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Wind tunnel test of snow redistribution on flat roofs

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ABSTRACT

In regions prone to heavy snowfall, an accurate estimation of snow redistribution on roofs under the action of wind is vital for structural engineers. The content of unbalanced snow loads of flat roofs caused by snow transport is indispensable in current load codes/standards. Hence, the wind tunnel tests were performed to investigate the redistribution of snow on flat roofs, in which high-density silica sand was used. The characteristics of snow redistribution on flat roofs are discussed, and common features are pointed out. The largest snow depth usually occurs near the windward region, and for a large-span flat roof the peak point could also occur in the rear region of the roof. In addition the locations of peak points after snow redistribution and the influence of wind velocity, wind duration and roof span on transport rates and mass fluxes are analyzed in detail. The transport rate increases as wind velocity or roof span increases but it is not a simple proportional relationship with roof span. Moreover, the transport efficiency of particles declines as wind duration becomes longer. Mass flux of the entire roof, which is the transport rate per unit length, asymptotically decreases with the increasing of roof span.

1. Introduction

For structural engineers the accurate prediction of snow distribution on roofs under the action of wind is important in regions with heavy snowfall. The question on unbalanced snow load caused by snow drifting, which is generally indicated by wind exposure coefficient, is indispensable in current load standards/codes. Although the current load standards/codes provide distribution of drift snow load on roofs with simple profiles, many studies still need to be performed to understand the mechanism of snow drifting on roof surfaces.

Some interesting studies on snow redistribution on roofs have been presented in recent years. Most studies used scaled models and alternative particles to simulate snow loads on roof surfaces. Isyumov and Mikitiuk (1990, 1992) employed bran as model particles in the wind tunnel tests to simulate the drift formation on the lower level of a two-level roof at different wind velocities and in two different approach terrains. O'Rourke et al. (2004) obtained the transport rates of different roofs from water flume tests using walnut shells, which matched reasonably well with full-scale transport rates. Furthermore, the simulated drift ratios and drift ratios resulting from ASCE (ASCE7-10, 2010) were compared by O'Rourke et al. (2005). Flaga et al. (2009) predicted snow loads on two large-span roofs through wind tunnel tests, taking the theory of dispersion into account (Flaga et al., 2009; Kimbar et al., 2013). Zhou et al. (2014) simulated the redistribution of snow loads on a stepped flat roof in a wind tunnel test using particles with different densities. The wind tunnel tests using these different kinds of particles were performed with nearly identical dimensionless wind velocity and dimensionless time to ensure comparability of test results. Some other works were based on the results of field observations to study the snow redistribution. Tsuchiya et al. (2002) studied the relationship between snowdrift patterns on model roofs observed from field measurements and wind acceleration in the vicinity of roof surface. Thiis and Ramberg (2008) studied snow loads on curved roofs through field measurements and found that the local snow load on parts of a curved roof exceeded four times the ground snow load for one case history, in which the ground snow load was approximately 0.5 kN/m^2. Thiis and O'Rourke (2015) analyzed a large database containing simultaneous field measurements of snow loads on roofs and ground snow loads, and established a simple empirical formula for the drift coefficient related with roof slope and exposure conditions. In addition, some other studies investigated drift snow loads on building roofs using analytical method. Irwin et al. (1995) used the finite area element method to study the effects of roof size, heat transfer, and climate on snow loads on flat roofs. Based on the previous research work, O'Rourke et al. (2005) established a convenient method to calculate drift snow loads for roof structures.

Snow loads on a flat roof are important for current load codes and standards. A wind exposure coefficient or similar coefficient, which is adopted in current load codes or standards to consider the effects of the roof's exposure to wind, is generally based on limited case histories and engineering judgment. Although some studies adopted the wind tunnel test method to research snow drifting on roofs, they did not systematically analyze the effects of some key factors on drift loads. Hence, through wind tunnel test, this paper attempts to investigate the

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characteristics of snow redistribution caused by snow transport on flat roofs under controllable experimental conditions.

First, the similarity criteria for snow drifting on roof surfaces are briefly summarized and a series of wind tunnel tests are presented. Then the characteristics of redistributions of particles and peak points are discussed. Finally, the influence of wind velocity, wind duration and roof span on transport rates and mass fluxes are analyzed in detail.

2. Similarity criteria

In the study, the wind tunnel test was used to explore the snow redistribution on flat roofs. A number of similarity requirements must be satisfied in a wind tunnel test on snow drifting on roofs, such as the similarity of model, nearby terrain and flow field, ejection process, particle trajectory, deposition pattern, and time similarity. The details can be found in the literature (Zhou et al., 2014) and here only a brief introduction is given below.

2.1. Similarity of model, nearby terrain and flow field

The similarity of the model, nearby terrain and flow field requires not only the model and its surroundings to have a similar geometry as the prototype, but also requires a correct similarity of the mean wind velocity profile and turbulence intensity. In addition, the similarity of snow cover depth on roof surfaces should be satisfied.

To ensure that the flow field in a wind tunnel test is a fully rough flow, Eq. (1) must be satisfied in a wind tunnel test (Tabler, 1980; Kind, 1976, 1986; Anno, 1984; Naaim-Bouvet, 1995),

$$\left(\frac{u_{*t}^3}{2g\upsilon}\right)_m \geq 30 \tag{1}$$

where, u_{*t} is the threshold friction velocity, g is the acceleration of gravity, and υ is the kinematic viscosity, which in the present study is taken as $1.45 \times 10^{-5}\text{m}^2\,\text{s}^{-1}$. Subscript m represents the model.

Zhou et al. (2014) deduced that the aerodynamic roughness height under saltation conditions could be expressed as below,

$$\left(\frac{\rho u_*^2}{\rho_p H g}\right)_m = \left(\frac{\rho u_*^2}{\rho_p H g}\right)_p \tag{2}$$

where u_* is the friction velocity, ρ is the air density, which in the present study is taken as 1.225 $kg\cdot m^{-3}$, ρ_p is the particle density, and H is the height of roof. Subscript p represents the prototype.

2.2. Similarity of saltation movement of particles

2.2.1. Correct modeling of ejection process

Using the threshold friction velocity based on the force balance analysis of a particle (Iversen, 1987), the densimetric Froude number can be expressed as Eq. (3),

$$\left(\frac{\rho}{(\rho_p-\rho)}\frac{u_{*t}^2}{gd_p}\right)_m = \left(\frac{\rho}{(\rho_p-\rho)}\frac{u_{*t}^2}{gd_p}\right)_p \tag{3}$$

where d_p is the particle diameter.

Kind (1976, 1986) and Kind and Murray (1982) reported that a similar ejection process of particles must satisfy Eqs. (4) and (5),

$$\left(\frac{\rho_p}{\rho}\right)_m \geq 600 \tag{4}$$

$$\left(\frac{U(H)}{u_{*t}}\right)_m = \left(\frac{U(H)}{u_{*t}}\right)_p \tag{5}$$

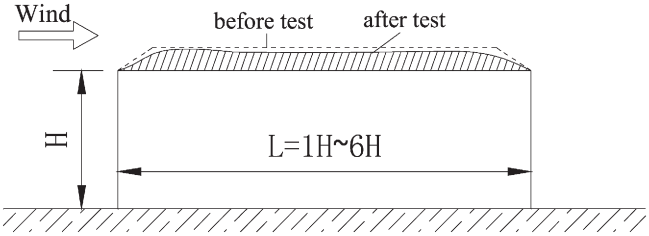

Fig. 1. Dimensions of flat roof.

where $U(H)$ is the velocity of approaching flow at the height of roof top. Kind and Murray (1982) and Kind (1986) believed that a large density ratio results in relatively correct snow erosion/deposition patterns and transport rates in a wind tunnel test. Eq. (5) presents the relationship between the velocity of approaching flow and threshold friction velocity.

2.2.2. Correct modeling of particle trajectory

In order to reasonably predict the trajectory of a particle, Kind (1986) considered that a similar ratio of inertial force to gravity, Eq. (6), which is another form of the densimetric Froude number, must be satisfied,

$$\left(\frac{\rho_p}{\rho_p-\rho}\frac{U^2(H)}{Hg}\right)_m = \left(\frac{\rho_p}{\rho_p-\rho}\frac{U^2(H)}{Hg}\right)_p. \tag{6}$$

To maintain the ratio of drag force to inertial force, the following equation must be also satisfied (Kind, 1986),

$$\left(\frac{w_f}{U(H)}\right)_m = \left(\frac{w_f}{U(H)}\right)_p \tag{7}$$

where w_f is the setting velocity of a particle.

2.3. Similar deposit patterns

A similar angle of repose is necessary to obtain similar snow deposit patterns (Kind, 1986),

$$(\theta)_m = (\theta)_p \tag{8}$$

where θ is the angle of repose when particles are at rest. A similar angle of repose is difficult to achieve when modeling particles are used in the snowdrift test. In their tests, Iversen (1980), Kind and Murray (1982), and Anno (1984) failed to achieve a satisfying similar angle of repose. Kind and Murray (1982) pointed out that a similar angle of repose is only important in snowdrift simulations on steep surfaces.

Table 1
Physical properties of natural snow particle and silica sand.

Name of particle	Snow particle	Silica sand
Diameter d_p (mm)	0.15	0.20
Particle density ρ_p ($\text{kg}\cdot\text{m}^{-3}$)	50–700	2784
Bulk density ρ_b ($\text{kg}\cdot\text{m}^{-3}$)	37.5–525	1670
Threshold friction velocity u_{*t} ($\text{m}\cdot\text{s}^{-1}$)	0.15–0.36	0.28
Angle of repose θ (°)	45–55	34
Setting velocity w_f ($\text{m}\cdot\text{s}^{-1}$)	0.2–0.5	0.6