APPLICATION OF SNOW-SIMULATION MODEL TESTS TO PLANNING AND DESIGN

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ABSTRACT

The use of snow-simulation model tests has become an integral part of the design and planning process of numerous new building projects. The model tests simulate many aspects of snow drifting, snow deposition, scouring and snow infiltration, thus enabling serious snow accumulation problems to be predicted in advance and providing a means for developing remedial measures, such as landscaping or building modifications. The authors' company has since 1972 conducted model studies at its Guelph and Edmonton laboratories on several hundred projects in Canada and the U.S.A. and has had many opportunities to compare the results with field experience. In this paper, selected examples of the application of model tests to various projects are described covering the topics of ground level drifts around buildings, roof accumulations, drifting over highways and railways, arctic drifting, snow infiltration into air intakes and special problems such as the influence of roof-mounted solar collectors on the roof snow accumulation. The model scaling laws for the simulation of snow drifting and snow deposition in water flumes and in wind tunnels are discussed. While a perfect simulation of all aspects of snow drifting is not in practice possible, it is shown, with the aid of comparisons of field observations and model results, how the judicious use of the water flume or wind tunnel to specific problems is nonetheless capable of providing extremely valuable information for design and planning applications.

1.0 INTRODUCTION

In northern climates snow accumulations due to wind action are a serious factor to be contended with in the planning and design of building developments, highways, railways and equipment. Every winter roof collapses occur due to unexpected local snow buildup, sometimes with fatal consequences, and hundreds of millions of dollars are spent in clearing snow drifts from everything from front porches to major expressways. It is thus highly desirable to be able to incorporate snow management methods into the design process in order to prevent collapses and minimize snow clearance costs.

The negative aspects of snow are partly compensated for by the development of skiing and other snow sports. However, these sports make other forms of management of the microclimate desirable, such as preventing the wind from scouring snow from ski slopes or trails and ensuring that they are not overly exposed to chilling winds.

Since the accumulation of snow due to wind action is a complex phenomenon it is difficult to predict the probable accumulations in any particular circumstances except by the judicious use of small scale model simulation techniques. These techniques have

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been used by Morrison Hershfield Limited on several hundred projects in Canada and the U.S.A. and in this paper some of these experiences are related. The discussion consists of both model test results and full-scale observations that throw light on the accuracy or shortcomings of the model simulations. Since a perfect simulation of all the various facets of snow drifting is not possible with current techniques, it is of great importance in interpreting model results to draw on past full scale experience. The model tests are in some instances capable of giving valuable quantitative data. In other cases they serve mainly as a diagnostic tool for identifying the locations, but not the exact size, of problematic drifts. Past full scale experience helps to fill in the picture. One of the model test's greatest strengths is the facility with which the model enables remedial measures such as landscaping or building modifications to be developed that will move snow drifts away from problem areas to locations where they no longer cause inconvenience or danger.

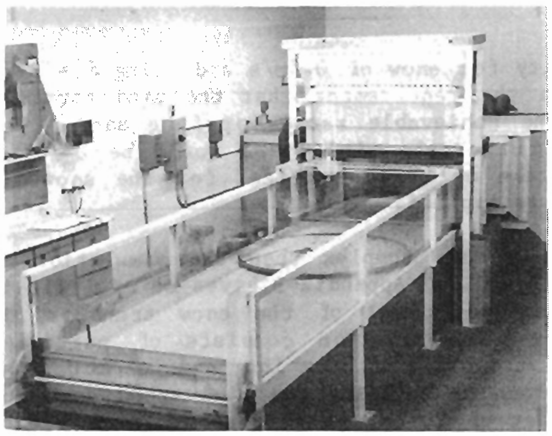

Figure 1 - Water Flume

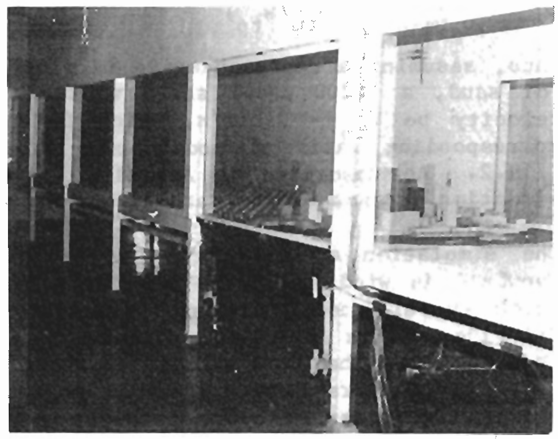

Figure 2 - Wind Tunnel

There are two main methods that have been used to model wind action on snow. One method uses a water flume and the other a wind tunnel. Figures 1 and 2 show Morrison Hershfield Limited's water flume and boundary layer wind tunnel. In the water flume the wind flow around the building is represented by the water flowing around the model and the snow particles are simulated by sand grains. The patterns of snow drifts at full scale are predicted from the patterns of sand accumulations observed on the model. The water flume method is used in most snow accumulation studies in Morrison Hershfield's laboratories. For some studies, however, we have found the wind tunnel useful for determining the wind speed distribution, from which drift patterns are then inferred. A number of investigations in university or government laboratories have experimented with different particles in wind tunnels to represent snow. Examples of wind tunnel particles that have been tried are sand, sawdust, glass beads, styrofoam and china clay. In all scale model studies it is essential to first consider how the model tests relate to full scale so this subject will be addressed first.

2.0 MODEL SCALING CONSIDERATIONS

Snow accumulates at a particular location due to a snowfall and also due to subsequent wind induced drifting. Considering the snowfall accumulations first, wind blowing at the same time as the snow is falling causes more snow to land in some areas than others. This phenomenon can be simulated at model scale fairly accurately and the theory behind the model scaling is given in Appendix A. The analysis in Appendix A is an extension of Etkin's 1971[1] theory which he developed when studying the effectiveness of air curtains as shelters from rain. The analysis shows that in order to obtain a correct model simulation in water, the terminal velocity of fall of the model particles, W_{tm}, must satisfy

$$W_{tm} = W_{tp} \; L_m/L_p \; ((\gamma - 1)/(\gamma + 1/2))$$

where W_{tp} = terminal velocity of fall for snow

L_m = length of model building

L_p = length of full scale building

γ = specific gravity of model particles

This relation incorporates the buoyancy and virtual mass effects for water. When the above relation is satisfied then the ratio of the water speed, U_m, of the model to the wind speed, U_p, at full scale is

$$U_m = U_p \; (W_{tm}/W_{tp})$$

Thus, assuming a representative terminal velocity for snow of 0.5m/s and using γ = 2.65 for sand, a 1:200 model scale would result in the requirement that the sand terminal velocity be W_{tm} = 2.6cm/s, which is within the achievable range for fine sand. The corresponding ratio of model water speed to full scale wind speed would be U_m/U_p = 1/19.2. As described in Appendix A the duration of the model test for the snowfall situation depends on the rate at which the sand is applied.

The simulation of snow drifting is considerably more complex than the simulation of snowfall in wind as may be seen in References 2 and 3. Appendix B gives an analysis in which overall model scaling parameters are derived. Most of the snow transport in drifting occurs by the process of saltation[4]. Saltation consists of particles bouncing over the snow surface in short hops of the order of 30cm long and not more than a few centimeters high. Since in most areas around a building the wind speed does not change significantly over distances of the order of 30 cm, it is reasonable to relate the local snow transport rate to the local wind speed only. In other words, the wind speed a particle sees at the point where it takes off is, by and large, the same as

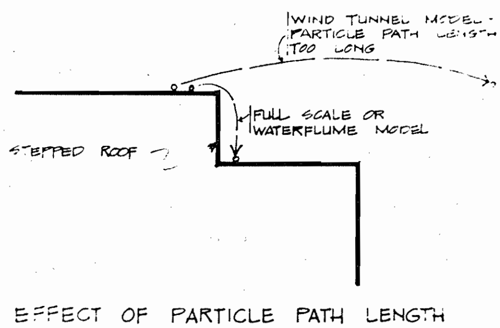

Figure 3

where it lands, and it does not know what the wind is doing elsewhere. Several simplifications arise as a result of the thinness of the saltation layer and the shortness of the particle paths. These are exploited in Appendix B. In the water flume it is found that the sand particle paths in saltation are very short, only a few grain diameters long, which is desirable since this results in the path length being short in relation to the model building size, thus duplicating the full scale condition. In the wind tunnel the particle path length remains about the same as at full scale, i.e. 30 cm, and this is a serious disadvantage since it means the particle path length is typically of the same order as, or larger than, the size of the model building. Rather than particles saltating around the building, as they would at full scale, on a wind tunnel model they would often jump right over the top. Figure 3 illustrates the problem of simulating the drifting of snow on a stepped roof in the wind tunnel as opposed to the water flume. The particles from the upper level tend to jump right over the step onto the ground in the wind tunnel whereas in the flume and at full scale, they drop onto the lower level causing significant build-up. The water flume thus tends to provide a superior simulation in many instances, but it does also have shortcomings. One is that there is a tendency in flat, open spaces for slowly moving dunes to form with their peaks and valleys running normal to the water flow direction. While similar dunes of snow have been observed in flat open terrain at full scale, the tendency for them to form appears to be not as strong as in the water flume. In the areas of interest near buildings the flow disturbances caused by the model buildings tend to prevent the formation and propagation of these dunes, so in most cases they do not seriously impair the value of the study. However, in some cases the dunes can complicate the interpretation of the model results, making it doubly important to draw on field experience.

3.0 SOME MODEL AND FULL SCALE EXPERIENCES

The most common type of accumulation is a leeward side drift which is caused by snow particles accumulating in a region of aerodynamic shade. The reduction in approaching wind speed found on the leeward side of a solid or porous object causes snow particles to be deposited, with the best example of this being the snowdrift formed by a conventional snow fence. Simulation techniques are quite reliable for predicting this type of accumulation. Figures 4 and 5 show full scale and model examples of leeward drifts at a settlement on Belcher Island in Hudson Bay.

Downwind Drift

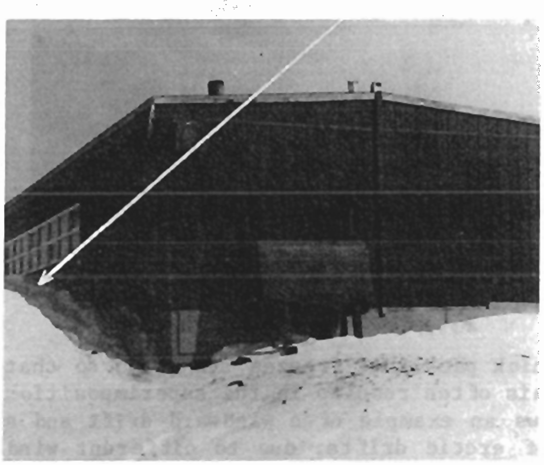

Figure 4

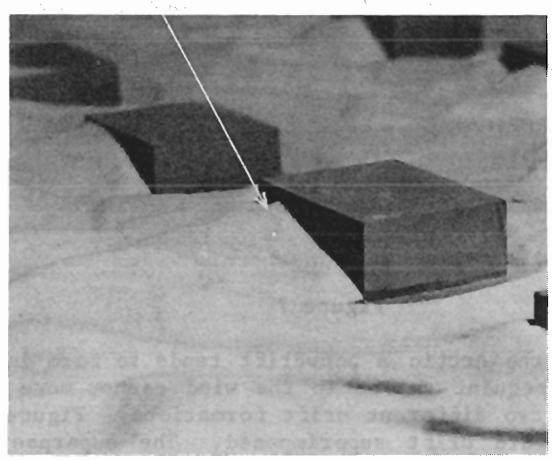

Figure 5

Snowdrifts which form on the windward side of a solid object are less common but under certain circumstances can be the major form of drifting at a site. This type of drift is formed as a result of the interaction between the vortex on the windward side of an object and the approaching wind flow as illustrated in Figure 6. Figures 7 and 8 show examples of full scale and model windward drifts, again at Belcher Island.

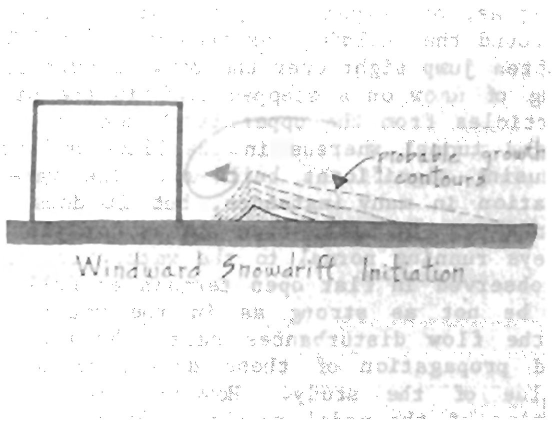

Figure 6

Upwind Drift Superimposed Downwind Drift

Figure 7

Upwind Drift

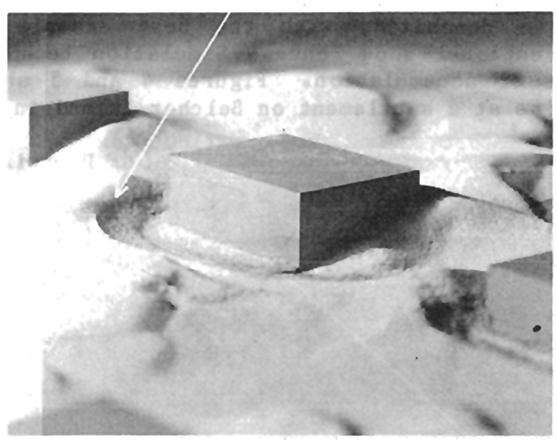

Figure 8

In the Arctic a snowdrift tends to form into a thick pack that freezes its shape so that subsequent shifts in the wind cannot move it. This often results in the superimposition of two different drift formations. Figure 7 shows an example of a windward drift and a leeward drift superimposed. The superposition of arctic drifts, due to different wind directions, could be simulated in the water flume in principle by fixing the sand shape artificially after completing tests for one direction and then testing for another wind direction with the previous drifts now held fixed. However, most of the more serious drifts at a site form during a particular storm while the wind is from a predominant direction. Thus the cumulative effect of winds from several wind directions is usually a secondary consideration. When information on the cumulative effects of several wind directions is required, the model test results must be combined with a mathematical model of the probabilities of wind speed, wind direction, snowfall and temperature in the region where the site is located and a computer analysis carried out. This type of analysis is fairly complex and therefore is not lightly undertaken. For the great majority of projects, the results of such an analysis would not justify the effort.

Another major type of drift formation which is found almost exclusively in arctic regions is the long smooth drift which has its length aligned with the wind direction. Figures 9 and 10 show ground level and aerial views of long drifts. Drifts of this type are caused by stable vortices originating from buildings or other obstructions as illustrated in Figure 11. In this figure the two vortices shown originating from the buildings sweep the snow into the long drift downwind of the gap between the buildings. Figure 12 illustrates a similar type of drift generated on a model. The model simulation is only partially successful in that it shows the start of a long drift but does not simulate the great length and size of the full scale snow accumulations that can occur. Complete buildings can be buried by these long drifts. Clearly it is essential to combine field experience with the model data in a case like this in order to predict what the eventual size of the long drift will be.

Figure 9

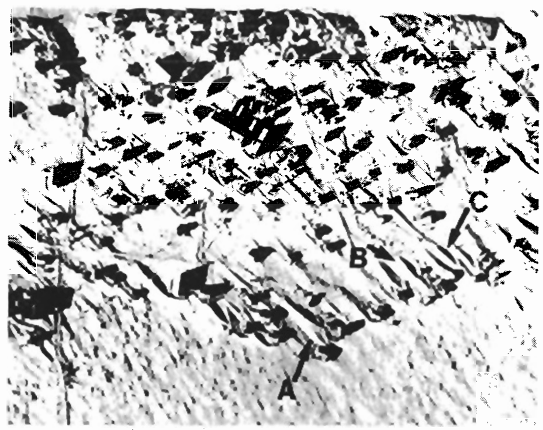

Figure 10

Start of long drift

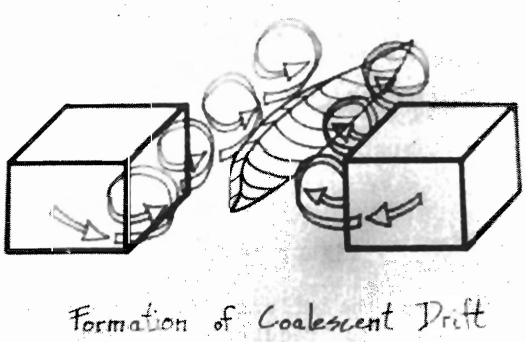

Figure 11

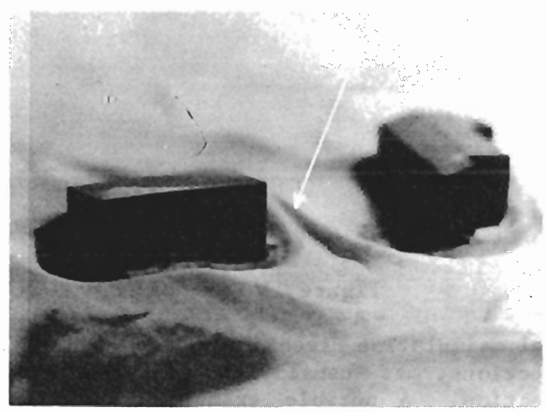

Figure 12

4.0 BUILDING AND SITE DESIGN APPLICATIONS

The facilities at Morrison Hershfield Limited have been used to conduct a multitude of snow simulation studies over the past ten years and have therefore accumulated many design recommendations that have been observed at full scale to be effective in controlling drifting snow. A few of these recommendations are presented here to demonstrate the usefulness and in some cases the limitations of snow simulations conducted using a water flume.

One of the primary requirements in siting a building located in an area of heavy snow accumulation is that the orientation be selected to minimize the accumulation of snow against critical areas on the building face. Many of the photographs in this paper show areas on a building which are relatively drift free while other areas are inaccessible due to drifting snow. It is often found that the corners of a building are relatively drift free, particularly if two or more wind directions occur at the site.

A model simulation will sometimes determine that an entrance has, at the design stage, been located in an area of severe snow accumulation. This occurred during the detailed design of a school at Coral Harbour, which is located on Southampton Island on the north side of Hudson Bay. Changing the orientation or the interior floor plan of the building was not possible due to the advanced stage of the design, resulting in entrances being located on the leeward side of the building. Therefore, wind deflector fins, which provided localized increased wind flows in the vicinity of the entrances, were tested using the sand and water snow simulation technique. The results are shown in Figure 13. The prediction that the entrances would remain clear of drifting snow proved correct as shown in Figure 14. The final design of the wind deflectors used angled sidewalls to ensure efficient operation during small variations in the direction of the wind.

Figure 13

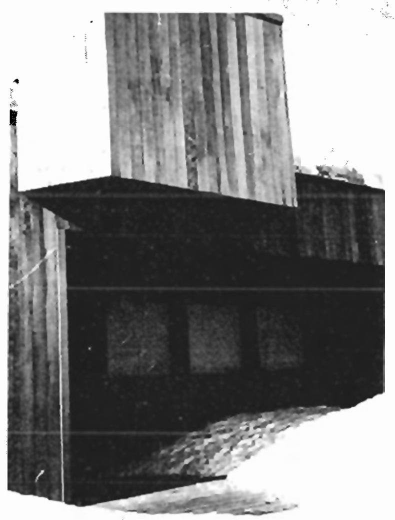

Figure 14

Model simulation techniques are useful for determining the effects of various wind directions, as usually a different solution geometry is required for each wind direction. A notable example of this is the T.T.C. Wilson Yard, Toronto, which had experienced severe problems within the yard before having a model simulation test conducted. The two prevailing wintertime winds required that a parallel and angled snowfence arrangement be used as shown in the aerial photograph of the site, Figure 15.

Figure 15

Testing of problematic areas on highways usually results in a better understanding of the reason for the drift formation and often provides an effective remedial solution. Highway 400 in Ontario is associated with severe drifting snow problems as illustrated by the photograph of the model simulation in Figure 16. The highway bridge provided a disruption to the windflow and the resulting reduced wind speed zone tended to fill with drifting snow. Collecting the snow particles with landscaping before they reach the critical area proved to be a successful solution as shown in Figure 17.

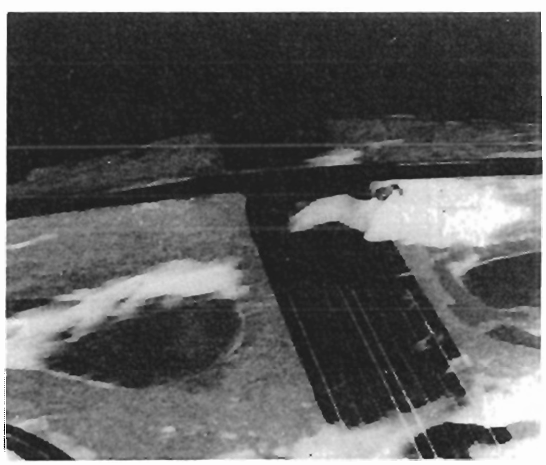

Figure 16

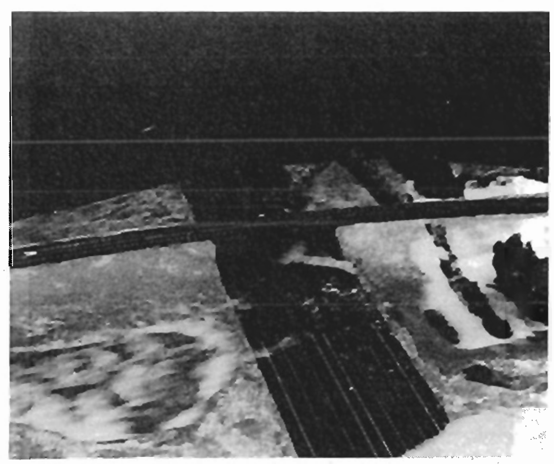

Figure 17

Figure 18

A knowledge of the wind flows in the vicinity of an entrance and the behaviour of snow particles often produces design details that ensure a drift-free entrance. Figure 18 shows a wall detail which has been designed to ensure that a sufficiently strong airflow exists at the deck level to prevent an accumulation of snow particles.

Air intakes for ventilation systems can ingest undesirable quantities of snow. Figure 19 shows a model of a ventilation building for a railway tunnel under the Rogers' Pass in British Columbia. Figure 20 illustrates the inside of the model into which water was sucked to simulate the air intake flow. Using the scaling of Appendix A to ensure a correct simulation of the snow particle paths, it was possible to predict the quantities of snow that would be ingested.

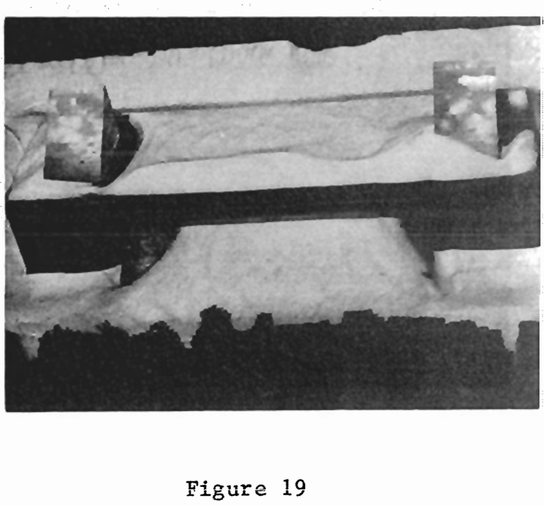

Figure 19

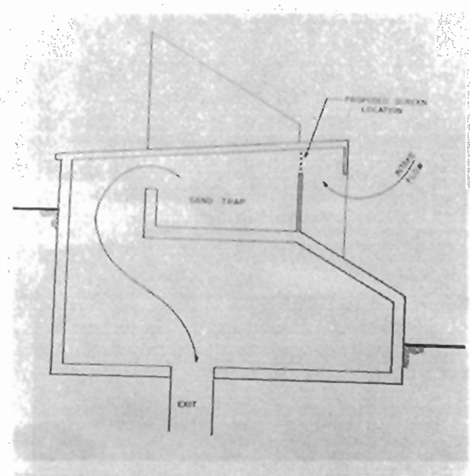

Figure 20

Another example of the application of model tests has been to do with snow accumulations around roof mounted solar collectors. In this case a combination of water flume and wind tunnel techniques were used to develop guidelines on how to avoid excessive snow build-up due to the presence of the solar collectors. The guidelines are of assistance particularly when mounting solar collectors on an existing roof which was designed assuming the roof was exposed to the scouring of wind, implying a snow load coefficient of less than one. The collectors can shelter the roof and give rise to considerably higher snow loads than those for which the roof was originally designed. A description of the work on the solar collector problem and guidelines for avoiding excessive snow buildup can be found in Reference (5).

5.0 CONCLUSIONS

Model simulations of snow accumulation are of significant benefit in the design of buildings and other structures but the results must be augmented by a broad experience in full scale conditions. There is a continuing need for further research into model simulation techniques in order to improve the accuracy of the model results and to extend the range of snow drifting phenomena that can be predicted.

6.0 REFERENCES

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APPENDIX A

SNOWFALL SIMILITUDE

The equations of motion for airborne particles upon which the predominant aerodynamic force is drag were given by Etkin[1]. For particles in water the buoyancy and added mass terms, which are negligible in air, cannot be ignored and so must be included. The resulting equations of motion of particles in water are:

$$(m + m_a)u = - k(u - u')q$$

$$(m + m_a)v = - k(v - v')q$$

$$(m + m_a)w = - k(w - w')q - mg(1 - 1/\gamma)$$

where u, v and w are the three components of particle velocity

u', v' and w' are the three components of fluid velocity

$$q^2 = (u-u')^2 + (v-v')^2 + (w-w')^2$$

k = drag constant of particle (drag = kq^2)

m = particle mass

m_a = added mass

g = gravitational acceleration

γ = particle density expressed as a multiple of the fluid density

The added mass can be approximately expressed as $m_a = m/2\gamma$. The terminal velocity of fall of the particles, W_t, is related to mg by $mg(1-1/\gamma) = k\ w_t^2$. Thus, introducing a characteristic length, L, and characteristic flow speed, U, the above equations can be written in nondimensional form as

$$d\bar{u}/d\bar{t} = -\Pi_1\ (\bar{u} - \bar{u}')\bar{q}$$

$$d\bar{v}/d\bar{t} = -\Pi_1\ (\bar{v} - \bar{v}')\bar{q}$$

$$d\bar{w}/d\bar{t} = -\Pi_1\ (\bar{w} - \bar{w}')\bar{q}-\Pi_2$$

where $\bar{u}$ = u/U (and similarly for all velocities)

$\bar{t}$ = tU/L

$\Pi_1 = (Lg/W_t^2)\beta$

$\Pi_2 = (Lg/U^2)\ \beta$

$\beta = (\gamma-1)/(\gamma+1/2)$

Since $\Pi_2 = \Pi_1\ (w_t^2/U^2)$ the first requirement for similarity is that Π_1 has the same value for model and full scale, taking note of the fact that for snow in air $\beta = 1$, whereas for sand in water β is typically 1/2. The second requirement is that the ratio W_t^2/U^2 be the same as at full scale.

APPENDIX B

SIMULATION OF SNOWDRIFTING

When the wind blows over snow above a certain threshold velocity, the snow particles begin to bounce along in a thin layer above the surface in short hops. This process is named saltation. As the wind speed increases further, the number of airborne particles increases and the layer of saltating particles grows in thickness. However, the thickness of the layer remains small, typically only a few centimeters. At very high wind speeds, when the vertical component of wind turbulence becomes comparable to or greater than the terminal velocity of fall of the snow particles, the particle trajectories become dominated by turbulent diffusion effects rather than saltation and the motion of particles is no longer confined to short hops within a thin layer adjacent to the surface. They may remain airborne for considerable distances. However, at the more common lower wind speeds, saltation tends to dominate. The threshold velocity for the onset of saltation depends greatly on the type of snow that is present.

To exactly simulate every facet of snowdrifting on a physical model is extremely difficult and will probably never be achieved. However, many aspects can be simulated and useful engineering results obtained by the sand - water analogue. The following analysis indicates why the sand - water analogue produces generally similar drift patterns to full scale.

Since saltation is the overriding mechanism of drifting at full scale (Reference 4) we restrict attention to this and use two simplifying factors which are:

(i) the typical particle path length, ℓ , is very short compared with the typical building sizes;

(ii) the thickness, h_s, of the saltating layer is very small in relation to the typical building height.

The implication of (i) is that significant changes in wind speed around a building will mostly occur over distances large compared with ℓ, i.e. a particle will, except in a few areas of extreme acceleration or deceleration of wind, land in an area where the wind speed is virtually the same as where it took off. The wind speed referred to here is that at a fixed reference height, h_o, slightly larger than h_s. Since h_s, and therefore h_o, is small compared with the building, the detailed shape of the wind speed profile below h_o will be unaffected by the building, taking on a universal form. These considerations lead to the simplifying assumption that for a given type of snow, the volume flux of snow per unit lane width, Q, is completely determined by the local wind speed, U, at height h_o.

$$Q = f(U) \tag{1}$$

Q is defined conveniently, so as to facilitate conversion to snow depths, as the volume the airborne snow would occupy when at rest on the ground, including all air spaces between particles. The path length, ℓ , does not enter into Equation 1 and will not do so as long as it is small compared with the distances over which significant accelerations or decelerations of wind occur. In non-dimensional form, Equation 1 may be written

$$\bar{Q} = Q/h_oU_T = Cf(\bar{U}) \tag{2}$$

where $\bar{U} = U/U_T$, U_T is the threshold wind speed for the onset of saltation and C is a dimensionless constant.

In the absence of snowfall, the rate of increase of snow depth, D, in two-dimensional conditions is given by

$$dD/dt = -dQ/dx \tag{3}$$

where x = the coordinate in the direction of the wind.

Equation 2 may be used to eliminate Q from Equation 3, resulting in

$$dD/dt = -Ch_oU_T\, df(\bar{U})/dx = -Ch_oU_Tf'\, d\bar{U}/dx \tag{4}$$

where $f' = df(\bar{U})/d\bar{U}$.

In non-dimensional form Equation 4 may be written

$$d\bar{D}/d\bar{t} = -f'\, d\bar{U}/d\bar{x} \tag{5}$$

where $\bar{D} = D/b$, $\bar{x} = x/b$, $\bar{t} = CU_Tth_o/b^2$, and b is a reference dimension of the building concerned.

Equation 5 describes drifting in two-dimensional wind flow. In three-dimensional flow additional terms arise on the right hand side but they would not change the essentials of the present discussion. The sand - water analogue simulates snowdrifting because it is essentially governed by a relation similar to Equation 5. It satisfies the criteria that ℓ and h_o are small compared with model buildings, and the function f in the transport rate relation, Equation 2, is of the same general form as for snow transport.

For snow we may arbitrarily set $C = 1$ in Equation 2 and, taking $h_o = 1m$, U_T is typically 3m/s. Measurements of volume flux of 0.12 mm diameter silica sand in water indicate $C \doteq 43$ and $U_T = 0.10$ m/s, where h_o is taken to be 5mm. Reference 5 of the main text gives data showing the function f is generally similar in the sand and water case to the function for snow in air. Thus, when geometrically scaled models in the sand - water analogue produce patterns of U that mirror closely those at full scale, the non-dimensional snow depths $\bar{D}$ tend also to mirror those at full scale.

To relate model time and speed to full scale time and speed, the fact that $\bar{t}$ and $\bar{U}$ are the same for both may be used. Denoting model values by m and full scale values by p (for prototype) it follows that

$$t_m = t_p \, C_p H_{op} U_{Tp} (b_m/b_p)^2 / C_m H_{om} U_{Tm} \quad \text{and} \quad U_p \, (U_{Tm}/U_{Tp})$$

Using the values of C, h_o and U_T given earlier for model and full scale it is deduced that for a typical 1:200 scale model $t_m = t_p/290$ and $U_m = U_p/30$. It is interesting to note that t_m is proportional to the model scale, $b_m:b_p$, squared. Thus, a doubling of the model size requires running the sand - water analogue for four times longer to produce the same non-dimensional snow depths. The physical reasons for this are that not only are the speed gradients reduced in proportion to 1/b on larger models, implying reduced deposition rate, but the depth of sand must also reach a physically greater value to give the same non-dimensional depth.

The above discussion describes the ideal way in which the sand - water analogue would work. Use of the simplifying factor of short particle path length enables the complexities of what determines the details of the path itself to be sidestepped. Thus parameters such as Reynolds number, Froude number, terminal velocity and density ratio which determine the particle trajectory do not need to enter into the discussion. It appears that in many circumstances such a simplification works but in others mismatch of the foregoing parameters leads to unrealistic model behaviour. The sand dunes that form in flat open spaces on the model and that appear to differ from full scale may be attributed to such mismatches. Also, if the fine details of drift shape are to be investigated, the precise particle path length becomes important as do such factors as the angle of repose. These imperfections bring to the fore the importance of combining model tests and field experience together in arriving at design recommendations.