Locating Snow Fences in Mountainous Terrain

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A series of tests with large snow fences to control snow accumulation in alpine areas of central Colorado has provided greater understanding of the effects of surrounding terrain on snowdrift control with fences. Cross-sectional profiles of the resulting snowdrifts show that an upslope approach to the fence causes a short, high drift to form compared to the long shallow drift formed with a downslope approach. In the downslope approach, however, the total volume of snow trapped by the fence may equal or exceed the volume in the drift behind a fence with an upslope approach. Problems of locating fences for maximum effectiveness in irregular terrain are complicated by the need to maintain a gap between the fence and ground throughout the snow season. Placing fences in the lee of a ridge crest or other natural terrain break often increases the adverse pressure gradient and results in snow deposition upwind of the fence. Some criteria for avoiding this situation are presented.

Snow deposition in irregular terrain can be viewed as the interaction of 2 mechanisms: (a) transport of snow by wind and (b) airflow over natural terrain. These 2 mechanisms are examined briefly to develop a general idea of how they interact to cause snow deposition. Although knowledge of either mechanism is presently far from satisfactory for quantitative predictions of snow deposition, the general concept is used to explain snowdrift configurations behind fences in several terrain situations.

Throughout the paper, flow is considered turbulent and two-dimensional, with neutral atmospheric stability. Although this is far from a realistic model for the overall problem, it provides a point of departure and in some situations perhaps meaningful results.

SNOW TRANSPORT BY WIND

A summary of the state of knowledge concerning snow transport was presented by Mellor (1) and more briefly by Radok (2). Data presented by Budd et al. (3) and the analysis by Budd (4) seem to provide a satisfactory expression for the relative snow concentration profile over horizontal terrain. For a given particle size, this relationship states that the logarithm of drift density is proportional to the logarithm of height. The proportionality is determined by the shear stress. As shear stress increases, drift density at a given level increases. In deriving this relation, shear stress was assumed constant with height.

The snow concentration profile is linked to the wind velocity profile by assuming that the exchange coefficient for snow is equal to the turbulent eddy viscosity. For a constant shear stress through the layer of flow, the eddy viscosity and therefore the exchange coefficient for snow increase in direct proportion to height. The results reported by Budd et al. (3) justify these assumptions, at least for a first approximation over a horizontal surface.

The analysis for a horizontal surface provides a framework for investigating snow transport over irregular terrain. Radok (2) argues that deposition or erosion at a snow surface should be reflected by changes in the mass flux of drift snow. Thus, changes in the snow concentration profile in the direction of flow should be balanced by net accumulation or erosion. These changes in the vertical distribution of drift snow should correspond to variations in the turbulent shear stress distribution and mean wind velocity profiles. This leads to the question, What is known of the mean wind velocity profiles and the turbulent shear stress distribution over topographic obstacles?

WIND OVER NATURAL TERRAIN

Like that of the mechanism of snow transport by wind, knowledge of airflow over natural terrain is more extensive for horizontal surfaces. In such cases, the pressure gradient in the direction of flow is assumed to be zero for the layer near the surface, and shear stress is taken as constant and equal to the surface shear stress. These assumptions lead to the logarithmic mean velocity profile, which describes measurements in this layer quite well for neutral atmospheric stability.

As air moves over irregular terrain, local pressure gradients develop in the direction of flow. Near the windward surface of a hill or ridge, for example, flow moves along a favorable pressure gradient; that is, the pressure decreases in the direction of flow. Air moving leeward from the crest of a hill or ridge does work against an adverse pressure gradient where the pressure increases in the direction of flow. Work is done by wind against an adverse pressure gradient at the expense of flow momentum near the surface. If this momentum loss is sufficient to reduce mean velocity near the boundary to zero, the flow separates. It is primarily momentum considerations that lead one to examine the local pressure gradients.

To see what changes these local pressure gradients might cause in the mean velocity profiles and turbulent shear stress distribution, one must look to laboratory experiments on airflow with pressure gradients. Only a few wind profiles have been measured near the surface of irregular terrain, and there are no data for the turbulent shear stress profile above such a boundary.

Studies on the development of a turbulent boundary layer with pressure gradients in the direction of flow have many practical applications in the design of aerofoils, diffusors, and other devices. Much of this work is summarized by Schlichting (5). Several more recent studies also provide measurements of the turbulent boundary layer developing in one or more pressure gradients (6, 7, 8).

Detailed pressure gradient data for atmospheric flow over a terrain obstacle are not available to compare with a particular set of wind tunnel measurements. The general pattern of mean velocity profiles and the shear stress distributions for favorable and adverse pressure gradients are shown in Figures 1 and 2. These diagrams are designed to show the general relationships from a number of laboratory experiments and are not based on a particular set of measurements. For a favorable pressure gradient, flow accelerates and the mean velocities increase in the direction of flow (Fig. 1). This corresponds to a maximum shear stress at the surface and increasing shear stress in the direction of flow. The mean velocity profiles in an adverse pressure gradient (Fig. 2) show a decrease in velocity along the flow, with the largest deficits near the surface. The general features of the shear stress distributions shown in Figure 2 are (a) a

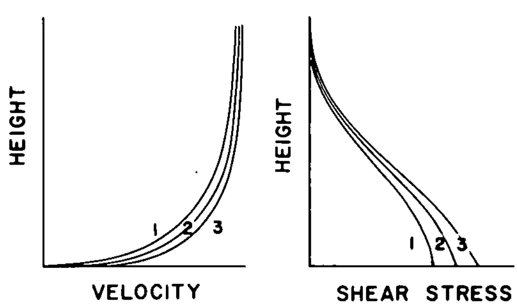

Figure 1. Generalized pattern of mean velocity profiles and shear stress distribution in a favorable pressure gradient (numbers indicate increasing distance downstream).

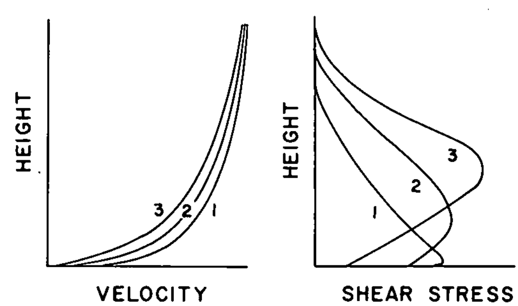

Figure 2. Generalized pattern of mean velocity profiles and shear stress distribution in an adverse pressure gradient (numbers indicate increasing distance downstream).

decrease in surface shear stress in the flow direction and (b) a maximum in the shear stress distribution that moves away from the surface as flow moves downstream.

To summarize: (a) For a given particle size distribution, the relative concentration of snowdrift depends on the vertical distribution of wind shear; (b) local pressure gradients developed by air flowing over irregular terrain result in changes in the vertical distribution of wind shear; (c) for favorable pressure gradients, the maximum shear stress occurs at the surface, and the surface shear stress increases along the flow; and (d) adverse pressure gradients result in decreasing surface shear stress along the flow, and a maximum shear above the surface. If the gradient is strong enough, flow separates from the surface.

For example, consider a two-dimensional turbulent flow across a snow-covered ridge. From experience, erosion is expected on the windward ridge face, with deposition of snow on the leeward slope. These 2 situations should be reflected by the snow concentration profiles. On the windward slope, with a favorable pressure gradient, the shear stress is largest at the surface. Therefore, the snow particle concentration should be larger near the surface than for the horizontal case. Because shear stress increases along the flow, drift concentration should increase as flow moves toward the crest. As flow moves into the adverse pressure region lee of the crest, surface shear stress decreases and some of the snow load in the lowest layers should return to the surface. At the same time, the concentration at higher levels may be increased by the developing shear stress maximum. This should give a profile with lower relative snow concentration near the surface, and a net decrease in mass transport.

An interesting point based on this argument is that deposition should begin before the flow separates. Snow may be deposited on the lee slope without flow separation. In this case the adverse pressure gradient is strong enough to retard flow near the surface. This decreases the shear stress and thus the snow concentration, but it does so gradually enough so that flow does not separate. At the other extreme, a strong adverse pressure gradient that results in separation may develop an eddy with reverse flow strong enough to transport snow up the lee slope. Much of the work on snow deposition, including the wind tunnel studies by Finney (9), is based on the assumption that the snowdrifts tend to fill the eddy zone. The successful application of these studies justifies this assumption for many situations. There are cases, however, where the arguments presented earlier must be considered, as the next section shows.

SNOW FENCES ON MOUNTAINS

The general concept developed earlier is used here to explain the effects of snow fences in several terrain situations. A snow fence represents an obstacle to the natural airflow that produces additional local pressure gradients. In each case presented, the adverse pressure gradient downwind of the fence is considered as an addition to the pressure gradient associated with the terrain configuration. The resulting drifts are examined from the standpoint of (a) total drift accumulation and (b) maximum drift length, 2 characteristics of major interest in snowdrift control.

Case 1—A Snow Fence on a Uniform Windward Slope

The adverse pressure gradient associated with the fence is added to the favorable pressure gradient created by flow up the windward slope. The effect of the fence is reduced by the terrain gradient. Both the total drift accumulation and the maximum drift length should be less than expected for the horizontal situation. Figure 3 shows that this is the case for the maximum drift length.

Case 2—A Snow Fence on a Uniform Leeward Slope

Here the adverse pressure gradient produced by the fence is added to the natural adverse pressure gradient. A larger fence effect should result in increased drift accumulation and maximum length compared to the horizontal case (Fig. 3). For example, a fence 4 m high with 1-m gap was located upwind of a depression in a long lee slope on Mt. Evans in Colorado. The resulting drift had a maximum length on the order of 30 times the fence height with a fairly uniform increase in depth (Fig. 4a).

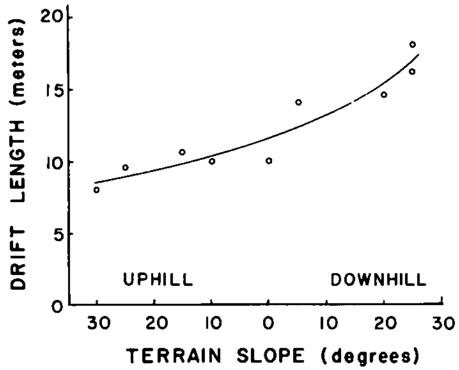

Figure 3. Maximum drift length as a function of terrain slope (10, Fig. 83).

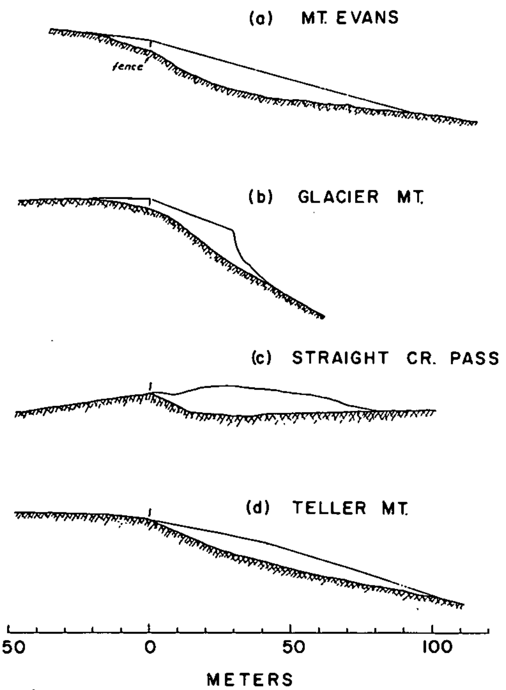

Figure 4. Snowdrift cross sections on 4 irregular terrain situations, showing variations of total drift length and snow accumulation (horizontal and vertical scale equal).

One problem that arises from locating a fence in a natural adverse pressure region is that the fence becomes buried in the drift. This results in expensive maintenance unless the fence is designed to withstand the snow settlement load.

Case 3—A Snow Fence Located Leeward From a Rounded Ridge Crest

The pressure gradient changes from favorable to adverse near the crest. The fence is located in an adverse pressure gradient, and the results depend on the strength of the natural adverse gradient. If the lee slope is gradual and flow does not separate, results should be similar to those of Case 2, where accumulation and length were increased and the fence became buried.

If the lee slope is steep and flow separates, the fence fixes the point of separation, and a cornice forms behind the fence. In this situation, velocities in the reverse flow are strong enough to transport snow. The drift is then shorter and contains less snow than expected for the same fence on a horizontal surface. Such a condition was examined at Glacier Mountain near Montezuma, Colorado (Fig. 4b). The fence was 35 m lee of the crest and the lee slope was steep. Again the fence was buried in the drift in spite of the gap between fence and ground.

Case 4—A Snow Fence at a Sharp Ridge Crest

If a fence is located at the point where the pressure gradient changes from favorable to adverse, the fence effect is again increased by the natural adverse pressure gradient in the lee of the crest. As in Case 3, the resulting drift depends on the steepness of the lee slope; it is larger and longer if the slope is gradual, and smaller if the slope is steep enough to cause strong reverse flow. However, the favorable pressure gradient upwind of the fence maintains increasing surface shear stress, which causes snow erosion and leaves the fence free of the drift.

The drift cross section shown in Figure 4c was measured at Straight Creek Pass on the Continental Divide in Colorado. The depression lee of the crest filled in rapidly, and the lee slope was then gradual enough to allow a rather spectacular drift to develop.

Case 5—A Fence Located at a Break From Horizontal to Lee Slope

In terms of pressure gradients, this fence is located at a point where the gradient changes from zero to adverse. The fence effect is again strengthened by the natural gradient, and the results depend on the strength of the gradient. A cliff is an extreme example of this case; separation is well defined at the drop-off, and a cornice typically forms. With a more gradual lee slope, both total accumulation and maximum drift length increase. Measurements at Teller Mountain (Fig. 4d) are an example of the latter situation.

Although the configurations of terrain and snow fence location described are only a few of the infinite possibilities, a few generalizations may summarize this section: (a) Snow fences that obstruct flow in a favorable pressure gradient yield smaller and shorter drifts than expected over horizontal terrain; (b) the effects of fences located at the change from a zero or favorable to adverse pressure gradient should increase as the gradient increases up to the point where reverse flow in the eddy begins to erode the downstream edge of the drift; and (c) fences located within an adverse pressure region should show effects that follow those given in statement (b), but usually become buried in the drift.

Statement (b) suggests that there is some terrain configuration that is optimum for accumulating snow behind a snow fence. The fact that there is a fence density less than 100 percent that gives maximum snow accumulation on horizontal terrain can be based on the same reasoning as statement (b). In both cases, the pressure recovery for optimum accumulation is more gradual than the maximum gradient that can occur. Perhaps pressure measurements on a fully developed snowdrift deposited on a horizontal surface would provide a starting place for model studies to determine if statement (b) is true, and at least the general configuration of the optimum situation.

Because favorable pressure gradients have been equated with windward slopes and adverse gradients with leeward slopes, one might wonder what is gained by considering pressure gradients in place of terrain gradients. There are at least 2 reasons. First, the pressure gradient is a basic parameter used to relate variables in the wind tunnel studies on development of turbulent boundary layers. To apply these studies to flow over natural terrain requires some idea of the natural pressure gradient. Second, the flow mechanism is governed primarily by the pressure gradient, and there is very little knowledge of the relationship between ground slope and pressure gradient. Scorer (11) has pointed out that the pressure gradient depends on the size and location of the lee eddy as well as the shape of the ridge. Perhaps a useful relation can be developed.

CONCLUSIONS

1. Changes in the shear stress distribution must be considered when snow transport theory is extended to irregular terrain.
2. Pressure gradient arguments and some field measurements support the idea that there is an optimum terrain configuration for snow accumulation. Information is not currently adequate to specify what the configuration would be.
3. Fences located within regions of adverse pressure gradient usually become buried in the snowdrift. These fences should either be designed to withstand snow settlement or be relocated near the start of the adverse pressure gradient.

REFERENCES

1. Mellor, M. Blowing Snow. U. S. Army Cold Regions Research and Eng. Laboratory, Monographs, Part 3, Section A3c, 1965.
2. Radok, U. Deposition and Erosion of Snow by the Wind. U. S. Army Cold Regions Research and Eng. Laboratory, Research Rept. 230, 1968.
3. Budd, W. F., Dingle, W. R. J., and Radok, U. The Byrd Snow Drift Project: Outline and Basic Results. In Studies in Antarctic Meteorology, American Geophysical Union, Antarctic Research Series, Vol. 9, 1966, pp. 71-134.
4. Budd, W. F. The Drifting of Nonuniform Snow Particles. In Studies in Antarctic Meteorology, American Geophysical Union, Antarctic Research Series, Vol. 9, 1966, pp. 59-70.

5. Schlichting, H. Boundary Layer Theory. McGraw-Hill, New York (Kestin, J., tr.), 1960.
6. Goldberg, P. Upstream History and Apparent Stress in Turbulent Boundary Layers. M. I. T., Cambridge, Gas Turbine Laboratory Rept. 85, 1966.
7. Spangenberg, W. B., Rowland, W. R., and Mease, N. E. Measurements in a Turbulent Boundary Layer Maintained in a Nearly Separating Condition. In Fluid Mechanics of Internal Flow, Elsevier Publishing Co., Amsterdam, 1967.
8. Herring, H. S., and Norbury, J. F. Some Experiments on Equilibrium Turbulent Boundary Layers in Favorable Pressure Gradients. Jour. Fluid Mech., Vol. 27, 1967, pp. 541-549.
9. Finney, E. A. Snow Drift Control by Highway Design. Michigan Eng. Exp. Station, Bull. 86, 1939.
10. Schneider, T. R. Snowdrifts and Winter Ice on Roads. National Research Council of Canada, Technical Translation 1038 (Sinclair, D. A., tr.), 1962.
11. Scorer, R. S. Theory of Airflow over Mountains: IV Separation of Flow from the Surface. Quart. Jour. Royal Met. Soc., Vol. 81, 1955, pp. 340-350.