DESIGN CRITERIA FOR ROADS IN SNOW-DRIFTING AREAS

Skuli Thordarson and Harald Norem
Norwegian University of Science and Technology,
Department of Road and Railway Engineering,
7491 Trondheim, Norway
TEL: +47 7359 4710/FAX: +47 7359 7020
E-mail: thordars@stud.ntnu.no

Abstract

During strong winds, drifting snow causes problems on roads in many harsh winter climate countries. Increased snow-removal costs, reduced access and safety problems are typical results of excessive snowdrift sedimentation and bad visibility along many roads in the exposed regions. This paper introduces some of the results from a research program including numerical experiments and field surveys. The research was done to enhance knowledge on drifting snow behavior on roads and to develop design criteria for better road and highway construction in mountainous areas and other areas where frequent snowfall and strong winds occur. The study is mainly based on CFD (Computational Fluid Dynamics) and field measurements. Simulations of wind flow were compared to snow cover surveys from roads in Iceland and Norway and the results have been used to develop recommendations for engineers. An important goal for this study has been to use CFD to develop geometric relationships that can be applied in road planning. The results presented herein include guidelines to evaluate the efficiency of natural snow deposition zones and their equilibrium snowdrift capacity. Furthermore, an example of three-dimensional flow under a steep road cut is presented. A theoretical study on the performance of different guard rail profiles in drifting snow is also present. We conclude that CFD is a suitable tool for developing recommendations for road engineering in snow-drifting areas.

1. Introduction

1.1 Background

Winter problems on roads can be severe in some harsh winter climate regions. Among the most important problems are slippery road surface due to ice and snow, excessive snow amount on the road due to snow fall and drifting snow and reduced visibility during snow storm. An EU-financed study [1] concludes that as much as half the annual road maintenance budget in Northern Scandinavia is dedicated to winter maintenance. Cost of snow removal alone can be as much as 80 % of the winter maintenance budget according to the same study.

Concerning problems caused by drifting snow, the severity of these is strongly dependent on the road design and the location of the road with respect to terrain features and climatic factors. Therefore, better roads in snow drifting areas will result in savings in road maintenance costs, higher safety level and better accessibility for the traffic.

1.2 Numerical wind flow simulations

By using CFD (Computational Fluid Dynamics), the wind flow over the terrain adjacent to the road can by calculated. Through known relations between the wind speed distribution and the behavior of snow drifting, such calculations give the opportunity to evaluate the quality of alternative design solutions. Problems of different geometric scales can be simulated, and hence both the path of the road through a difficult snow drifting site and road cross section can be investigated. More advanced use of CFD implements simulation of the snow drifting together with the wind flow, so called two-phase flow modeling. Some experiments with two-phase numerical simulation of snow drifting and sedimentation have been done by several investigators. However, most snow drifting models have limited use in engineering applications due to questionable accuracy, but great improvements have been achieved in the recent years. Plain wind flow simulations are more realistic and allow for qualitative comparison of snow drifting conditions without raising questions on the validity of the calculated drift formations. For this reason, the current study is based on wind flow calculations supported by in situ field observations on roads.

1.3 Objective

In 1998, a Ph.D. study program was started at the Norwegian University of Science and Technology. The goal for the program is to enhance knowledge on, and develop engineering guidelines for road design in snow-drifting areas. The current paper summarizes some topics and results of the project, which final report is scheduled for defense in 2002.

Previous studies that have been reviewed in the project is the work of Norem [2,3] and Tabler [4]. Norem did model experiments with sand in water to simulate snow drifting on roads and has also presented detailed field observations. The guidelines of Tabler are mainly based on statistical analysis of field measurements. The current study is based on many common problems treated by these authors. The advantage of the current study is the ability to numerically analyze the wind flow around roads and confirm fluid-dynamically assumptions from previous studies, as well as to investigate new topics that previously have remained unexplored. In this study, a commercially available engineering flow solver is used, Flow3D (Flow Science, NM USA). The system is very suitable for this purposes because different geometric forms can easily be integrated into the model.

2. Methods

2.1 Wind flow simulations

Outline of the simulation process is as follows:

1. Integration of terrain and road geometry into the model.
2. Choice of suitable wind profile and boundary conditions.
3. Simulate until a steady state solution is achieved.
4. Analysis of wind velocity distribution and streamline pattern.

For relative comparison of design alternatives, geometric details can be changed and the four steps repeated. Regarding the last step, it should be explained briefly here how wind velocity and streamlines can be helpful to interpret drifting snow behavior. Experiments and theory have shown that the snow transport capacity of the wind (saturated flow) is related to the wind speed by a third power relationship:

$$Q \approx C(U - U_{th})^3$$

where Q is the snow drifting rate in kg per meter width across the flow, U is the local wind speed measured at reference height and U_{th} is the threshold wind speed necessary to initiate snow transport. The constants C and U_{th} are dependent on the snow cover conditions such as cohesion and surface structure. Assuming that the wind is fully saturated with snow particles at a given location, any decrease in the wind speed downstream from that location should lead to snowdrift build up on the ground, as the snow transport capacity of the wind decreases by the third power of the wind speed reduction. The more the wind speed drops along a given path along the flow, the faster the sedimentation or drift build up occurs. As the sedimentation gradually builds up a drift formation on the ground and consequently raises the ground surface, the wind speed increases again and the sedimentation slows down. When the equilibrium snowdrift surface is reached, the wind speed is practically as high as in the upstream area above the initial sedimentation zone. Should the wind not be saturated with snow in the area before the wind speed reduction, sedimentation need not necessarily occur, since the wind still may have excess capacity to transport the snow particles further downstream. This concept is confirmed in section 3.2.

In a three-dimensional flow situation, the picture is usually not as simple. Sedimentation can then happen at relatively high wind speeds, because the snow concentration in the air can differ greatly from place to place when three-dimensional flow is present. Under these conditions, streamlines can be very helpful to understand the flow. Streamlines represent the path of fluid particles through the flow, and make it possible to graphically sketch the flow behavior.

2.2 Field data

When designing a road through a snow drifting area, some minimum data has to be available. Besides topographic data, some weather information is necessary. The most important is knowledge on which wind directions bring the largest quantities of drifting snow. These are the directions associated with the highest wind speeds and precipitation. It is important to note that these need not be the same as the prevailing or most frequent wind directions in the area.

In an open landscape, data from meteorological observation stations near the actual area can be used. On the other hand, if the road is located in mountainous and steep surroundings, some local investigations might be appropriate because of how strongly the landscape can modify and redirect the wind flow. The total average winter precipitation or snow depth on the ground is also important. The design should be chosen with respect to the expected snow amount on the site.

For the purposes of the current project, detailed weather information was acquired at two actual road sites during the winters of 1999 and 2000. Automatic weather stations were installed at road no. 1 at Bolstadarhlidarbrekka in Northern-Iceland and at road Fv-232 through Kaperdalen valley on the island of Senja in Northern-Norway. At the latter site, detailed observations on visibility along the road during snow-storms were also done. The results from the visibility observations are presented in the project final report.

3. Results

3.1 General Issues

The demands to a road in a snow-drifting area have previously been summarized by Norem [2,3]. The most important of these are to avoid snow deposits on the road, to ensure little snow transport across the road for better visibility and to facilitate for the maintenance of the chosen design. In practice, the road design often has to be a compromise between construction costs, safety, accessibility and maintenance costs.

When an existing road section is to be rebuilt or modified because of snow drifting problems, or when a new road is planned, some principal questions have to be answered. For this first step of the planning process the road should be divided into suitable sections of uniform terrain characteristics and the expected flow conditions. For each section it is important to find out whether the flow will behave two- or three-dimensionally when the prevailing snow drifting wind direction is present. An example of a two-dimensional situation is treated in section 3.2. Under such conditions, the chosen cross section for the road may function properly along the whole road section if changes in topography and the direction of the road with respect to the wind are moderate.

An example of a three-dimensional flow is presented in section 3.3. When the wind flow behaves three-dimensionally, the snow problems can sometimes be found at unexpected places.

Another important question is whether the road is located in a high wind speed area where snow is eroded from the ground or if it lies in a snow sedimentation area. It is to prefer that as long sections as possible lie in an erosion zone, as long as the wind speed itself is not hazardous to the traffic. Under such conditions, a road cross section that ensures a self-cleaning road surface can be chosen. However, road sections where the drifting snow is blown over the road without the sedimentation of snow on the road can present visibility problems if the upwind fetch of available snow cover is long. Snow fences have often proved helpful for better visibility in such situations.

If the road on the other hand must be placed in a natural snow sedimentation area, a sufficient storage capacity for sedimented snow should be offered. The snow storage capacity should be large enough to prevent that the equilibrium snowdrift surface reaches the road.

3.2 Two-dimensional drift equilibrium

In mountainous or hilly terrain, some sections of a road will inevitable lie in leeward facing slopes. Consequently, the road may be located in a natural snow deposition zone, which may lead to excessive snow amounts on the road. In such places, the possible amount of drifting snow and the equilibrium shape of the drift on the ground has to be known and accounted for in the road design to avoid problems. When very large quantities of drifting snow are expected, or when providing high enough storage capacity for sedimented snow is not feasible, the road should either be placed down-stream of the equilibrium snowdrift pattern or up-stream of the deposition zone.

To better understand the snow drifting conditions on down-slopes, we simulated the wind flow along several terrain profiles [5]. Our results indicate that the horizontal wind speed gradient close to the surface, dU/dx, gives information on the rate of drift build-up and the stage of drift development towards equilibrium. A schematic presentations of our findings is displayed in Figure 1. The calculated wind speed is used together with the equation in section 2.1 to write the curve of relative transport capacity along the surface, Q_{rel}.

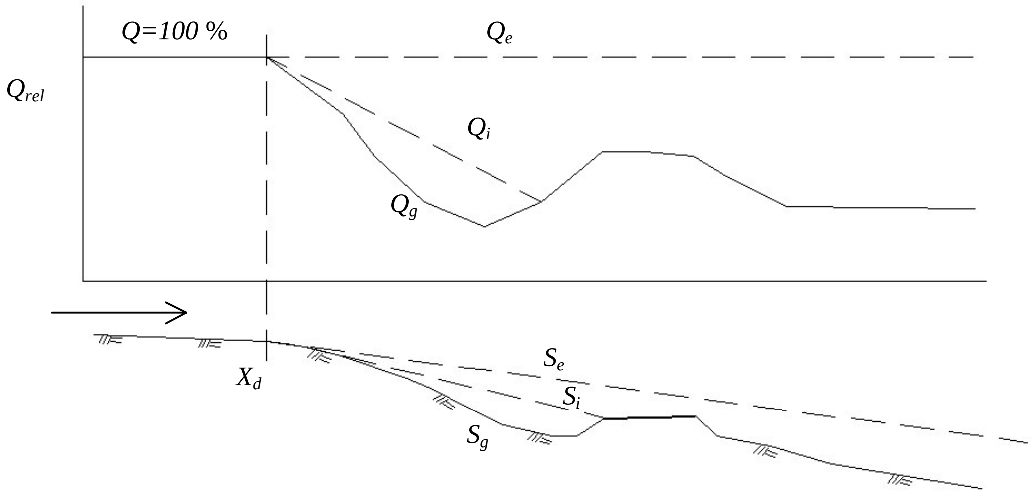

Figure 1. Snowdrift development, wind from left to right. The upper figure shows the calculated relative transport capacity and the lower one is an example of a typical terrain profile on a leeward slope together with drift surfaces. Symbols are explained in the text.

Upwind (to the left) of location X_d, the wind speed and hence the transport capacity is usually constant if the terrain slope is constant (Figure 1). It can be stated that the value of Q_{rel} at X_d represents the actual snow transport rate, since the fall in Q_{rel} downwind from that point results in sedimentation. It means in other words that the wind is fully saturated with drifting snow and can sustain no drop in speed without depositing snow on the ground. Therefore, it is convenient to normalize Q_{rel} to that value and set the transport capacity to 100 % at X_d.

Before any sedimentation has happened, the original ground surface, S_g, gives the Q_{rel} curve marked Q_g. During an intermediate stage of snowdrift build up, snow surface S_i, the snow transport capacity and the snow drifting rate fall according to curve Q_i. In theory, a drift surface has reached it's maximum or equilibrium stage, S_e, when the wind speed or snow drifting rate no longer falls along it's surface. Hence, the equilibrium curve Q_e is constant at the same value as at location X_d.

When we write the drift slopes S_i and S_e as the tangens of the slope angle ($dz/dx \times 100$ %) and the slope of the Q_{rel} curve as percentage drop per meter ($dQ_{rel}/dx \times 100$ %), our results indicate a linear relationship between the slope of Q_i and (S_i - S_e). This is illustrated in Figure 2.

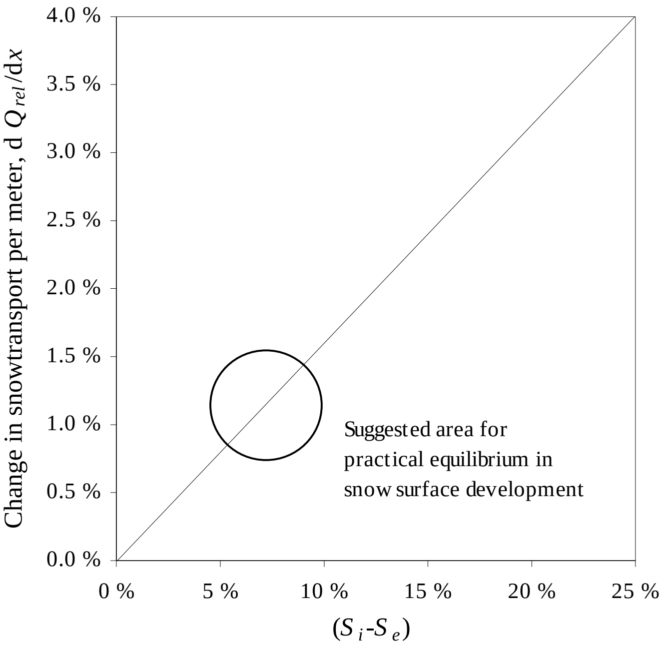

Figure 2. The linear relationship between drop in snow transport rate, Q_{rel}, and the deviation of the intermediate drift surface, S_i, from the theoretical equilibrium surface, S_e.

The diagram in Figure 2 indicates that as the intermediate drift surface slope S_i develops towards S_e, the drop in snow transport rate decreases towards zero. Steep Q_i indicates high loss of snow transport along the surface, hence the sedimentation of snow on the ground occurs fast at this stage. As the slope of Q_i gets smaller, the rate at which snow deposits becomes lower. Therefore, in many practical situations, the snow surface will not have reached the theoretical maximum, S_e, by the end of the winter. This will of course depend on the drifting snow amounts and the storage capacity of the deposition area.

According to our field measurements and simulations, a practical equilibrium level for dQ_{rel}/dx might be between 1 % and 1.5 % per meter downwind from the drift starting point at X_d (Figure 2). This is equivalent to (S_i - S_e) of about 5 % to 10 %. Before applying the principle presented here, the theoretical equilibrium slope, S_e, has to be estimated. In many situations, S_e, will be a direct extension of the terrain slope upwind from location X_d, but must nevertheless be evaluated with respect to the landscape both upwind and downwind from the road.

3.3 Three-dimensional flow in road cuts

Steep terrain or rock cuts along the road will usually result in strong lateral flow deflection or even separated flow. The resulting flow must be described three-dimensionally. Common snow problems on roads underneath steep cuts is high accumulation of snow particles in the air, resulting in poor visibility, and snow deposits on the road.

As an example of this, we present results from wind flow simulations of two different cut designs. Both present a 300 m long road cut through a simplified ridge that reaches the maximum height of 7 m halfway along the road. The example reflects an actual situation found at a the site for a new road align that is planned on road no. 1 at river Thjorsa in South-Iceland. The two alternatives are shown in Figure 3. Plots of relative wind speed distribution at ground level and streamlines for the two examples are presented in Figure 4. The incident angle of the wind is chosen as 95° or almost perpendicular to the road.

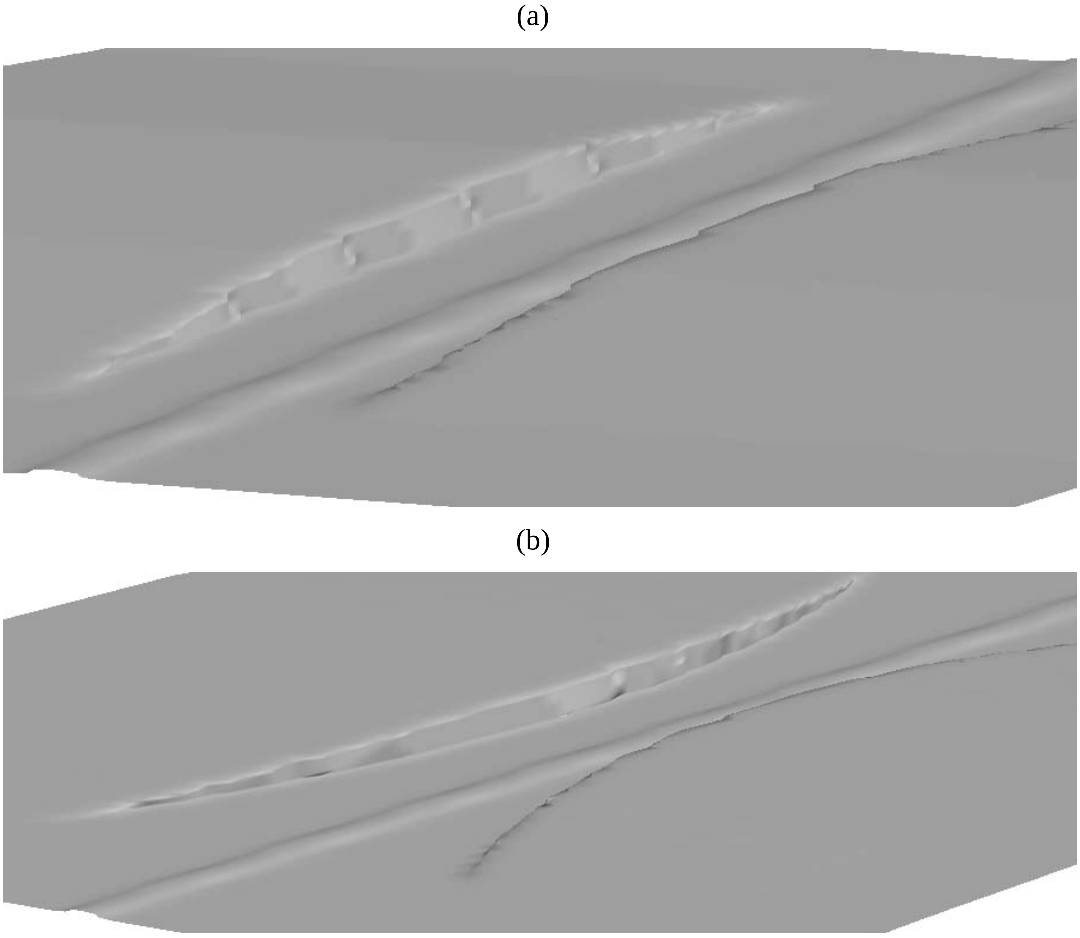

Figure 3. The two design alternatives of road cuts through a terrain ridge treated in the report. Alternative (a) is a conventional steep cut along a straight line, (b) is a steep cut along a path that forms and arc in the horizontal plane and therefore the ditch widens out in both ends.

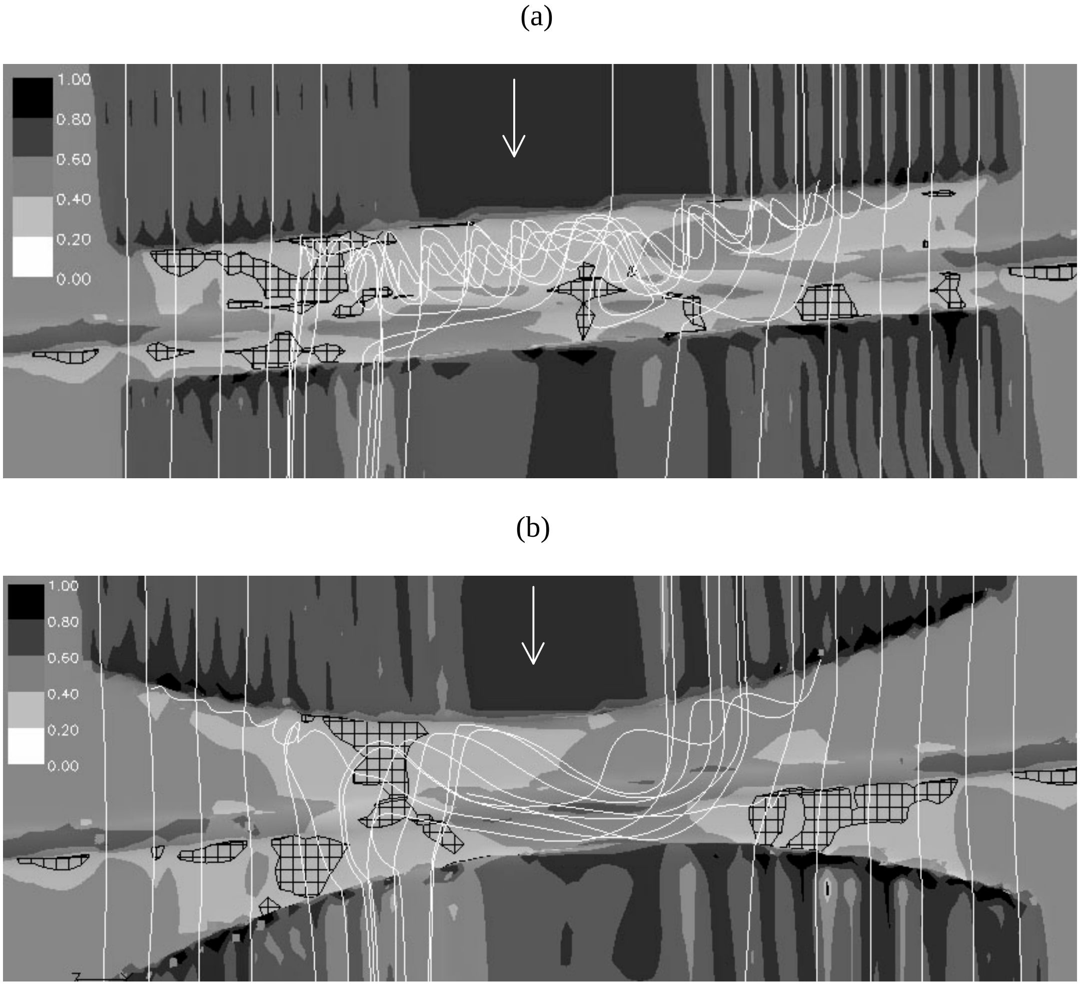

Figure 4. Plots of relative wind speed distribution and streamlines. Wind direction is indicated by the arrow. The areas marked with black squares indicate the lowest relative velocity, 10 % of the reference value. The streamlines are crossing the road at 1.5 m above the road, the eye level of the drivers.

The streamlines in Figure 4 show how the flow is deflected in a vortex underneath the steep wall and travels along the road. The main difference between alternatives (a) and (b) is the higher velocity over the road in (b) and less circulation of air over the road. Simulations for the case where the incident angle of the wind is 30° to the road show even more difference in the expected snow problems in favor of alternative (b).

3.4 Guard rails

Guard rails on the road shoulder are well known to cause snow drifting problems. The use of guard rails is avoided in many regions and special guard rails that cause less problems have even been used.

The ability of a specified guard rail type to collect snow on the road and cause visibility problems can be evaluated by the air resistance or drag force that the rail exerts on the flow. The drag force that a body exerts on the flow is written as;

$$F_D = \frac{1}{2}\rho \cdot U^2 \cdot A \cdot C_D$$

where F_D is the drag force, ρ is the density of the air, U is the flow speed, A is the projected frontal area of the body and C_D is the drag coefficient assosiated with the body shape.

High drag profile type generates more turbulence in the flow and also reduces the wind speed more than a low drag profile type, and will consequently cause larger snow problems on the road. In addition to providing low drag, a suitable guard rail profile for use in snow-drifting areas also has to be durable against the forces from creeping snow-banks and forces from the snow removal equipment.

A theoretical comparison of some chosen guard rail profiles is presented in Table 1. The reference guard rail profile has a circular cross section. The oval shapes in the table are dimensioned such that the mechanical strength of the profile in the horizontal direction is the same (the moment of inertia about the vertical axis, I_z, divided by half the profile width).

Table 1. Example of guard rail shapes. The calculated profile strength is based on solid cross sections, for example wood beams.

Profile shape	Aspect ratio *b/h*	C_D	Profile strength $\frac{I_z}{\frac{1}{2}b}$ (mm^3) /10^5	Profile width b (mm)	Profile height h (mm)	Relative F_D ($C_D \cdot \frac{h}{200}$)
Circle	1.0	1.0	7.85	200	200	100%
Oval shape	1.5	0.75	7.84	229	153	57%
Oval shape	2.0	0.55	7.85	252	126	35%

The comparison shows that the air resistance and hence the snow collecting ability of the guard rail can be reduced dramatically by choosing an oval shape in stead of a circular one, without decreasing the profile strength against horizontal impact from cars. A conventional W-shape guard rail of 300 mm height would give relative drag force of approximately 300 % compared to the shapes in Table 1.

Numerical wind flow simulations have been done in the current study to analyze the effect of different guard rail shapes on the wind flow over the road. The results are well suitable as a basis for comparing profile shapes, but for more realistic comparison, some full scale outdoor experiments are necessary.

4. Conclusions and further works

The paper has introduced the use of Computational Fluid Dynamics for snow drifting studies on roads. We find numerical wind flow simulations a useful method to learn new things about the subject of snow drifting on roads and develop guidelines for engineers.

The practical results presented in the text deal with drifting snow depositions on leeward slopes, three-dimensional flow in steep road cuts and the evaluation of guard rail profiles. For snow sedimentation on leeward slopes, we introduce the concept of theoretical equilibrium snowdrift surface as a reference value for evaluating the most likely practical snow surface to use when choosing cross section for the road and the adjacent terrain. The example on steep road cuts indicates that there is an advantage of widening the ditch at the ends of the cut to pass the drifting snow through with less generation of turbulence and reduction of the potential sedimentation areas. At last some theoretical considerations on the air resistance of guard rail profiles is presented. An oval shape profile with aspect ratio (width/height) equal to 2 is a promising profile for further testing.

More detailed results from the topics treated in this report and results from other experiments on snow drifting in road engineering are presented in the final report that is scheduled in 2002. Among the other topics treated there are studies on the effect of road embankment slope and height and the effect of lateral slope of the road surface (superelevation).

5. Acknowledgements

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