = 583 Pa; Z_f = 1.34 m
From Table 5.7, $C_{E,T} = 1.09 - (15/200)(0.03) \approx 1.09$
From Table 5.8, C_p = 1.12
$P_w = (583)(1.09)(1.12) = 711.7$ Pa (14.87 lbf/ft^2)
$F_w = (711.7)(2.4)(3.0) = 5124$ N (1152 lbf)
Bending moment = (5124)(1.34) = 6866 N·m (5061 ft·lbf)

5.4 Deflector Snow Fences

Although deflector fences are not commonly used in the United States, they are the primary form of drift control in Japan, and are used in India, China, and other countries. Deflectors are also used in Europe to prevent snow cornices from forming in avalanche starting zones.

The three most common forms of deflectors are the blower fence; the long, solid deflector (non-porous two-dimensional vertical deflector); and the three-dimensional lateral deflector.

5.4.1 Jet Roofs and Blower Fences

The jet roof consists of a single, broad, roof-like deflection member that has a horizontal longitudinal axis. The structure is sloped so that the downwind edge is closer to the ground than the upwind edge (Figures 5.38 and 5.39). By accelerating the airflow and deflecting it downward, this structure promotes turbulent entrainment of the blowing snow particles and causes the snow to be carried farther downwind before it is deposited. These effects can be used to eliminate snow cornices at the tops of cuts or in avalanche starting zones downwind of mountain ridges.

Jet roofs can be any length, but the width of the roof is typically 1.5 to 4 m (4 to 13 ft). For best performance, the slope of the roof should be about the same as that of the slope being protected, and the lower (downwind) edge of the roof should be 1 to 1.5 m (3 to 5 ft) above the ground.

In Japan, very large jet roofs have been used to reduce snow deposition in road cuts, and constitute one example of blower fences, or *yudō saku*. Large blower fences designed to reduce snow accumulation in road cuts (Figures 5.40 and 5.41) can be effective in reducing snow deposition (Figure 5.42). Although collector fences can be much more efficient, the value and agricultural use of land in Japan has resulted in the preferential use of blower fences placed close to the road.

The Japanese commonly use blower fences to improve visibility by reducing the amount of snow blowing off roadside snowbanks at windshield level. There is an endless variety of fences used for this purpose, but one of the more common consists of multiple slats for deflecting the airflow downward. Figure 5.43 shows the use of smoke to visualize the airflow behind such a blower. The accelerated wind also reduces snow deposition downwind of the fence, but this effect extends only for a distance of 1 to 1.5*H*. Blower fences must therefore be placed immediately alongside the area to be protected, and the protected area must be relatively narrow. Although these requirements limit applicability on U.S. highways, this type of control measure might be acceptable for use on private roads.

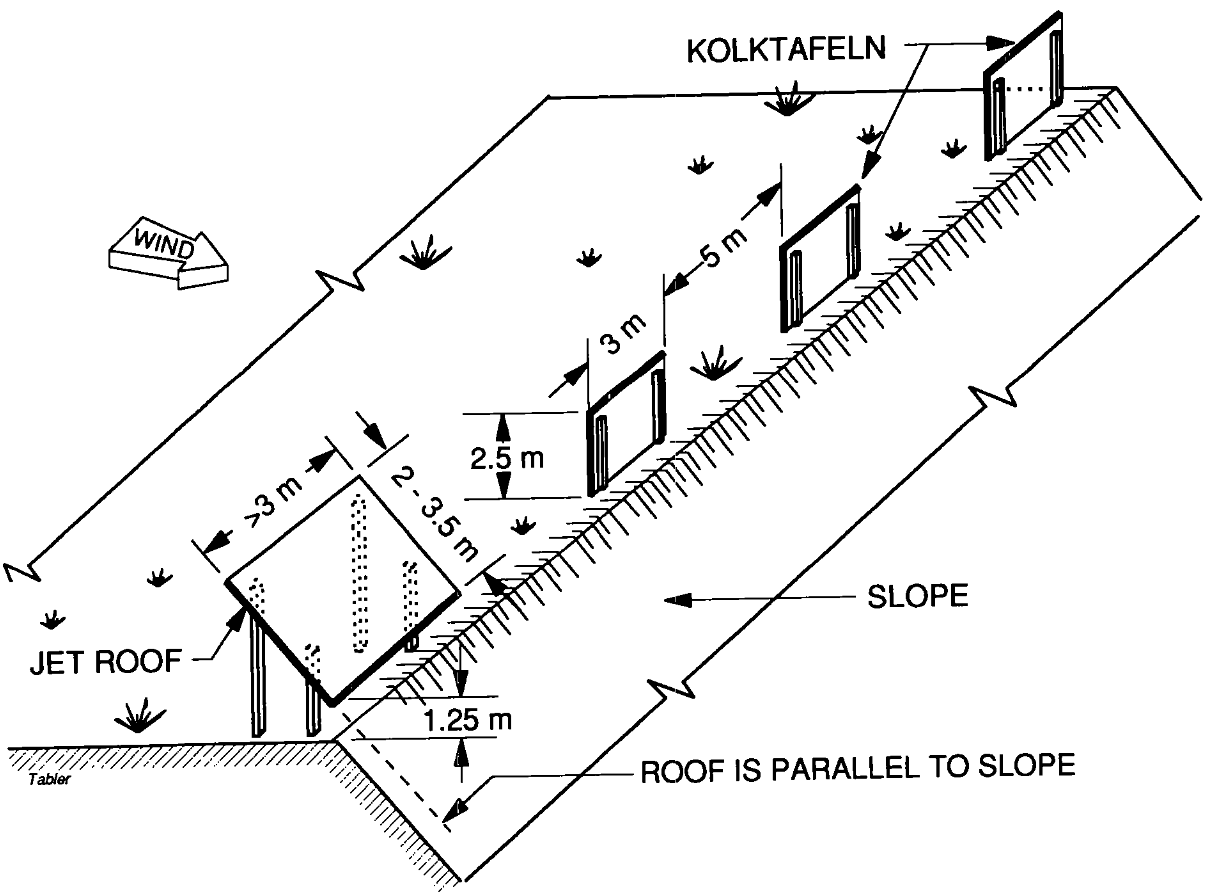


Figure 5.38. Jet roofs and *Kolktafeln* (turbulence generators) prevent the formation of snow cornices in avalanche starting zones.

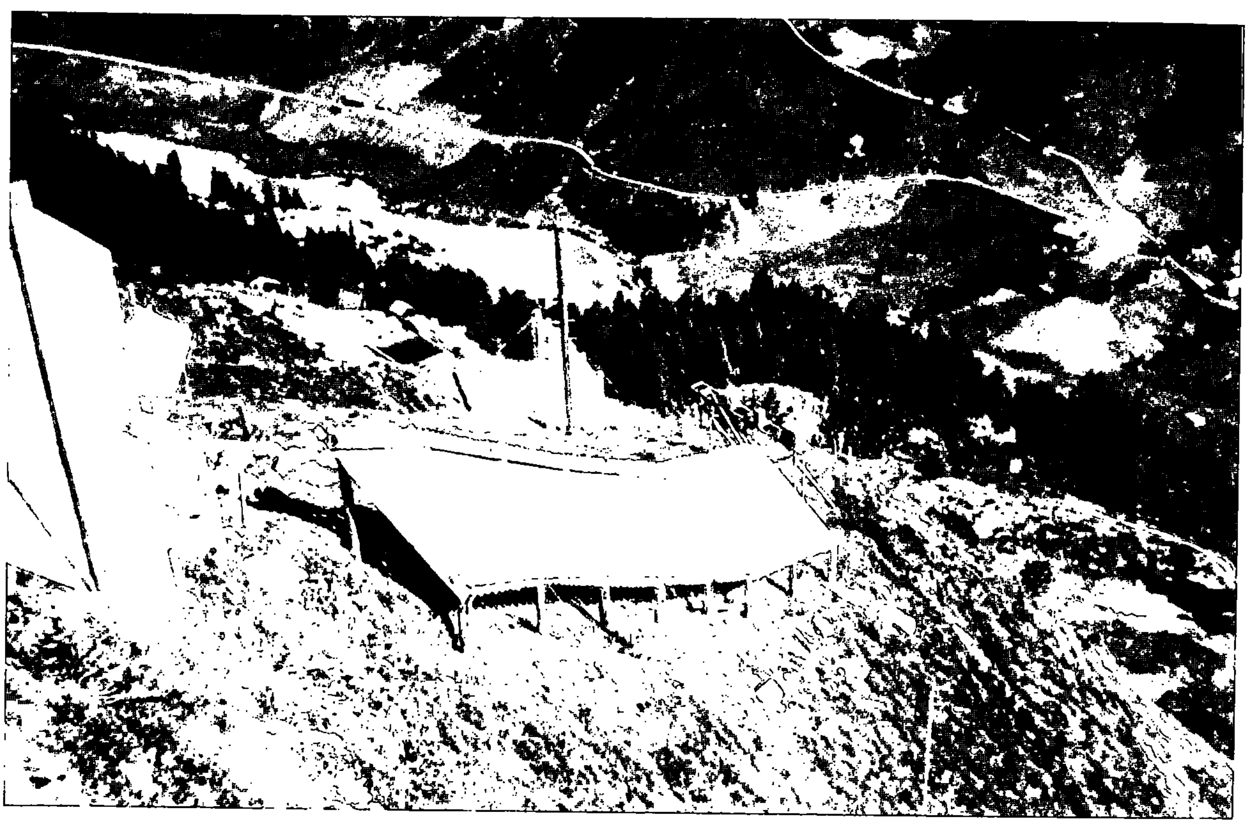


Figure 5.39. Jet roof in Switzerland. Courtesy of Dr. M. "Pete" Martinelli.

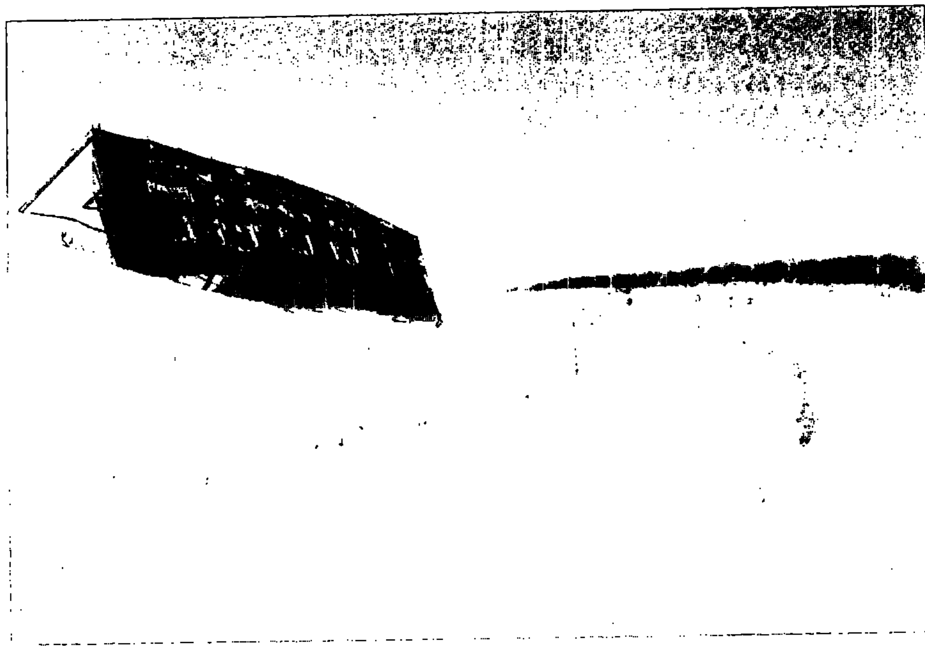


Figure 5.40. The effectiveness of blower fences in reducing snow depths in cuts can be seen in this photograph by Tetsuya Uchiya, Hokkaido Development Bureau.

Figure 5.41. A large deflector installed on a road cut in Hokkaido, Japan. Photograph by Tetsuya Uchiya, Hokkaido Development Agency.

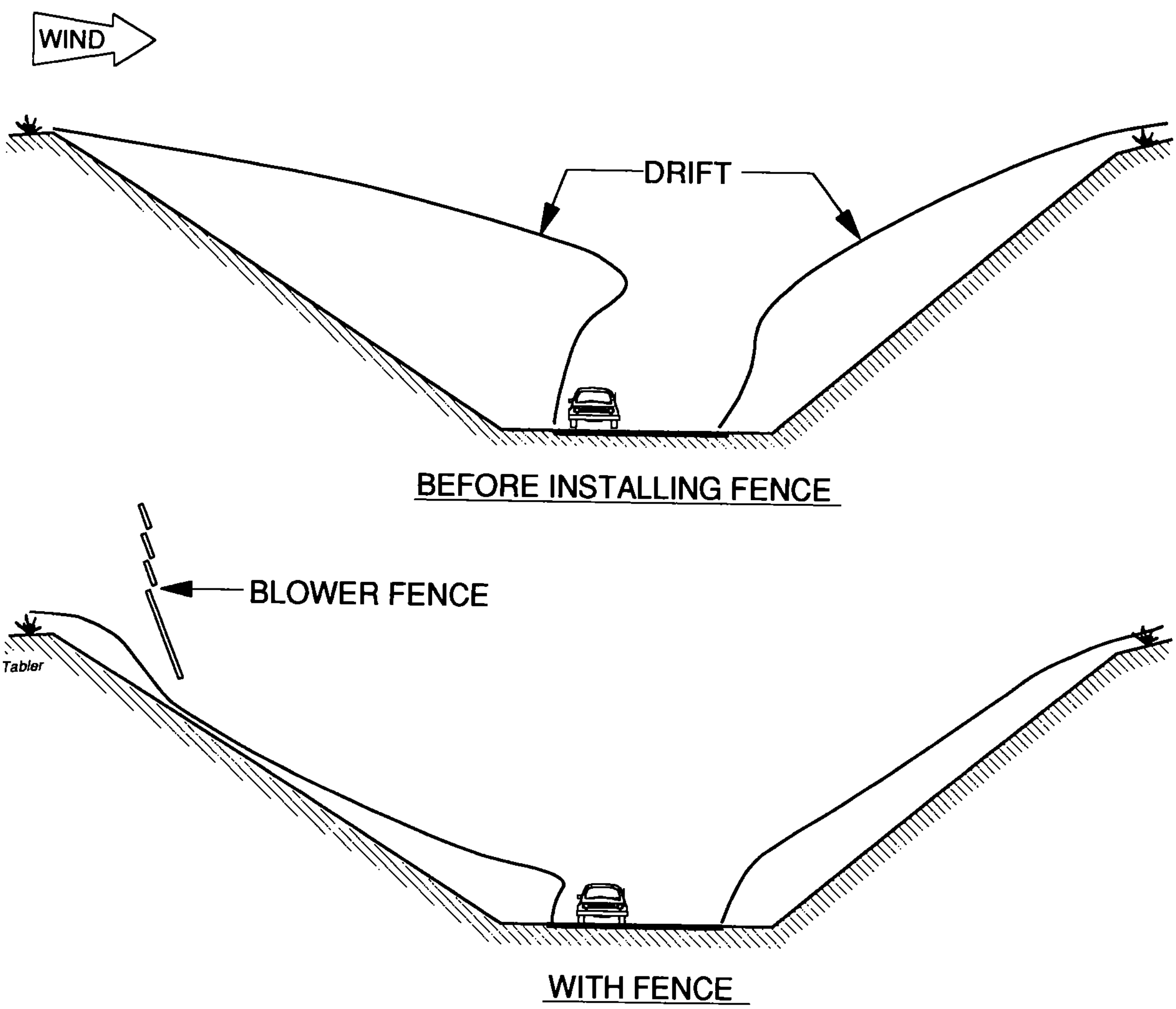


Figure 5.42. Snowdrift depths in road cut before and after installing deflector shown in Figure 5.41. Redrawn from Hokkaido Development Bureau 1974, p. 19.

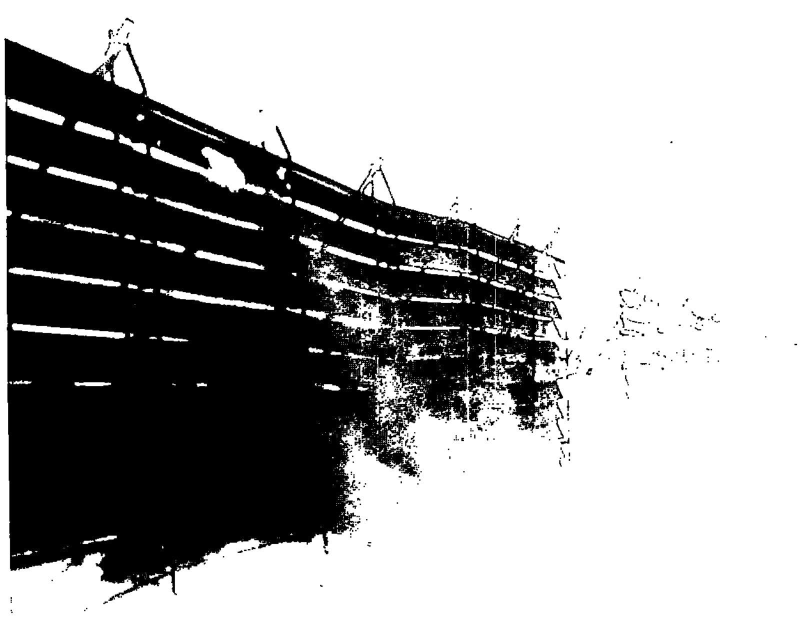


Figure 5.43. Smoke was used to show the airflow behind typical blower fence used in Japan to reduce snow blowing off roadside snowbanks at windshield level, with wind from left (Tabler 1986b). Courtesy of Tetsuya Uchiya, Hokkaido Development Bureau.

5.4.2 *Long Solid Deflectors*

Long solid deflectors can consist of solid fences or embankments constructed from earth or snow. The long solid deflector injects the snow particles into the accelerated jet flow over the top of the fence, allowing the particles to become entrained in the turbulent flow and carried past the protected area before they settle to the surface (Figure 3.58). Turbulent diffusion also reduces the concentration of the particles. Long solid deflectors also collect snow, although not as efficiently as do porous fences.

For maximum effectiveness, such deflectors should be placed at a distance equal to ten times their vertical height (10*H*) upwind from the area to be protected. When embankments are used as solid deflectors (Figure 5.4.), slopes should be as steep as possible, and the tops should be smoothed to eliminate protruding chunks of snow that disrupt the wake boundary and favor deposition rather than entrainment. Placing a porous fence on embankments eliminates their ability to deflect snow, and promotes deposition downwind of the crest (Jairell and Tabler 1985).

5.4.3 *Lateral Deflectors*

Lateral deflectors force the snow particles to pass around the sides of the protected region. As shown in Figure 5.44, the wake downwind of objects can be essentially free of blowing snow in the absence of concurrent snowfall. This snow-free zone can extend for great distances downwind because the direction of rotation of the lateral vortices, and the pressure gradient between the wake and the outside flow, combine to retard the influx of snow into the wake. Livestock shelters offer the best example of lateral deflectors (Figures 5.45 and 5.46). For highway applications, the primary disadvantage of lateral deflectors is the formation of wing-shaped snowdrifts at the boundary between the wake region and the outer flow (Jairell and Tabler 1985).

Blunt shapes are somewhat more efficient deflectors than streamlined forms, and model tests of livestock shelters show slightly less snow to be deposited behind a V-shaped deflector than behind a semicircular one (Jairell and Tabler 1985). The width-to-height ratio of lateral deflectors is a primary factor that affects performance. Shelters that are too wide act like long, solid deflectors, promoting snow deposition on the downwind side. To minimize snow deposition on the downwind side, the width (or diameter) of a shelter should not exceed fifteen times its height (15*H*).

Kolktafeln are solid rectangular panels, typically on the order of 3 m (10 ft) square, that are used to prevent cornice formation (Figure 5.38). The turbulence generated by these panels prevents snow from being deposited at the location where the cornice would otherwise form. This approach can also be used to change the location of snowdrifts that form around buildings.

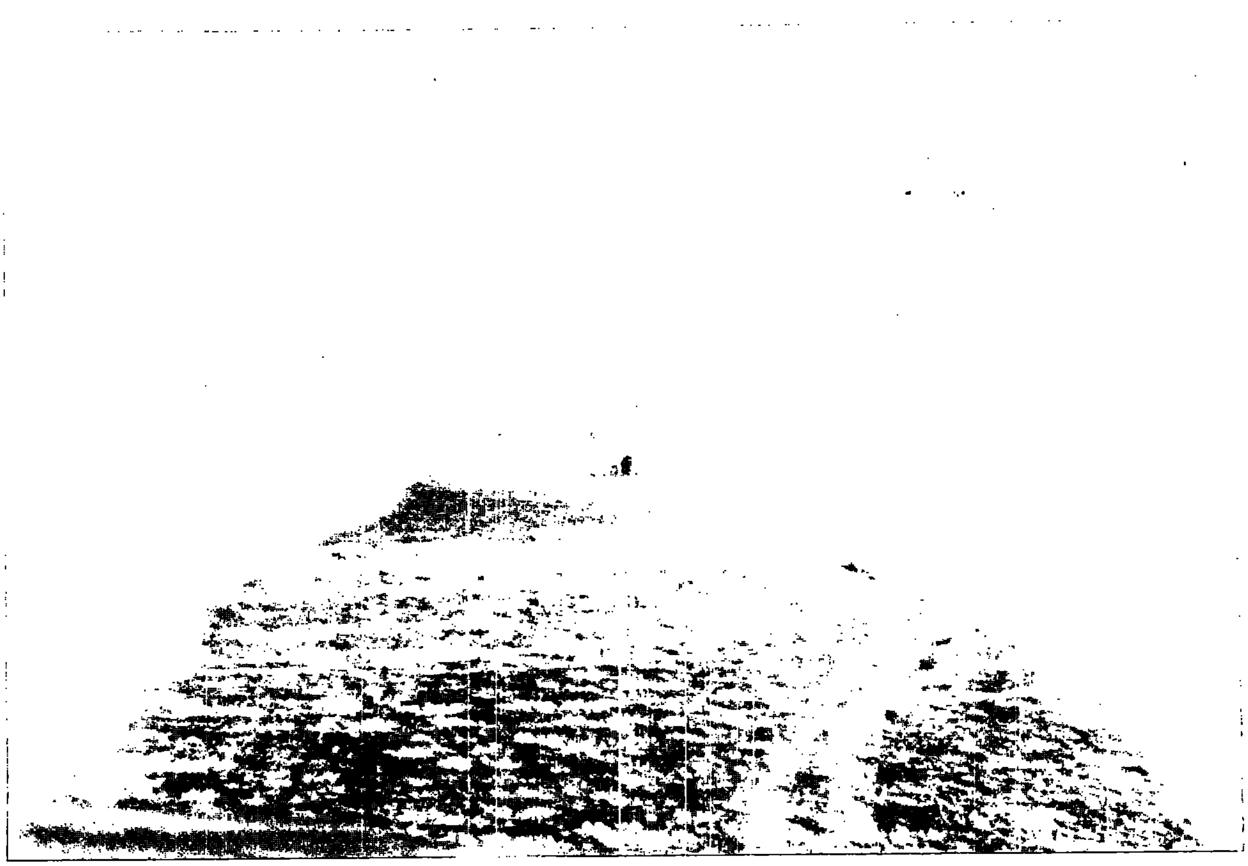


Figure 5.44. Blowing snow is deflected around three-dimensional objects, resulting in relatively snow-free air in the wake region (Tabler 1984). This view is looking upwind toward a trailer 2.4 m tall, 2.2 m wide, and 5 m long (8 × 7 × 16 ft).

Figure 5.45. A livestock shelter that acts as a lateral deflector.

Figure 5.46. This 1:30 scale model of the livestock shelter shown in Figure 5.45, illustrates the effectiveness of lateral deflectors in preventing snow deposition on the downwind side, and the wing-shaped drifts that form along the side of the wake (Tabler 1986b).

5.5 Placement

The optimum placement of a snow fence depends on topography, ownership and use of the land, vegetation, soil conditions, location and nature of nearby buildings or other structures, scenic considerations, and many other more subtle but equally important site-specific factors. Not all of the features that affect fence performance and acceptability are discernible from maps and plans. Field evaluation is essential because of these limits to guidelines. The criteria presented in this section provide only a starting point in determining where a fence should be placed.

5.5.1 Orientation

The orientation of a fence refers to its alignment with respect to the prevailing direction of snow transport. The angle between the transport direction and a perpendicular to the alignment of the snow fence is referred to as the angle of attack, α (Figure 5.47).

5.5.1.1 Importance of Orientation

Although storage capacity per unit length of fence decreases as the wind becomes more oblique to the fence, the capacity per unit of width across the wind is not appreciably affected by orientation, at least not for attack angles greater than 45° or so (section 3.8.5.2.6). Trapping efficiency, however, probably declines as winds become more oblique to the fence. If the fence is not exactly perpendicular to the wind, the cross-wind component causes the recirculation vortex aft of the slip face to develop a corkscrew motion that transports some of the particles along the length of the drift until they are swept away in the slipstream at the end of the fence.

If fences are oriented perpendicular to the prevailing transport direction, on the other hand, and if the wind direction is not perpendicular to the road, then the effectiveness of the fence decreases as the distance between the fence and the road increases.

5.5.1.2 Basic Rule

In general, fences should be oriented parallel to the road if the prevailing wind direction is within 25° of being perpendicular to the road (i.e., $\alpha > 65°$). For more oblique winds, fences should be aligned perpendicular to the prevailing direction. Attack angles less than 65° are acceptable if necessary to avoid adverse terrain, or to take advantage of favorable topography. The orientation of a fence is much less important than its proper extension on either side of the area to be protected.

5.5.1.3 Parallel Versus Oblique Fences

Fences parallel to the road are referred to as "parallel" (Figure 5.47), and those aligned at an angle to the road are referred to as "oblique" (Figure 5.48). Parallel fences require a shorter total fence length, have fewer openings to detract from trapping efficiency, and are more effective because of the reduced space between the fence and the area to be protected.

Where oblique fences must be used, adding a parallel fence between the road and the oblique fences affords the most complete protection. The capacity of the parallel fence should be sufficient to store all of the snow relocated over the maximum distance between the parallel fence and the oblique fences.

Where the average wind direction is nearly parallel with the road, blowing snow conditions can be improved by placing fences on both sides of the road in a herringbone pattern. Instead of aligning the fences perpendicular to the wind, the fences should be angled so that the outside end is farther downwind than the end closest to the road (Figure 5.49). This orientation helps to deflect the blowing snow away from the road.

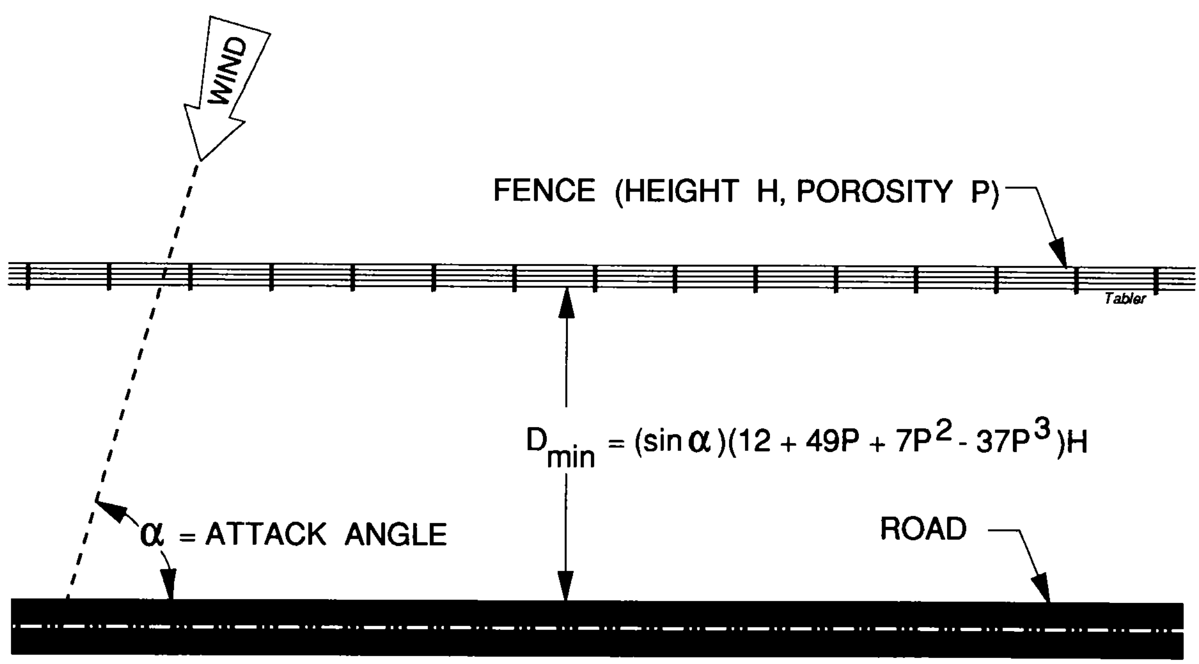


Figure 5.47. Fences should be aligned parallel to the road if the attack angle is 65° or more.

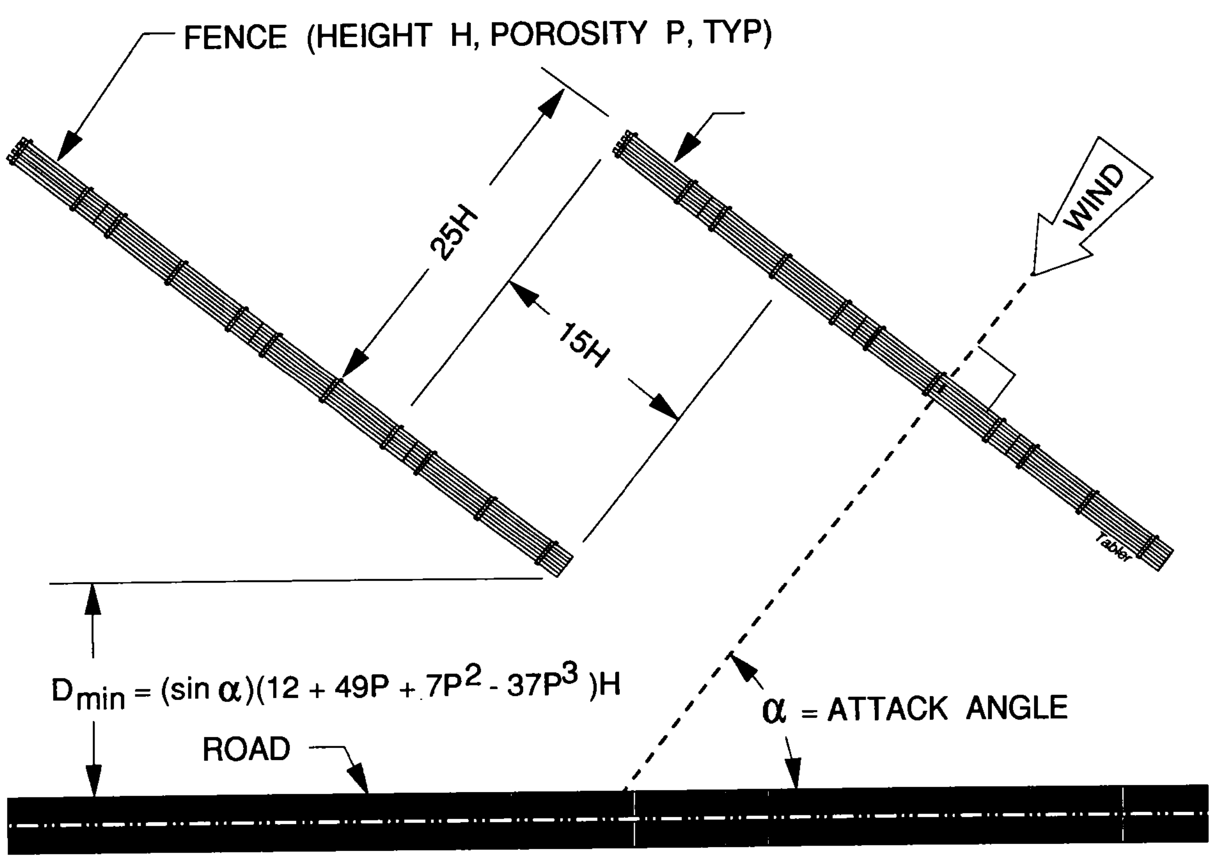


Figure 5.48. **Fences should be aligned perpendicular to the prevailing wind if the angle between the road and the wind is 65° or less (Tabler 1993).**

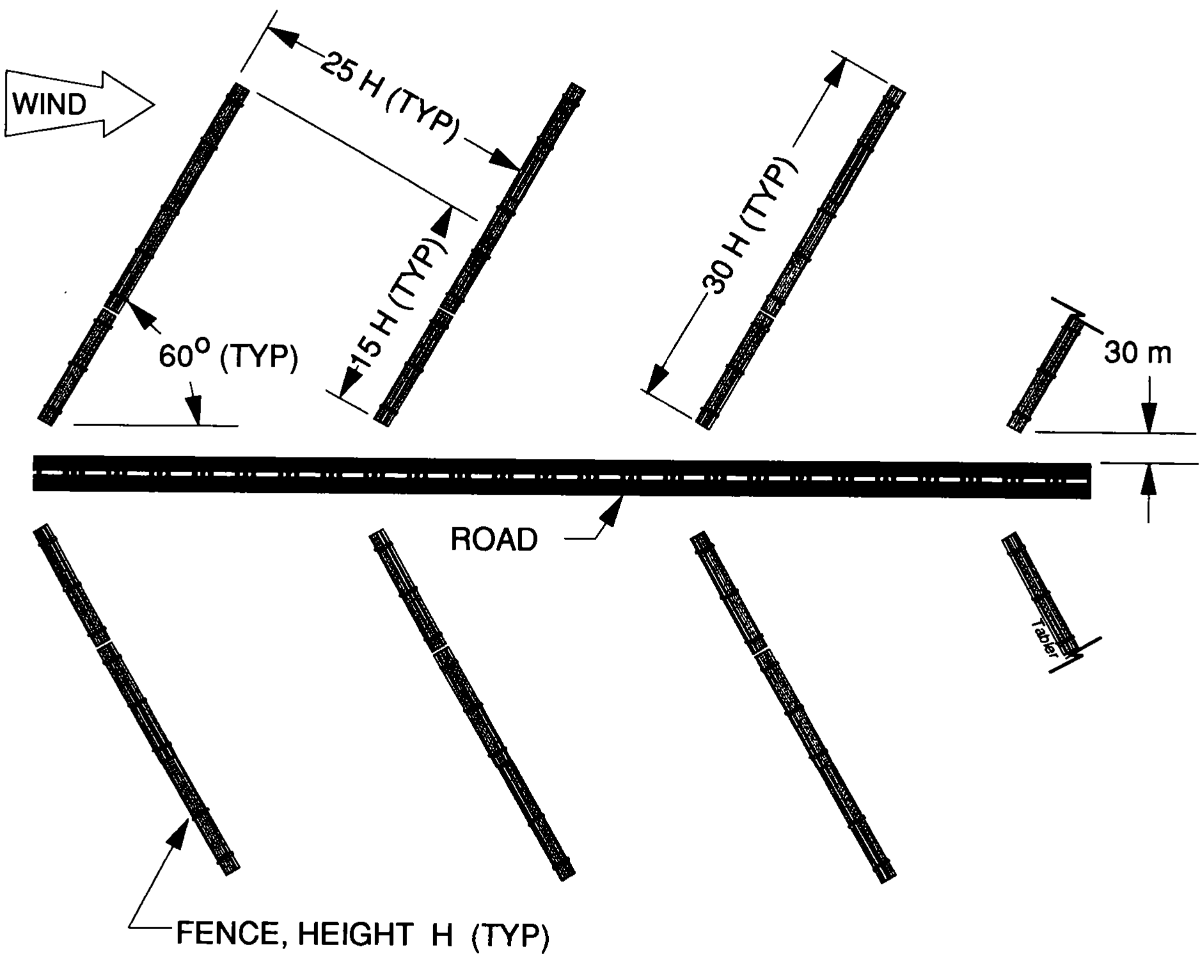


Figure 5.49. Swept-back herringbone fences to be used where winds are aligned with the road centerline.

5.5.1.4 Other Considerations

Compromise may be necessary or desirable for compatibility with land use. On cultivated land, for example, it may be preferable to employ a single parallel fence rather than a series of staggered fences that would create more inconvenience for tillage operations, or to reduce the width of right-of-way acquisition required. This consideration should be addressed before initiating negotiations for easements or property acquisition.

5.5.2 Setback from Road

Setback is the distance that a fence is placed from the shoulder of the road, or some other reference location, measured perpendicular to the road. Because the required setback is on the order of 20 to 35*H*, depending on fence porosity, the required space may not be available within the existing right-of-way or easement. This factor should not in itself be a limiting constraint on fence height, however. If more space is needed than is currently available, then the necessary easements or right-of-way should be obtained to allow the proper fence height to be used. It is often possible to obtain a perpetual easement for fences at less cost than purchasing additional right-of-way. Where necessary, condemning land can be justified by the well-documented benefits of properly engineered snow fence systems (chapter 2). Where necessitated by conflicting land uses, fences can be installed in the fall and removed in the spring using temporary fences described in section 5.3.9.

Because drift length is proportional to fence height, setback guidelines are given in terms of multiples of fence height. Although the setback requirements are based on *effective* fence height, H, conservative design requires that *structural* height, H_s, be used instead. This insures that drifts will not encroach on the road even during a winter when the fence is fully exposed (that is, not partially buried, as described in section 3.8.5.2.1).

5.5.2.1 Minimum Setback for Parallel Fences

Fences should be far enough away from the road that the downwind drift does not extend onto the road or onto any other feature (ditch or right-of-way fence) that should be kept drift-free. On flat terrain, the length of the downwind drift, L/H, varies with fence porosity according to Equation (3.24):

$$L/H = 12 + 49P + 7P^2 - 37P^3 \qquad (5.15)$$

where P is the porosity ratio of the fence. The setback, D, required for parallel fences on flat terrain is therefore

$$D = H(\sin \alpha)(12 + 49P + 7P^2 - 37P^3) \qquad (5.16)$$

where α is the angle of attack for the prevailing transport direction. Fences having $P = 0.5$ have the greatest snow storage capacity, and should therefore be used where space permits. But where setback distance is limited, using a lower fence porosity can reduce space requirements.

Example:

Given: H_{req} = 2.4 m (8 ft)
α = 65°
P = 0.5

Required: Minimum setback, D

Solution: Equation (5.16):

$$D = 2.4(0.91)[12 + 49(0.5) + 7(0.5)^2 - 37(0.5)^3] = 73 \text{ m}$$

Topography must also be considered in specifying setback distance. As described in chapter 3, an upward approach to the fence can elongate the equilibrium downwind drift. But if the increased storage capacity caused by this topographic effect exceeds the snow transport, the equilibrium drift may never be attained and the downwind drift may be shorter than on level terrain.

A similar situation can exist where a fence is placed upwind of a depression that increases capacity. In both these cases, fences can be placed closer to the protected area than indicated by Equation (5.16). The snow control specialist can make a determination using the information in this book, but simplified guidelines have not yet been developed.

Other effects of topography can be inferred from the qualitative description in section 3.8.5.2.8.

5.5.2.2 Minimum Setback for Oblique Fences

Because drift length is proportional to fence height, reducing the fence height near the road allows oblique fences to be placed closer to the road (Figure 5.50). Although the storage capacity of shorter "stepped-down" sections may not be sufficient to store all of the seasonal transport, partial protection is better than none. Stepped-down sections also improve the trapping efficiency of the main portion of the fence by reducing the end-effect that would exist without the shorter panels.

If the prevailing transport direction is known, and if it is consistent, the end effect (Figures 3.42, 3.43, 3.44) allows the ends of oblique fences to be placed closer to the road than the setback distance given by Equation (5.16). Placement is best determined by making a template of the drift curvature to the same scale as the map, photo, or layout drawing. The proper location for the end of the fence is determined by positioning the template along the proposed fence line so that the drift curvature is tangent to the road shoulder. Some allowance should be made, however, for the possibility that the wind direction might vary, or that it might differ from that assumed for the design. It is therefore recommended that the centerline of the ditch be used as a protection limit rather than the shoulder of the road. Coordinates for an end-effect template can be taken from Figure 3.44 or calculated from Equation (3.21).

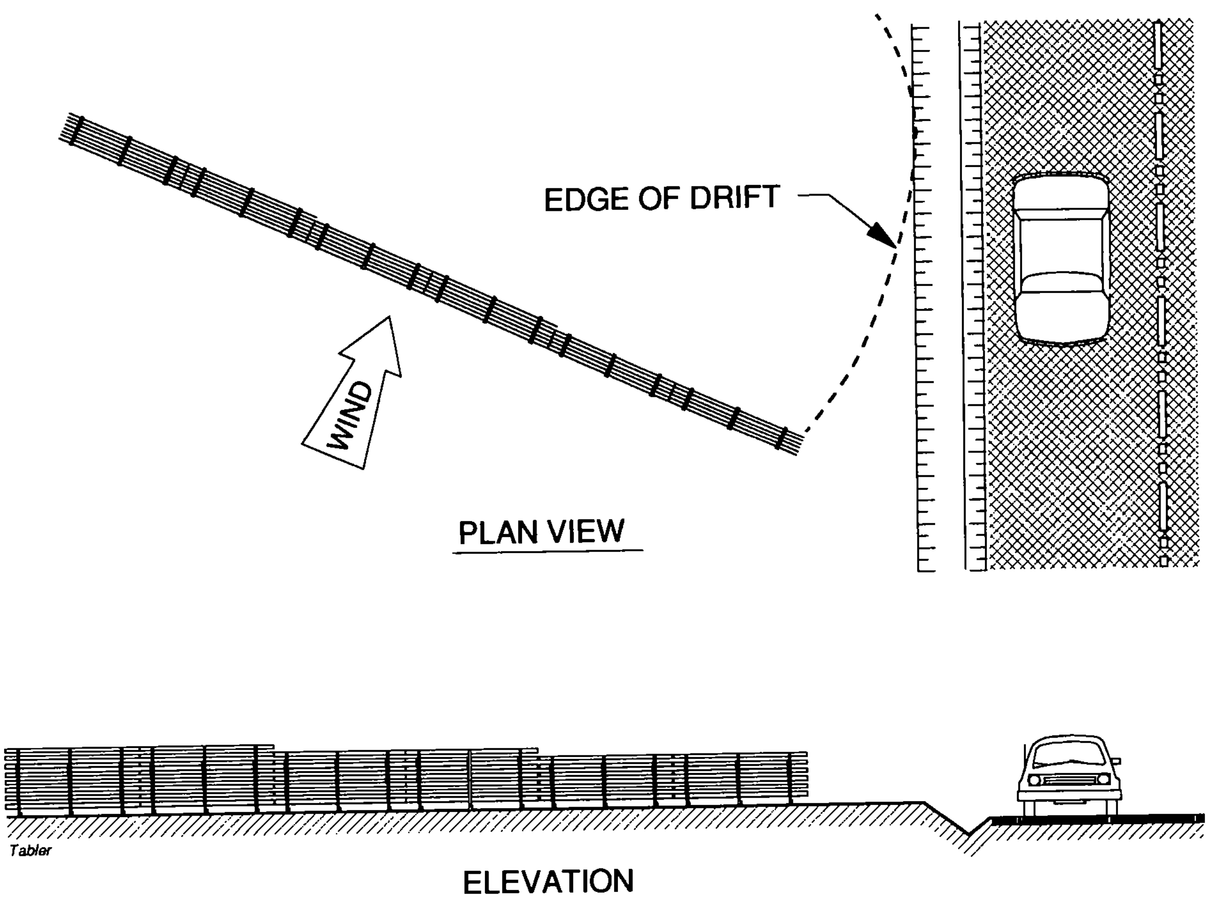


Figure 5.50. Reducing the fence height allows oblique fences to be placed closer to the road.

5.5.2.3 Reducing Setback by Over-Designing Height

By considering how drifts grow, it is possible to use a fence much taller than that needed for snow storage, such that the base of the slip-face just terminates at the protected area during the design year (Figure 5.51). As described in section 3.8.3, drift length varies with snow accumulation according to

$$L/H = 10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2 \tag{5.17}$$

where A is the cross-sectional area of the drift at any time during the winter, and A_e is the cross-sectional area of the equilibrium drift for the fence in question.

As an example, consider a location where a 2.4-m (8 ft), 50%-porous fence provides the required storage capacity. On level terrain, this fence would have to be placed at least 84 m (275 ft) upwind. If a fence 4.3 m (14 ft) tall were used instead, then it would be expected to be about 30% full with the design transport; that is, $A/A_e = 0.3$. From Equation (5.17), the drift length would be about $14H$ or 60 m (197 ft). Thus, the taller fence could be placed 24 m (79 ft) closer to the road, *if the risk posed by encroachment of a larger drift were acceptable*. If this technique is used, it is wise to select a design year having a low exceedance probability (section 4.8.1). As a default, designing storage capacity for twice the mean annual transport ($Q_c = 2Q_{t,ave}$) is consistent with an exceedance probability less than 1%. Setting $A/A_e = 0.5$ in Equation (5.17) gives a drift length equal to $18H$. The additional storage volume provided by the cut section should be included in such a calculation.

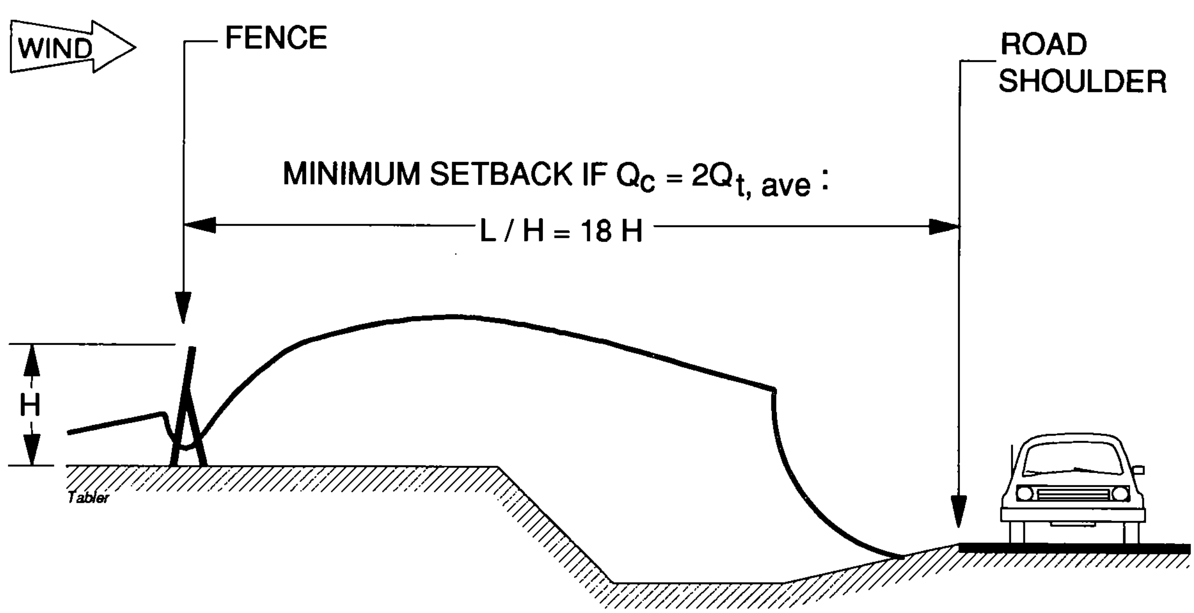


Figure 5.51. Setback distance can be reduced by using a fence taller than required for storage of the design transport (Tabler 1993).

5.5.2.4 Topographic Considerations

Although the minimum distance guidelines are important to prevent the drift from encroaching on the road, other considerations are equally important in selecting fence locations. It is sometimes preferable to place fences farther away than the minimum distance to take advantage of favorable sites, or to avoid unfavorable locations (Figure 5.52)

To avoid burial, fences should not be placed in locations where drifts form naturally, such as in depressions or on the downwind side of hills. Steep upwind-facing slopes should be avoided because this topographic situation reduces both trapping efficiency and storage capacity. Favorable locations include the crests of ridges or hills, and sites upwind of stream channels or other topographic depressions that increase storage capacity.

As a general rule, fences should not be placed on embankment slopes, but instead should be located upwind of the toe of the slope. If placed too close to the shoulder of the embankment, a fence can cause a deep drift on the road. Although fences on the windward side of steep embankments are relatively inefficient, there are situations where there is no alternative. In this case, the spacing between fences should be equal to $H/\tan a$, where a is the slope angle measured from horizontal (Figure 5.53).

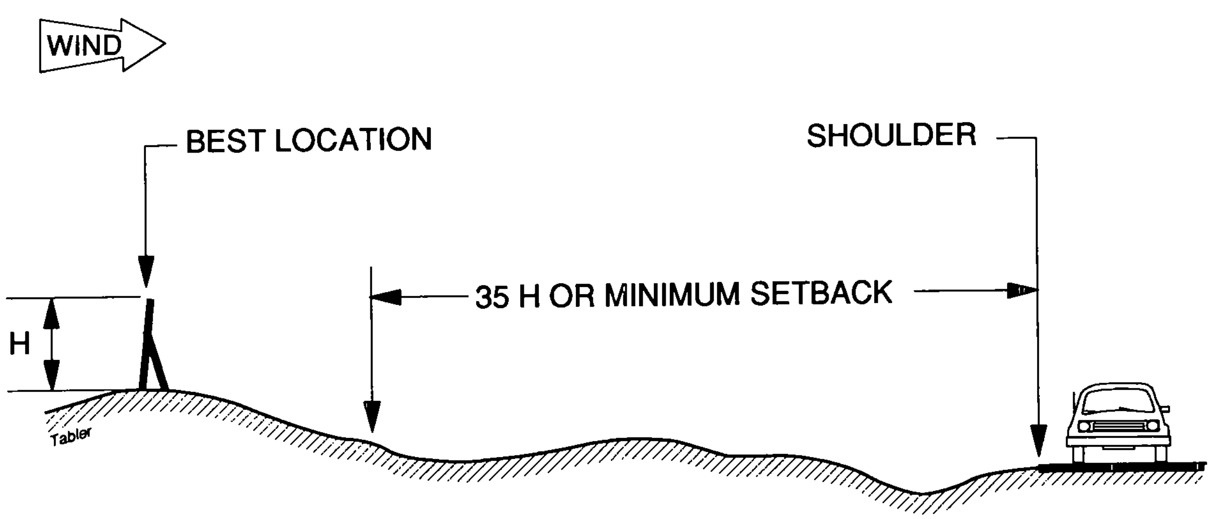


Figure 5.52. The best location for a snow fence may be farther away from the protected area than the minimum setback distance. Topography should also be considered in determining setback.

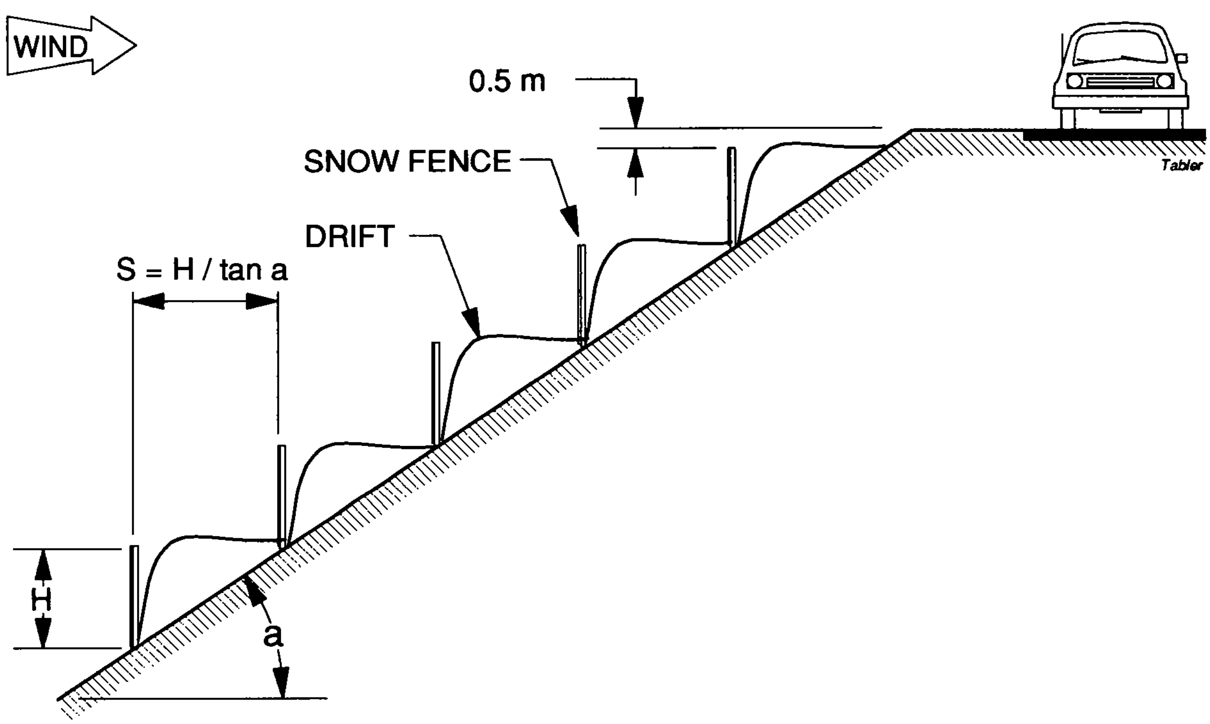


Figure 5.53. Fences on embankment slopes should be spaced as shown in this illustration.

5.5.2.5 Maximum Setback

The maximum distance a fence should be placed from the protected area (the setback) depends principally on the nature of the drifting problem. At sensitive locations, such as shallow road cuts, where even a small amount of blowing snow can cause drift encroachment on the road, fences must be closer. Fences can be farther away from deep cuts that store more snow before drifts encroach on the road. A fence can be too far from the area to be protected. The actual reduction in snow transport depends on the setback and the fetch distance (Figure 5.54). For a very long fetch (> 6 km / 3.7 miles), a fence set back as far as 300 m (1000 ft) from the road will reduce snow transport by 82%.

Maximum protection can be provided by building two rows of fence, with the first having a larger capacity than the design transport, and the second row placed 20*H* from the road shoulder. The rationale for placement is the pre-equilibrium drift length given by Equation (5.17). Snow transport must be estimated accurately when using such a design.

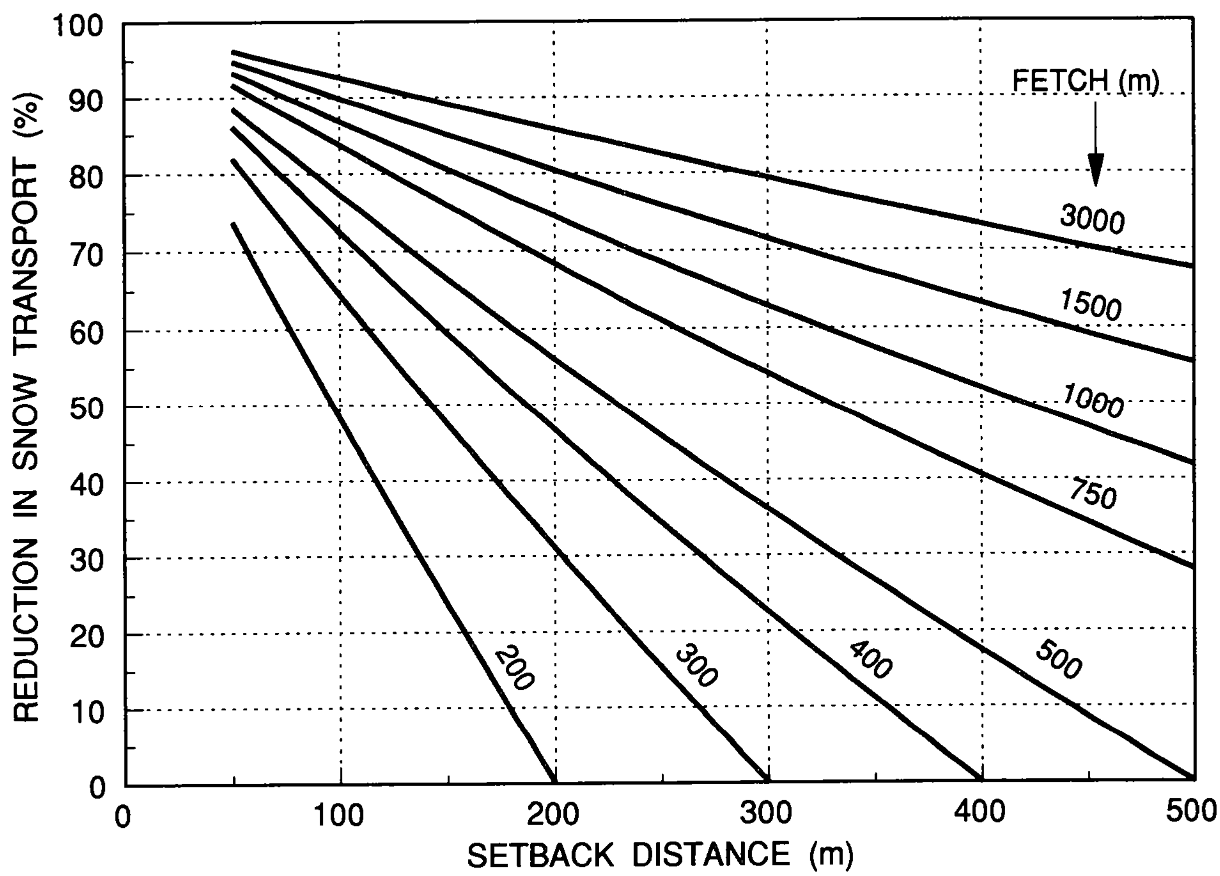


Figure 5.54. Reduction in snow transport as determined by the distance between fence and road, and fetch distance. This model assumes a 100% trapping efficiency for the fence, but that all snow between the fence and the road is relocated.

5.5.3. Spacing Between Tandem Rows

A single tall fence traps more snow and is more cost-effective than multiple rows of shorter fence. There are situations, however, where multiple rows are necessary, such as where fences are installed and removed on a seasonal basis. Multiple rows of fence must be spaced so that downwind rows are not buried. This is important to achieve maximum storage and trapping efficiency of each fence, and to avoid structural damage.

The spacing guidelines given here are distances *as measured in the direction of the prevailing wind*. On flat ground, $30H$ is a satisfactory spacing; on ground sloping downward with the wind, a greater spacing may be advisable if upwind fences are likely to fill to capacity. Where snow transport is sufficient, fences on ridges and hill crests are certain to form long, deep drifts that can easily crush downwind fences. Figure 5.55 shows a 1.8-m-tall (6-ft) fence on a hillcrest that formed a lee drift twice as long (130 m = 420 ft = $70H$) as would be expected on flat terrain, because of the effect of the upward approach slope described in section 3.8.5.2.8. As a result, the drift buried a downwind fence 3 m (10 ft) tall, causing the damage shown in Figure 5.56. The proper spacing in this case depends on so many factors that a simple guideline is impossible, but the best advice is to avoid using more than a single row of fence in such situations.

The spacing of median fences (Figure 5.57) should be about 10 times their maximum height (as measured from the lowest elevation in the median).

Figure 5.55. Wind blowing up a hill (from the right) toward a 1.8-m-tall (6-ft) fence caused a "super-drift" that buried the second 3-m-tall (10 ft) fence even though they were spaced 55 m (180 ft) apart. The drift contained four times as much snow as a 1.8-m-tall fence on flat terrain (Tabler 1986b).

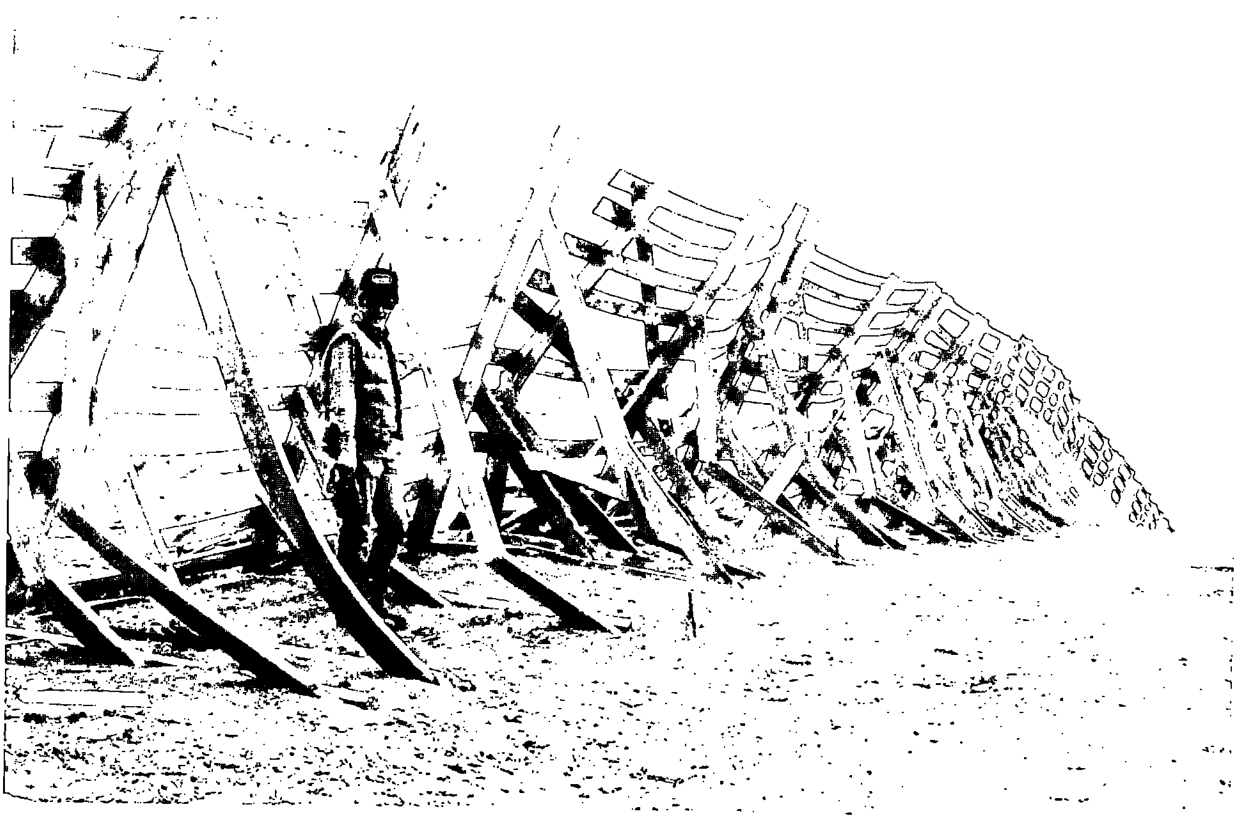


Figure 5.56. Damage to the buried fence shown in Figure 5.55 (Tabler 1986b).

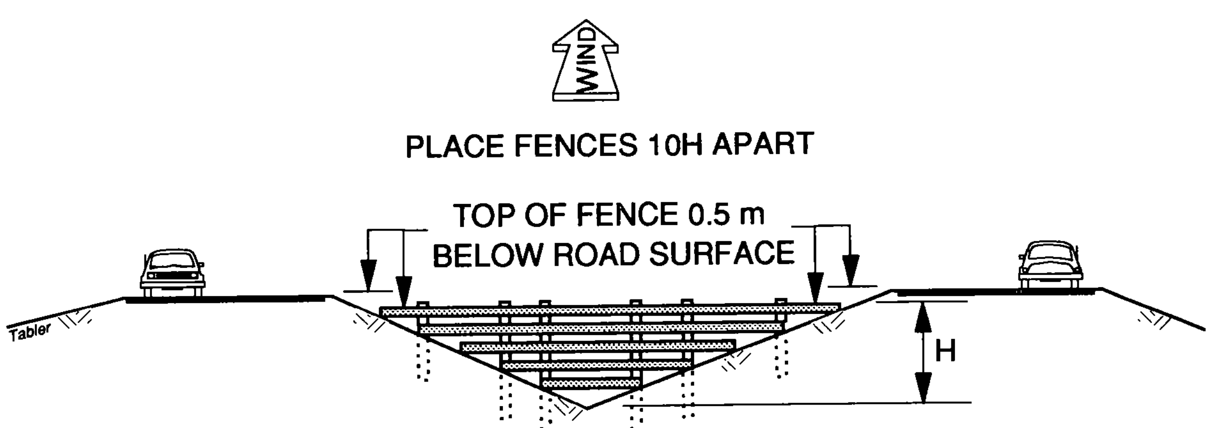


Figure 5.57. Median fences should be spaced 10 times their greatest height.

5.5.4 *Fence Length and Overlap Criteria*

5.5.4.1 Overlap of Protection Limits

One of the most common mistakes in fence layout is the failure to extend fences a sufficient distance beyond the limits of the area to be protected. Fences should extend far enough to intercept snow transported by the anticipated range of wind directions. Additional overlap is necessary to compensate for the end effect.

Wind direction fluctuates, even during a drifting event with a steady average direction. Atmospheric turbulence causes this variability, just as it causes fluctuations in wind speed. How large these variations are depends on meteorologic conditions and local topography, but in the absence of specific information, fences should be planned for a 25° variation on either side of the prevailing direction. To account for variations in wind direction *and* the end effect, fences should extend far enough on either side of the protected area to intercept winds from 30° on either side of the prevailing wind direction(s) (Figure 5.58). The minimum overlap length is therefore equal to 0.6 times the distance (as measured in the direction of the wind) from the fence to the shoulder of the road.

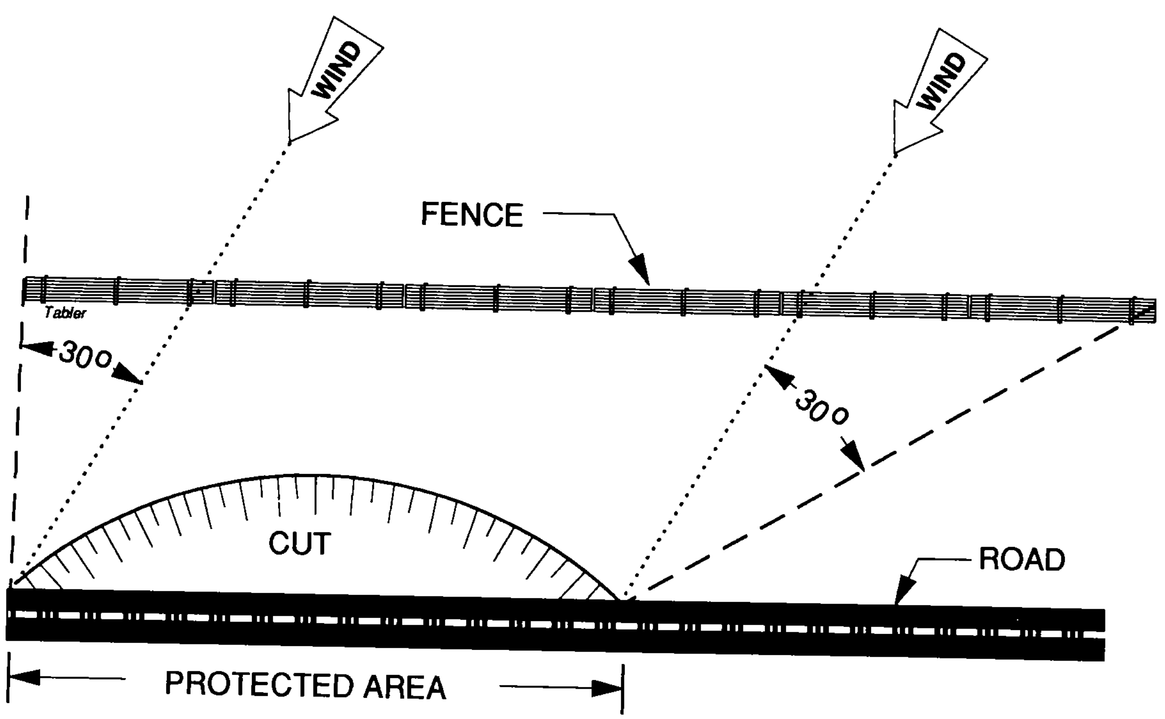


Figure 5.58. Parallel fences should overlap the protected area sufficiently to intercept winds from 30° on either side of the prevailing transport direction.

5.5.4.2 Overlap and Spacing of Staggered Oblique Fences

When wind direction requires that fences be aligned obliquely with the road, it often becomes necessary to use staggered rows of fences to keep the fence close enough to the protected area to achieve the desired degree of control. The required length of these rows depends on the angle between the road and the fence, the spacing between rows, and the overlap required to compensate for the end effect and variations in wind direction. This latter requirement is determined by the 30° angle specified for the overlap at the end of a fence. The overlap is sufficiently substantial that the equilibrium drift could bury a portion of the fence immediately downwind. Considering the length and depth of equilibrium drifts, the *minimum* spacing between staggered rows should be $25H_s$. At this spacing, required overlap is $25H(\tan 30°) = 14\ H$. For a straight section of road, the required length, L_f, of staggered fences would be given by

$$L_f = 14H + 25H/\tan(90° - \alpha); \text{ if } L_f < 25H; \text{ set } L_f = 25H \qquad (5.18)$$

as plotted in Figure 5.59. The $25H$ limit on fence length is not related to the spacing criterion, but instead is an independent guideline for minimum fence length that reflects the decreased efficiency of short fences (section 3.8.5.2.2).

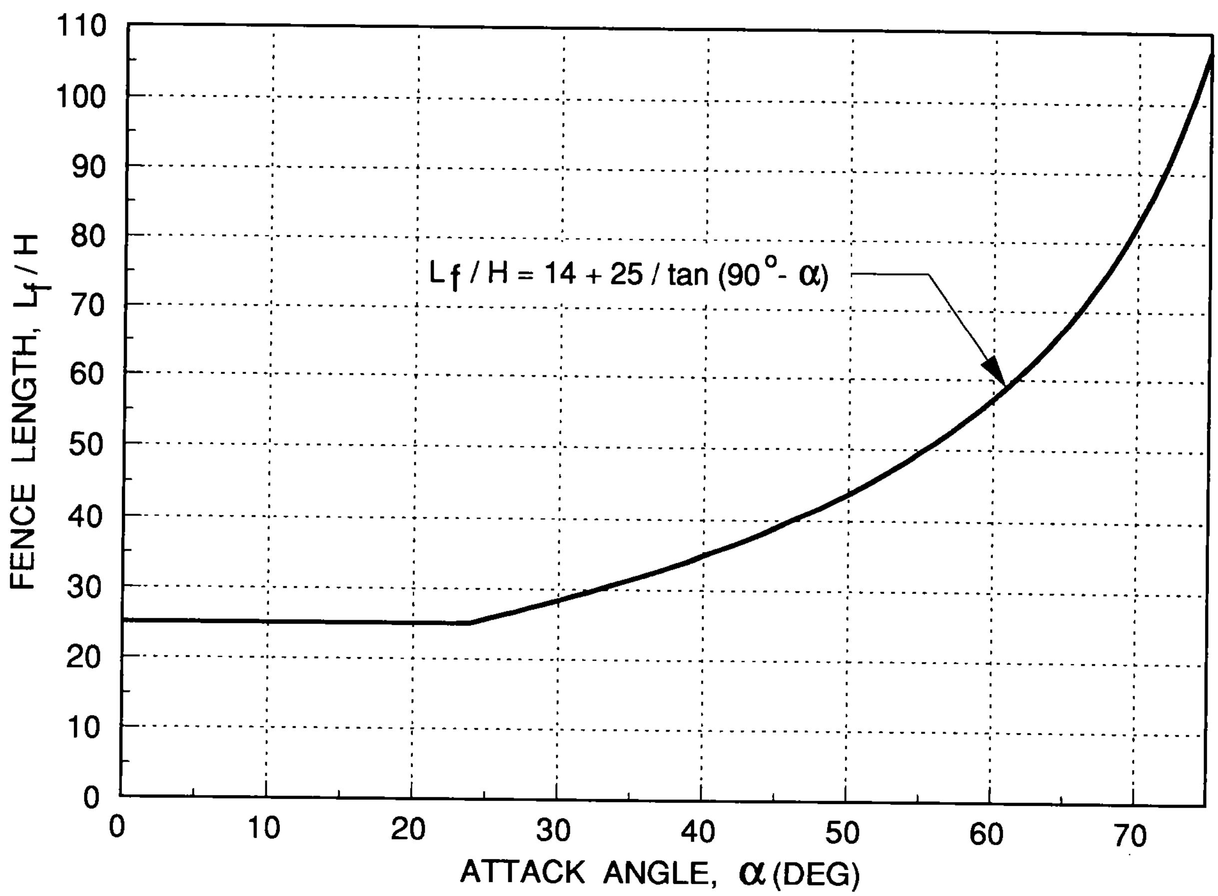


Figure 5.59 Minimum length (L_f) of staggered fences in relation to wind attack angle, α, providing 30° overlap angle.

5.5.4.3 Openings in Fence Lines

Fences should be as long as possible, without holes or openings. Wind acceleration through openings adversely affects snow deposition over an area much larger than the opening itself. This may surprise those who assume that, because porous fences are comprised of holes, a few additional openings could not make much of a difference. Even leaving 15-cm (6-in.) spaces between panels of the Wyoming fence causes appreciable erosion and scalloping of the drift nose, with significant loss of snow storage capacity. As a result, spaces between panels should not exceed 2.5 cm (1 in.). To achieve this requirement, panels must be partially overlapped when traversing irregular terrain (Figure 5.11).

Knowing that openings compromise effectiveness, the snow fence planner should resist giving in to the requests of landowners, wildlife officials, and others who want to leave openings for livestock or wildlife. Animals are capable of walking around barriers much longer than a snow fence, and they don't have much else to do anyway.

Where openings must be left for off-road summer use only, offsetting and overlapping fence lines, shown as type A in Figure 5.60, is the preferred method. Where a road must be kept free of snow for winter use, the best solution is to protect the opening with a section of fence farther upwind, if the alignment of the road permits. If not, the best that can be done is to minimize the width of the opening, which requires reliable information on prevailing wind direction. In locations with a consistent wind direction, fence ends should be at least $5H$ from the road shoulders where travel is restricted to the road (Figure 5.60, type C). This spacing should be considered a starting point, with the possibility that additional widening may prove necessary.

Where off-road access is sufficient, however, a narrow opening 5 m (16 ft) or so is best because the acceleration of the wind through the opening scours a snow-free path through the drift (Figure 5.60, type B).

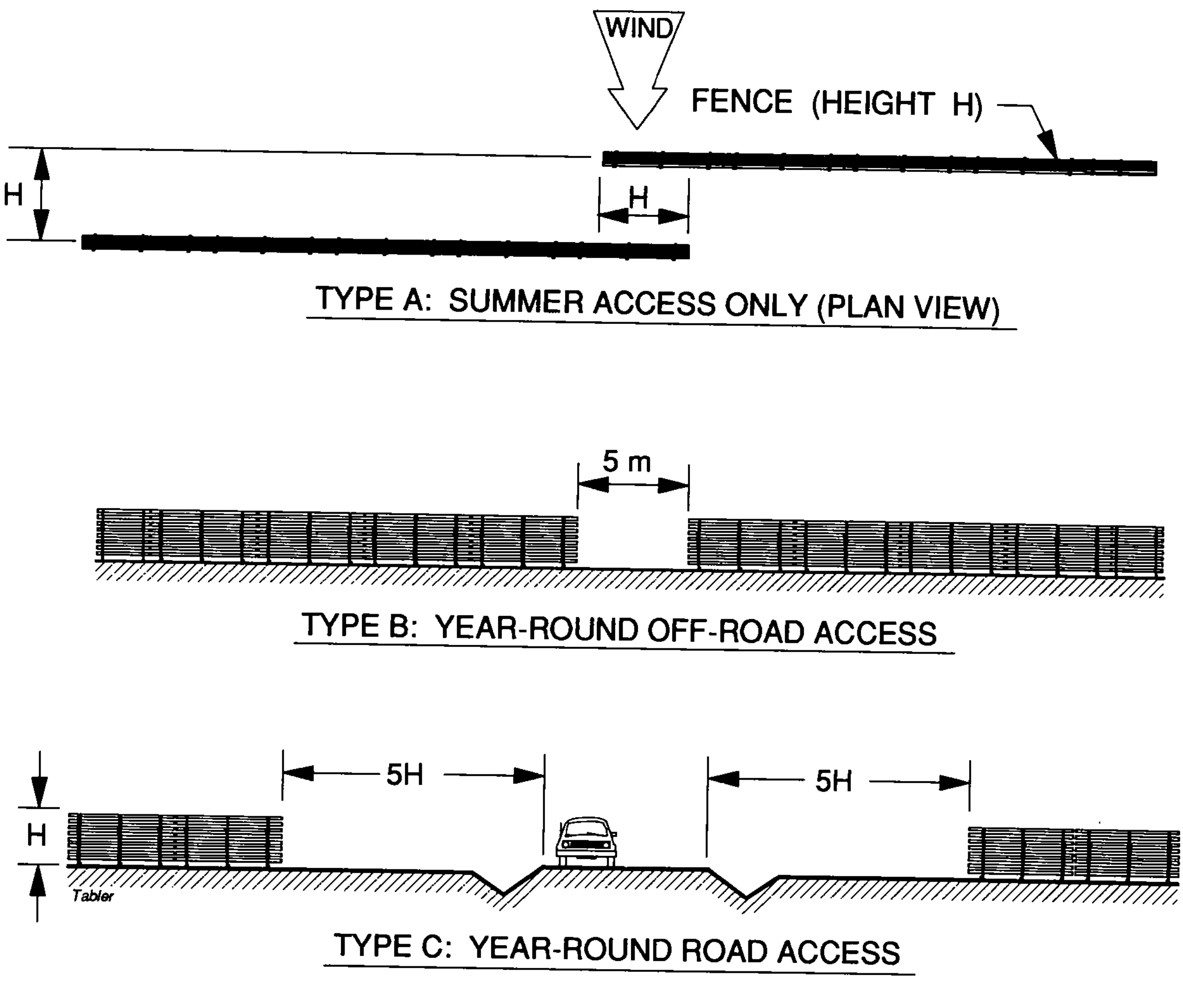


Figure 5.60. Access openings in fence lines.

5.5.4.4 Avoiding Dangerous Transitions

As demonstrated in chapter 2, fences can be extremely effective in improving visibility and reducing the formation of slush and ice (Figure 2.8). As a consequence, the snow fence planner can inadvertently create a serious hazard by creating an abrupt transition from protected to unprotected conditions. This is illustrated by Figure 5.61, showing a stream of blowing snow passing through an unprotected gap between a snow fence 3.8 m (12.4 ft) tall, and tall bushes growing along a watercourse.

The following mitigation strategies can be employed to avoid creating dangerous transitions from protected to unprotected conditions at the ends of a fence system:

- Tying in fences with natural features, such as trees and brush, that reduce blowing snow;
- Filling in gaps between fence systems;
- Tapering out protection by reducing the fence height, or increasing fence porosity, near fence ends.

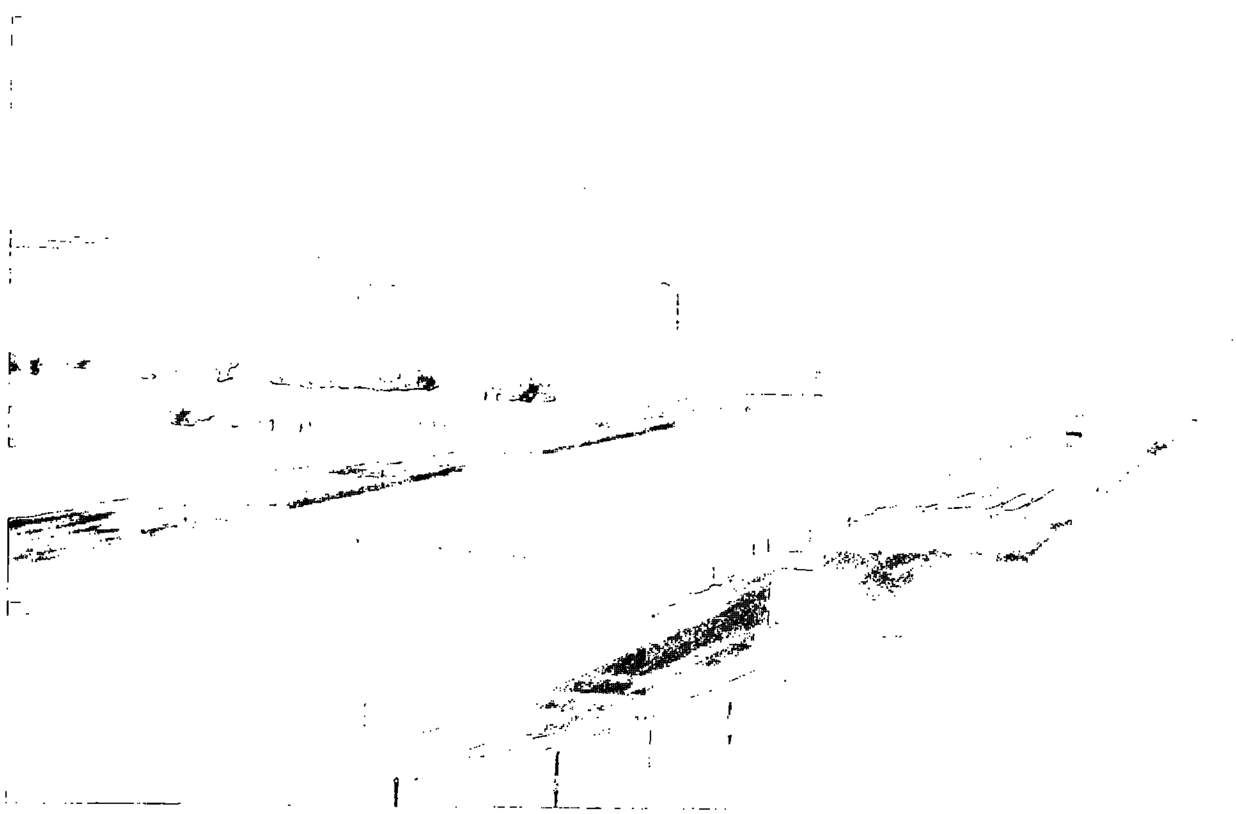


Figure 5.61. The strip of blowing snow across the road, just above center of the photograph, coincides with an unfenced corridor between the fence system in the background, and brush growing along a watercourse. Many accidents occur at this location on I-80 in Wyoming.

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6. Living Snow fences

6.1 Scope

Living snow fences refer to vegetative barriers used to control drifting snow. Plant materials include trees, shrubs, grass, or agricultural crops, such as corn or sunflowers, left standing over the winter. This chapter presents engineering guidelines for vegetative barriers based on the same principles and quantitative relationships used for structural snow fences. The presentation assumes that the reader is familiar with the material in chapters 3, 4, and 5.

6.2 Highlights

- Rows of trees or tall shrubs act like structural snow fences to collect blowing snow originating outside the right-of-way. Mass plantings of shrubs (*snow retention plantings*) can be used to stabilize snow within the right-of-way.

- The same principles and quantitative relationships developed for structural fences also apply to living fences. Guidelines for structural fences also apply to living barriers, but are modified to take into account the changes in height and porosity as the plants grow.

- Living barriers can be as effective as structural fences if properly designed. Key requirements include adequate storage capacity, absence of gaps, and sufficient setback to prevent the downwind drift from encroaching on the road at any stage of development.

- Changes in the porosity and height of a barrier as the plants grow changes the length of the downwind drift. As the barrier becomes less porous, more snow is stored in the upwind drift and the downwind drift becomes shorter. The increase in barrier height, however, tends to make the drift longer.

- It is possible to develop guidelines for specific species and planting patterns using the relationships for trapping efficiency and drift length as functions of height and porosity that were developed for structural fences. A computer simulation using spruce trees is used to justify some of the guidelines presented in this chapter.

- Trees are considered fully effective when their average snow trapping efficiency reaches 75% — the same average efficiency as that of a structural snow fence from the first drifting event to the time when the fence is filled to capacity. The height of the trees when this level of efficiency is reached is referred to as the "fully effective height."

- The fully effective height varies with the quantity of snow transport, and represents the minimum required barrier height. Examples provided by the spruce tree simulation are 1.2 m (4 ft) for very light snow transport (10 t/m or 3.4 tons/ft), and 2.8 m (9.2 ft) for moderate transport conditions (80 t/m or 27 tons/ft). With average growth rates, these heights may be attained 5 and 10 years after planting, respectively.

- The required setback depends on the attack angle of the wind, and the amount of snow transport. For light to moderate snow transport conditions, the setback distance is equal to $(\sin \alpha)35H_{req}$, where H_{req} is the required height of structural fence at that location.

- The minimum setback for trees planted on the southern side of a road should allow the sun to shine on the road surface at noon on the shortest day of the year. In Maine where the minimum sun angle is about 22°, for example, the setback should be at least 2.5 times the mature height of the trees.

- The setback can be reduced by using a temporary snow fence to prevent drift encroachment until the trees reach their fully effective height. Such a fence should have sufficient capacity to store all of the design transport, and should be placed at least 20 times its height upwind of the tree planting.

- Shrub rows between the road and tree plantings provide temporary control until the trees become fully effective.

- Wide, dense plantings of trees, called "snowbreak forests," cause all snow to be deposited on the upwind side of the barrier, and require a setback of about 30 m (100 ft).

- The best in-row spacing for coniferous trees is approximately 2.4 m (8 ft), with rows spaced 2.4 to 3 m apart (8 to 10 ft). Three rows are recommended to reduce the possibility of gaps forming when trees die.

- Considering both direct and indirect costs, living snow fences cost about the same as structural fences.

- Rows of corn left standing in the field can provide effective and economical control of blowing snow. The best practice is to leave two strips of corn, each comprised of 8 rows, separated by a space of 50 m (164 ft). The strip nearest to the road should be set back 65 m (213 ft) from the shoulder.

6.3 Comparison with Snow Fence Guidelines

All of the principles pertaining to snow fences apply to vegetative barriers as well, but guidelines for plantings must consider the variability or irregularity of height and porosity, and how these factors change with time. In addition, biological requirements must be considered in the planting and maintenance of living snow fences, as well as ecological factors that affect survival and growth. For these reasons, designing living snow fences requires the knowledge of agronomists, foresters, landscape architects, and engineers.

In the past, guidelines for living snow fences have been developed without regard for the quantity of snow transport, the changes in the snow-trapping efficiency of the plant material, or the physical processes involved. This oversight has all too often resulted in tree plantings that eventually had to be removed because their drifts encroached on the road. In addition, the guidelines that did prove satisfactory were so site-specific that they could not be applied successfully to other areas. The progress in quantifying snow transport and in understanding how structural snow fences work, as outlined in chapters 3 and 4 of this book, now make it possible to develop engineering guidelines for living fences.

6.4 Basic Strategies

There are two basic approaches to the use of plant materials to control blowing snow:

Snow collection — Trapping incoming blowing snow with rows of trees or shrubs; and

Snow retention — Holding the snow in place with grass, shrubs, or trees. These control measures will be referred to as *retention plantings*.

The latter strategy is applicable where the source of the blowing snow is confined to the immediate vicinity of the road, such as embankment slopes, medians, and interchange gore areas.

6.5 Species

Trees and shrubs suitable for drift control should have relatively dense foliage that extends to ground level. Self-pruning species should be avoided. They should be fast growing; resistant to drought, frost, and disease; unpalatable to livestock and wildlife; suitable for a wide range of soil conditions; tolerant of crowding without shedding lower branches; and should have a service life of 30 to 50 years. Secondary considerations include ornamental value and value for cover and food for wildlife. Coniferous species have the advantages of year-round dense foliage and relatively low palatability for wildlife. Deciduous trees and shrubs can also be used, but more rows are generally required and many species are browsed preferentially by livestock and wildlife.

Among coniferous species, spruces, cedars, and junipers are preferable because their foliage is more dense than that of pines, and they can be planted close together without losing lower branches as they mature and their lower branches meet.

Deciduous trees such as Russian olive (*Elaeagnus angustifolia*) and American plum (*Prunus americana*), can also be used for living fences, but more rows are required to achieve the necessary porosity. Dense branching habits, tolerance to crowding, and sprouting make many species of shrubs ideal for snow control.

Species must be suited to local climate and soil conditions. The county extension service can provide information regarding general conditions, but the advice of a forester or agronomist should be sought for recommendations at specific sites. For this reason, specific recommendations for species are not given in this book.

6.6 Effectiveness

If properly designed, tree plantings can be as effective as structural snow fences.

6.6.1 Requirements

The requirements for effective living snow fences are the same as those for structural snow fences:

- Adequate snow storage capacity
- Absence of openings or gaps
- Adequate setback

6.6.2 Factors That Affect the Effectiveness of Living Fences

Trees and shrubs have characteristics that make their snow trapping function different from structural fences. As the crowns close together and the canopy becomes more dense, more snow is stored on the upwind side, and the downwind drift tends to become shorter (Figure 3.51). Simultaneously, the increase in height tends to make the downwind drift longer. The degree to which these two changes offset one another depends on the quantity of snow transport at the site.

Because of the dynamic changes that occur in the physical configuration of living barriers, and the site-dependent factors controlling these changes, it is understandable why some living snow fences have exacerbated drifting problems rather than improving them.

The time required for living fences to become fully effective depends on the growth rate, spacing, and growth habit of the trees, and the quantity of snow transport. Where growing conditions are favorable and where snow transport is light (< 10 t/m; 3.4 tons/ft), tree rows can be fully effective five years after seedlings are planted. At the other extreme, 20 years are required for tree plantings to become fully effective in Wyoming, where snow transport is on the order of 100 t/m (34 tons/ft) (Powell et al. 1992).

The relationships determining the time required for a living snow fence to become fully effective are complex, but useful insight can be obtained by computer simulation of snow-trapping efficiency utilizing the relationships presented for snow fences in chapter 3.

6.6.3 Computer Simulation

Given that trapping efficiency varies as a fence fills with snow (section 3.8.3), and how porosity affects the snow storage capacity (3.8.5.2.4), it is possible to infer how trapping efficiency changes as a living snow fence grows. Consider, for example, the typical example of two rows of dense trees that have triangular silhouettes, height H, and base diameter $0.7H$. They are planted in a staggered offset pattern at spacing S, with the same spacing between rows (Figure 6.1). For simplicity, let us assume that the porosity of the barrier is equal to the ratio of open space between the individual canopy silhouettes, to the total area bounded by the ground and the top of the trees. This model assumes that the area bounded by the outline of the crowns is non-porous. As an additional simplification, let the average porosity be defined as the average of the highest porosity aspect (at 45° from perpendicular to the tree rows) and the lowest porosity aspect (perpendicular to the trees).

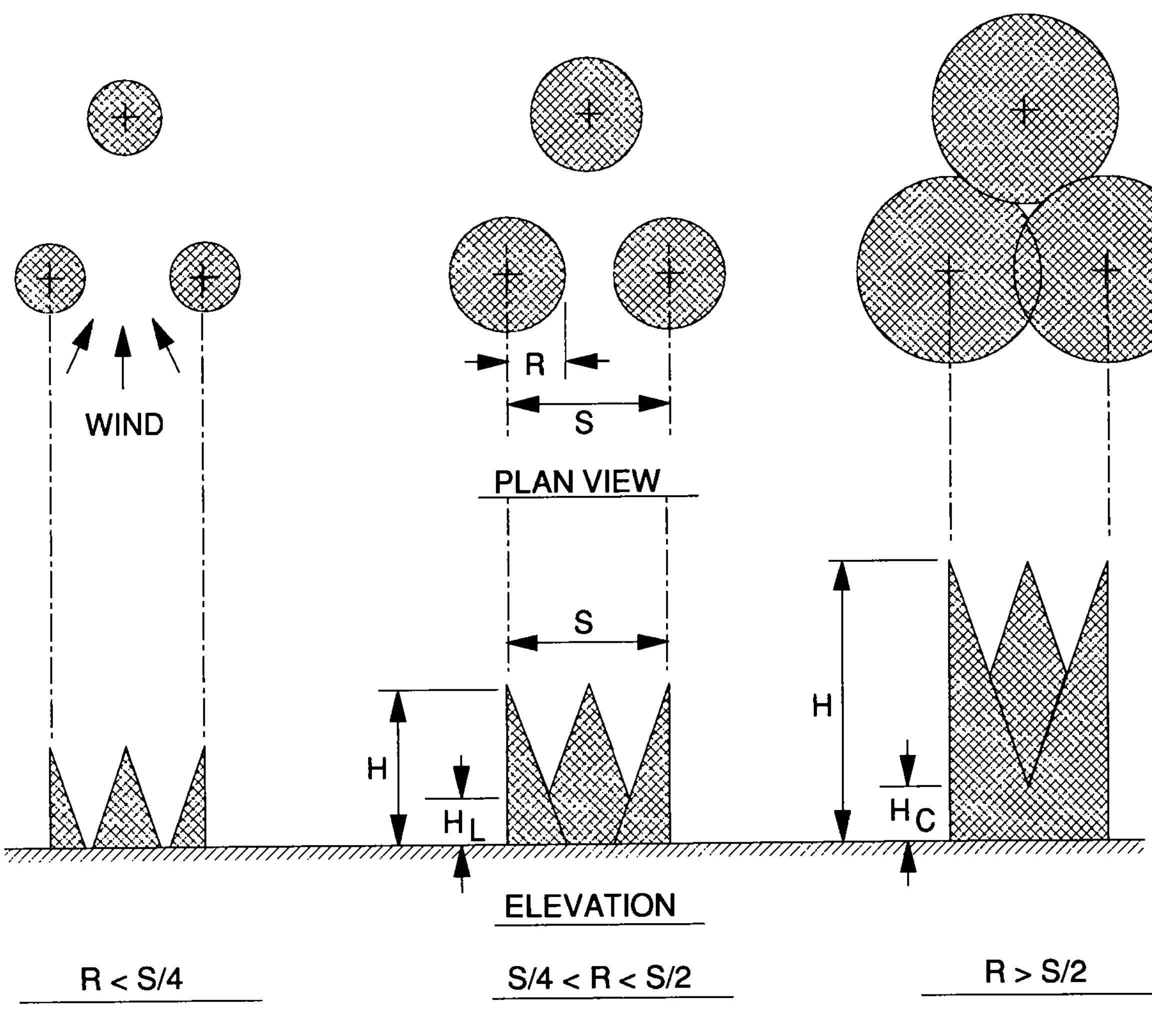

Figure 6.1. Model of living snow fence (spruce trees) used for computer simulation of porosity, snow-trapping efficiency, and drift length in relation to tree height, spacing, and snow transport.

Finally, to interpret tree heights in terms of years after planting, it is assumed that the seedlings are 20 cm (8 in.) tall when planted, grow 15 cm (6 in.) per year for the first two years, and 30 cm (12 in.) per year thereafter. Given these assumptions, the average porosity of such a barrier would vary with tree height, age, and spacing as shown in Figure 6.2.

To determine how snow-trapping efficiency varies with tree height, spacing, and snow transport, assume that the following relationships for structural fences apply also to living fences, and substitute the average porosity ratio as determined above.

- Equation (3.25): $Q_c = (3 + 4P + 44P^2 - 60P^3)H^{2.2}; \quad P < 0.88$ (6.1)

- Equation (3.31):

$$E_{ave} = [1/A_f/A_e)]E_o\{0.5(A_f/A_e)[1-(A_f/A_e)^2]^{0.5} + 0.5\sin^{-1}(A_f/A_e)\}, \quad Q_t \leq Q_c \tag{6.2}$$

- Equation (3.32): $E_{ave} = E_o(0.79)(Q_c/Q_t), \quad Q_t > Q_c$ (6.3)

For moderate snow transport (80 t/m; 27 tons/ft), snow-trapping efficiency would vary with spacing, tree height, and age, as shown in Figure 6.3. The line drawn at 75% trapping efficiency corresponds to the average trapping efficiency of a snow fence ($P = 0.5$) over a winter with just enough snow transport to fill the fence (section 3.8.6.4). Applying this same criterion to the trees, a 75% efficiency marks the height (or age) of "full effectiveness."

6.6.4 Conclusions from Simulation

For the triangular tree shape and form factor (diameter = $0.7H$) assumed in the model:

- The effect of spacing on trapping efficiency is less than 10% over the range of spacings 1.83 to 3.05 m (6 to 10 ft).

- Although a closer spacing initially increases efficiency, it reduces efficiency after porosity falls below 0.5. The closest spacing (1.83 m) requires a year longer to become fully effective than the wider spacings. This result is in opposition to the intuition that reducing the spacing increases snow-trapping efficiency. The wider spacings may also improve growth rate, which would add to the difference in performance.

- The trapping efficiency and age at full effectiveness are strongly dependent on snow transport, as shown in the comparison of efficiency for trees at 2.4-m spacing, for two different levels of transport (Figure 6.4). With 40 t/m (13.4 tons/ft), trees reach full effectiveness 7 years after planting, compared to 10 years required for 80 t/m (27 tons/ft).

- A 2.4-m (8-ft) spacing would be optimum for the spruce planting simulated here.

These conclusions are strictly applicable only to the tree geometry used in the model. However, the underlying principles are universally applicable, and a similar simulation could be used to develop guidelines for other shapes of trees.

Spacing is much more critical for more porous canopies, especially deciduous trees and shrubs.

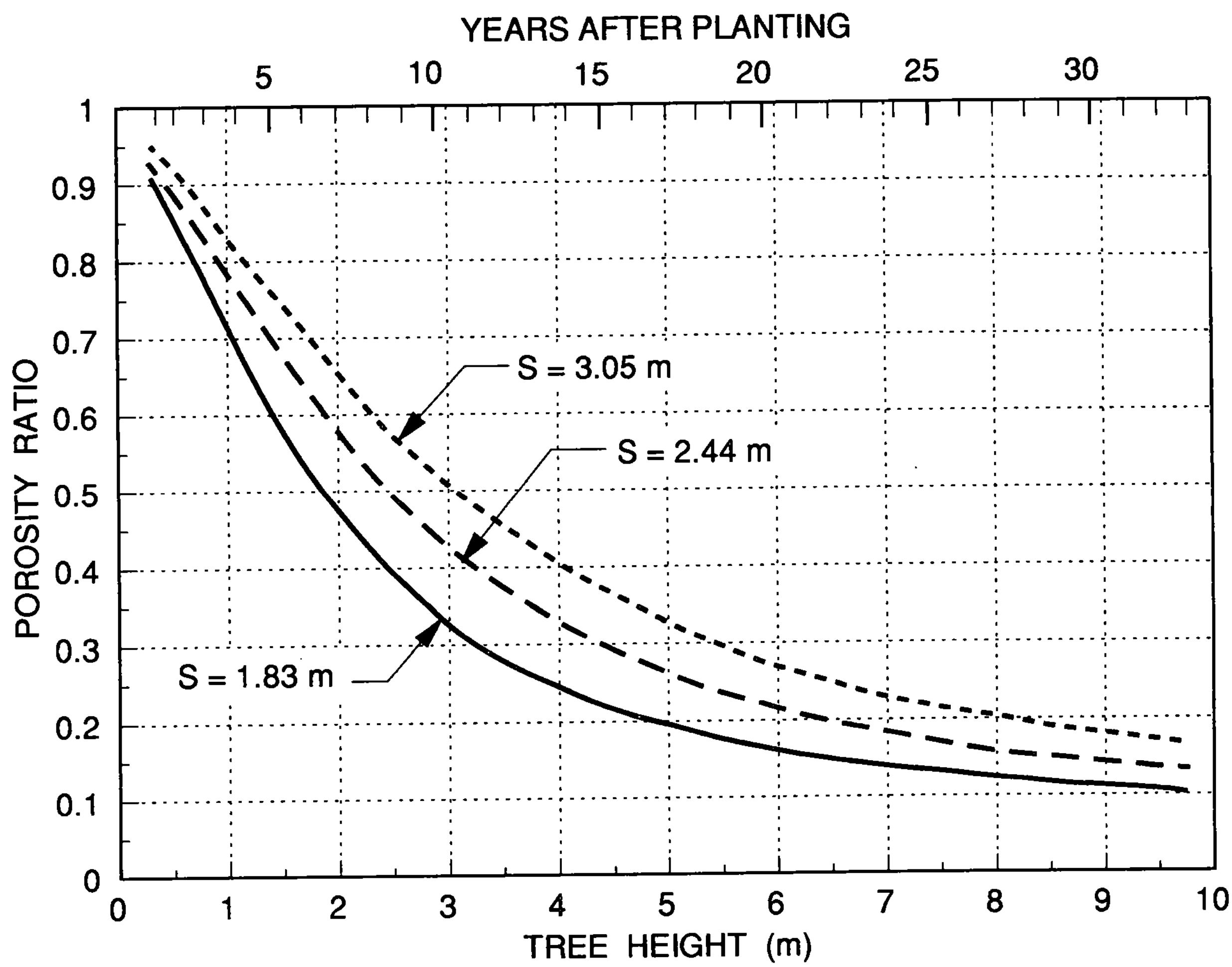

Figure 6.2. Variation of the porosity of the model shown in Figure 6.1 with changes in the spacing, height, and age of trees.

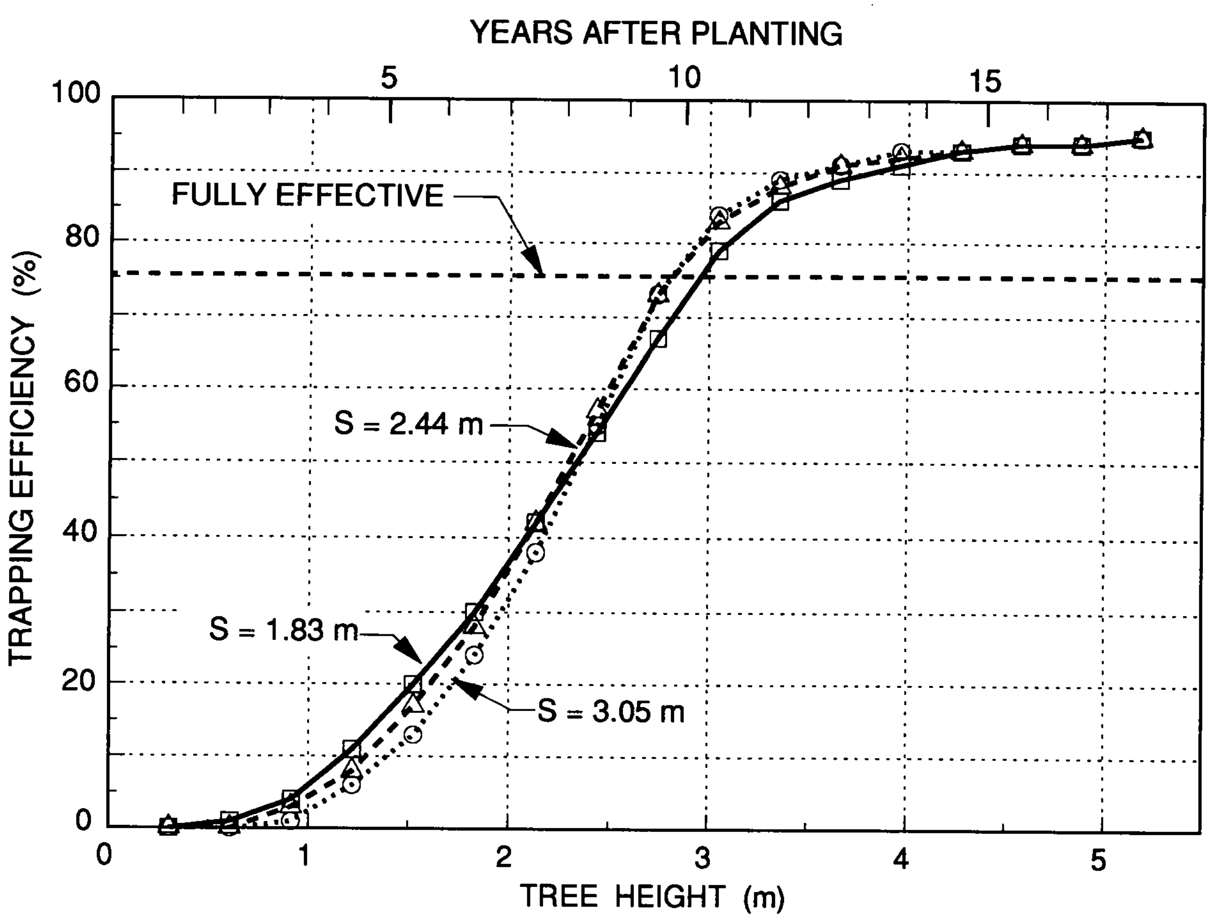

Figure 6.3. Variation of snow-trapping efficiency with spacing, height, and age of trees using the model shown in Figure 6.1.

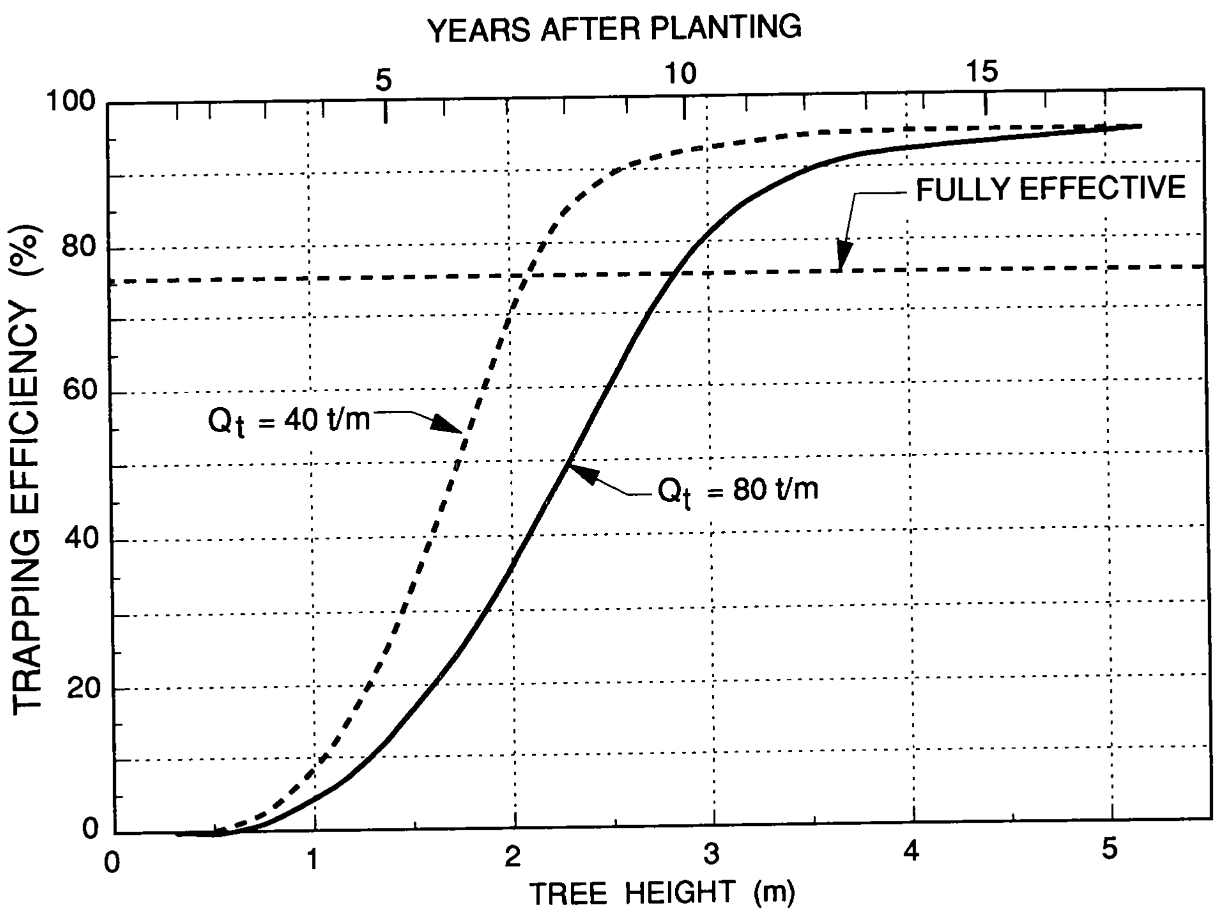

Figure 6.4. Variation of snow trapping efficiency with a spacing of 2.44 m (8 ft), snow transport, tree height, and age, using the model shown in Figure 6.1.

6.6.5 *Openings*

When plants die and leave gaps in the living snow fence, the fence is less effective. The drifts that form downwind of such openings often extend onto the road because they are much longer than the drift behind the remainder of the barrier. Preventive measures include using three or more rows for collector-type plantings; selecting species based on site conditions; replanting to fill openings where plants have died; and assiduous maintenance.

6.7 Required Height of Living Fences

Given that the required height of the barrier is equal to the *height at full effectiveness* (the height at which average snow-trapping efficiency equals 75%), the required tree height can be calculated in the same manner as for structural fences (section 5.3.2). Using the simulation described in section 6.4.1, Figure 6.5 indicates that for light to moderate snow transport regimes, the height of trees must be the same as that required for structural fences. For snow transport greater than 80 t/m (27 tons/ft), trees must be somewhat taller than structural fences. The heights required for full effectiveness at different levels of snow transport are shown in Table 6.1.

Terrain must be considered in determining the required height of trees, in the same way as for structural snow fences. In some instances, shrubs planted near the top of a cut can supply all of the required snow storage (Figure 6.6). Snow transport must be accurately determined, however, if drift encroachment probability is to be acceptable.

Table 6.1. Height and age required for full effectiveness in relation to snow transport, for the model shown in Figure 6.1 with 2.4-m (8-ft) spacing.

Seasonal Snow Transport (t/m)	Blowing Snow Classification	Fully Effective: Height (m)	Age (yr)
<10	Very light	1.2	5
20	Light	1.5	6
40	Light moderate	2.1	8
80	Moderate	2.7	10
160	Moderately severe	4.0	14
320	Severe	6.1	21

1 metric ton = 2,205 lb
1 m = 3.281 ft

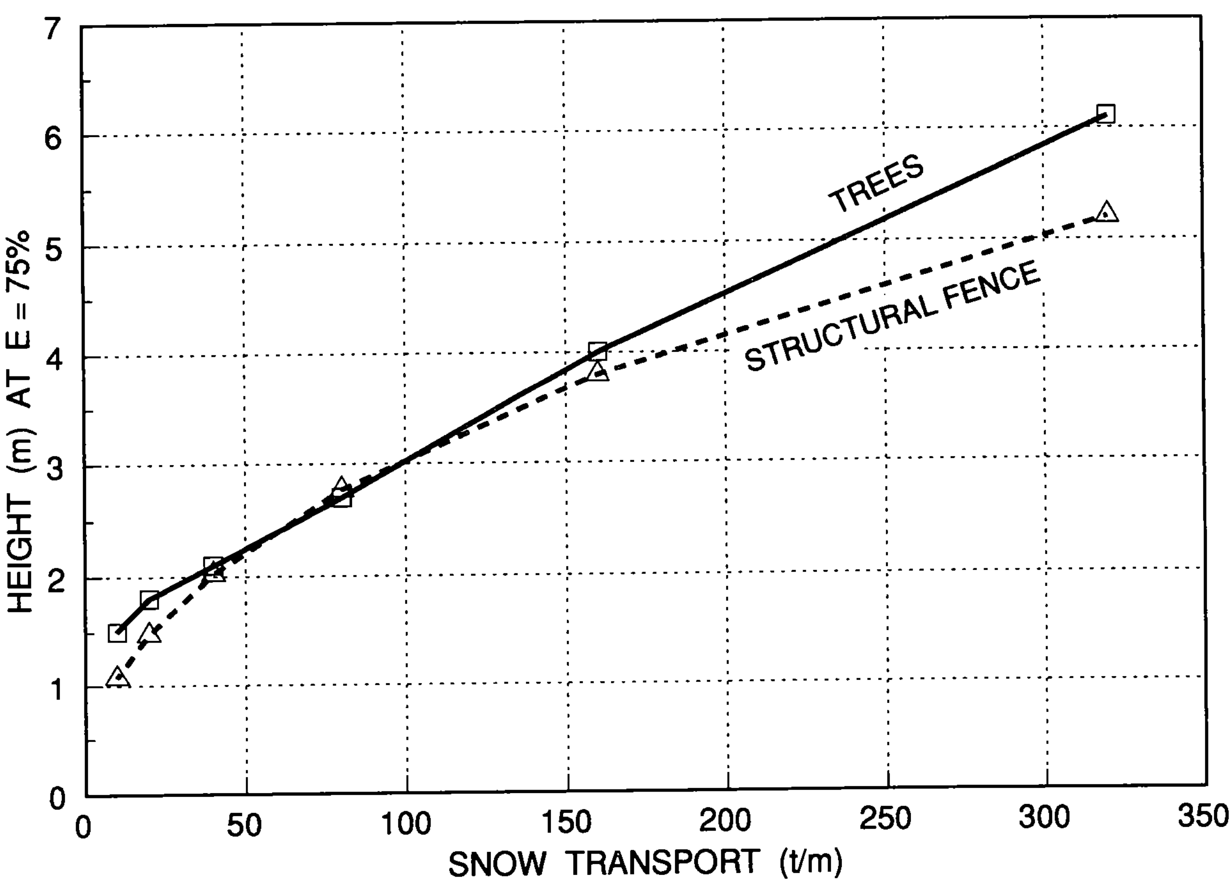

Figure 6.5. Required height of trees and structural fences in relation to snow transport.

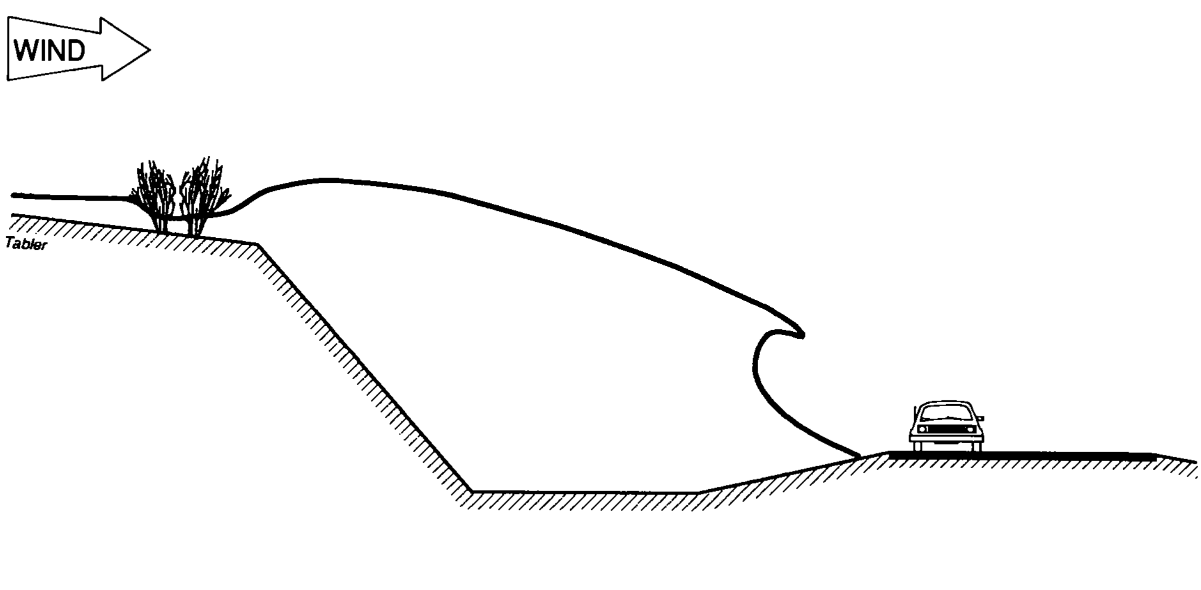

Figure 6.6. Shrubs planted at the top of a cut can be used in place of taller barriers placed farther upwind. Snow transport must be accurately determined, however, if the probability of drift encroachment is to be acceptable.

6.8 Setback Distance for Living Fences

Planting shrubs near the top of a cut, as illustrated in Figure 6.6, is usually not feasible. The same requirement applies as for structural fences — the combined storage capacity, from the shoulder to the planting, should be twice the design snow transport, and the setback should be at least 18 times the height of the shrubs (section 5.5.2.3).

The more common situation requires the setback to be determined by the length of the downwind drift at equilibrium. There is one especially important difference between structural fences and living fences, however — dense plantings of trees and shrubs act as solid barriers. As described in section 3.8.4, there is no significant snow deposition on the downwind side of a solid fence until the upwind drift approaches equilibrium. If the storage capacity in the upwind drift is sufficient to store all of the design transport, then no significant drift will form on the downwind side of the barrier. This concept is used in Japan to plant wide belts of trees to form "snow break forests" along railroads and highways (Figure 6.7), and the same principle can allow living fences to be planted relatively close to the road, although the trees will cast a drift on the road until they reach a certain height and porosity.

The problem in specifying setback distance for trees is that height, porosity, and snow storage capacity all change as the trees grow, so that the length of the downwind drift changes with time. In Montana, Laursen and Hunter (1986) recommend that the windward row of plantings be set back a minimum of 61 m (200 ft). Shaw (1989) recommends a minimum setback of 91 m (300 ft) for open prairie country with large volumes of relocated snow.

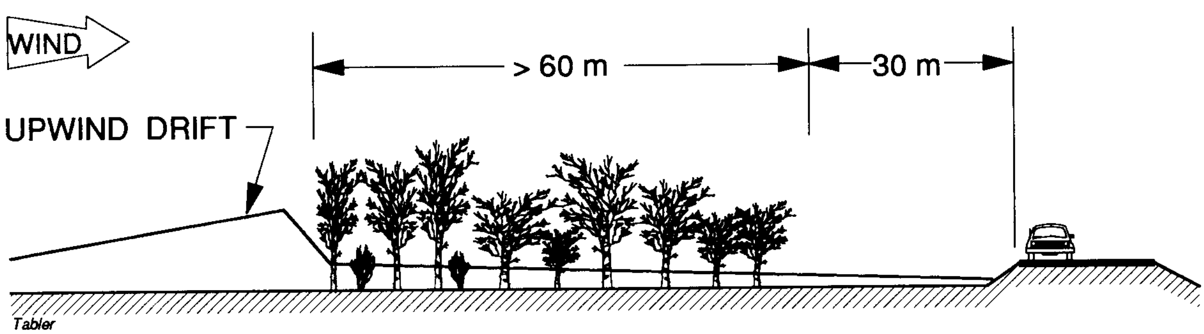

Figure 6.7. Snowbreak forests used in Japan utilize the principle that dense plantings act as solid barriers to induce snow deposition on the upwind side.

6.8.1 Computer Simulation of Downwind Drift Length

By comparing the storage capacity of the trees with the incoming snow transport, the computer simulation for the model illustrated in Figure 6.1 can be used to demonstrate how drift length changes as the trees grow.

For this purpose, assume that in addition to Equations (6.1) to (6.3), the following relationships developed for structural fences also apply to the tree model:

- Equation (3.24): $L/H = 12 + 49P + 7P^2 - 37P^3$ (6.4)
- Equation (3.14): $L/H = 10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2$ (6.5)

Combining these equations gives an expression for the length of the pre-equilibrium downwind drift:

$$L/H = \{[10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2]/34.3\}(12 + 49P + 7P^2 - 37P^3) \quad (6.6)$$

Snow storage capacity on the upwind side of the barrier, $Q_{c,up}$, can be estimated by assuming that this drift is a right-triangle in cross-section, with base $12H$, maximum depth (Y_{max}) equal to $(1-P)H$, and average snow density given by Equation (3.13):

$$\rho_s = 522 - [304/(1.485Y_{ave})][1 - e^{-1.485Y})] \quad (6.7)$$

where $Y_{ave} = Y_{max}/2$.

With these assumptions, the simulation model suggests that length of the downwind drift changes with tree height and snow transport as shown in Figure 6.8 for a 2.4-m (8-ft) tree spacing. The rising limb of the curves coincides with the period when the downwind drift is filled to equilibrium, as given by Equation (6.1). The falling limbs coincide with the period when so much of the transport is retained in the upwind drift that the downwind drift no longer attains equilibrium. In this stage, length is given by Equation (6.6). The abrupt drop to zero signifies that all of the snow is stored on the upwind side of the trees.

Plotting the *maximum* length of the downwind drift that occurs at the peak of the curves in Figure 6.8, expressed as multiples of the required height of structural snow fence (Equation 5.3) for these snow transport amounts, shows that drift length is essentially the same as that formed by structural fence (Figure 6.9).

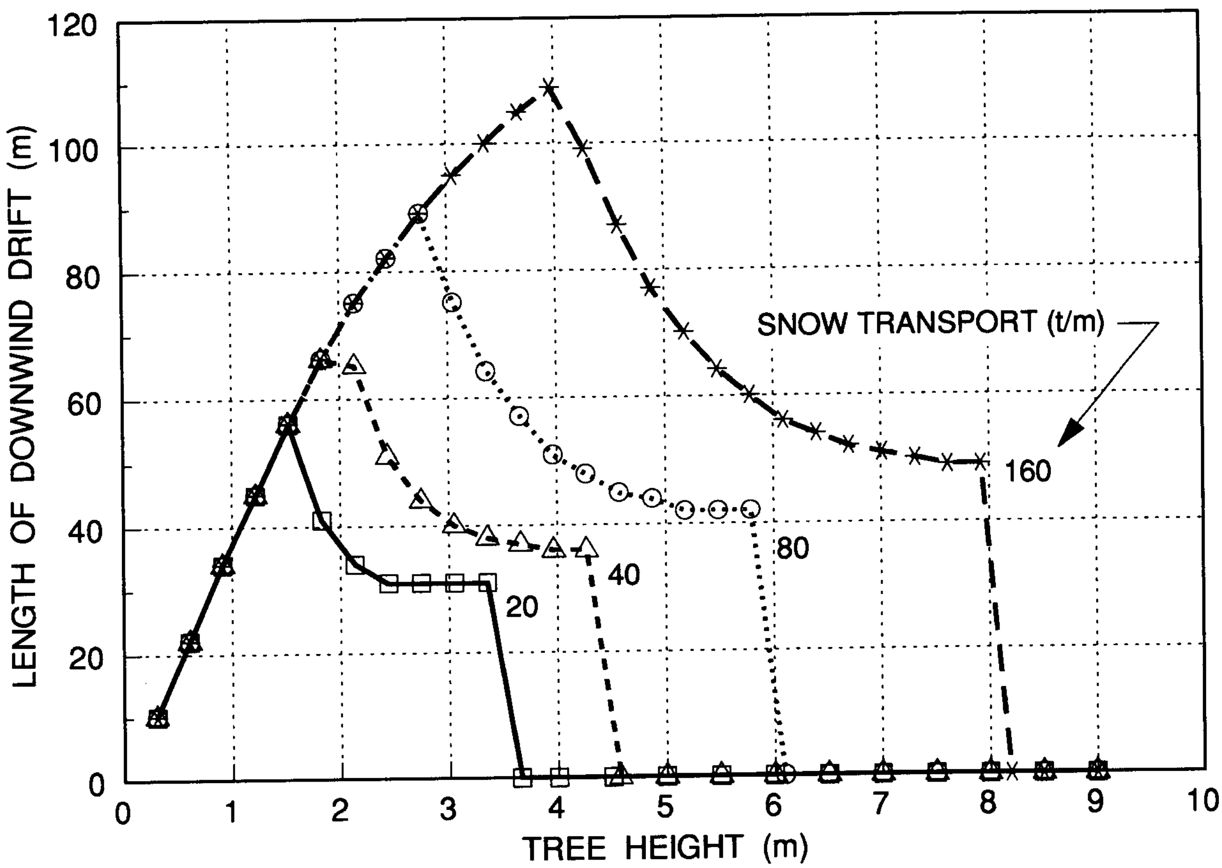

Figure 6.8. Length of downwind drift formed by the tree model shown in Figure 6.1, as a function of tree height, age, and snow transport. Tree spacing is 2.4 m (8 ft).

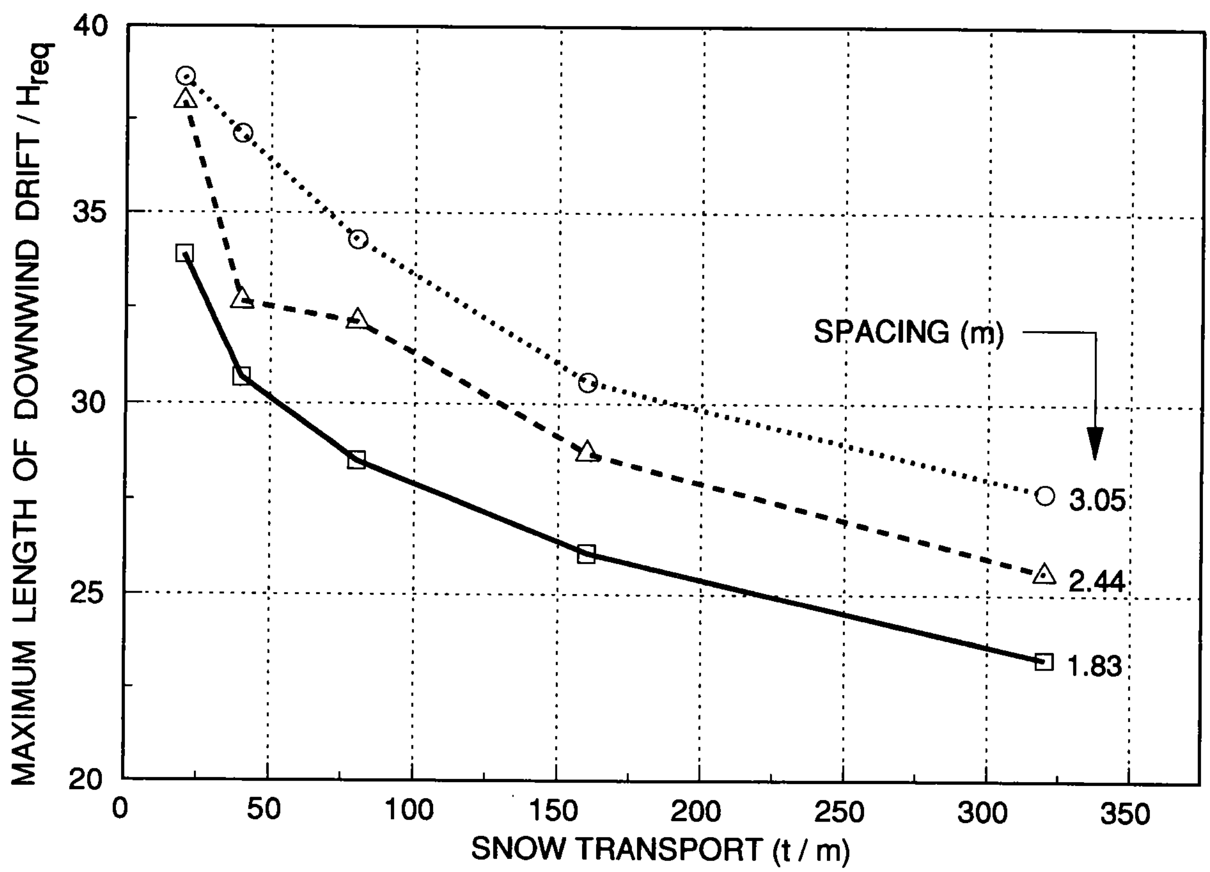

Figure 6.9. Maximum length of downwind drift formed by tree model shown in Figure 6.1, as a function of snow transport and tree spacing. H_{req} is the height of structural fence required to store the indicated snow transport.

6.8.2 Setback Guidelines

The simulation model suggests that for light to moderate drifting conditions ($Q < 80$ t/m), the setback distance, D, for a living snow fence on flat terrain should be the same as the required height, H_{req}, for structural snow fence having $P = 0.5$:

$$D = 35(\sin\alpha)H_{req} \tag{6.8}$$

where α is the attack angle of the wind. The setback can be less for higher snow transport rates, however. The application of this guideline is best explained by example. Consider a site where design transport, as calculated using the methods described in section 4.7, is 80 t/m (27 tons/ft). From section 5.3.2.1, H_{req} would be 2.8 m (9.2 ft). If the prevailing transport direction were perpendicular to the road ($\alpha = 90°$), then Equation (6.8) gives a setback of 98 m (322 ft). At this spacing, the downwind drift would not encroach on the road at any stage of growth.

An advantage of the relatively long setbacks recommended for living fences is that they prevent sun shading that slows melting of snow and ice on the road.

The relationship between drift length and snow transport (Figure 6.7) helps to explain why appropriate setback distances can range from 30 m (100 ft) or less in Maine, to 45 or 60 m (150 or 200 ft) in Minnesota, to 90 m (300 ft) in many locations in the northern plains states. The most important lesson to be learned is that the required setback depends on snow transport, and guidelines should be customized on this basis.

Shorter setbacks can be used if drift encroachment can be tolerated for a few years before the trees attain their fully effective height. Alternatively, temporary structural fence could be installed upwind of the trees during this critical period. The fence should be placed far enough upwind that its downwind drift does not damage the trees, at a distance equal to or greater than 20 times the fence height (Figure 6.10). At this distance, the fence still provides some protection for the trees, but the drift will not be deep enough to damage the trees. The 50-m (164-ft) setback for the trees is a minimum for a dense planting of trees with a branches extending to the ground, and requires that the storage capacity of the structural fence be equal to the design transport. Although this guideline is derived from experience, it is also supported by the simulation results in Figure 6.8.

The required setback often proves excessive during the many years required for the trees to reach maturity. A solution is to plant two or more rows of fast-growing shrubs that will reach 1.8 to 2.4 m (6 to 8 ft) tall at maturity, at a setback equal to 35 times their mature height.

The minimum setback for trees should allow the sun to shine on the road surface at noon on the shortest day of the year. In Maine, for example, the minimum noontime solar angle is about 22° above the horizon. The sunshine criterion would therefore require trees planted on the southern side of a road to be set back from the shoulder at least 2.5 times their mature height.

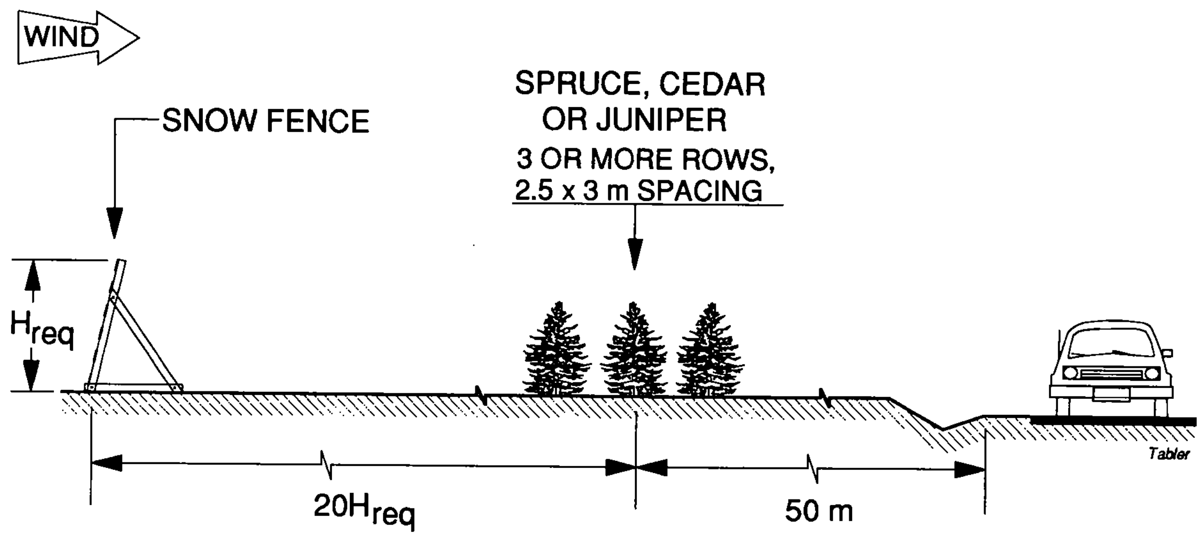

Figure 6.10. Recommended placement of temporary snow fence with storage capacity equal to design transport, and minimum setback of living snow fence.

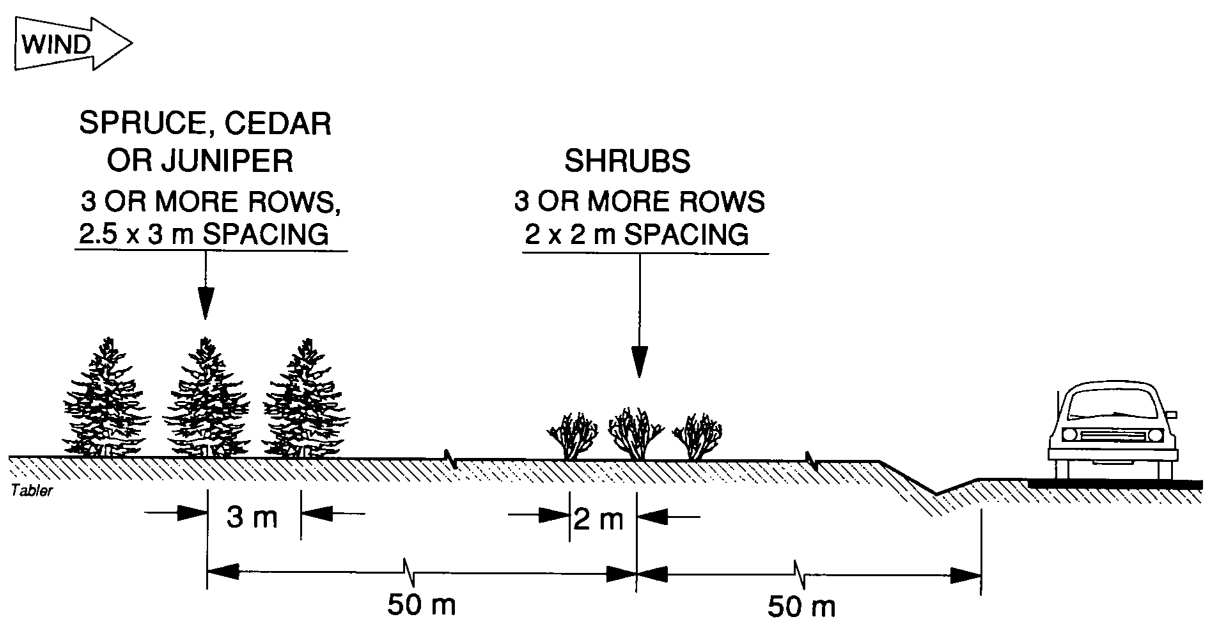

Figure 6.11. Shrub rows planted between the road and tree rows improves snow control during the years before the trees become fully effective.

6.9 Planting Patterns for Living Fences

To minimize the number of trees and land area required, trees are typically planted parallel to the road regardless of wind orientation.

Spacing between plants should assure "crown closure" at maturity. Holes and openings in the planting should be avoided for the same reasons described for structural fences. The layout should be planned to avoid burying trees and shrubs in deep drifts formed by upwind rows.

A minimum of two rows of coniferous trees, spaced 2.4 m (8 ft) apart, should be planted in a staggered pattern to reduce corridors between trees through which snow can pass. Three-row coniferous plantings become effective more quickly and are less likely to develop openings. In-row spacing depends on the species used, but is typically 2.4 m (8 ft) for trees, and 1.2 m (4 ft) for shrubs. For dense, coniferous species, 2.4-m spacing is recommended.

Planting a row of shrubs on the windward side of the conifers improves survival and early growth by providing protection from desiccating winds, and by increasing snow accumulation to augment soil water recharge. Standard practice in Minnesota is to plant one row of *Caragana* (Siberian pea shrub) 1.5 m (5 ft) upwind of the conifers, at a within-row spacing of 0.9 m (3 ft). Although 1.2-m snow fences have been used to protect newly planted trees, low-growing shrubs are preferable because the deeper drift formed behind a snow fence damages trees downwind.

6.9.1 Deciduous Trees

Deciduous trees and shrubs can provide an effective snow fence if a sufficient number of rows are used to achieve a porosity ratio less than 0.6. Three rows of trees with the branching characteristics shown in Figure 6.12, can provide an adequate porosity ratio. The visual or physical porosity is greater than the aerodynamic porosity, because the resistance to airflow is proportional to the *swept area* rather than the frontal area of the branch or twig itself (Hoerner 1965). Because most hardwood trees tend to be relatively open near the ground, it is also necessary to plant one or more rows of shrubs on the upwind side to reduce blowing snow under the canopy.

Two approaches are possible for deciduous plantings. In locations lacking native tree cover, a minimum of three rows of trees and two rows of shrubs are required to achieve the necessary canopy density. Species diversity is an important requirement to reduce the likelihood of losses to insects or disease. In areas originally occupied by forest vegetation, such as many areas in the northeastern United States, fewer rows need to be planted because volunteer trees and other vegetation will supplement the plantings and increase canopy density. In this case, planted stock should include species dominant in old-growth forests.

Figure 6.12. Three rows of deciduous trees with branching habits similar to the Russian olive shown here provide a satisfactory porosity ratio for efficient snow-trapping.

6.9.2 Snowbreak Forests

The 60-m (200-ft) minimum width required for snowbreak forests, as illustrated in Figure 6.7, is for deciduous trees. Narrower widths would be satisfactory for spruce and other coniferous species with dense foliage. The 30-m (100-ft) setback requires that the storage capacity in the upwind drift be at least as great as the design transport.

6.9.3 Methods of Protecting Grade Separations

A combination of trees and shrubs provides the most complete protection for grade separations that have the kind of problem illustrated in Figure 6.13.

In Minnesota, a triangular pattern (Figure 6.14) is used to reduce drifting at grade separations. This design is referred to as a snow trap. In addition to providing excellent cover for wildlife, the snow trap also has a higher trapping efficiency than a conventional two-row planting.

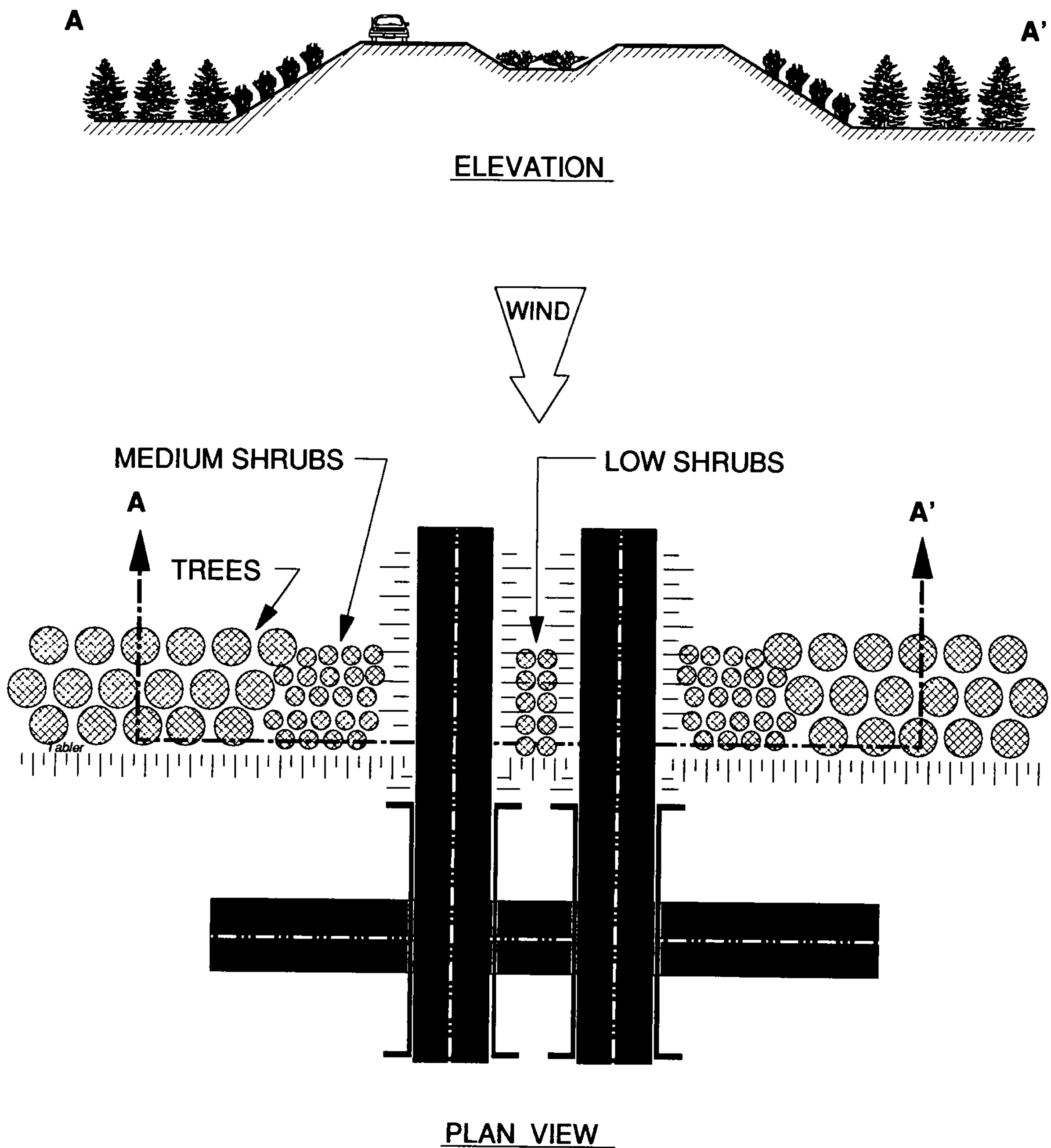

Figure 6.13. Combining trees and shrubs can reduce blowing snow problems at grade separations.

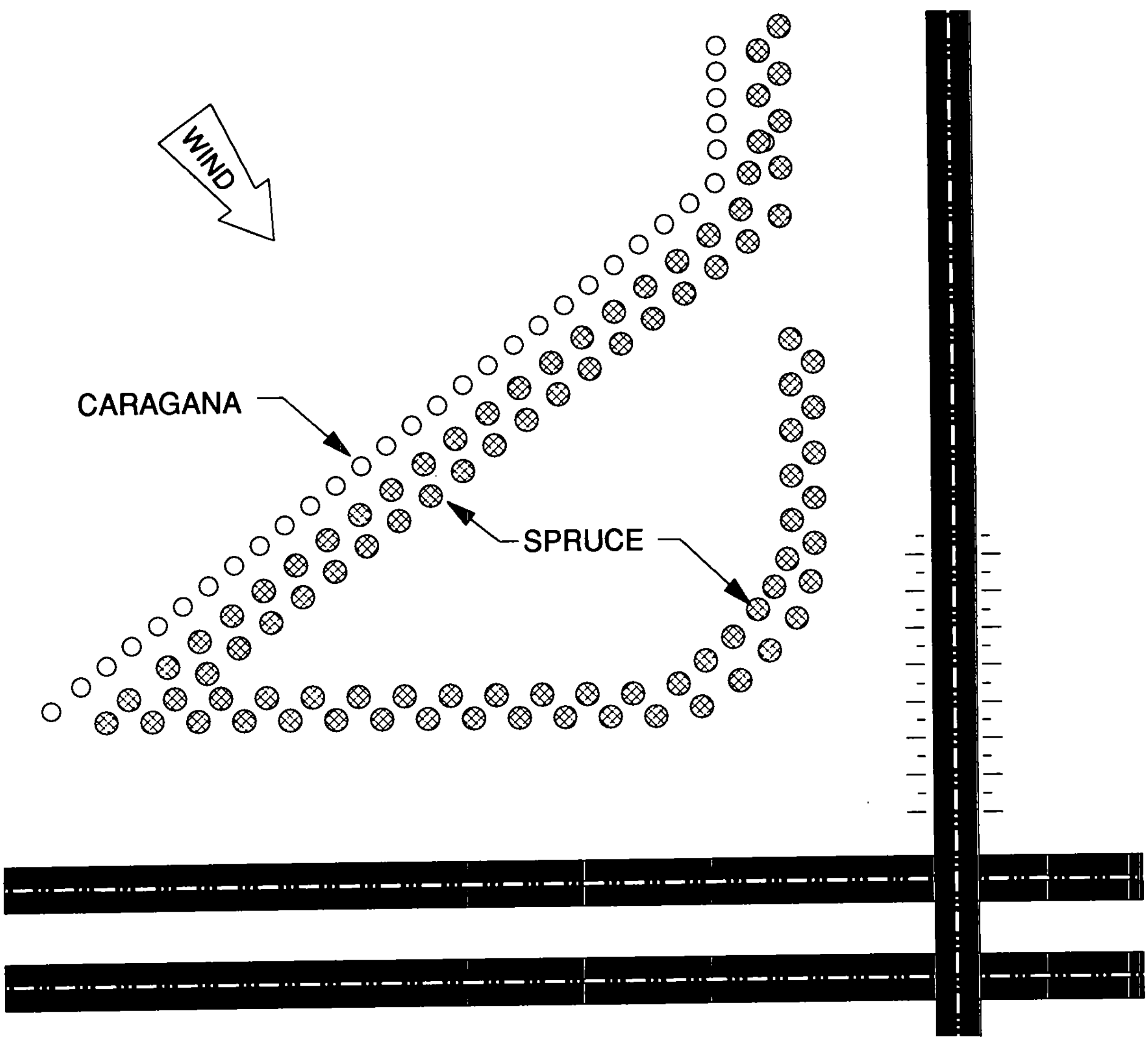

Figure 6.14 Snow trap used in Minnesota to reduce drifting at grade separations.

6.9.4 *Plantings for Snow Retention*

A mass planting of shrubs and trees can be effective in reducing blowing snow that originates in open areas within the right-of-way, such as medians and gore areas at interchanges. Such plantings may aggravate the snowdrifting problem, however, if improperly designed. Roadside plantings for headlight screening, curve delineation, access control, and beautification, have had to be removed because of the drifting problems they created. A study in Illinois (Illinois Department of Transportation 1978) concluded "...the design intent advantages of... shrub beds are now overshadowed by the problem of snowdrifting, which in severe cases can cause roadway closures and endanger the traveling public."

Shrub plantings for snow retention should only be used for Class 1 (Light) snow transport conditions (< 10 t/m), because shrub beds are intended only to retain snow on the ground, and not to collect transport arriving from upwind. If the source of blowing snow is outside the right-of-way, some other control measure is required.

Unless all of the area within the right-of-way is stabilized, shrubs should be planted so that the tops of the plants that are immediately adjacent to the road are below the surface of the road. Shrub height should be equal to, or greater than, the depth of the snow cover at the time of peak accumulation.

6.10 Planting Stock

Coniferous Seedlings 20- to 30-cm (8- to 12-in.) tall are most commonly used for snow control plantings because larger trees are much more expensive. The cost of seedlings is small, however, compared to other expenses for establishing and maintaining a tree planting. The price of seedlings should be secondary to considerations of survival and rapid growth. As a general rule, container-grown conifer seedlings will survive and grow better than bare-root stock. In Montana, a two-year study showed survival of container-grown stock to be 40 to 55% greater than for bare root seedlings (Laursen and Hunter 1986). The potting mix contains a reserve of moisture and nutrients, and protects the roots from exposure during handling and planting, reducing transplant shock. Types of containerized stock are tar-paper-potted, Styrofoam block, and plug-grown seedlings.

Deciduous Two-year-old rooted cuttings are preferred, but only one-year-old stock is available for some species. Members of the poplar family — willow, aspen, and poplar — are often started from unrooted cuttings. This practice can significantly reduce costs for plant procurement and planting.

6.11 Site Preparation and Planting

Helpful guidelines for site preparation and planting are provided in the publications by Laursen and Hunter (1986) and Shaw (1989). Some of the more important aspects are summarized in the following sections.

6.11.1 Seedlings

Because competition for water, nutrients, and sunlight are determining factors in seedling survival and growth rate, careful site preparation is essential. In late summer the year before planting, weeds should be controlled with an herbicide. In the fall, the planting bed should be plowed and disked. Seedlings should be planted as early as possible the following spring. Container-grown stock may be planted later than bare-root seedlings.

The importance of following proper planting procedures is emphasized by Laursen and Hunter (1986):

> Planting needs to be performed as though everything in the success of the windbreak project were dependent on it. Seedling quality and viability deteriorate rapidly during the period of handling and planting. A seedling out of the ground or improperly planted is just like a fish out of water. The idea is to keep the rate of deterioration at a minimum. A few seconds of sun exposure can kill root tissue of evergreens...

Weed control is essential for the first 3 to 5 years after planting. Options to herbicides and mowing include the use of deep wood chip mulches or weed barrier — a geotextile that allows water and air to pass through the membrane while preventing weed growth (Figure 6.15). The width of the material should be 1.8 to 2.4 m (6 to 8 ft). Seedlings can be planted either before or after the weed barrier is laid. In Colorado, seedlings are typically planted by machine first. As the barrier-laying machine moves down the row, an operator cuts slits in the fabric and pulls the seedlings through the openings. It is essential that the edges of the weed barrier be firmly anchored to prevent the wind from lifting the material. Standard practice is to bury the edges in a trench. If sun-resistant material is used, the remainder of the barrier can remain exposed.

In dry areas, polyacrylamide placed in the soil at the time the seedlings are planted reduces post-planting watering and improves growth rate.

Figure 6.15. Geotextile weed barrier is a cost-effective way to control weeds and conserve moisture.

6.11.2 Larger Transplants

Larger transplants that have bare roots or root balls ("B and B" stock) also must be planted properly to insure survival and satisfactory growth.

Planting soil should be of a loam texture suitable for the species being planted. As a general rule, 20-20-10 fertilizer should be mixed with the planting soil at the rate of 0.6 kg/m^3 (1 lb/yd^3), although this rate may need to be adjusted for certain soil types.

As shown in Figure 6.16, planting holes must be excavated 60 cm (24 in.) wider than the diameter of the roots or ball, and 20 cm (8 in.) deeper than the ball or lower extremities of the roots. Carefully tamped planting soil should be used for backfill. The ball or lower extremities of the roots should rest on 15 cm (6 in.) of tamped planting soil placed in the hole before setting the tree, so that the top of the root ball is approximately on grade. A layer of mulch, 10- to 13-cm (4 to 5 in.) thick, should be placed around the tree to conserve moisture and reduce weed development. Thicker layers of mulch provide excessive insulation, delaying the rise of soil temperature in the spring.

All trees having a caliper of 5-cm (2-in.) or more must be staked for support. The preferred method is to use three, 2.1-m (7-ft) steel T-posts driven vertically outside of the root ball, equally spaced circumferentially. Twisted wire guys from the posts are connected to polypropylene or polyethylene straps that hold the tree trunk. Sections of hose should not be used in place of the straps.

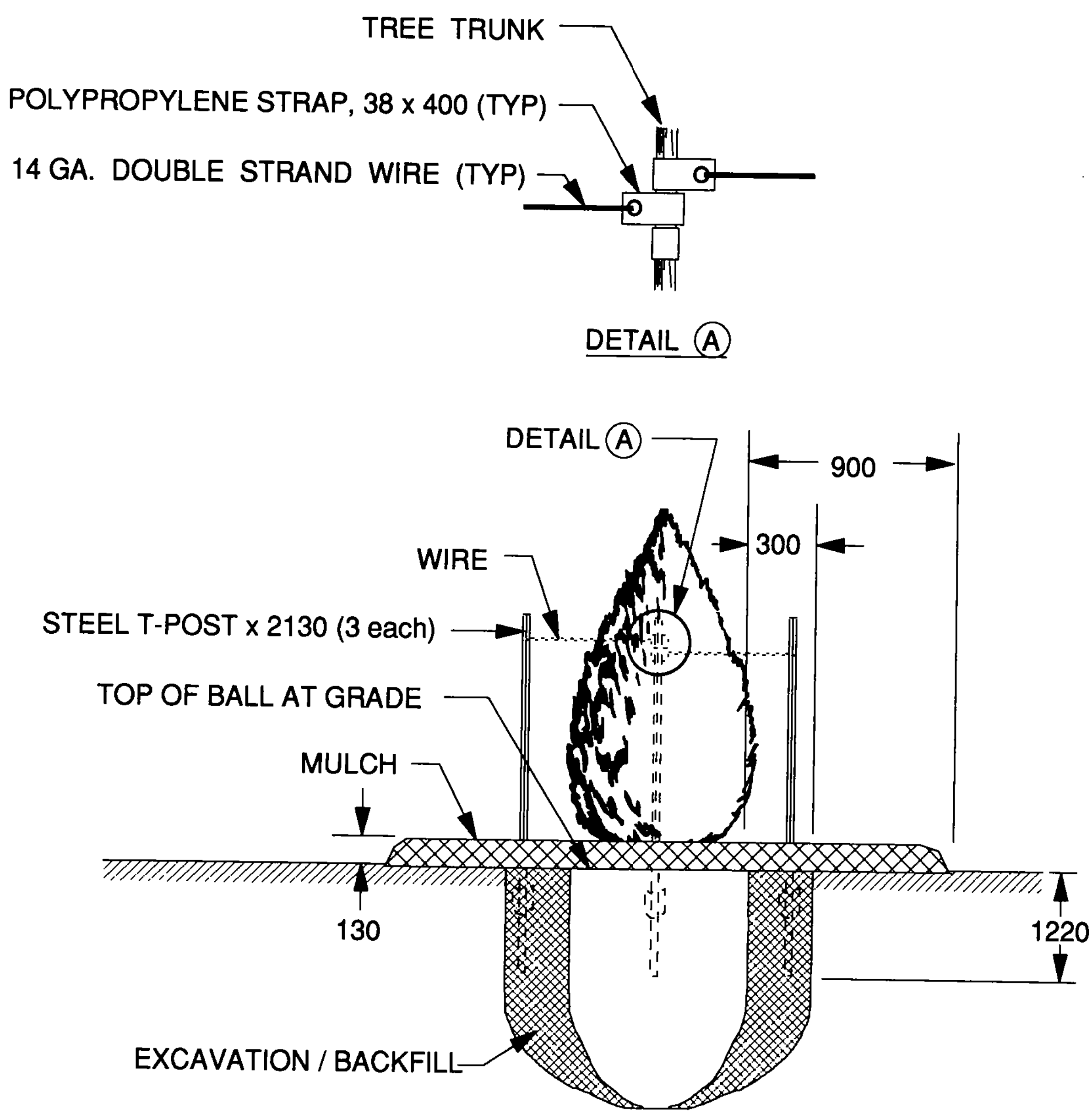

Figure 6.16. Planting guidelines for large transplants.

6.12 Post-planting Care

Tree plantings must be watered and protected from excessive weed competition for the first five years or so until they become fully established and are able to compete with surrounding vegetation. If a weed barrier was not installed, weeds must be chemically or mechanically controlled until the trees dominate the surrounding vegetation. The weed barrier will provide passive weed control for at least 5 years if it remains securely fastened to the ground. By the time the fabric deteriorates, the planted material will be large enough to shade the soil and reduce the growth of herbaceous weed species.

Periodic inspections to monitor plant health and the stability of the weed barrier, if used, are critical maintenance tasks. Loose portions of the membrane must be immediately secured because strong winds will lift the barrier and damage the plantings. Trees and shrubs should be inspected periodically for insects and disease, and treatments applied when necessary.

The trees and shrubs should be watered as necessary for the first 3 years or so after planting. In dry areas, drip irrigation systems can be an economical alternative to using a watering truck.

6.13 Pruning

Because snow deposition within the living snow fence is unfavorable for wildlife, pruning has been recommended as a way to reduce deposition within the trees. Removing lower branches has the same effects as widening the bottom gap under a structural fence. Pruning reduces snow deposition on the upwind side, elongates the downwind drift, and may adversely affect drift control performance. Because pruning increases wind speed and snow transport under the canopy, this practice may be deleterious for some wildlife species. A better way to reduce snow deposition under the trees is to *increase* the density of the leading edge of the planting, using shrubs or a structural fence if necessary, to encourage snow deposition upwind of the trees.

6.14 Cost

Direct costs for living snow fences include those for planting stock, site preparation, planting, fertilizer and other soil additives, weed barrier, mulch, and watering. Fencing is also often required to prevent damage by livestock and wildlife. Powell et al. (1992) compared installation costs for living snow fences and structural snow fences 4.3 m (14 ft) tall in Wyoming, taking into account the interest foregone on the initial investment during the time required for the trees to become fully effective. Their analysis (Table 6.2) indicates that installation costs for these two types of snow fences are almost the same over their respective service lives.

Contract costs for living snow fences in Minnesota were reported to range from $31,075 to $52,830/km ($50,000 to $85,000/mile) for deciduous trees, and $77,690 to $124,300/km

($125,000 to $200,000/mile) for plantings with both evergreen and deciduous species (Walvatne 1991). The cost for a 3.6-m (12-ft) fence required in the more exposed locations in southern Minnesota is estimated to be $49,100/km ($79,000/mile) at current prices.

In Iowa, contract costs for installing living fences in 1989 were reported by Shaw (1989) to be about $13,050/km ($21,000/mile).

Considering the costs for snow removal and interest over the 5 to 20 years required for the living snow fences to become effective, it seems clear that living snow fences cost about the same as structural fences.

Table 6.2. Installation costs in 1983 for living snow fence and Wyoming snow fence 4.3 m (14 ft) tall (Powell et al. 1992). "Effective installation cost" is the value of the initial installation cost at 5.25% interest compounded annually, at the time the snow fence becomes fully effective.

Fence type	Installation cost ($/km)	Effective installation cost ($/km)	Service life (years)	Unit cost ($/km/year)
Living snow fence	22,625	62,957	60	1049
Wyoming snow fence	36,096	36,096	35	1031

km = 0.622·mile

6.15 Advantages and Disadvantages of Living Snow Fences

Under favorable conditions, living snow fences can be less costly to establish than structural fences. In addition, living snow fences are aesthetically desirable, and provide habitat for wildlife. These benefits must be weighed against the following disadvantages:

- On some sites, climate, soil, or biotic conditions make the establishment of trees difficult or impossible.
- Even under optimum growing conditions and light blowing snow conditions, six years or more are typically required before plants become tall enough to be effective (Table 6.1 and Figure 6.3). In Wyoming, 20 years or more are required for full effectiveness (Powell et al. 1992).
- Barrier height and porosity, and hence drift length and storage capacity, change with time.

- The irregularity of growth form and branch arrangement can cause openings and excessive bottom gaps, reducing the effectiveness of the barrier. Even small openings can cause big problems.

- Vegetative barriers are subject to damage by insects, disease, fire, drought, winter kill, wind, snow, freezing rain, excessive water, and browsing by livestock and wildlife.

6.16 Standing Corn

At least two states have experimented with leaving rows of corn standing in fields adjacent to the highway right-of-way. The consensus is that this strategy is effective and economical (Figure 6.17). The number of standing corn rows varies with the size of the picker, but for effective drift control the minimum is six to eight rows. The most effective strategy is to use two strips of corn separated by a space 50 to 60 m (164 to 197 ft) wide. In effect, the corn rows perform as 50%-porous snow fences. Two strips of standing corn 2 m (6.6 ft) tall will store approximately 75 metric tons per meter of length (25 tons/ft), or as much as a 2.7-m-tall (8.8-ft) snow fence.

Past practice in Minnesota has been that farmers are paid for the corn left standing in the field based on the market value for the crop on the day of harvest, with the option of salvaging the corn in the spring. Costs for the Minnesota program in 1984 averaged $810/km ($1,300/mile). Over a 6-year period starting in 1985, one district in Minnesota reported an average cost of $480/km ($775/mi.) — *about 95% less than the cost of placing and removing regular 1.2-m (4-ft) snow fence.*

The minimum setback from the road shoulder should be the same as for structural fences: 35 times the effective height of the standing corn (Figure 6.18). Standard practice in Minnesota is a minimum setback of 46 m (150 ft) *from the right-of-way*. A setback of 30 m (100 ft) has proven too close.

Figure 6.17. Standing corn makes an effective and economical snow fence.

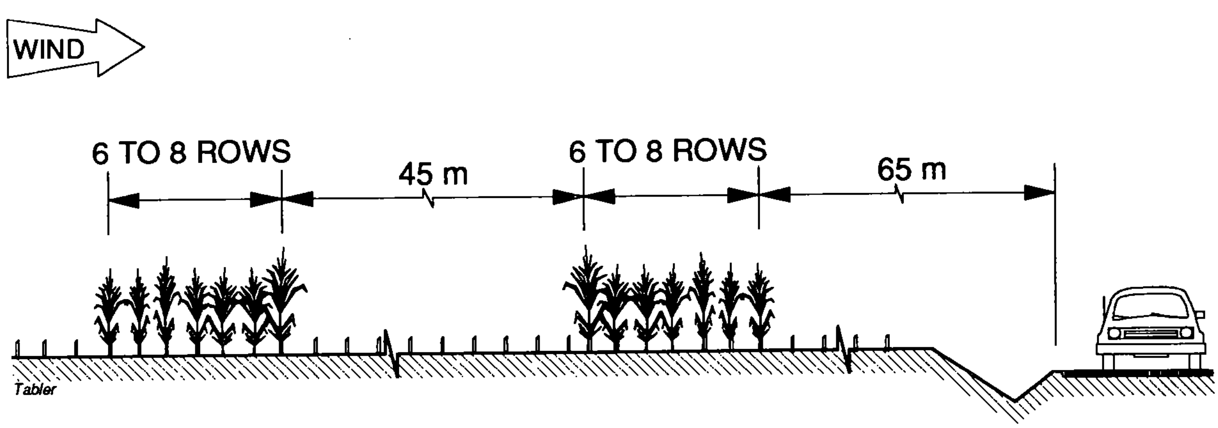

Figure 6.18. Guidelines for standing corn, assuming effective height of corn to be 1.8 m (6 ft).

6.17 References

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7. Designing Drift-Free Roads

7.1 Scope

This chapter provides guidelines for locating and designing roads to minimize blowing snow problems, derived from a combination of theoretical considerations, observation, and a mathematical model for predicting snowdrift profiles. The presentation assumes that the reader is familiar with the material in chapters 3 and 4.

To the extent practicable, the guidelines proposed here are consistent with the recommendations in the *Roadside Design Guide* (AASHTO, 1989). However, the designer is responsible for assuring conformance with all applicable standards and regulations. These guidelines presuppose sound engineering judgement, and a thorough evaluation of potential blowing snow problems, as described in chapter 4.

7.2 Highlights

- Road design can be effective in preventing snowdrifts, but this method of drift control cannot be expected to improve visibility and road surface conditions to the extent possible with fences.

- Roads should be designed for drift-free conditions to the extent possible. However, snow fences are less expensive than reconstruction to change the cross-section of an existing road.

- Blowing snow and snow removal operations should be considered in all aspects of road design.

- A mathematical model for predicting snowdrift profiles from ground profile information can be used to design drift-free roads using the guidelines presented here.

- Blowing snow problems can be greatly reduced or prevented by proper route location and alignment. Considerations include location in relation to terrain, alignment and clearing widths in wooded areas, safety barrier requirements, location in relation to sources of blowing snow, and avoidance of shallow cuts.

- Roadside snow accumulations reaching a height of 0.5 m (1.6 ft) or more above the shoulder create serious safety hazards by reducing motorist visibility.

- The road surface should be elevated above the mean annual snow depth, with additional allowance for plowed snow. A 4:1 front slope helps keep plowed snow accumulation below the shoulder. Safety considerations require, however, that the toe of the slope be generously rounded, and that a clear area exists over the required recovery distance.

- High fill sections should be designed to eliminate the need for safety barriers. A barn-roof section with 6:1 front slopes reduces deposition of blowing snow, and paved shoulders facilitate snow removal operations.

- Laying back slopes to 6:1 is not always successful in preventing drift encroachment. Cuts should be designed to *promote* snow deposition on the back slopes to allow the wind to form an equilibrium drift that tails out below the shoulder of the road. This design strategy also allows the cut to store some of the blowing snow, thereby improving visibility and road surface conditions.

- Wide ditches are an important and effective feature for drift prevention because they prevent reduced sight distance on curves, provide space for plowed snow to accumulate, keep snow from sliding onto the road from back slopes, allow the equilibrium snow slope to tail out below the shoulder, and provide clear-zone requirements.

- Ditch depth is important for drainage as well as for exposing the road surface to the wind, and for providing storage of plowed snow below the shoulder. The minimum depth for drift control is 1.2 m (4 ft) below the shoulder point-of-intersection (PI).

- Because most of the cast from displacement plows is deposited within 3 m (10 ft) from the edge of the plowed lane, front slopes in cuts (rock cuts are an exception) should not be flatter than 4:1 to allow plowed snow to accumulate below the shoulder.

- Recommended distances from shoulder to toe and top of back slope vary with depth of cut and attack angle for the prevailing transport direction.

- For sidehill cuts in rock, the distance to toe of backslope should be at least 3.7 m (12 ft) to contain snow that slides off backslopes and to provide space for plowed snow to accumulate. A 6:1 front slope should be used to facilitate snow removal by off-road equipment. Paved 2.5-m (8-ft) shoulders on both sides of the road facilitate snow removal operations and reduce deposition of blowing snow.

- Super-elevated curves promote deposition of blowing snow. Avoid curves in windward-facing sidehill cuts where the cut is on the inside of the curve.

- The relative elevations of divided lanes should be such that the upwind lane does not cause snow to be deposited on the downwind lane.

- Safety barriers cause snowdrifts and interfere with snow removal by deflecting plow cast. A road design should strive to minimize barrier requirements by using recoverable slopes on embankments, preferred ditch sections, and clear-zone widths specified in the *Roadside Design Guide* (AASHTO 1989).

- Concrete barriers create the worst problems, including reduced visibility in blowing snow. Box-beam and cable barrier offer less obstruction to wind and plow cast than W-beam rail. Permanent curbs under barriers tend to accumulate snow and should be replaced with temporary sand-filled curbs where possible. Curbs can also degrade barrier performance in controlling errant vehicles.

- Shirt-tail drifts that form at the ends of safety barrier can be eliminated by anchoring ends in the back slope, or flaring ends away from travel lanes. Although turned-down terminals would also be effective in eliminating these drifts, their use is not recommended because they can cause vehicles to vault or roll following impact.

- Drifts caused by abutments at grade separations can be reduced with tree and shrub plantings, or by lengthening the overhead span so that the abutments are as far away as practicable from the shoulders of under-passing lanes. Clear-zone widths should be adequate to eliminate the need for safety barrier.

7.3 Road Design as a Solution to Drifting Problems

Experience since the 1930s has proved that road design can prevent snowdrifts. In the snowbelt, roads should always be designed to minimize blowing snow problems and facilitate snow removal operations. Road design cannot improve visibility and road surface conditions to the extent possible with snow fences, however, and should not be construed as eliminating the need for such measures. Optimum snow control is achieved by using proper road design *and* snow fences. Reconstruction of an existing section to eliminate drift encroachment is invariably more expensive than alternative control measures.

7.4 History

Guidelines for designing roads to prevent drifts have been proposed since the 1930s. All of these were based on observation. In 1939, Finney summarized existing road design practices for states within the snowbelt, and combined these with wind tunnel experiments to develop recommendations that provide the foundation for most guidelines used today.

In 1975, the author proposed a method for designing drift-free roads using a mathematical model to predict profiles of drifts formed by terrain features. This model was based on an empirical equation relating the slope of the equilibrium drift to terrain slopes both upwind and downwind of the point where deposition begins (Tabler 1975). The resulting snowdrift profiles were generally consistent with Finney's wind tunnel results, but provided better approximations in complex terrain. In 1976, this snowdrift prediction routine was used to develop a "Snowdrift Prediction Computer System for Earthwork Design," which the Wyoming Department of Transportation interfaced with the Road Design System (RDS) earthwork program (Christensen 1976).

The Snowdrift Prediction System forecasts snowdrift profiles, but it does not automatically design the cross-section to eliminate the drift on the road, nor does it indicate what changes might be required. As a result, the design engineer must decide how best to change the section to eliminate the drift. Without experience, an optimum solution is purely accidental.

The guidelines presented here are intended to provide the designer with the information needed to design drift-free sections, but they can also be substituted for the snowdrift prediction routine now used in conjunction with the RDS program.

7.5 Factors Contributing to Drifting Problems

Almost every aspect of road design affects deposition of blowing snow. Although it is common knowledge that embankment height and cut geometry are important factors, other aspects that affect snow control include safety barrier placement and design, location and front slopes of super-elevated curves, median depth and relative elevations of lanes on divided highways, and proximity of abutments and horizontal alignment of roads at grade separations. Snow should be considered in all aspects of design.

7.6 Predicting Snowdrift Profiles

The basis for designing drift-free roads is the ability to predict the snowdrift profile that a given section will generate. This prediction can be based on experience, small-scale modeling, mathematical modeling, or theoretical analysis. Experience can be entirely adequate if the rules it utilizes are effective, and if they cover all possible combinations of wind attack angle, snow transport quantities, surrounding terrain and vegetation, types of cross-section, and design constraints. The vast number of combinations requires experience-based rules to be locale-specific. Reduced-scale modeling can be effective, but it is obviously impractical to model every project. Aerodynamic theory, such as turbulent mixing, provides useful insight, but has not yet been used to develop quantitative guidelines for road design. Mathematical modeling involves using an empirically-derived mathematical predictor for the drift profile. This latter approach is combined with experience-based rules to develop the guidelines presented here. Derivation of the mathematical model is described in sufficient detail that its validity and limitations are evident to the user. Also, it is hoped that this information will encourage future testing and improvement.

7.6.1 Basic Algorithm and Application for Generating Profiles

As discussed in section 3.7, any topographic accumulation area is assumed to have a maximum snow retention capacity that cannot be exceeded regardless of the amount of blowing snow. The snow surface corresponding to this maximum drift is said to be at equilibrium, and exhibits an *equilibrium slope.*

The snowdrift prediction model (Tabler 1975) is based on a regression analysis of snowdrift profiles measured in the field, to determine which combination of terrain slopes provides the best prediction for the equilibrium slope. The data used for this analysis came from 17 sites in Wyoming and Colorado where snow accumulation appeared representative of equilibrium conditions. The sites were selected to provide a wide range of upwind and downwind terrain. The equilibrium slope is the part of the drift profile that has a smooth, uniform slope, from near the upwind end of the accumulation and extending to the beginning of the concavity where the profile is influenced by the ground's proximity at the downwind end of the drift (Figure 7.1). In the case of very large terrain features that were not completely filled (Figure 7.2), the snow slope selected for the analysis was terminated about 20 m (65 ft) upwind of the slip face dropoff. The length of the slope segment selected under these criteria varied from 12 m (40 ft) for the smallest terrain features, to 69 m (225 ft) for the largest. Terrain profiles were measured during the summer by differential leveling along transects parallel to the snow profile measurements.

Multiple linear regression analysis was used to determine the combination of upwind and downwind slopes having the best predictive value for the snow slopes, as indicated by the smallest residual variance.

To use terrain slopes to estimate the slope of uniform shear stress, it is necessary to specify some maximum limit for the downwind slope corresponding to the threshold for flow separation — that is, the maximum slope that the wind can follow without forming a region of reverse flow near the surface. The best value for this maximum slope limit was determined as part of the regression analysis.

The following regression was selected as the final predictor on the basis of its small residual variance (mean-square regression 69.74, mean-square residual = 3.40, R^2 = 0.87), and because the resulting coefficients were intuitively logical, their sum was 1.00, and the regression constant was approximately zero:

$$
\begin{gathered}
Y_s = 0.25X_1 + 0.55X_2 + 0.15X_3 + 0.05X_4 \\
\text{if measured } X_2, X_3, \text{ or } X_4 < -0.20, \text{ set } X_2, X_3, \text{ or } X_4 = -0.20
\end{gathered}
\tag{7.1}
$$

where

Y_s = snow slope (%) over the main portion of the drift,
X_1 = average ground slope (%) over a distance of 45 m (150 ft) upwind of the catchment lip,
X_2 = ground slope (%) from 0 to 15 m (50 ft) downwind of the trap lip,
X_3 = ground slope (%) from 15 to 30 m (50 to 100 ft) downwind of the trap lip, and
X_4 = ground slope (%) from 30 to 45 m (100 to 150 ft) downwind of the trap lip.

Slopes upward in the direction of the wind are taken as positive, and downward slopes as negative.

Equation (7.1) can be used to approximate the slope of snow deposits caused by terrain features, but it provides no information on how the drift surface is curved, and this information is needed to predict accurately where the drift begins and ends. A more accurate representation of snowdrift profiles can be obtained by using Equation (7.1) in an incremental fashion to generate the snow surface. Because the upwind portion of the drift approaches equilibrium even while the downwind portion remains to be filled in (section 3.7), each increment of growth takes place as though the snow profile up to the top of the slip-face defined in itself a topographic trap (Figure 7.3). With this reasoning, Equation (7.1) can be used to estimate the slope of successive increments (such as 1 m/3.3 ft or less) of the profile, allowing the drift to be constructed in segments by beginning calculations at the upwind end of the snow deposition area, and continuing to the drift's intersection with the ground (Figure 7.4). In these calculations, X_2 is taken as the slope from the snow surface to the ground at a horizontal distance of 15 m (50 ft). Using the case in Figure 7.3 as an example, the slope (Y_s) predicted for the next 1 m (3.3 ft) segment beyond point *P* would be calculated as

$$Y_s = 0.25(-8) + 0.55(-20) + 0.15(-2) + 0.05(+3) = -13.2\%$$

In applying this model using computer programs, incremental snow storage is calculated by computing the cross-sectional area of each incremental addition, converted to mass using Equation (3.12):

$$\rho_s = 522 - [304/(1.485Y)](1 - e^{-1.485Y}) \tag{7.2}$$

where ρ_s is average snow density (kg/m^3) and Y in this case is the average vertical snow depth (m) across the increment. If the accumulated snow storage up to the last increment exceeds the mean annual snow transport (estimated by the methods presented in section 4.7.6), the *end of drift* is computed by assuming a slip face slope of 1.5:1 (run/rise, section 3.7.1).

Snowdrift profiles generated in this way agree with a wide range of profiles from the plains and mountains of Colorado and Wyoming.

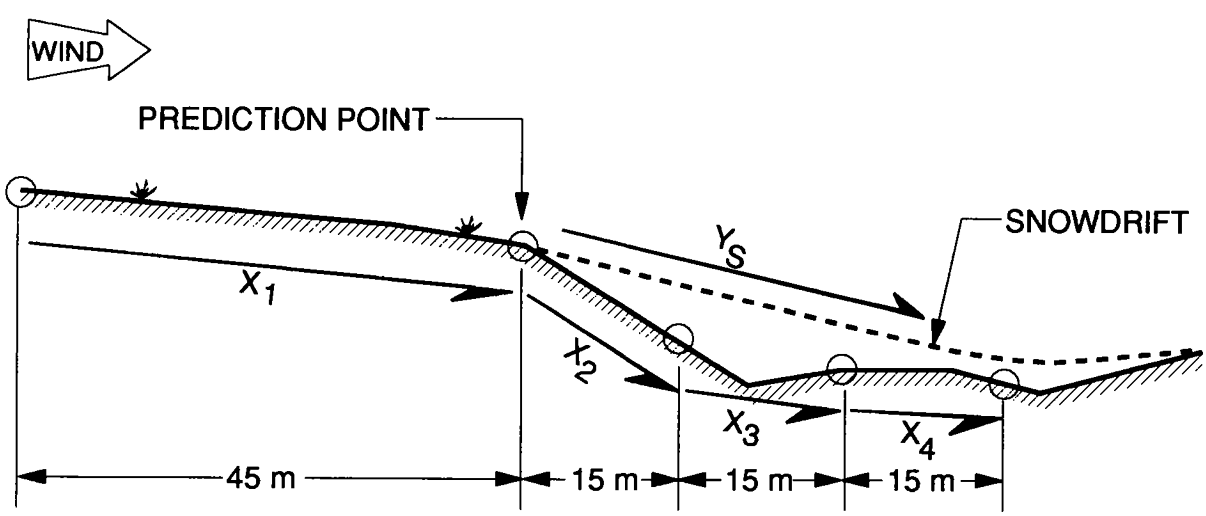

Figure 7.1. Illustration of slopes and distances used in Equation (7.1).

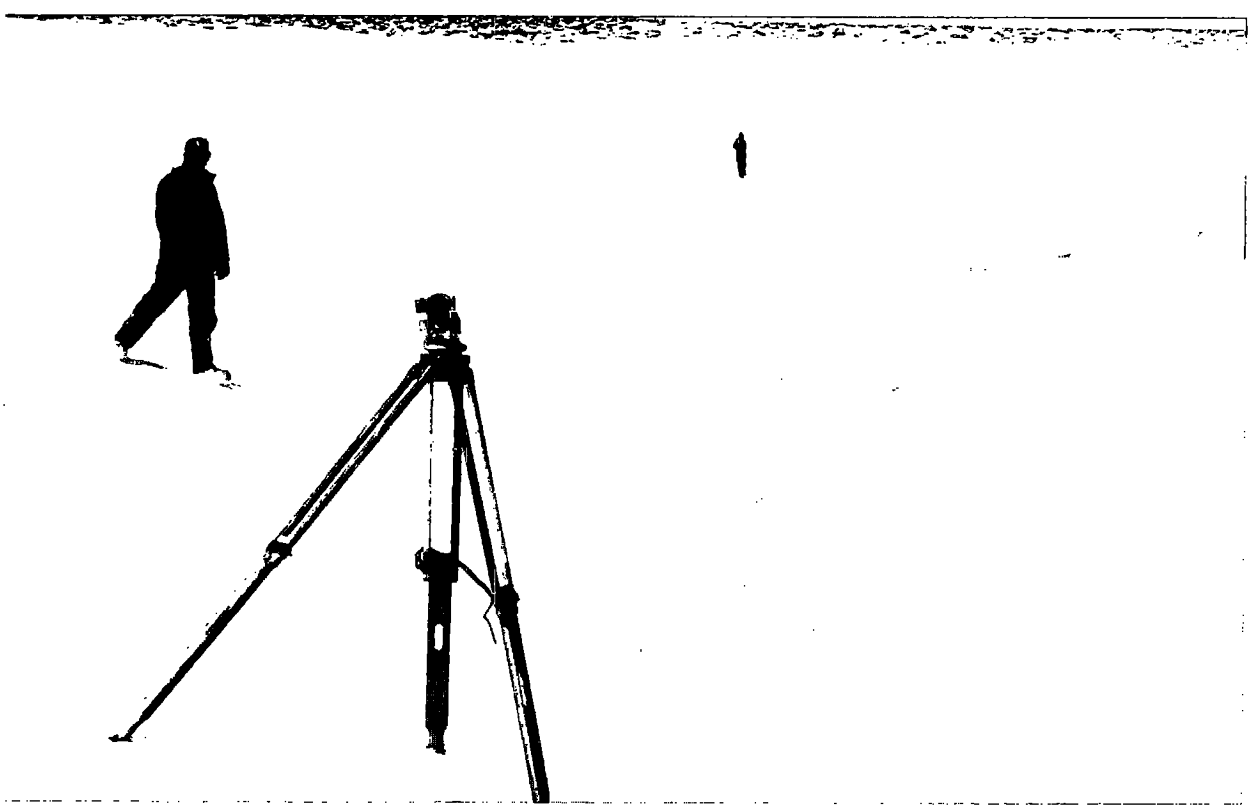

Figure 7.2. One of the larger topographic accumulation areas used to derive Equation (7.1). This site is at 2450 m (8,038 ft) elevation in south-central Wyoming.

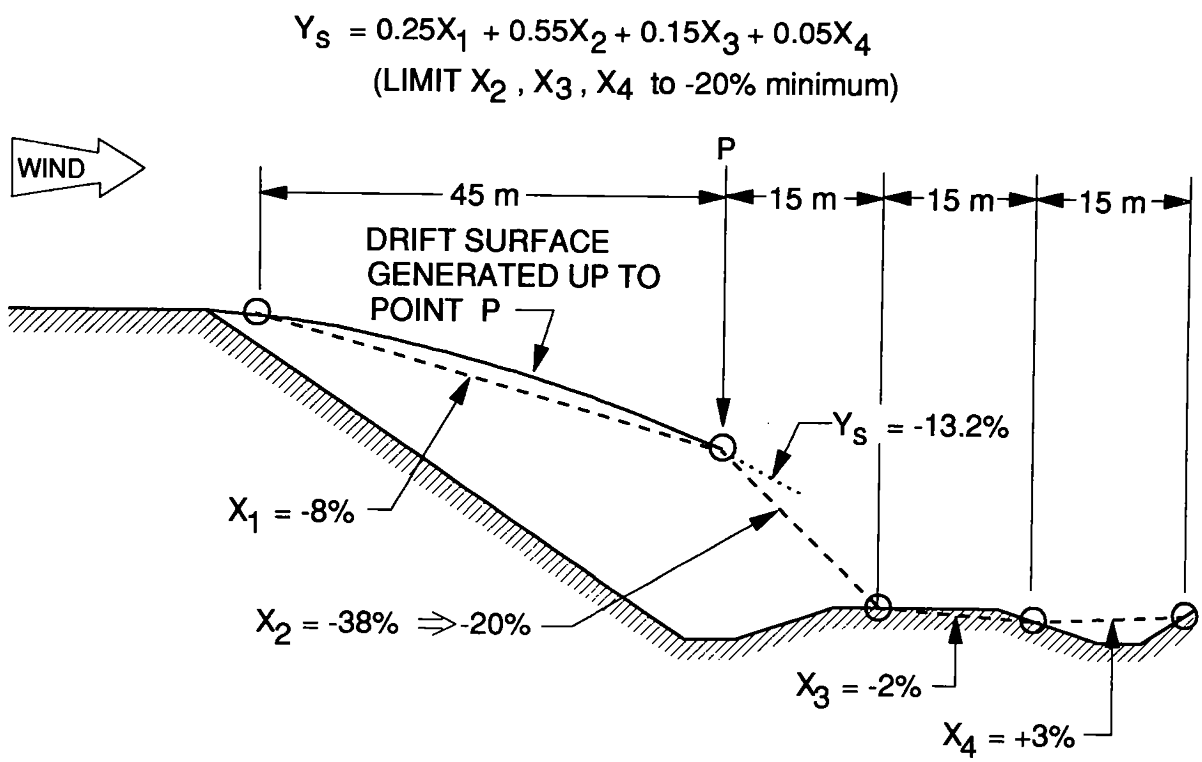

Figure 7.3. Example of distances and slopes used in Equation (7.1) to estimate the slope of the next snow profile increment.

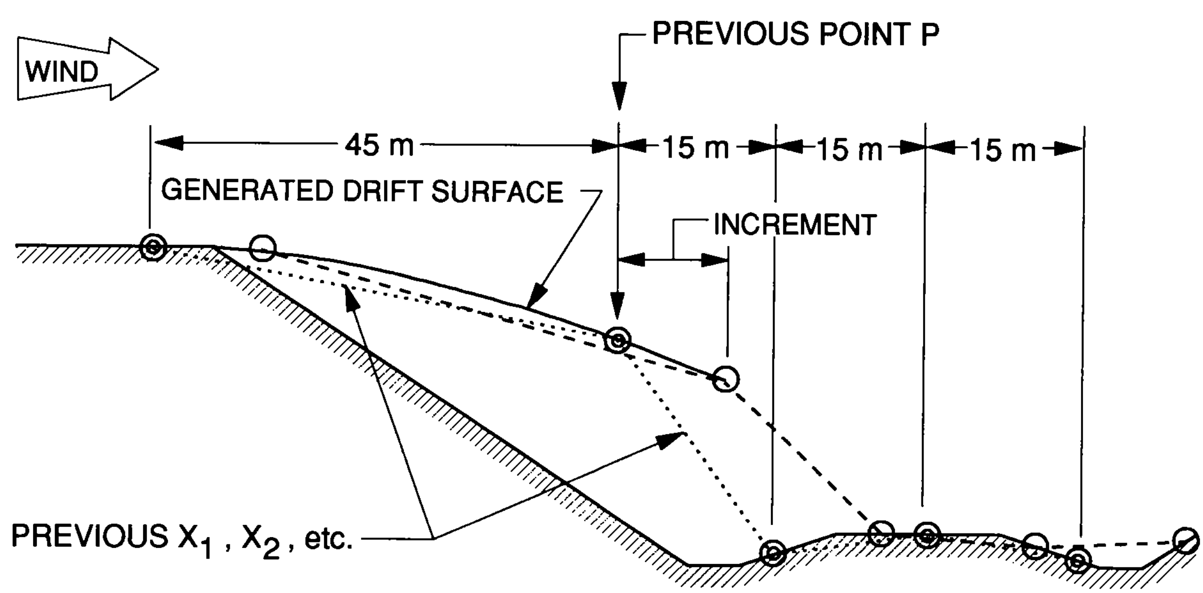

Figure 7.4. Illustration of how Equation (7.1) is used to generate a snowdrift profile.

7.6.2 *Required Data*

The ground profile (distance and elevation) must be known for at least 45 m (150 ft) upwind of the windward end of the snowdrift, and extend 45 m (150 ft) beyond the downwind shoulder of the road (Figure 7.5). The profile data upwind of the road cross-section are critical for accurate prediction. The ground profile should be aligned parallel to the prevailing transport direction, if known (section 4.7.3). Otherwise, it should be oriented perpendicular to the road to provide a "worst case" prediction.

Ground profile data should be obtained at all locations where changes in terrain slopes are evident to the surveyor, and should include measurements and notation coinciding with locations at the right-of-way, edge of pavement, and edge of travel lanes.

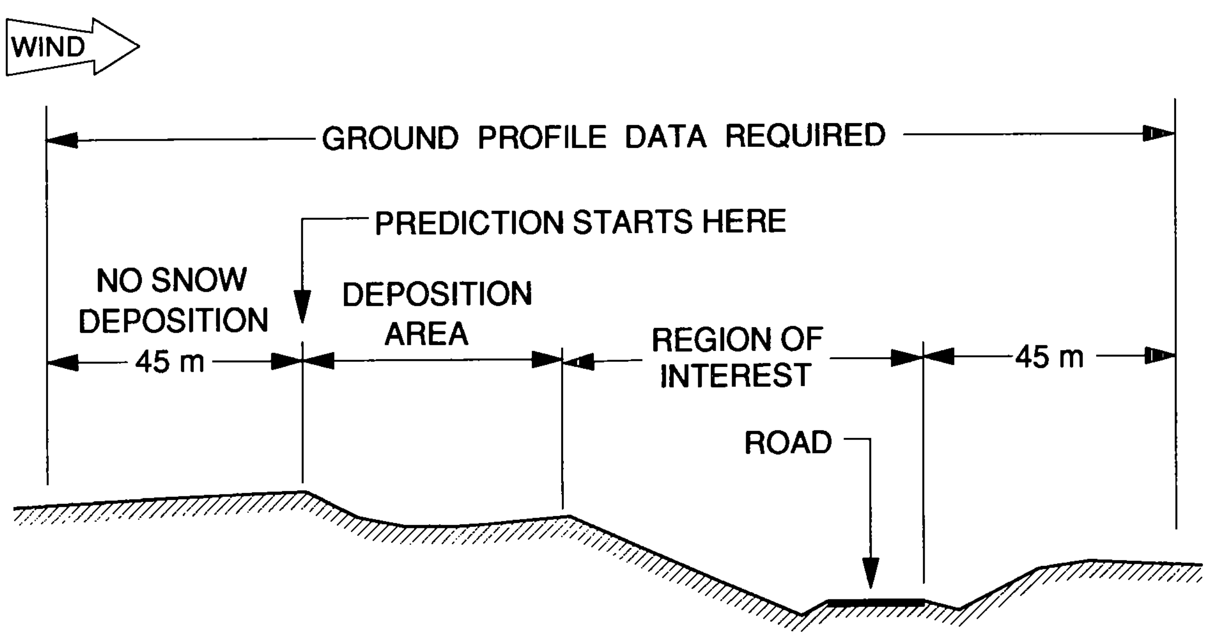

Figure 7.5. Ground profile data required to estimate the snowdrift profile in the region of interest.

7.6.3 Limitations and Applications

The following limitations apply to Equation (7.1) and to its use to generate snowdrift profiles:

- Most of the data used for the development of the equation were from gentle to moderately rolling terrain. The greater turbulence expected in rugged, mountainous country could cause slopes steeper than predicted, although experience to date has not indicated this.

- Future research or experience might indicate that the prediction accuracy could be improved by revising the coefficients, or mathematical model, proposed here.

- The equation is applicable only to two-dimensional terrain features.

The snowdrift prediction model described here can be included as a subroutine in the earthwork computer program to yield drift-free designs automatically based on rules provided by the designer, such as those presented in section 7.8. The model can also be used in spreadsheet programs for personal computers, as was used to develop the quantitative guidelines for road design described in section 7.8.

7.7 Guidelines for Route Location and Alignment

Many problems arising from blowing snow could be prevented or at least minimized by considering environmental factors in route location.

7.7.1 Procedure

The following procedure is recommended for route location in areas subject to blowing snow:

1. Identify preferable location(s) using the usual criteria.

2. Obtain wintertime aerial photos using criteria described in section 4.6.2.

3. Conduct *wintertime* field reconnaissance to determine suitability of proposed locations and to identify potential problem locations.

4. Determine the mean annual snow transport and prevailing direction at the potential problem locations, as described in chapter 4.

5. Revise route where possible to avoid problem areas or reduce severity.

6. To provide basis for final route selection, determine mitigation measures required for alternative locations.

7.7.2 *Guidelines for Route Location*

There are numerous opportunities to reduce drifting problems with careful route location, but few design engineers have the experience to recognize them. The following guidelines for location and horizontal alignment will reduce winter maintenance costs and improve public safety.

- Avoid locations where snowdrifts form naturally, and take advantage of natural shelter such as trees, shrubs, or terrain (Figure 7.6)
- Select locations that have the least snow transport by considering the fetch, winter snowfall, and wind exposure. Features such as stream channels, wooded areas, and buildings can significantly reduce blowing snow even though they may be several kilometers away. Where possible, select locations in the snow erosion zone, 150 to 200 m (500 to 660 ft) downwind from a deposition area.
- Avoid locations downwind of frozen lakes or other bodies of water that ice over during the winter.
- Avoid long, straight sections (tangents) parallel to wind, especially through wooded areas (Figure 7.7).
- Plan alignment of roads at grade separations to allow placement of fences or living barriers (Figure 7.8).
- Enter wooded areas in locations sheltered from the prevailing transport direction (Figure 7.9).
- Use wide curves to reduce super-elevation when center of curvature is on downwind side of road.
- Minimize grades in the vicinity of interchanges, intersections, and grade separations, to allow maximum plowing speeds and to reduce "stopping sight distance" on ice- or snow-covered roads.
- Avoid locations requiring safety barrier in exposed locations. Plan for future lane expansion to avoid concrete safety barrier between lanes.
- Select sheltered locations for interchanges, intersections, and grade separations.
- In areas exposed to blowing snow, avoid shallow cuts (< 2.5 m/8 ft).
- Where exposure to blowing snow is unavoidable, select sites where snow fences or other drift control measures can be installed upwind. Downwind of frozen lakes, provide adequate space between the shoreline and the road to allow placement of fences that are the proper height, H_{req} (section 5.3.2).

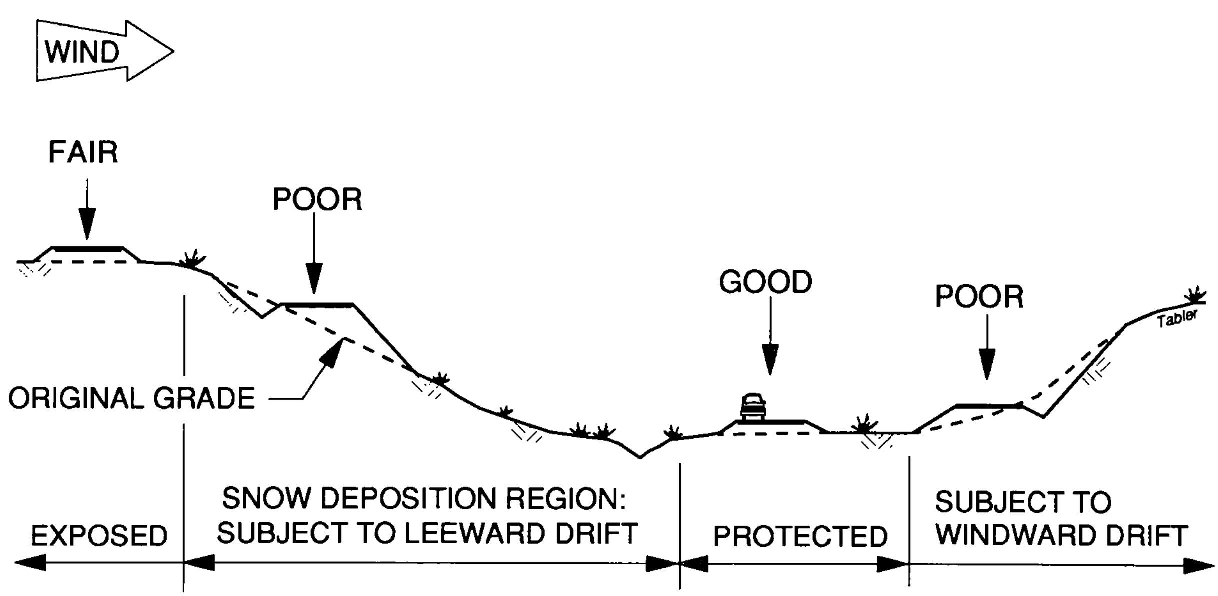

Figure 7.6. Guidelines for locating roads in irregular terrain to minimize blowing snow problems (Tabler 1993).

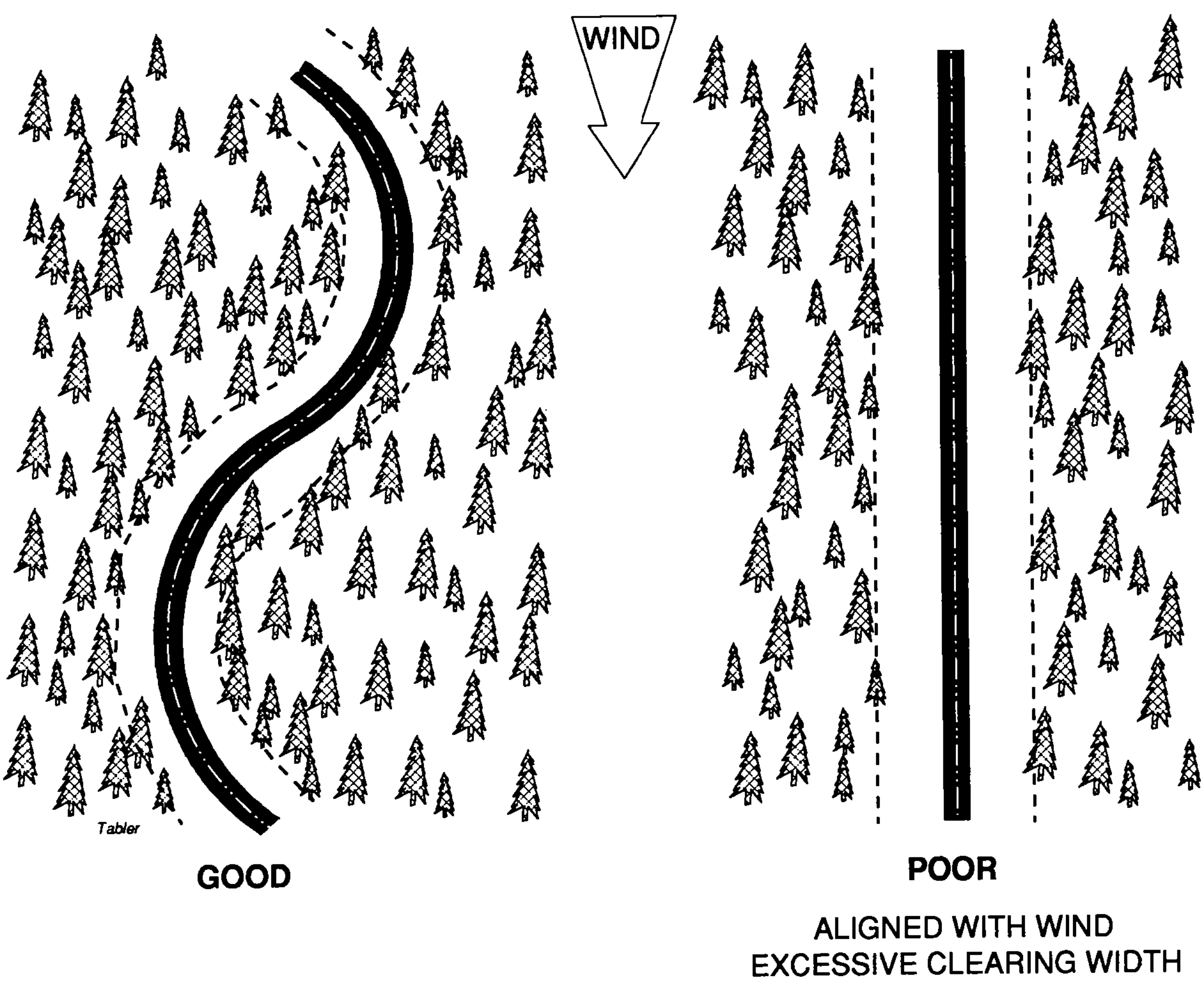

Figure 7.7. Road alignment and clearing width in wooded areas should minimize exposure to wind (Tabler 1993).

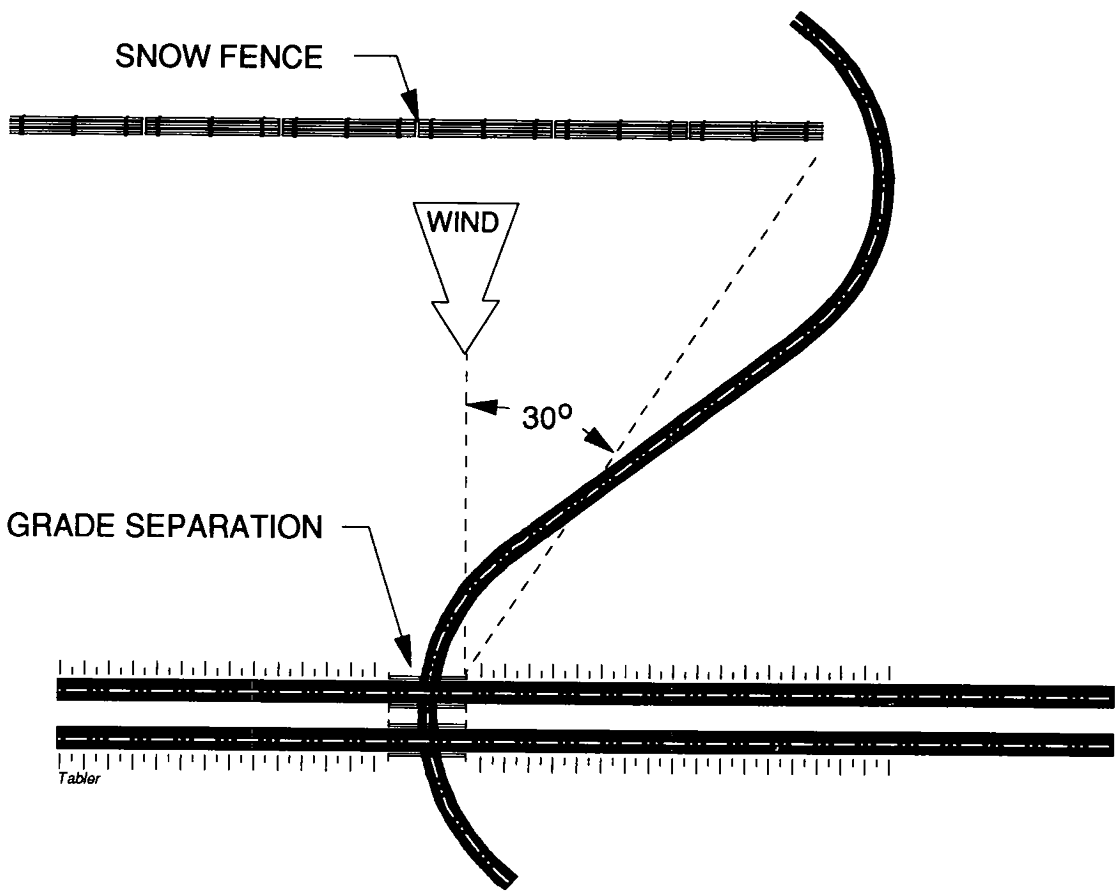

Figure 7.8. Roads passing under a grade separation should be designed to allow protective measures to be installed upwind.

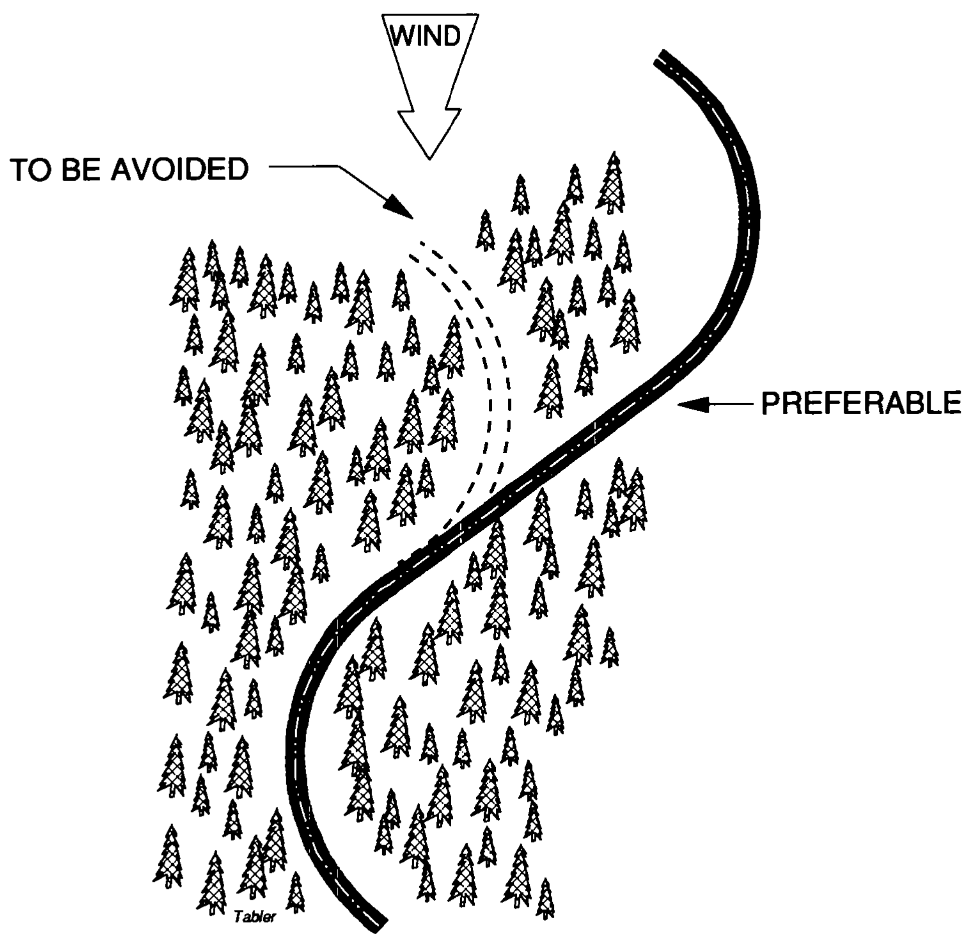

Figure 7.9. Transitions from wooded to open areas should be located to minimize exposure to blowing snow.

7.8 Guidelines for Cross-Sections

To the extent practicable, the guidelines proposed here are consistent with recommendations in the *Roadside Design Guide* (AASHTO, 1989). However, the designer is responsible for assuring conformance with all applicable standards and regulations. These guidelines presuppose sound engineering judgement and a thorough evaluation of potential blowing snow problems, as described in chapter 4.

7.8.1 Embankments (Fill Sections)

7.8.1.1 Minimum Height Above Grade

Snow blowing off roadside snow accumulations at windshield level can create a serious safety hazard (Figure 7.10). Visibility is seriously impaired by the high concentration of blowing snow particles, and snow accumulates rapidly on the road.

To prevent these problems, the road surface should be higher than the surrounding snow surface to allow the wind to blow snow off the surface of the road. The grade-line elevation must also be sufficient so that the accumulation of plowed snow does not extend above the shoulder. If snow is removed with motor graders or other low-speed displacement plows, however, the build-up of a snow berm alongside the road is unavoidable.

The minimum height of the road surface above the surrounding terrain, H_e, is given by

$$H_e = 0.4S + 0.6 \qquad (7.3)$$

where S is mean annual snowfall (m), and H_e is in meters (Figure 7.11).

These heights should be increased where necessary to elevate the road surface above a snowdrift. The 4:1 slope is preferable to flatter ones in this case to help keep the plowed snow below the shoulder. The tendency for flow separation at the top of the embankment is not as great as for high embankments because snow deposition at the toe reduces the effective slope.

The coefficient (0.4) in Equation (7.3) adjusts snowfall for density after settlement to 250 kg/m^3 (15.6 lb/ft^3), and is therefore a quantification of Finney's (1939) recommendation that the grade-line be maintained above the average snow depth. The equation assumes that snowfall accumulates over the winter without melt losses, and is therefore conservative for most climates. The constant (0.6 m) is the required height of the embankment above the snowcover required to expose the road surface to the wind, and allows for plowed snow accumulation below the shoulder.

Saarelainen and Kivikoski (1990) report that favorable results were obtained in northern Finland with the road surface 0.5 m (1.6 ft) above the highest snow profile occurring once in 10 years. The exceedance probabilities presented in Table 4.6 could be used to estimate the snowfall depth for a particular return period.

Example:

Given: S = 200 cm (79 in.) = 2.0 m

Required: 1) Required minimum height of road surface
2) Required minimum height using 10-year snowfall

Solution: 1) Equation (7.3): $H_e = 0.4(2.0) + 0.6 = 1.4$ m (4.6 ft)
2) From Table 4.6: $K = 1.38$ for 0.10 exceedance probability
Therefore, $H_e = (0.4)(1.38)(2) + 0.6 = 1.7$ m (5.6 ft)

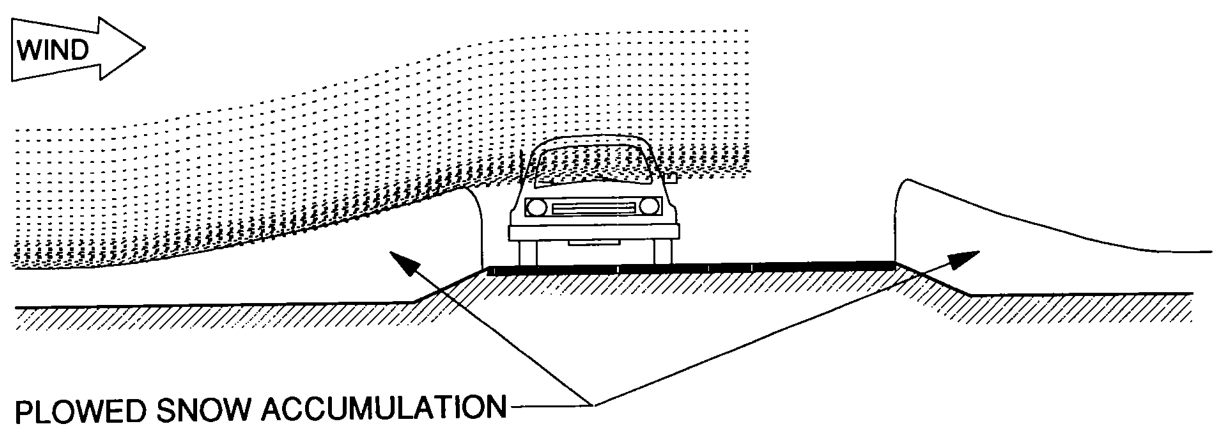

Figure 7.10. Snow accumulations alongside roads cause poor visibility by increasing particle concentration at windshield level.

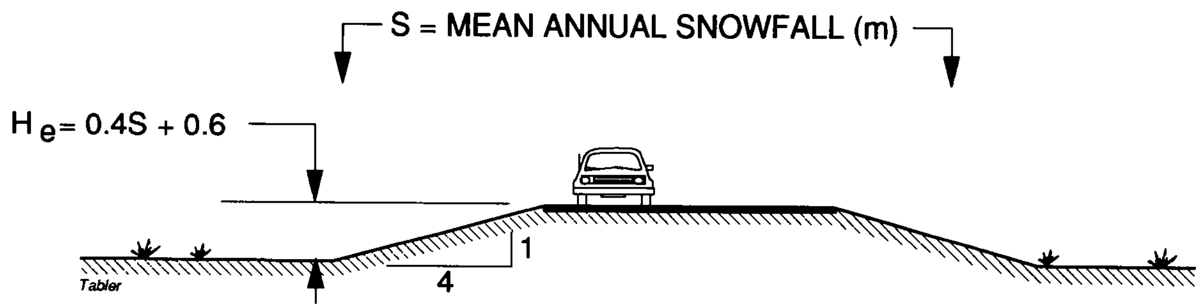

Figure 7.11. Guidelines for minimum height above grade (Equation 7.3).

7.8.1.2 Fill Sections with Height > 2 m (6.6 ft)

As the wind passes over the crest of an embankment, an eddy area forms at the windward edge if the slope changes so rapidly that the wind cannot follow the curvature (Figure 7.12). As a result, snow tends to be deposited at the top of embankments, and this tendency increases with the steepness of the sideslope, and the height of the embankment (Figure 7.13). A major deposition problem can result if safety barrier is present, and serious visibility problems can also occur if the traveled way is close to the slope break. This is because the high concentration of snow particles being transported near the surface on the embankment slope become entrained in the turbulent flow in the "eddy region," and can reach heights where they obstruct visibility.

The height of the upper boundary of the eddy region (Figure 7.13) increases as the logarithm of distance from the slope break, and exhibits a curvature similar to the nose of a snowdrift behind a fence (section 3.8.5.2). The eddy areas for the various slopes in Figure 7.13 show this function drawn to scale, with the logarithmic curve displaced to windward so that its curvature is tangent to the embankment slope. Field observations have shown that embankment slopes must be about 9:1 (11%) to eliminate deposition on the crest. The mathematical model of the separation boundary (Figure 7.13) shows the eddy area is essentially eliminated — in other words, the wind can adjust to this slope change without flow separation. Vegetation and plowed snow accumulations also affect snow deposition at the top of a fill section embankment, however, and the 9:1 slope itself may therefore not be optimum from a practical standpoint.

Safety barrier at the top of an embankment will cause snow to be deposited regardless of the geometry of the section. Thus, the most important objective of design should be to eliminate the need for safety barrier. The recommended treatment for a straight road section with parallel side slopes, consists of a "barn-roof" cross-section (Figure 7.14) designed to eliminate barrier requirements and reduce snow deposition on the traveled way. The widths of the various slope segments meet clear-zone requirements for most traffic volumes and design speeds. The segment having a 3:1 slope serves to round the shoulder for the case of embankment slopes 2:1 or steeper. The paved shoulder allows snow removal by truck-mounted plows — keeping the shoulder plowed provides a buffer against snow encroachment on the traveled way, thereby allowing more time between duty cycles.

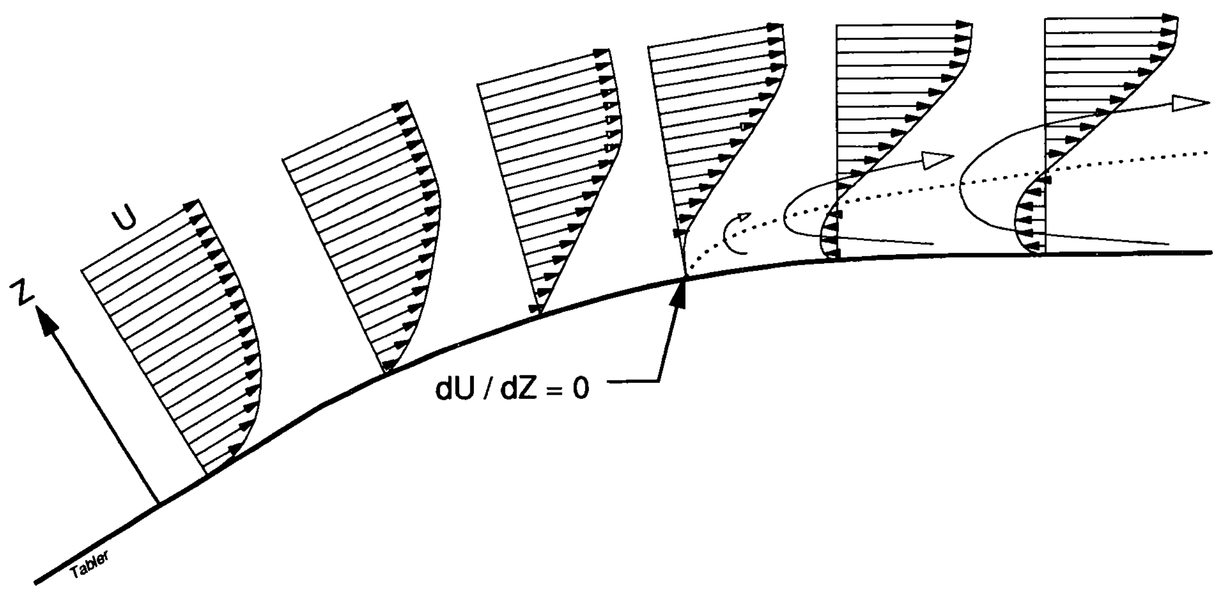

Figure 7.12. "Separation" of airflow at the top of an embankment causes the "eddy areas" where blowing snow is deposited. *dU/dZ* is the vertical velocity gradient.

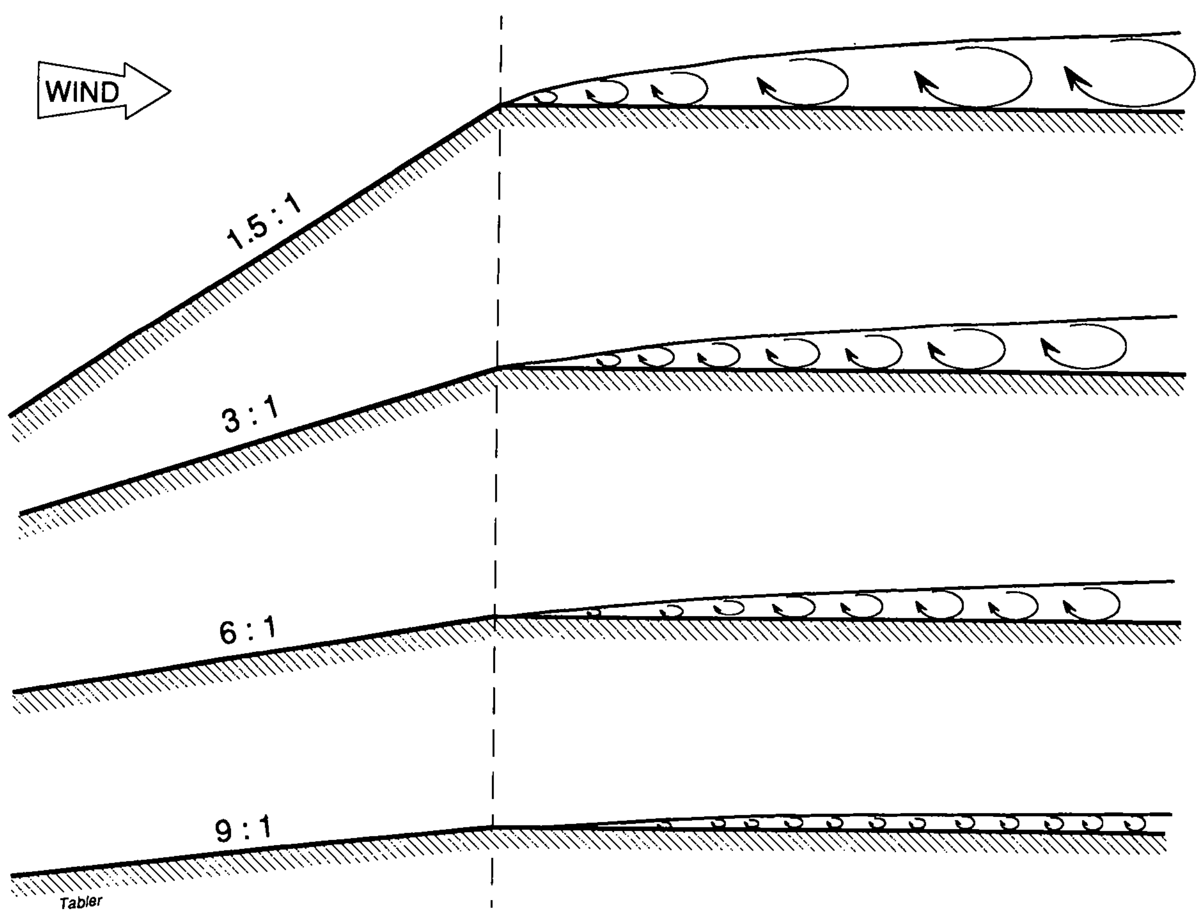

Figure 7.13. The tendency for snow to be deposited on the top of an embankment is proportional to the height of the eddy area, shown here as a function of embankment slope.

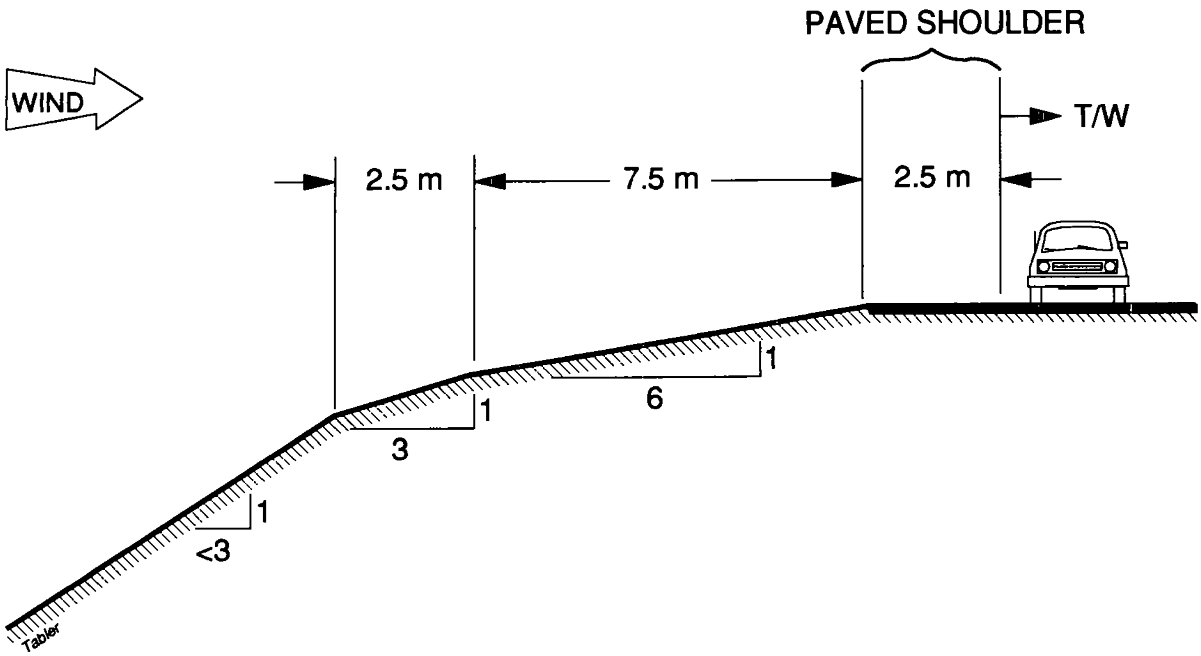

Figure 7.14. Suggested barn-roof section for high fill embankments.

7.8.2 Cut Sections

7.8.2.1 Types of Snowdrifts Forming in Cut Sections

Snowdrifts tend to form in road cuts regardless of wind direction. Although the downwind drift is common knowledge, design engineers are often unaware that drifts also form in cuts on the upwind side of hills (Figure 7.15). These upwind drifts are not as deep as those in downwind cuts, but can be just as troublesome. As a result, ditch width and backslope on the downwind side of the road can be as important as on the upwind side. The slope of the terrain upwind of the cut can have a significant effect on the length and volume of a leeward drift (Figure 7.16), but this effect decreases as cut depth increases.

Although rules for slope treatments to prevent downwind drifts have long been available, the upwind drift has generally been ignored. One of the advantages of the snowdrift prediction model described in section 7.6.1 is its ability to predict upwind drifts with reasonable accuracy. When used to redesign the section shown in Figure 7.17, the model showed that the downwind ditch had to be widened to eliminate snow accumulation on the road. The redesigned section has remained free of drifts.

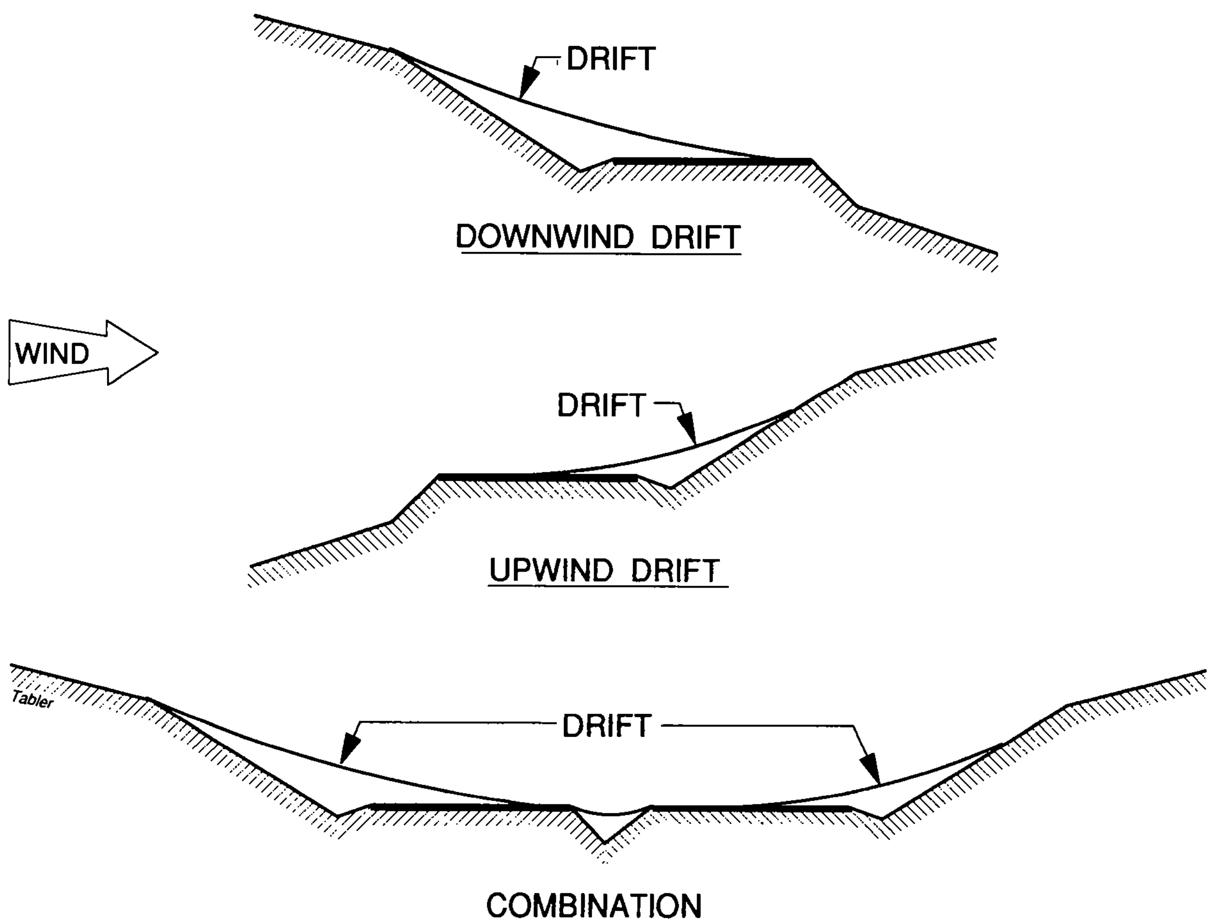

Figure 7.15. Types of drifts that form in cut sections.

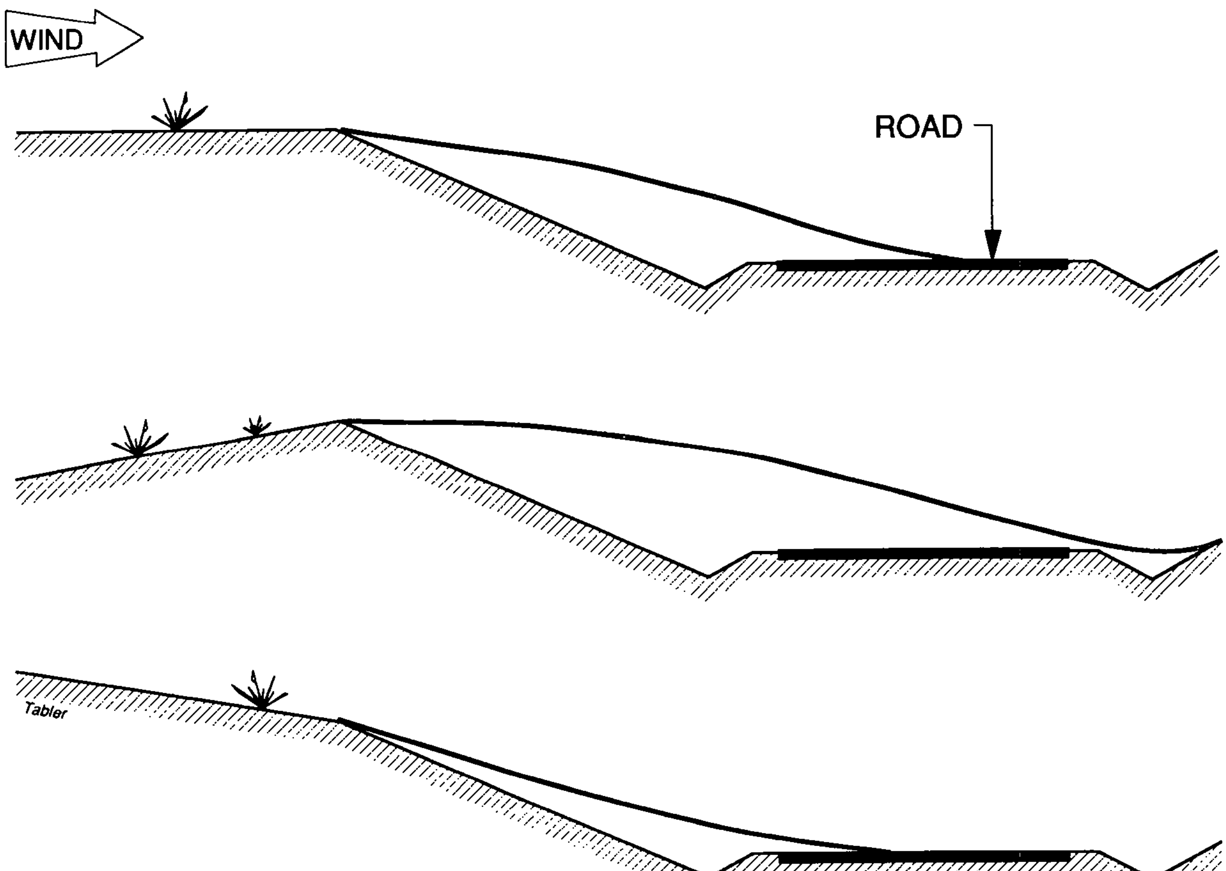

Figure 7.16. How the upwind terrain affects the profile of snowdrifts in cuts.

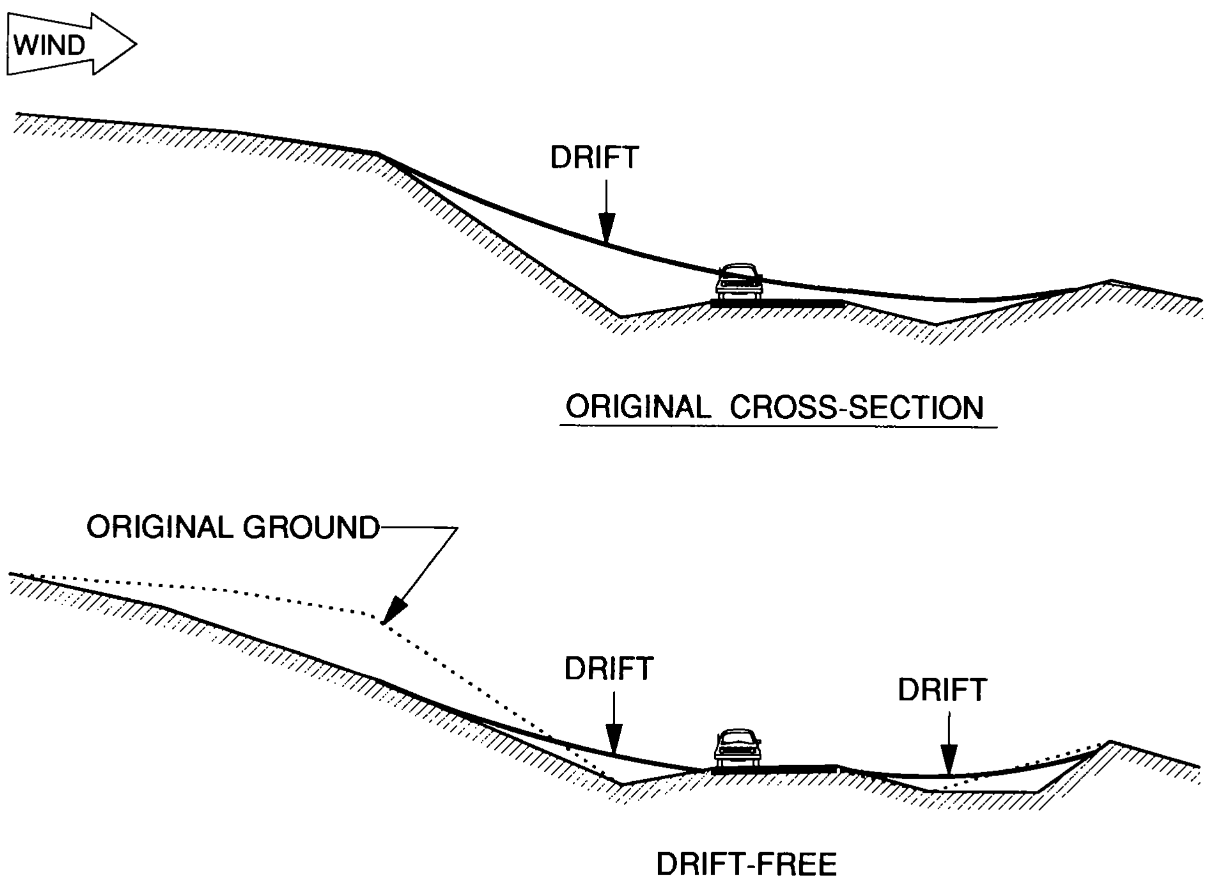

Figure 7.17. This successful cross-section modification, designed using the snowdrift prediction model, illustrates how geometry on the downwind side of centerline must sometimes be modified to eliminate the drifting problem (Tabler 1975).

7.8.2.2 Basis for Recommended Guidelines

The following rationale was used to develop the guidelines presented here:

1. Theory, reduced-scale models, mathematical models, and experience, all support the generalization that the distance from shoulder to the top of cut is the single most important geometric parameter that determines the snowdrift depth on the road. By comparison, the effects of back slope, ditch width and ditch depth are relatively subtle.

2. The back slope should be steep enough to promote deposition. This allows the wind to form its own equilibrium profile, which presumably varies with surrounding vegetation, wind speed, and other factors. As illustrated in Figure 7.18, this constraint is important because it allows the snow surface to intersect the road embankment *below* the point of intersection of the side-slope and road surface (PI). Designing to *eliminate* a drift on the backslope assures that the snow surface will intersect *at* the shoulder. In other words, "laying back" slopes to eliminate snow deposition on the backslope results in the same problem as fill sections that are not elevated sufficiently above the surrounding terrain. Finally, storing some snow in the cut reduces the blowing snow crossing the traveled way, improving visibility and road surface conditions.

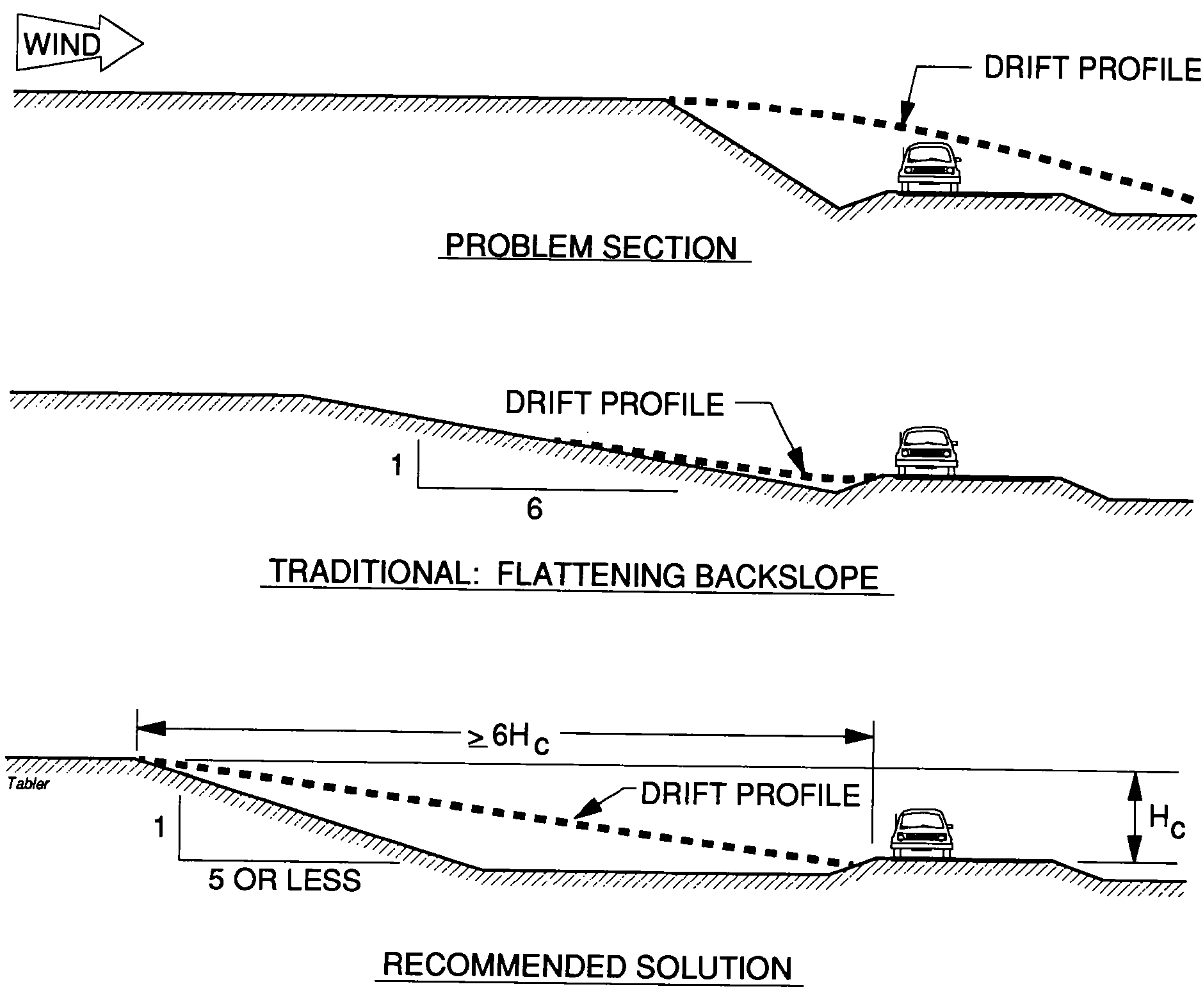

Figure 7.18. Comparison of the traditional and recommended strategies for designing cuts to prevent snowdrift encroachment.

3. The back slope should be flat enough to be easily vegetated for erosion stability, and should not require excessive excavation or right-of-way.

4. The slope from the shoulder point-of-intersection (PI) to the top of the cut should not be steeper than 6:1. Although this rule is similar to Finney's 1939 recommendation, the slopes proposed here vary with cut depth, and are much flatter than 6:1 for shallow cuts. The necessity for this is based on the observation that the 6:1 rule does not eliminate drifts in shallow cuts.

5. Wide ditches:

   - prevent drifts from reducing sight distances on curves;
   - facilitate snow removal operations by providing space for storing snow after heavy snow storms;
   - allow space for falling snow cornices and, in the case of steep rock cuts, snow sloughed off backslopes;
   - allow the equilibrium snow slope to tail out on the front slope below the PI;
   - meet clear zone requirements as specified in the *Roadside Design Guide* (AASHTO, 1989).

6. The minimum ditch width should meet clear zone requirements for all traffic volumes and design speeds, as specified in the *Roadside Design Guide*.

7. Ditch depth is important for drainage, exposes the road surface to the wind, and provides storage for plowed snow below the shoulder. A depth of 1.2 m (4 ft) below the road surface was used for all of the guidelines developed here.

8. Because most of the cast from displacement plows is deposited within 3 m (10 ft) from the edge of the plowed lane, front slopes should be as steep as possible to allow plowed snow to accumulate below the shoulder. However, front slopes must also meet the requirements for recoverability, as described in the *Roadside Design Guide* (AASHTO 1989), and slopes steeper than 3:1 impede off-road snow removal. The compromise proposed here is 4:1.

With the above constraints and considerations, the snowdrift prediction model (section 7.6) was used to determine the minimum distance from shoulder PI to the top of the cut, required to give a zero snow depth at the PI for cut depths ranging from 0.3 to 20 m (1 to 66 ft). Different back slopes and ditch widths were tested to determine if a particular combination significantly reduced excavation volume or section width. The results indicated that the required distance to top of cut was linearly related to cut depth over the range of heights of interest. The resulting equations were tested for inconsistencies with theoretical considerations, Finney's 1939 recommendations, and the author's experience.

These determinations were run separately for both upwind and downwind sidehill cuts, and for the combination of these in through-cuts (Figure 7.15).

7.8.2.3 Guidelines for Sidehill Cuts (Not Rock)

The primary design requirement is that the distance, W_{top}, from the shoulder to the top of cut, be

$$W_{top} = 29 + 5.8H_c(\sin \alpha) \tag{7.4}$$

where H_c is depth of the cut measured from the road surface, α is the attack angle of the wind (the angle between the road centerline and the prevailing transport direction), and all variables are in meters. This equation assumes a 1.2 m (4 ft) embankment height and 4:1 front slope, as specified in section 7.8.2.2. Any back slope steeper than 5:1 is satisfactory, but snow storage increases as the slope becomes steeper. Snow storage capacities for a 4:1 backslope are shown for different cut depths in Figure 7.21.

These guidelines apply to horizontal terrain upwind of leeward cuts, so that design will be conservative if the terrain slopes downward toward the cut. When the terrain is sloping upward toward the cut (Figure 7.20), the recommended procedure is to excavate a nearly horizontal surface extending for at least 15 m (50 ft) upwind of the top of the backslope.

Other recommendations and conclusions include:

- The 4:1 front slope is flat enough to meet safety requirements and to allow snow removal by off-road equipment, while being sufficiently steep to help keep the plowed snow accumulation below shoulder level.

- Minimum ditch depth should be 1.2 m (4 ft).

- A 14-m (46-ft) minimum distance from shoulder to toe of back slope meets requirements for clear-zone widths in most cases.

- The trapezoidal ditch cross-sections illustrated here would have to be designed for proper drainage, and could be replaced with broad U- or V-shaped sections if desirable.

- If W_{top} is measured from the upwind end of excavation, rounding the top of the cut, as proposed by Finney (1939), does not significantly reduce the required width or excavation volume.

- Earthwork volumes can be reduced by using terraced cuts designed so that the outer edge of each terrace falls within the cross-section defined by Equation (7.4), as shown in Figure 7.22.

It is not always practical or possible to design roads to ensure that drifts do not form on them. Snowdrift prevention through road design is most cost-effective for shallow cuts, but even these should be avoided by route location or vertical alignment where possible.

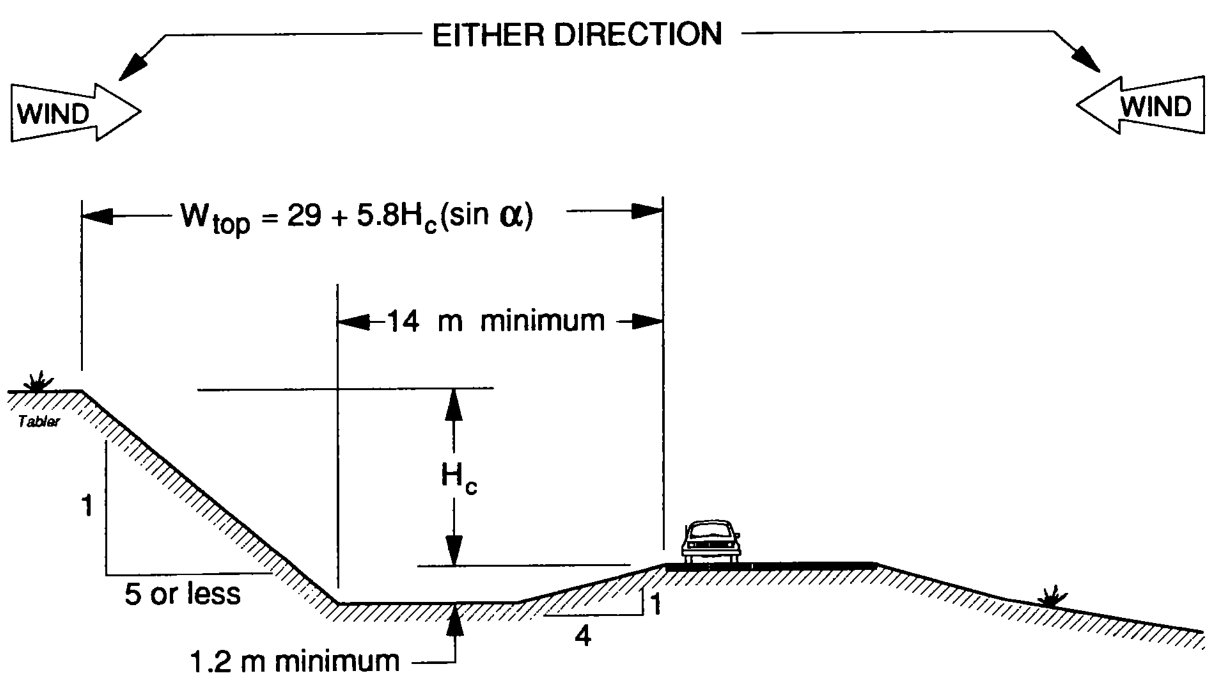

Figure 7.19. Proposed section for cuts to prevent drift encroachment where upwind terrain is flat or slopes downward toward the road (Tabler 1993).

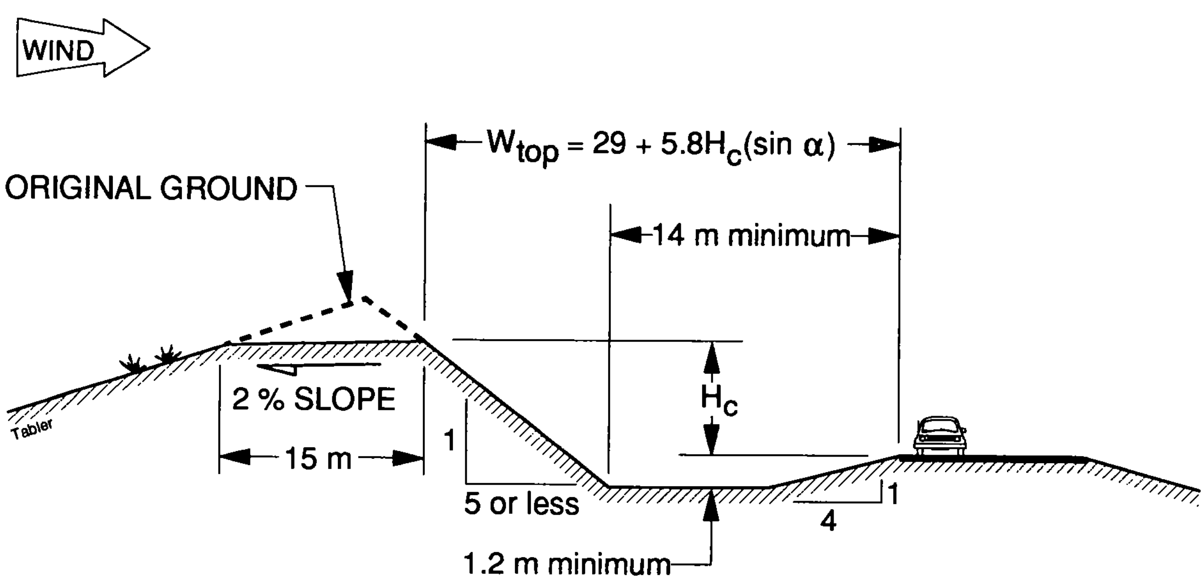

Figure 7.20. Proposed section for cuts where approaching terrain slopes upward toward the road.

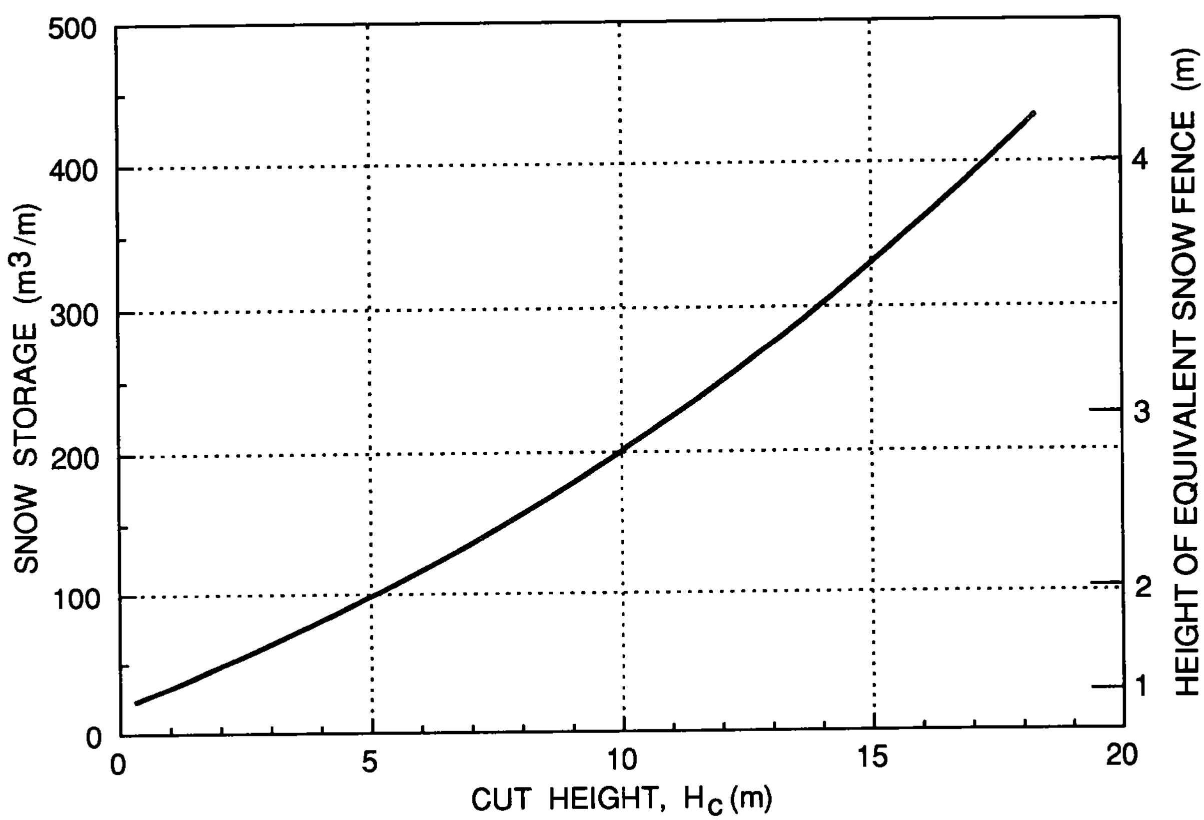

Figure 7.21. Snow storage versus cut height for 4:1 backslopes, using cross-section in Figure 7.19.

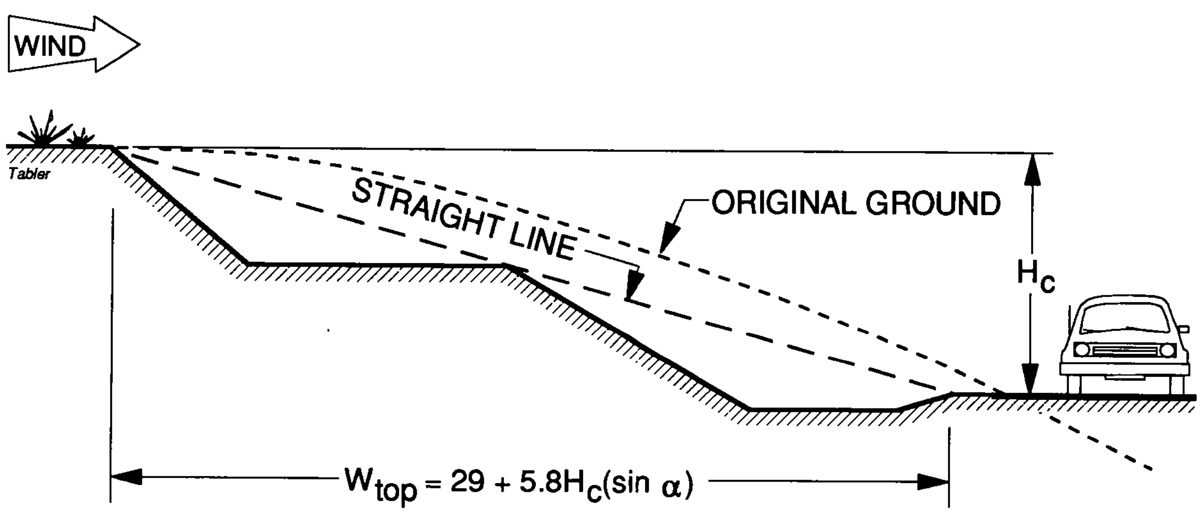

Figure 7.22. Terraced cuts reduce excavation, but store less snow.

7.8.2.4 Guidelines for Sidehill Cuts in Rock

The guidelines presented in the previous section must be altered for rock cuts because of the high costs for excavation. The proposed minimum section, as shown in Figure 7.23, is suitable for mountainous terrain with deep snowfall, and is applicable regardless of wind direction. The principal features of this design are:

- The minimum ditch width of 3.7 m (12 ft) provides space to contain snow sliding off backslopes, and to store snow removed from the inside lane, over the course of a storm lasting several days. This minimum width may not be wide enough to meet requirements for rockfall containment, however, depending on rock characteristics and height of the cut and back slope.

- The 2.5-m (8-ft)-wide paved auxiliary lane on the inside of the cut allows more efficient use of truck-mounted displacement plows, and serves four important functions:

  * provides extra width to allow highway users to pass snow removal equipment and slower traffic,

  * allows high-speed plows to remove snow from the shoulder (keeping the shoulder plowed provides a buffer against snow encroachment on the traveled way, thereby allowing more time between snow removal duty cycles),

  * displaces snow berm farther away from traveled way, which reduces the tendency for snow blowing down road to accumulate on travel lanes,

  * provides better rockfall protection.

- The 2.5-m (8-ft) paved shoulder on the outside serves the same purposes as the snow lane on the inside, and also provides the required shy-line offset for a 97-km/h (60-mi/h) design speed, as specified in the *Roadside Design Guide* (AASHTO 1989) (the shy line offset is the minimum distance from the edge of the traveled way that an object will not be perceived as hazardous by a driver). The paved shoulder also allows high-speed plows to work close to the safety barrier.

- The 6:1 front slope allows off-road equipment, such as front-end loaders and graders, to remove snow from the ditch during clean-up operations between storms.

- The safety barrier should be placed as far from the driving lane as barrier type and topographic conditions permit. Placement near the slope breakpoint minimizes the buildup of plowed snow outside of the barrier.

The minimum section recommended here can have significant economic benefits. A study on the Klondike Highway in southeast Alaska showed winter maintenance expenditures to be about 50% less on sections of highway where the width from centerline to toe of backslope was 10 m (33 ft) or more, than where this width was 7.3 m (24 ft) (Tabler and Cavagnaro 1993).

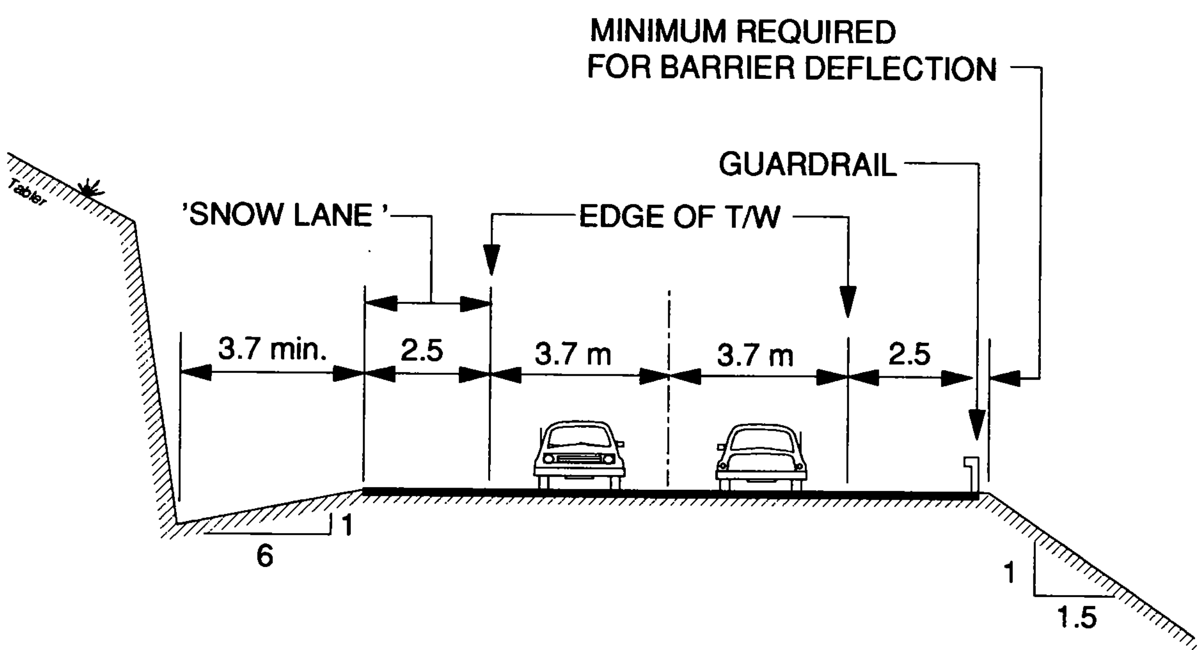

Figure 7.23. Proposed section for rock cuts to facilitate snow removal operations (Tabler and Cavagnero 1993).

7.8.2.5 Guidelines for Cut Slopes on Both Sides of Road

The criteria developed for sidehill cuts also apply to through-cuts, with required widths calculated using the cut heights shown in Figure 7.24.

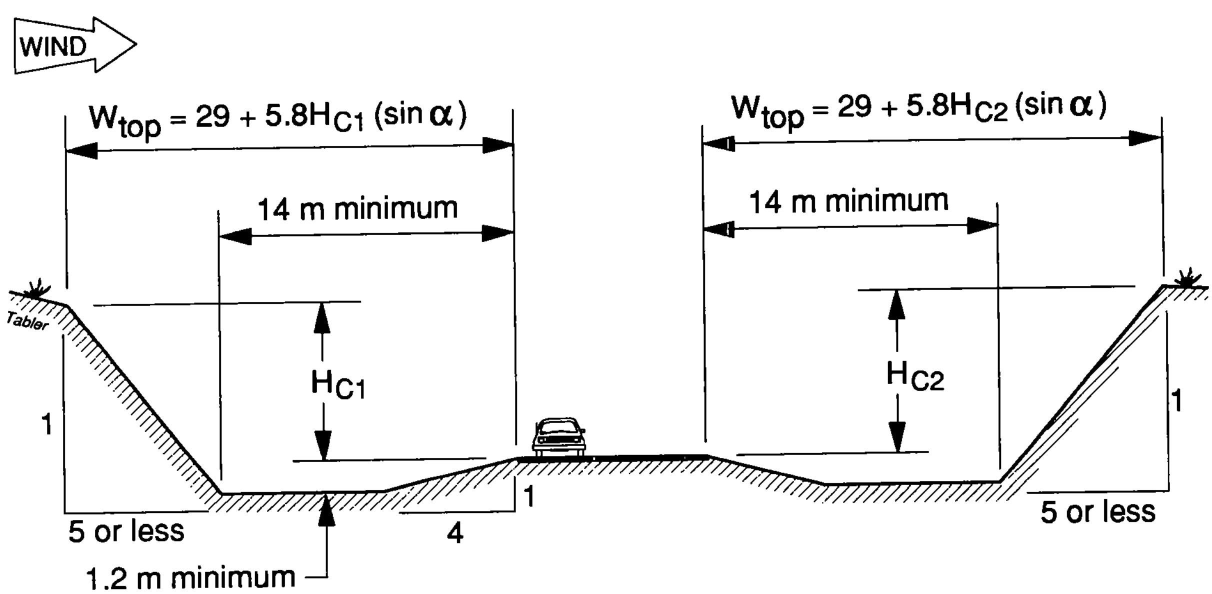

Figure 7.24. Proposed section for cuts on both sides of road.

7.8.3 Super-elevated Curves

The tendency for snow deposition on a road is significantly increased when the super-elevated shoulder is on the upwind side. This tendency arises from the combination of the windward front slope and the drop in elevation across the road surface, and can create serious deposition problems when a sidehill cut is on the inside of the curve (Figure 7.25). The guidelines for avoiding this problem are as follows:

- avoid curves in sidehill cuts facing upwind where the cut is on the inside of the curve;
- use curves with a low degree of curvature;
- use spiral transitions to achieve the flattest curve possible;
- use flat front slopes on the upwind side of curves when the center of curvature is on the downwind side. The optimum slope is given by:

$$\text{Steepest front slope gradient} = 0.18 + \text{Road surface gradient} \tag{7.5}$$

  where gradients upward toward the center of curvature are positive, and downward gradients are negative.

Example:

Given: Super-elevation = - 0.06 m/m (-0.06 ft/ft)

Required: Steepest front slope to minimize snow accumulation

Solution: Equation (7.5): Steepest front slope = 0.18 + (-0.06) = 0.12 m/m = 8:1.

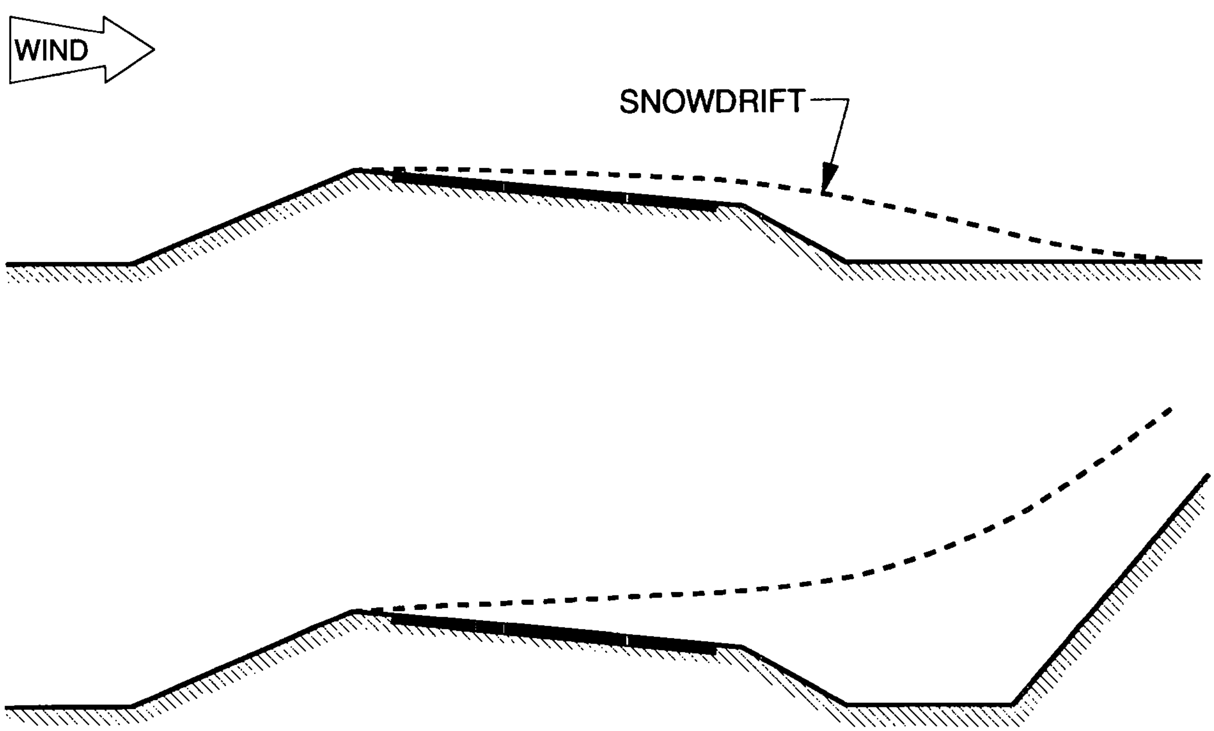

Figure 7.25. Effect of super-elevation on snow deposition, and interaction with downwind geometry.

7.8.4 Divided Highways

When opposing lanes of divided highways are close to one another, the downwind lane should be at the same elevation, or slightly higher, than the upwind lane. As the median width, *W*, increases, the downwind lane can be as much as $0.04W$ below the upwind lane without drift encroachment (Figure 7.26). This guideline was derived with the snowdrift prediction model, allowing for a snow berm along the edge of the upwind lane.

When practical, medians should be depressed to retain snowfall. Shrub plantings can also increase snow retention in these areas (section 6.9.4). Use of the steepest allowable front slopes in the median helps to provide storage space for plowed snow.

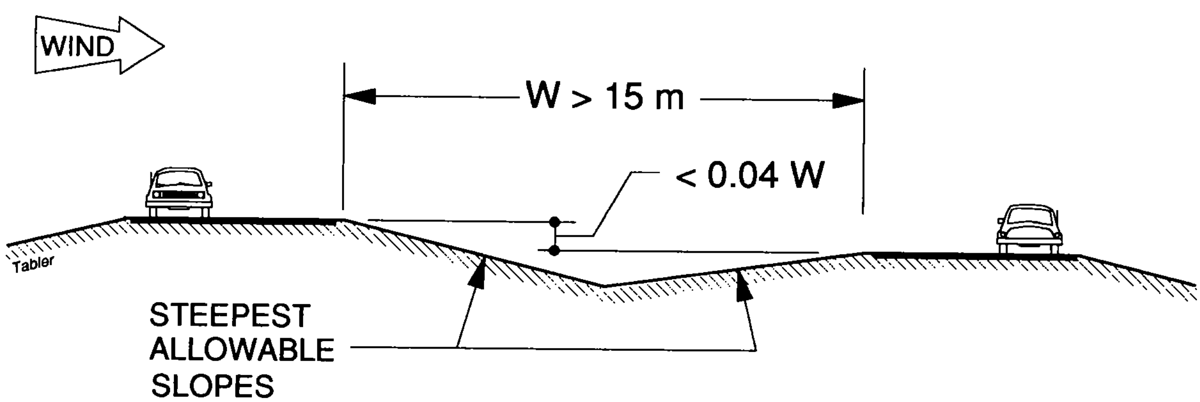

Figure 7.26. Proposed guideline for relative elevations of divided lanes.

7.8.5 Safety Barrier Requirements

Safety barriers can cause deposition of blowing snow, but they also interfere with snow removal by deflecting snowplow cast. A basic concept in designing roads for winter maintenance, even in areas where blowing snow is not a problem, is to minimize safety barrier requirements. This can be accomplished by using recoverable slopes on embankments, preferred ditch sections, and maintaining clear zone widths as specified in the *Roadside Design Guide* (AASHTO 1989). On mountain roads, guard-rail can be reduced by using a lower design speed, and by eliminating roadside obstacles such as isolated rock knobs.

Concrete safety barrier creates the most serious snow accumulation and snow removal problems, and should be avoided wherever possible by planning future lane expansion that will not require median barrier.

Barrier types will be discussed in section 7.9

7.9 Guidelines for Structures and Appurtenances Inside the Right-of-Way

7.9.1 Safety Barrier

Where barrier cannot be avoided there is some opportunity to mitigate snow problems by using barrier designs offering the least obstruction to plow cast and blowing snow.

7.9.1.1 Concrete Barrier

Concrete barrier is often used in the median to separate opposing lanes of traffic because of its safety and lower maintenance cost. Disadvantages for its use in the snowbelt include:

- impairment of visibility in blowing snow (Figure 7.27);
- formation of drifts on the traveled way (Figure 7.28); and
- obstruction of plow cast.

For these reasons, concrete barrier should be avoided where possible. Designers should plan for future lane expansions that do not require median barrier. Concrete barrier should not be used for bridge rail or bridge rail transitions. Where concrete barrier must be used in open, exposed areas, snow fences should be included as part of the design.

Height is the only shape factor of concrete barriers that affects snow accumulation. Barrier height should *not* be greater than safety considerations require.

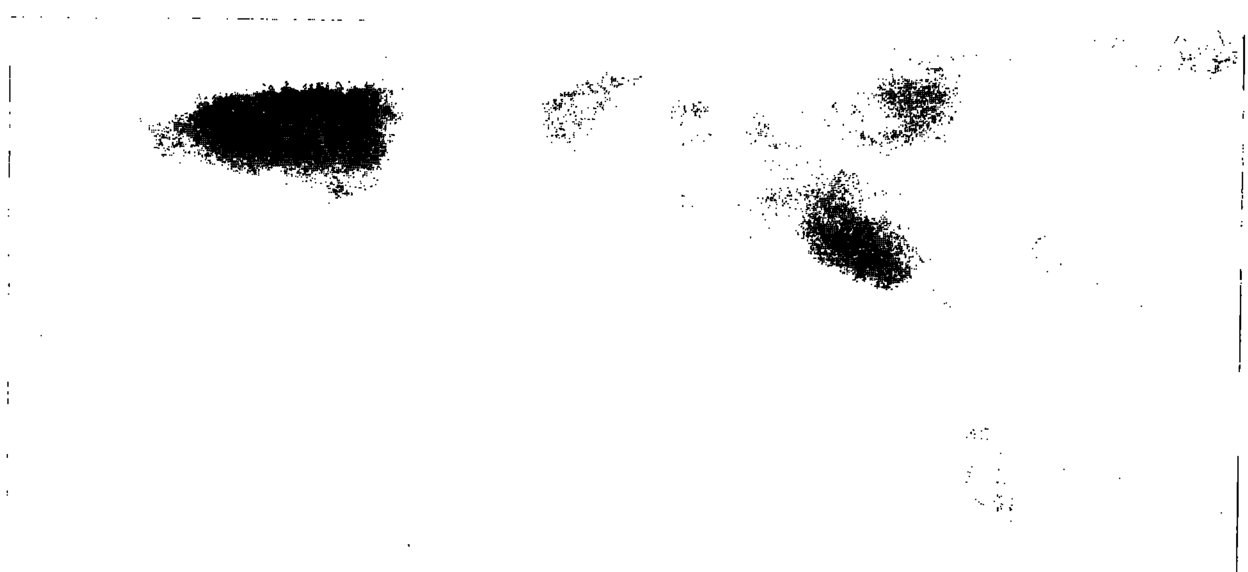

Figure 7.27. Snow blowing over the top of concrete barrier can impair motorist visibility (Tabler and Jairell 1980).

Figure 7.28. Concrete barrier caused a snowdrift that blocked Interstate Highway 25 in Colorado, during the Christmas blizzard of 1982.

7.9.1.2 W-Beam Versus Box Beam and Cable Barrier

The W-beam configuration is second only to the concrete barrier in obstructing plow cast and airflow. The presence of a bituminous curb exacerbates these problems (Figure 7.29). Where W-beam rail must be used, permanent curbs should be replaced with temporary sand-filled tubes (Figure 7.30) placed outside of the barrier, to control drainage.

As a result of model tests that demonstrated the advantages of box-beam rail over W-beam (Figure 7.31), the Wyoming Department of Transportation now uses box beam wherever possible, and also employs the temporary curbs described previously (Figure 7.30). Cable barrier is equally satisfactory for minimizing snow accumulation.

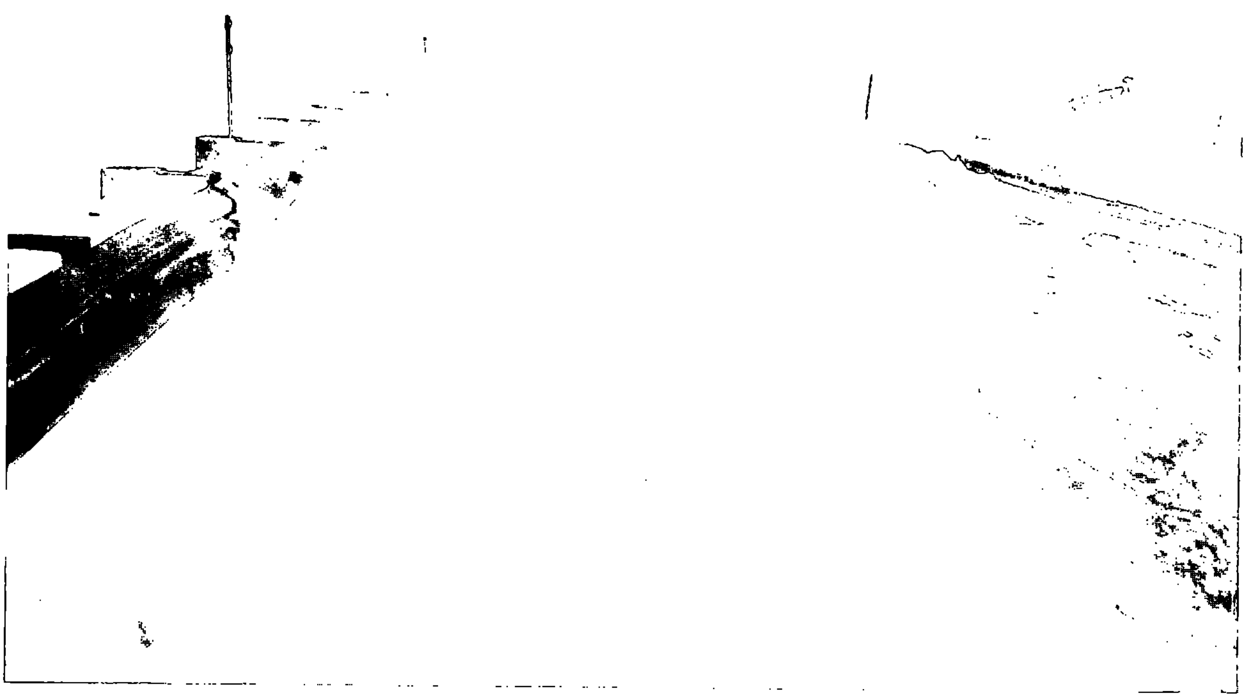

Figure 7.29. W-beam safety barrier causes snowdrifts and obstructs plow cast.

Figure 7.30. A temporary curb comprised of a sand-filled canvas or plastic sleeve, should be used in preference to permanent curbs under rail.

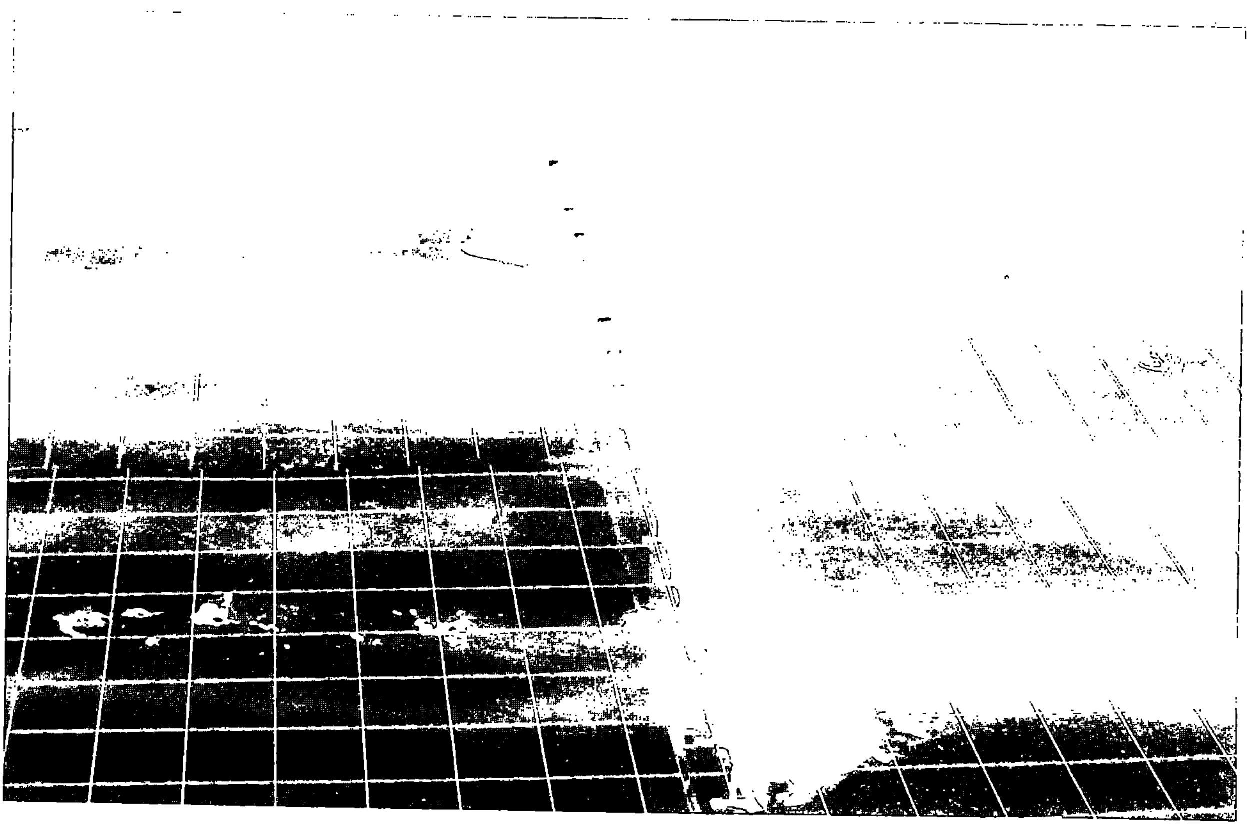

Figure 7.31. Small-scale (1:30) models show difference in snowdrifts formed by W-beam (top) and box-beam (bottom) barrier (Tabler and Jairell 1980). Photo by Robert L. Jairell.

7.9.1.3 Safety Barrier Terminations

"Shirt-tail" drifts that form at the ends of barriers (Figure 7.32) can be prevented by anchoring ends in the back slope, or by flaring out the end of the barrier so that the termination is located at least 15 times the barrier height away from the travel lane (11.4 m for 76-cm W-beam rail) (37 ft; 30 in.). Although turned-down ends and controlled releasing terminals would also prevent drifts, these terminations can cause vehicles to vault or roll following impact.

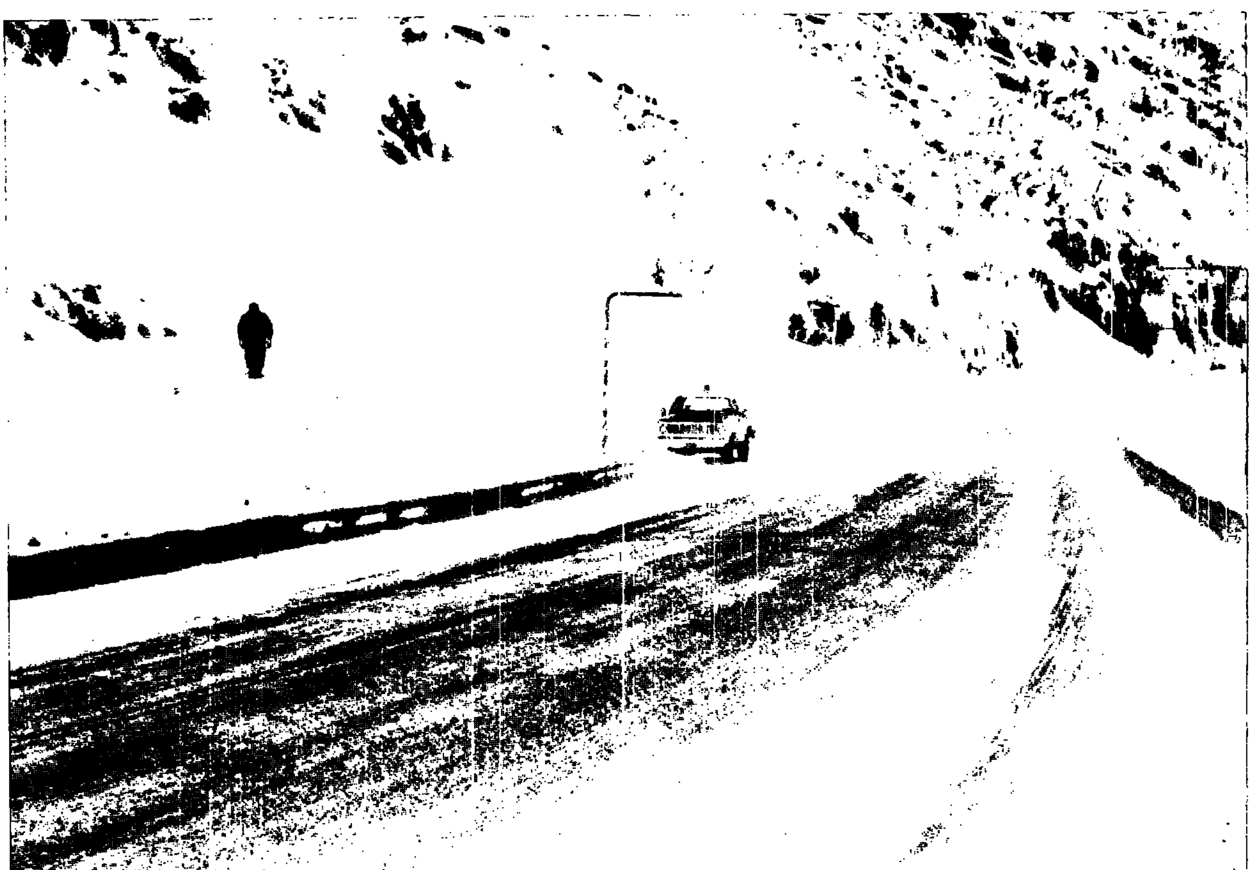

Figure 7.32. Shirt-tail drifts form at the ends of safety barrier. The snow on which the person is standing was piled up intentionally in an attempt to prevent this drift by closing off the opening at the end of the guard-rail.

7.9.2 *Abutments for Overhead Structures*

Drifts are formed by abutments for overhead structures in both the upwind and downwind lanes (Figure 7.33). The least costly solutions to this problem are structural snow fences or tree and shrub plantings, as described in section 6.9.4.

The severity of the problem can be essentially eliminated in the downwind lane, and greatly reduced in the upwind lane, by lengthening the overhead span so that the abutments are as far away as practicable from the shoulders of the under-passing lanes. Again, safety barrier greatly exacerbates the snow problem, particularly the windward drift that forms on the downwind side of the separation (Figure 7.33). Design should therefore strive to eliminate the need for barrier using the criteria in the *Roadside Design Guide* (AASHTO, 1989).

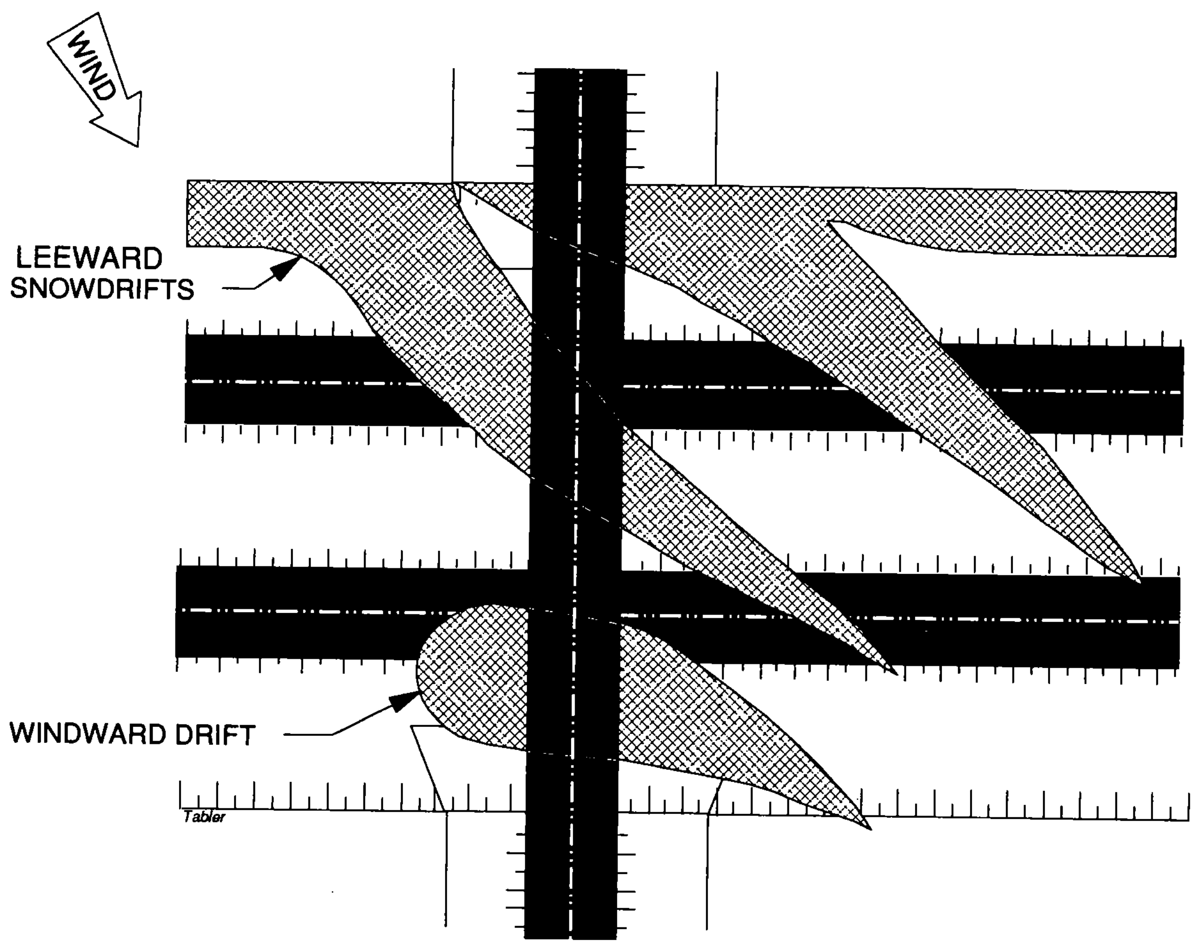

Figure 7.33. Pattern of equilibrium drifts formed by abutments at grade separations.

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Problem Evaluation Checklist

Site name: ____________________ **Date:** ____________________
Site I.D. ____________________ **Evaluator(s):** ____________________
____

Location:
District/County:____________
Designation:____________
Location (to nearest .01 mile (0.1 km): ______ to ______ Length: ______
Elevation: ____________
Notes:____
____
____

Priority Ranking by:
Maintenance foreman:____________
Evaluator:____________
Other:____________
Overall:____

Problem Type: (Check all that apply)
____________ Drift on road (Downwind drift/upwind drift)
____________ Poor visibility
____________ Slush/ice
Other:____
____

Problem Cause:
____________ Road section
____________ Safety barrier
____________ Bridge abutment
____________ Vegetation (trees/brush/other)
____________ Building
____________ Fence
Other:____
____

Problem Evaluation Checklist (Page 2)

Site Name: ______________________ **Date:** ________________
Site I.D. ______________________ **Evaluator(s):** ______________________
____

Problem Consequence (check all that apply):

________ Snow removal expense
________ Pavement damage from meltwater
________ Safety hazard
 ________ Loss of vehicle control
 ________ Reduced sight distance
 ________ Intersection obscuration
 ________ Sign obscuration
 ________ Reduced effectiveness of safety barrier
 ________ Reduced visibility by blowing snow
 ________ Slush or ice on pavement
 ________ Accident history

Other (explain): ____

Road Information:

Orientation: ________
Horizontal geometry: Tangent _____ Curve/spiral _____
Feature: None _____ Intersection _____ Exit/Entrance Ramp _____
Typical section:
 Right-of-way: Shoulder to Property line __________
 No. of lanes and width (sketch below):

WIND →

Problem Evaluation Checklist (Page 3)

Site Name: ______________________ **Date:** ______________________
Site I.D. ______________________ **Evaluator(s):** ______________________
____

Road Information (Continued):

Typical Section (Continued):

On-grade:___________
Embankment: Height _____ Slope _____ Safety barrier? _____

Through-cut: Height _____ Shoulder to toe of backslope _____
Backslope _____ Foreslope _____

Sidehill cut: Cut: Height _____ Shoulder to toe of backslope _____
Backslope _____ Foreslope _____

Fill: Height _____ Slope _____
Safety barrier type _____

Weather Data (Preliminary):
Prevailing drifting directions:

N NNE NE ENE E ESE SE SSE S SSW SW WSW W WNW NW NNW N

How determined? ________

Is there a "problem storm" direction? ________
Estimated annual snowfall: ________
Other:____

Fetch:
Type of transport boundary:___________
Distance to transport boundary: ___________________
Topography:___________
Vegetation:___________
Depth of snow retention?___________
Land use:___________
Ownership:___________
Other:____
____
____

Problem Evaluation Checklist (Page 4)

Site Name: ______________________ **Date:** ______________

Site I.D. ______________________ **Evaluator(s):** ______________________

____

Possible Solution(s):

Structural snow fences: ____________

Tree or shrub barriers: ____________

Shrub plantings: ____________

Section modification: ____________

Other: ____

____

____

____

____

Additional Data/Measurements Required:

____

____

____

____

____

____

Glossary

Absolute trapping efficiency the proportion of incoming wind-transported snow to 5 m (16 ft) height that is permanently retained by a barrier.

Aerodynamic roughness height (Z_o) the height above the ground or snow surface at which wind speed is zero.

Attack angle the angle between the prevailing snow transport direction and the alignment of the road or snow fence.

Blower fence a fence that accelerates wind to prevent snow deposition or to improve visibility.

Bottom gap a space between the ground and the bottom edge of a snow fence. The bottom gap reduces deposition of snow in the immediate vicinity of the fence.

Capacity the most snow a fence or other barrier can hold. Measured in metric tons per meter of fence length, or tons per foot.

Collector fence a snow fence that induces the deposition of blowing snow. See also *deflector fences*.

Contributing distance see *fetch*.

Cornice A lip of overhanging snow at the top of a slip face. A cornice is formed by the electrostatic attraction of snow particles.

Creep snow or sand particles that are too heavy to be lifted off the surface which roll along the surface, forming "snow waves" or dunes that migrate downwind.

Deflector fences fences that force the wind, and the blowing snow it carries, around or over the area to be protected. See also *collector fences*.

Delineator posts posts that mark the edge of a road's pavement or shoulder.

Densification the increase in the density of a snowdrift as particles are rearranged by plastic yielding, particle fracture, and sliding in response to the pressure imposed by overlying snow.

Design modulus (K) the ratio of design transport to the average annual snow transport.

Design snow transport the snow transport for which a snow control measure is designed. See also *snow transport*.

Downwind drift the snowdrift that forms on the downwind, or leeward, side of a snow fence or other object.

Drag coefficient the coefficient of proportionality between the force exerted on an object, and the dynamic pressure ($0.5\rho_a U^2$) of the wind.

Dust levee earthen embankments constructed to protect railroads from blowing sand or topsoil.

Effective fence height (H) vertical height of fence above the surrounding snow surface, including the bottom gap.

End effect the rounding of a snowdrift near the ends of a snow fence or other barrier.

EPDM elastomeric roofing membrane. Used to grip synthetic fencing materials at attachment points.

Equilibrium drift the snowdrift formed by a snow fence, terrain feature, or other barrier when filled to capacity for the existing wind conditions.

Equilibrium slope (Y_s) the slope of the surface of an equilibrium drift, measured parallel to the prevailing transport direction.

Fence height (H) see *effective fence height*, *structural fence height*.

Fetch (F) the length of the area that is a source of blowing snow to a downwind location. The upwind end of the fetch is any boundary across which there is no snow transport, such as forest margins, deep gullies or stream channels, rows of trees, ice pressure ridges, and shorelines of unfrozen bodies of water.

Fully effective height the height of trees or shrub plantings when their average snow-trapping efficiency reaches 75%.

Herringbone snow fences an oblique array of snow fences on both sides of a road. Used to reduce drifting problems where prevailing transport direction is parallel to road alignment.

Initial trapping efficiency (E_o) the trapping efficiency of a snow fence at the beginning of the first drifting event when there is no appreciable accumulation of snow.

Jet roof a wooden or steel panel inclined from the horizontal that accelerates wind passing underneath to prevent a cornice from forming at the top of a cut slope or avalanche starting zone.

Kolktafeln a rectangular wood or steel panel set vertically that prevents cornice formation at the top of a cut slope or avalanche starting zone by generating turbulence.

Lateral deflectors barriers that deflect snow laterally around the protected area. Livestock shelters are the most common example.

Leeward drift see *downwind drift*.

Living snow fence trees, shrubs, or crops that are used as barriers to control drifting snow. See also *snow fence*.

Maximum transport distance (T) the distance that the average-sized snow particle can travel before completely evaporating. The maximum transport distance varies greatly from one storm to the next (depending on relative humidity, air temperature, and wind speed), but season-long averages appear to be relatively stable (approximately 3000 m/2 miles).

Minnesota snow trap a triangular planting scheme used for blowing snow protection at grade separations and interchanges.

Norwegian snow fence see *Swedish snow fence*.

Nose the windward portion of a snowdrift that extends from the leading edge to the crest of the drift.

Oblique fences fences aligned at an angle to the road.

Parallel fences fences aligned parallel to the road.

Pole crib fence fence made from wooden poles stacked vertically in a zigzag configuration, eliminating the need for vertical posts.

Porosity the holes or spaces between slats or rails, excluding the bottom gap.

Porosity ratio ratio of openings to frontal area, excluding the bottom gap.

Potential snow transport the mean annual snow transport that would occur downwind of an infinitely long fetch with an unlimited snow supply. When calculated from historical wind records, potential snow transport is designated Q_{upot}. When calculated from snowfall data, potential transport is designated Q_{spot}.

Precipitation water-equivalent of the snowfall.

Prevailing transport direction the mean wind direction that corresponds to the mean annual snow transport.

Protected area a section of road that is protected by a snow fence.

Protection limits the locations (stations or mile markers) that mark the beginning and ending of the protected area.

Rails the solid elements, oriented horizontally, that comprise the face of a fence. See also *slats*.

Rebar reinforcement steel. Used to anchor Wyoming snow fence.

Recirculation zone a region where an eddy of wind forms immediately downwind of a drift's slip-face, or downwind of any solid barrier.

Relocated precipitation precipitation that is moved by the wind. Relocated precipitation excludes snow retained by vegetation, topographic features, and snow that hardens or melts in place.

Relocated snow water-equivalent (S_{rwe}) relocated precipitation, expressed as water-equivalent.

Relocation coefficient (θ) the proportion of winter snowfall water-equivalent relocated by the wind.

Required fence height (H_{req}) the effective fence height required to store the design snow transport.

Saltation movement of snow or sand particles by bounding or intermittently jumping (saltating) along the surface. This is the dominant mode of travel for particles that are too heavy to be suspended in the air. Although most saltating particles travel within 5 cm (2 in.) or so of the surface, most of the blowing snow is transported in this way at wind speeds below about 65 km/h (40 mi/h).

Sastrugi name given to a variety of snow surface features, the most common being anvil- or tongue-shaped features formed when wind erodes softer snow from beneath a more resistant surface layer.

Separation the formation of an eddy near the ground that occurs when the surface slope in the direction of the wind changes more rapidly than the wind can follow.

Setback the distance between the fence and the road shoulder, as measured in the direction of the prevailing wind.

Shear velocity (U_*) the square root of (surface shear stress divided by the air density).

Shy line offset the distance from the edge of the traveled way, beyond which a roadside object will not be perceived as hazardous and result in a motorist's reducing speed or changing vehicle position on the roadway. (AASHTO 1989)

Slats the solid elements of a snow fence, usually oriented vertically. See also *rails*.

Slip-face an abrupt dropoff that forms near the end of a downwind drift during the intermediate stages of growth. The slip-face assumes an angle of repose for sloughing snow cornices.

Snow accumulation season the season of drift growth, beginning with the first blowing snow event that causes drifts that persist through the winter, and ending when snowdrifts reach their maximum volume for the winter.

Snowbreak forest tree plantings 60 m (200 ft) or wider parallel to the wind that act as solid barriers.

Snow fence structural barrier that protects an area from wind-transported snow. See also *living snow fence*.

Snow shadow a region downwind from features that disrupt the flow of saltating particles by deflection or deposition. The opposite of snow streams.

Snow stream a stream of saltating snow particles downwind from a snow source after most of the snow has blown out from the rest of the terrain.

Snow transport (Q_t) the mass of blowing snow that is transported by the wind over some specified period of time, per unit of width across the wind. Snow transport normally refers to the total within the first 5 m (16 ft) above the surface, per meter of width across the wind.

Snow trap see *Minnesota snow trap*.

Snow water-equivalent (S_{we}) the depth of water, usually expressed in millimeters (or inches) that would result from complete melting of the snowfall or snowpack.

Structural fence height (H_s) the vertical height of a snow fence measured from the ground surface. See also *effective fence height*.

Surface shear stress the force exerted on the snow or ground surface by the wind, proportional to the square of the vertical velocity gradient.

Suspended particles snow particles that are carried by the wind for extended distances without contacting the surface.

Swedish snow fence snow fence 2 m (6.5 ft) tall, comprised of horizontal boards attached to wooden trusses, with the top third of the fence inclined toward the wind. Also referred to as *Norwegian* snow fence.

Trapping efficiency (E) the proportion of incoming wind-transported snow, moving at or below the height of the barrier, that is permanently retained by the barrier.

Turbulent diffusion the mechanism by which particles are transported in suspension without the periodic surface contact that typifies saltation. A snow particle becomes entrained in the air flow when the gravitational force on the particle is less than the drag force imposed by upward-moving air currents. Because the turbulent diffusion process favors smaller particles, suspended particles are smaller than those moving in saltation. As suspended particles become smaller through evaporation, they tend to be carried higher above the surface. This sorting process causes particle size to decrease with increasing height above the surface.

U-clip U-shaped steel plate used to connect Wyoming snow fence panels to rebar anchors.

Upwind drift the snowdrift that forms on the upwind, or windward, side of a snow fence or other object.

Weed barrier geotextile used to prevent weed growth around seedlings.

Wind speed wind speed refers to that at the standard height of 10 m (33 ft), unless otherwise specified.

Windward drift see *upwind drift*.

Wyoming snow fence snow fence 1.8 to 4.3 m (6 to 14 ft) tall comprised of horizontal boards attached to wooden truss frames, usually anchored with driven rebar.

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