Trapping Efficiency of Snow Fences and Implications for System Design

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The trapping efficiency of a snow fence is the quantity of wind-transported snow retained in proportion to the incoming snow transport over the height of the fence. Trapping efficiency declines as a fence fills with snow, and this relationship determines the efficacy of a snow fence system in reducing snow removal costs and improving visibility. A numerical simulation illustrating how initial trapping efficiency varies with wind speed is described, including field measurements indicating how trapping efficiency changes with time. Engineering equations developed from these results show how savings in snow removal costs vary with the design capacity of snow fence systems. A snow storage capacity just equal to the mean annual snow transport will reduce costs by about 80 percent over the long term. The ratio of benefits to costs is maximized with a storage capacity equal to 90 percent of the mean annual snow transport.

Trapping efficiency of a snow fence is defined here as the proportion of snow blown over the height of the barrier that is permanently retained by the fence. Trapping efficiency changes as a fence fills with snow, and this relationship determines the effectiveness of a snow fence system in reducing snow removal costs and improving visibility throughout a winter.

To be effective, snow fences must have adequate capacity for storing snow. Methods are available for estimating snow transport at a site and for determining the height or number of rows of fencing needed to provide the required storage (*1–3*). However, a design year must first be specified, and it is not intuitively evident that the average winter would be the optimum choice. Knowing how trapping efficiency varies with snow accumulation allows a benefit-cost analysis to determine the optimum design year.

This paper describes some of the factors affecting trapping efficiency and uses field measurements to develop engineering approximations describing how trapping efficiency changes with time.

SNOW TRANSPORT

Blowing snow particles range in size from infinitesimally small to as large as 0.5 mm (0.02 in.) in diameter. Particle size decreases with height above the surface, with mean diameter ranging from about 0.2 mm (0.008 in.) at 5 cm (2 in.) to less than half this size at 100 cm (3.3 ft). Snow particles derived from freshly fallen snow are smaller than those originating from a snow cover that has remained undisturbed for a few days. As snow particles are carried by the wind, they become progressively smaller and more rounded from fragmentation, abrasion, and evaporation.

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Snow trapping efficiency varies with the mode of particle movement. Particles too large to be lifted by the wind roll or creep along the surface. Creeping particles are easily trapped by a fence, but only a small proportion of blowing snow (less than 20 percent) is transported in this manner, except at low wind speeds.

Most saltating particles (those that appear to jump along the surface) are contained in the first 5 cm (2 in.) or so above the surface. Although trajectories vary with particle size, wind speed, and surface conditions, a typical jump is a parabolic arc 1 cm (0.4 in.) high and 25 cm (10 in.) long (*4*). Saltating particles are also readily trapped by a snow fence, and because their impact is an important mechanism for dislodging other particles, removing saltating particles from the airstream can disrupt erosion of the snow surface and reduce transport for great distances downwind. This is one reason for the effectiveness of snow fences.

"Turbulent diffusion" refers to the mechanism by which particles are transported in suspension without the periodic surface contact that typifies saltation. A saltating snow particle becomes entrained in the airflow when the gravitational force on the particle is less than the drag force imposed by upward-moving air currents. The diffusion process favors smaller particles, and suspended particles are therefore smaller than those moving by 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. The numerical model developed by Pomeroy (*5*) indicates that most blowing snow is transported in the turbulent diffusion mode but that the greatest portion of the total suspended particle mass is contained in the first meter or so above the surface. Suspended particles can be caught by a snow fence if they settle to the surface in a region sufficiently sheltered to prevent subsequent dislodgement.

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,

$$\tau_o = \rho |du/dz|^2 \iota^2 \quad (1)$$

where

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

"Snow transport" refers to the mass of blowing snow transported by the wind over some specified period of time, expressed per unit of width across the wind. An engineering approximation for total snow transport in the first 5 m (16 ft) above the snow surface, Q_{0-5}, is

$$Q_{0-5} = u_{10}^{3.80}/233{,}847 \quad (2)$$

where u_{10} is wind speed in meters per second at 10 m above the surface and Q_{0-5} is transport in kilograms per second per meter of width across the wind (*3*).

SNOW DEPOSITION PROCESSES AT SNOW FENCE

A fence exerts a restraining force on the wind, reducing wind speeds and changing the shape of the wind profile. These effects reduce the surface shear stress, allowing creeping and saltating particles to come to rest. Some of these particles are deposited on the windward side of the fence as surface winds decelerate approaching the barrier. According to Takeuchi, saltating particles are deposited on the windward side of barriers and suspended particles settle out on the leeward side (*6*). However, many of the suspended particles passing through a snow fence do not reach the ground before they are carried beyond the sheltered area.

At the start of the snow accumulation season, the aerodynamic effect of the fence controls the deposit of snow entering the sheltered region. But as the snowdrift develops, it exerts an additional influence on the flow field that progressively changes as the shape and dimensions of the drift change. The complexity of the problem become apparent when one considers how drifts grow.

In the initial stages of drift growth, particles passing through a porous barrier encounter a zone of greatly diminished winds and decreasing surface shear stress, extending downwind for a distance of about 12 times the height (*H*) of the fence, or 12*H*. Most particles reaching the ground within this region come to rest, forming a lens-shaped drift that becomes progressively thicker in the middle as deposition continues.

This initial lens-shaped deposit thickens until the airflow can no longer adjust rapidly enough to follow its curvature, and at this stage the flow separates from the surface in the same way as it does over an airplane wing when the stall angle is reached. This results in the formation of the slip-face and recirculation zone (Figure 1) that characterize the second stage of drift growth. The recirculation zone extends downwind from the slip-face for a distance equal to about six times its height. During this stage of development, the drift itself adds significant resistance to the approaching wind. The added resistance slows the airflow passing over the drift, allowing snow to be deposited on the nose of the drift and reducing 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, but stronger winds can cause particles to be carried beyond the recirculation region before reaching the ground. If the snow cover contains newly fallen snow, the electrostatic charge on the particles causes them to adhere to the surface, forming a snow cornice at the top of the slip-face and enhancing 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 2.

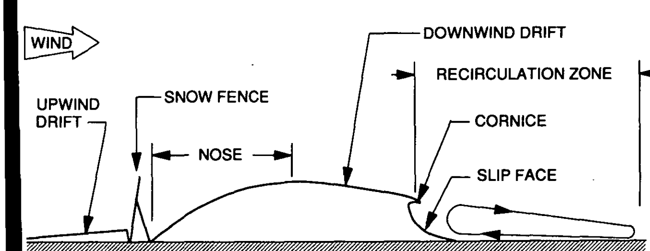

FIGURE 1 Slip-face and recirculation region formed by 50 percent–porous snow fences during intermediate stages of drift growth.

As the lee drift depth approaches its maximum, which for 50 percent–porous fences is 1*H* to 1.2*H*, the third stage of growth begins, characterized by a filling in of the recirculation zone as the drift lengthens downwind and represented by Measurements 4 through 6 in Figure 2. As long as a slip face is present, however, trapping efficiency remains relatively high.

The fourth stage of growth begins when the drift first assumes a smooth profile without the slip-face, marking the disappearance of the recirculation zone. At this point the drift is about 20*H* in length, as indicated by Measurement 6 in Figure 2. This stage should be marked by rapidly declining trapping efficiency, and only creeping and saltating particles are deposited. Subsequent growth is therefore relatively slow as the drift elongates to its ultimate length of 30*H* to 35*H*, as represented by Measurement 7 in Figure 2.

The fourth stage ends when the drift ceases to grow—that is, when it reaches equilibrium for the existing wind conditions. Typical dimensions of equilibrium drifts formed by 50 percent–porous fences are shown in Figure 3. After equilibrium is achieved, trapping efficiency remains at zero.

FACTORS AFFECTING TRAPPING EFFICIENCY

Trapping efficiency varies with length, height, and porosity of a snow fence. The presentation in this paper is restricted to very long fences (more than 30*H*) having 50 percent open area and a bottom gap equal to *H*/10. But so many other factors affect trapping efficiency, either directly or indirectly, that a meaningful quantitative evaluation is difficult at best. If the angle of attack between wind and fence is not exactly

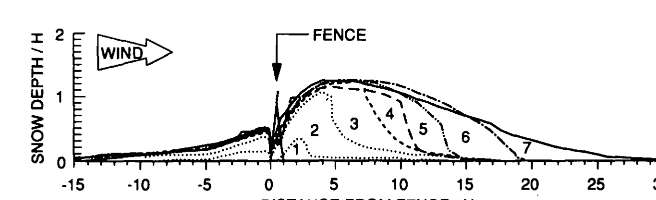

FIGURE 2 Profiles of snowdrift formed by a 3.8-m-tall Wyoming-type snow fence, on seven measurement dates (*2*).

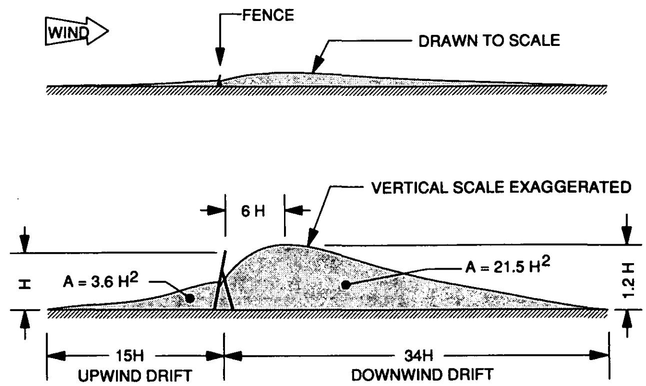

FIGURE 3 Shape of equilibrium drift formed by a 50 percent–porous snow fence on flat terrain (*2*).

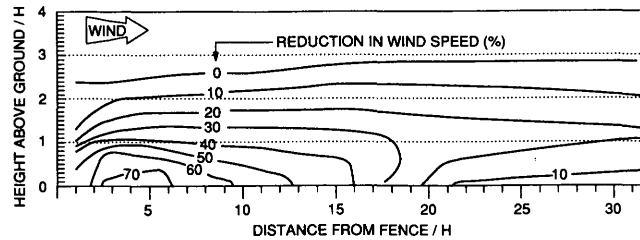

FIGURE 4 Curves of equal wind speed reduction, in percent, behind a snow fence 4 m tall (13 ft) having 50 percent open area and 15-cm (6-in.) bottom gap.

90 degrees, for example, a crosswind component on the leeward side can transport some of the particles along the length of the fence until they are swept away in the slipstream around the end of the fence. Trapping efficiency also varies with the chronology of changes in wind speed or direction. Susceptibility to erosion depends on the strength of the ice bonds between deposited particles, and the strength of such bonds changes rapidly with time, doubling in 2 days and trebling in 3 days (*7*). But the dominant factors affecting trapping efficiency are ambient wind speed and the influence of the developing drift; these considerations are the focus of this paper.

Wind Speed

The initial trapping efficiency (E_o), at the time of the first drifting event when there is no appreciable accumulation of snow, is amenable to numerical simulation to determine how ambient wind speed affects trapping efficiency. Knowing the vertical size distribution and fall velocity of snow particles, and the general characteristics of the flow field behind a fence, it is possible to trace the trajectories of particles to determine the distance at which they reach the ground. If this distance exceeds the region of decreasing surface shear stress behind the barrier, it can be assumed that the particles will not be trapped.

The wind field behind 50 percent–porous snow fences was assumed to be that shown in Figure 4, as determined from intensive wind profile measurements behind 1.2- and 4-m-tall snow fences, using the equipment described elsewhere (*8*). These studies indicated that, to a reasonable approximation, the representation in Figure 4 is valid for all heights and ambient wind speeds.

For various fence heights and ambient wind speeds, a computer simulation was used to determine a critical interception height, defined here as the maximum height at which the average-sized particle would reach the ground within a distance equal to 15*H*. Trapping efficiency was then calculated as the mass flux contained below the interception height in proportion to the total transport summed over the height of the fence, as given by the vertical distribution of mass flux proposed by Tabler (*3*).

The simulation was made at 5-cm height increments, starting at the ground and ending when the interception height was reached. For each height, the simplifying assumption was made that particle size was uniform and equal to the mean of the distribution at that height:

$$\overline{D} = 303\, z^{-0.27} \quad (3)$$

where $\overline{D}$ is the average particle diameter in microns at height z in centimeters above the surface (*9*).

The fall velocity, V, for each particle size was calculated from the following relationships:

$$F_D = mg = 0.5\rho C_D v^2 A \quad (4)$$

$$C_D = (24/R_e)\,(1 + 0.0806 R_e) \quad (5)$$

$$R_e = DV/\nu \quad (6)$$

where

F_D = drag force on the particle,
m = particle mass,
g = gravitational constant,
C_D = drag coefficient,
A = particle cross-sectional area,
R_e = Reynolds number, and
ν = kinematic viscosity (*10,11*).

The calculations reported here used air characteristics at −10°C (14°F).

It was assumed that the particle follows the mean flow field behind the barrier (*11,12*) so that the particle's horizontal speed ($u_{p,z}$) can be taken as the ambient wind speed ($u_{z,\text{up}}$) at the height of the particle, adjusted for the wind speed reduction, R (%), shown in Figure 4:

$$u_{p,z} = u_{z,\text{lee}} = u_{z,\text{up}}\,[1 - (R/100)] \quad (7)$$

The wind reduction field in Figure 4 was approximated by multiple regression equations relating wind speed reduction to height above surface and distance from barrier, with different equations being developed for different regions. The ambient wind profile was assumed to be

$$u_{z,\text{up}} = 2.5\, u_*\, \ln(z/z_0) \quad (8)$$

where u_* is shear velocity and z_0 is the height at which $u = 0$. For blowing snow conditions on snow-covered flat terrain, $u_* \approx u_{10}^{1.18}/98.3$ and $z_0 \approx u_*^2/31{,}250$, where velocities are in centimeters per second and heights are in centimeters (*8,13*).

With this information, it was possible to determine the location at which the particle reached the ground by routing the particle through the flow field, using time increments of 0.01 second to recalculate particle positions. If the fallout distance was less than $15H$ from the barrier, the particle was assumed to be permanently trapped. This procedure was repeated for incremental increases of initial particle height until the critical interception height was reached.

As shown in Figure 5, this analysis indicates that initial trapping efficiency decreases somewhat as fence height increases, attributable to the decreasing particle size (and hence fall velocity) with increasing height. However, the 10-m ambient wind speed has a much more pronounced effect on efficiency. For a 2-m-tall fence, for example, E_o varies from 0.99 at u_{10} = 10 m/sec to 0.68 at u_{10} = 30 m/sec.

Although the preceding analysis could be refined by taking into account the nonuniform distribution of particle sizes at each height, as Schmidt and Randolph did in their analysis of snow deposition at a downwind-facing step (*11*), it is not expected that such a refinement would significantly change the results obtained here. The question of how trapping efficiency changes as a fence fills with snow is of far greater importance for designing snow fence systems, and the rest of this paper is devoted to this subject.

Developing Snowdrift

The effects of a snowdrift on trapping efficiency are indicated by a similar simulation analysis of snow deposition behind downwind-facing step-like terrain breaks (*11*). As reproduced in Figure 6, results from that study suggest that trapping efficiency is reduced by an uphill approach to the step but increases rapidly as the downhill angle increases. From the previous 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 of growth. Through much of the third stage the approach angle remains relatively constant, averaging about 3 degrees, consistent with a relatively high efficiency. Another significant observation from Figure 6 is that step height has little effect on trapping efficiency. These results suggest that trapping efficiency changes in a complex way as a drift grows, and there may be intervals when trapping efficiency increases with time.

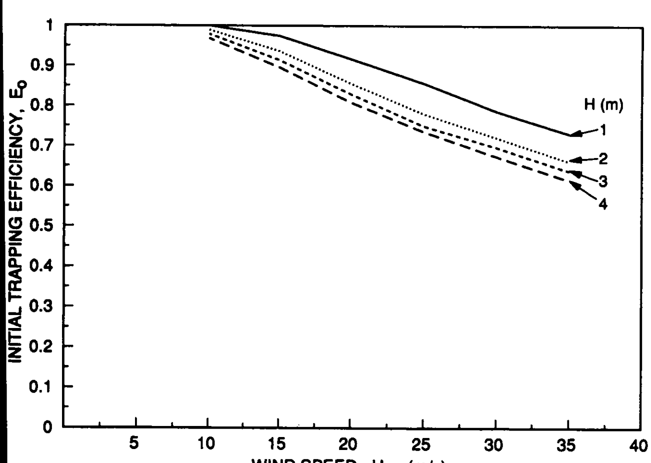

FIGURE 5 E_o **versus fence height and 10-m wind speed, as determined by numerical simulation.**

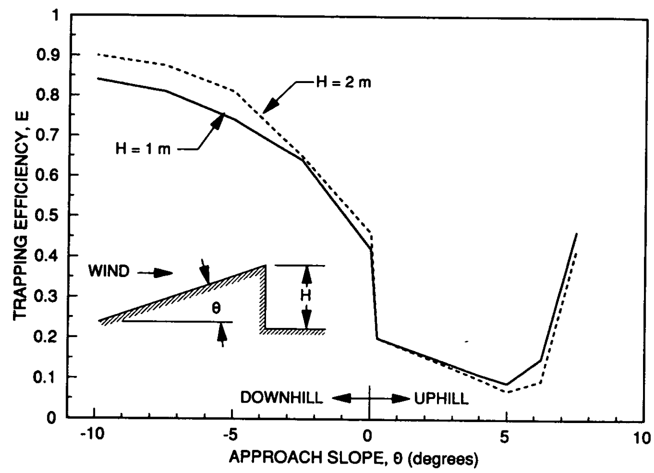

FIGURE 6 Initial trapping efficiency of downwind-facing steps in relation to approach slope and step height (*11*).

FIELD MEASUREMENTS OF TRAPPING EFFICIENCY

This paper combines results from three types of field measurements to develop engineering equations to describe how trapping efficiency changes as a fence fills with snow. In a "three-fence study," trapping efficiency was estimated by measuring changes in snow accumulation in a tandem series of three tall snow fences. Results from this study were published previously (*14*) but have been recalculated using improved estimates for the storage capacity of the fences involved. In the second study—the "snow removal study"—the progression of snow deposition behind a fence 2.4 m tall (7.9 ft) with an undisturbed drift was compared with that behind an adjacent section of the fence where the snow was removed after each measurement. These results have not been reported previously. The results from these formal studies of trapping efficiency are supplemented with measurements of snow accumulation changes behind two tandem rows of 3.8-m-tall fences. Although providing less-precise estimates of trapping efficiency, these "two-fence study" measurements help to define the general functional form of the relationships between trapping efficiency and residual storage capacity.

Study Area and Experimental Methods

All measurements used Wyoming-type snow fences (*14*) on Interstate 80 about 55 km (34 mi) northwest of Laramie, Wyoming. The sites are on relatively flat terrain covered with low-growing herbaceous vegetation, at an elevation of about 2370 m (7,776 ft). Snowfall averages about 250 cm (98 in.), and snow transport over the past 20 years has averaged about

90 t/m of width (31 tons per foot) across the wind. The fences used for these studies are perpendicular to the prevailing winds.

Snow depth and water equivalent were sampled behind the study fences after each major drifting event. Snow depths and water equivalent were measured at intervals of 3 m (10 ft) along permanent transects oriented perpendicularly to the fences. An aluminum probe was used to measure snow depths, and water equivalent was sampled with a Mount Rose snow tube. Snow sampler densities were multiplied by 0.91 to correct for the overmeasurement known to be characteristic of this type of sampler (*15*).

Three-Fence Study

This experiment used measurements from three tandem fences having a combined snow storage capacity of 300 t/m (112 tons per foot), about four times greater than the average annual snow transport. This fence system is 490 m (1,608 ft) long and consists of a 2.4-m-tall (7.9-ft) lead fence, followed by a 3.8-m (12.5-ft) fence spaced 61 m (200 ft) downwind, followed by a second 3.8-m fence 91 m (299 ft) farther downwind. After each major drifting event over two winters, snow depth was measured on four permanent transects passing through all three fences, and water equivalent was sampled along one transect selected at random.

It was assumed that the second and third fences were perfectly efficient in trapping snow (i.e., $E = 1$). Although this assumption cannot be strictly true, the fact that the second fence was less than 15 percent full the first year, and 25 percent the second, suggests that the trapping efficiency would be comparable with that of an empty fence. The assumption of 100 percent trapping efficiency for the second fence is supported by the fact that the snow caught by the third fence was approximately equal to the precipitation relocated between the second and third fences. In addition, the close spacing of the fences results in a cumulative shelter effect, with wind speeds approaching the second fence being 10 to 20 percent less than those upwind of the lead fence (Figure 4). Trapping efficiency, E, was therefore calculated as

$$E \approx \Delta Q_1/[\Delta Q_1 + \Delta Q_2 - (2/3)\Delta Q_3] \quad (9)$$

where ΔQ_1, ΔQ_2, and ΔQ_3 are the changes in mass storage over a measurement period, and the (2/3) factor accounts for the different spacing between the last two fences (61 and 91 m, respectively). The resultant trapping efficiencies are plotted against the average cross-sectional area, $\bar{A}$, of the drift over the measurement interval, expressed in proportion to the cross-sectional area A_e of the equilibrium drift:

$$\bar{A}/A_e = \bar{A}/(25H^2) \quad (10)$$

where areas are in square meters (*2*).

Snow Removal Study

The fence used for this study is a single row of fences 2.44 m (8 ft) tall and 146 m (479 ft) long, located about 3 km (1.9 mi) from the fence system used for the three-fence study. Over one winter, snow on the downwind side of half of this fence was removed with a dozer after each major drifting event. On the other half of the fence, the snow was left to accumulate naturally. Before removing the snow, snow depth and water equivalent were measured along two permanent transects in each half. Both pairs of transects were spaced 12.2 m (40 ft) apart and bracketed the middle of the two fence sections. The ratio of the changes in the water equivalent of snow storage between these two treatments provided a measure of the trapping efficiency of the nonremoval section relative to the initial trapping efficiency, E_o, as represented by the snow removal section:

$$E/E_o \approx \Delta Q_n/\Delta Q_r \quad (11)$$

where ΔQ_n is the change in snow storage in tonnes per meter behind the nonremoval section and ΔQ_r is the change behind the section of fence where the drift was removed after each measurement. The relative cross-sectional area of the nonremoval section was computed from Equation 10.

Although the trapping efficiencies calculated from the snow removal study are not exactly the same as those derived from the three-fence study, this experiment provides an independent measure of how trapping efficiency changes as a fence fills with snow.

Two-Fence Study

The observation that the trapping efficiency of the second fence in the three-fence study was approximately 100 percent suggests that two rows of fences having comparable height and spacing can also be used to estimate trapping efficiency. Unlike the three-fence measurements, this calculation does not account for the portion of the second fence drift contributed by snowfall that fell between the two fences, but this error is relatively small for major drifting events and would tend to compensate for the overestimated efficiency of the second fence.

Trapping efficiency was therefore calculated from snow measurements at two rows of 3.8-m-tall fence, spaced 91 m apart, using the equation

$$E \approx \Delta Q_1/(\Delta Q_1 + \Delta Q_2) \quad (12)$$

These measurements were made over 15 years for other studies at several locations on Wyoming I-80.

ENGINEERING APPROXIMATIONS

As might be expected from the complex interactions of the various factors affecting trapping efficiency, the data from these studies show considerable variability (Figure 7). The general trend, however, is consistent with the intuition for how trapping efficiency might change as a drift grows, as previously described. The relationship can be approximated by

$$E \approx E_o[1 - (A/A_e)^2]^{0.5} \quad (13)$$

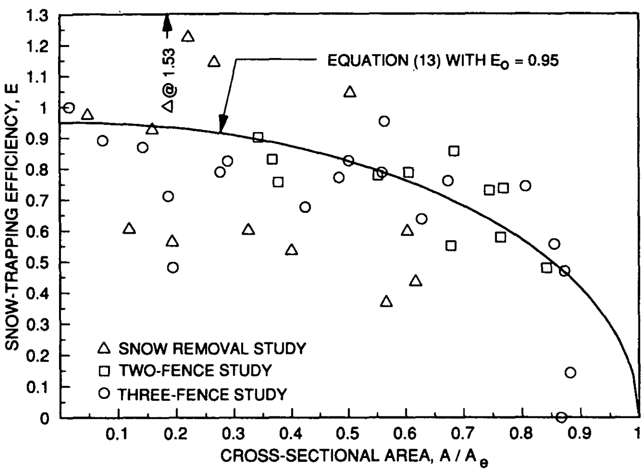

FIGURE 7 Trapping efficiency versus cross-sectional area of snowdrift, as determined from field measurements.

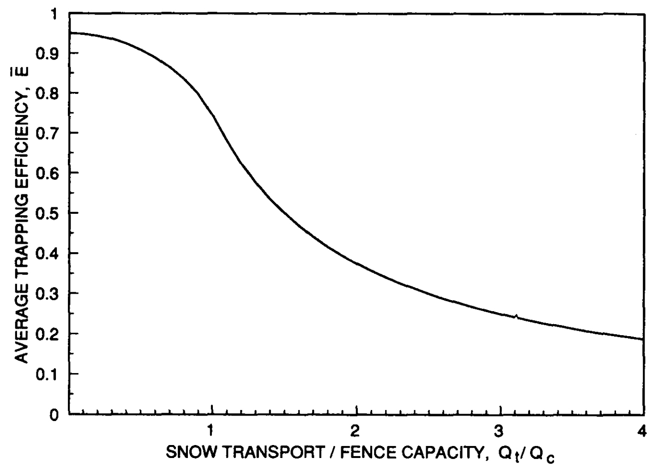

FIGURE 8 Average trapping efficiency over a season as a function of A_f relative to A_e (Equation 14), taking E_o = 0.95.

where E is trapping efficiency expressed as a fraction and 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. For the field data reported here, E_o appears to average about 0.95, which is consistent with the results of the numerical simulation.

The average efficiency, $\overline{E}$, 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 13 from $A = 0$ to A_f, the value at the end of the season:

$$\overline{E} = [1/(A_f/A_e)]\,(E_o)\,\{0.5(A_f/A_e)[1 - (A_f/A_e)^2]^{0.5} + 0.5\sin^{-1}(A_f/A_e)\} \qquad Q_t \le Q_c \tag{14}$$

For the case in which transport was just sufficient to fill the fence, the average trapping efficiency given by Equation 14 is $0.79E_o$. For years in which snow transport is greater than the capacity of the fence,

$$\overline{E} = E_o\,(0.79)\,(Q_c/Q_t) \qquad Q_t > Q_c \tag{15}$$

The plot of average efficiency as given by Equations 14 and 15 (Figure 8) indicates that fences provide considerable benefits even in years in which snow transport exceeds the design storage capacity of the fence.

IMPLICATIONS FOR SYSTEM DESIGN

If the probability distribution for snow transport is known, Equations 14 and 15 can be used to estimate the reduction in snow removal costs, averaged over the physical life of the snow fences, in relation to the design storage capacity of the system. For any particular storage capacity design modulus, $K = Q_c/\overline{Q}_t$, the expected long-term average trapping efficiency, $\overline{E}_k$, is given by

$$\overline{E}_k = \int_0^k F(M)\overline{E}_{K,M}M\,dM \Big/ \int_0^k F(M)M\,dM \tag{16}$$

where $M = Q_t/\overline{Q}_t$. The frequency, $F(M)$, is given by the snow transport distribution. Although the frequency distribution of snow transport has received little attention in the past, inference is possible from the distribution reported for winter precipitation (*16*) and from potential snow transport as calculated from wind records using Equation 2 (*3*). For illustrative purposes, it is assumed here that the frequency distribution for the modular coefficients of seasonal snow transport is the same as that for winter precipitation, that is, mean 1.0 and variance $\sigma^2 = 0.1$:

$$F(M) = (2\pi s^2)^{-0.5} \int_{-\infty}^{k} \exp\{-(M - 1)^2/(2s^2)\}dM \tag{17}$$

This assumption is supported by one study of the potential snow transport estimated from wind speed records at Prudhoe Bay, Alaska (*3*). For locations having persistent snow cover throughout the winter, the assumption is probably close enough to reality that there would be no appreciable effect on the outcome of this analysis. Equations 14 through 17 were used to calculate average trapping efficiencies as a function of design modulus K. Assuming that reduction in snow removal costs would equal trapping efficiency, these results are plotted in Figure 9. A value of 1 for K, for example, indicates that the storage capacity of the system is exactly equal to the average annual snow transport. For $K = 0.5$, the storage capacity would be half of the mean annual snow transport. From Figure 9 it can be seen that using the average winter as the design year reduces snow removal costs by about 80 percent. Doubling the storage capacity reduces costs only by another 11 percent.

Even underdesigned systems reduce snow removal costs appreciably. A system having storage capacity to contain only half of the average annual snow transport, for example, reduces snow removal costs by more than 50 percent because significant savings accrue in all years, even those when the snow transport greatly exceeds the capacity of the fence (Equation 15).

Expected annual benefits, B, from a snow fence system are given by

$$B = P_{sr}\overline{E}_k\overline{Q}_t \tag{18}$$

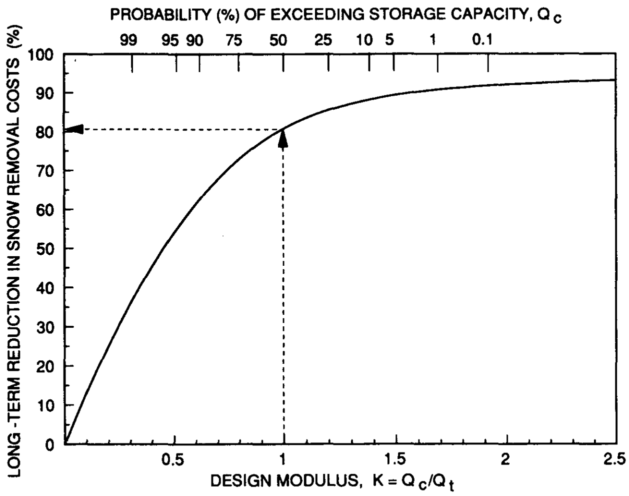

FIGURE 9 Long-term reduction in snow removal costs as a function of snow fence design year, for a road where all snow would be deposited without fences (Equations 14 and 15); model assumes no cost for snow falling directly on road surface.

where P_{sr} is the unit cost for mechanical snow removal. The storage capacity of a snow fence varies with fence height according to

$$Q_c = 8.5\, H^{2.2} \quad (19)$$

where Q_c is in tonnes per meter of fence length (*17*). Because the cost of snow fence construction increases linearly with height (*2*), average annual cost, C, of a snow fence system is related to design modulus K according to

$$C = O + a_{iT}F = O + a_{iT}P_f(K\overline{Q}_c/8.5)^{1/2.2} \quad (20)$$

where

O = annual maintenance expense,
a_{iT} = annual capital charge per dollar of fixed investment for interest rate i and amortization period T, and
P_f = capital investment cost per meter of fence height.

If maintenance cost is taken to be directly proportional to capital investment, then it can be shown by example that for all values of Q_t, Q_c, O, a, i, and T, the benefit-cost ratio (B/C) reaches a maximum at $K = 0.90$, that is, when storage capacity equals 90 percent of mean annual snow transport. Considering the uncertain frequency distribution of snow transport, designing snow fence capacity equal to mean annual snow transport is consistent with economic optimization.

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REFERENCES

1. R. D. Tabler, *Snow Fence Guide*. Strategic Highway Research Program, National Research Council, Washington, D.C., 1992.
2. R. D. Tabler. *Snow Fence Technology: State of the Art*. Special Report 89-6. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1988, pp. 297–306.
3. R. D. Tabler. Snow Transport as a Function of Wind Speed and Height. *Proc., Cold Regions 6th International Specialty Conference TCCP/ASCE*, New York, N.Y., 1991, pp. 729–738.
4. T. Kikuchi. A Wind Tunnel Study of the Aerodynamic Roughness Associated with Blowing Snow. *Cold Regions Science and Technology*, Vol. 5, 1981, pp. 107–118.
5. J. W. Pomeroy. A Process-Based Model of Snowdrifting. *Annals of Glaciology*, Vol. 13, 1989, pp. 237–240.
6. M. Takeuchi. Snow Collection Mechanisms and the Capacities of Snow Fences. *Annals of Glaciology*, Vol. 13, 1989, pp. 248–251.
7. H. H. G. Jellinek. *Compressive Strength Properties of Snow*. Research Report 34. U.S. Army Snow, Ice, and Permafrost Establishment, 1957.
8. R. D. Tabler. Self-Similarity of Wind Profiles in Blowing Snow Allows Outdoor Modelling. *Journal of Glaciology*, Vol. 26, No. 94, 1980, pp. 421–434.
9. R. A. Schmidt. Vertical Profiles of Wind Speed, Snow Concentration, and Humidity in Blowing Snow. *Boundary Layer Meteorology*, Vol. 23, 1982, pp. 223–246.
10. L. W. Lee. *Sublimation of Snow in Turbulent Atmosphere*. Ph.D. dissertation. University of Wyoming, Laramie, 1975.
11. R. A. Schmidt and K. L. Randolph. Predicting Deposition of Blowing Snow in Trenches from Particle Trajectories. *Proc., Western Snow Conference*, Vol. 49, 1981, pp. 34–42.
12. E. A. Finney. *Snow Control on Highways*. Bulletin 57. Michigan Engineering Experiment Station, Michigan State College, 1934.
13. R. D. Tabler and R. A. Schmidt. Snow Erosion, Transport, and Deposition in Relation to Agriculture. *Proc., Symposium Snow Management for Agriculture*, Great Plains Agricultural Council, 1986, pp. 11–58.
14. R. D. Tabler. New Engineering Criteria for Snow Fences. In *Transportation Research Record 506*, TRB, National Research Council, Washington, D.C., 1974, pp. 65–78.
15. R. D. Tabler, N. H. Berg, D. Trabant, H. Santeford, and P. A. Rechard. Measurement and Evaluation of Winter Precipitation. In *Cold Regions Hydrology and Hydraulics, ASCE Technical Council on Cold Regions Engineering Monograph*, 1990, pp. 9–38.
16. R. D. Tabler. Frequency Distribution of Annual Peak Water-Equivalent on Wyoming Snow Courses. *Proc., Western Snow Conference*, Vol. 50, 1982, pp. 139–148.
17. R. D. Tabler, J. W. Pomeroy, and B. W. Santana. Drifting Snow. In *Cold Regions Hydrology and Hydraulics, ASCE Technical Council on Cold Regions Engineering Monograph*, 1990, pp. 95–145.
