Experiments on snow-avalanche dynamics

K. NISHIMURA & N. MAENO
The Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan 060

ABSTRACT A small snow-avalanche system was constructed in a cold laboratory and the following measurements were carried out: flow and particle velocities by using a high-speed video system; particle concentrations by measuring the electric capacitance; impact forces with strain-gauge-type pressure-transducer; induced wind speed, etc.

Vertical profiles of particle velocities were obtained and discussed with reference to four fluid models (Newtonian, Bingham, Dilatant, Turbulent); among those models the Bingham body model represented the experimental data best. The yield stress of a snow flow was estimated as 40~100 N/m².

Impact forces (P) measured in this experiment showed rapid oscillations corresponding to collisions of snow particles; the magnitudes were reasonably expressed as \( P = \rho u^2 \) where \( \rho \) and \( u \) are respectively the density and velocity of snow flow.

Expériments sur la Dynamique d'Avalanches de Neige

RESUME Un système a petit échelle d'avalanches de neige a été construit dans une salle froid, et les mesures suivantes ont été conduites: vitesses de l'écoulement de neige et des particles en utilisant un appareil de video de haute-vitesse; concentration des particles en mesurant la capacité électrique; forces d'impact avec un transducteur de pression de jauge de deformation, vitesse du vent induit, etc.

Les profiles verticaux des vitesses des particles ont été obtenus et discutés en les référant à quatre modeles de fluidité (Newtonien, Bingham, Dilatant, Turbulent); entre ces modèles, celui de Bingham a été le meilleur représentant des données. Les tensions d'étirage des ecoulements de neige ont été estimées en 40~100 N/m².

Les forces d'impact (P) mesurés dans cet experiment, ont montrées des oscillations rapides qui correspondent aux collisions des particles de neige; les magnitudes ont été raisonnablement bien exprimés comme \( P = \rho u^2 \) où \( \rho \) et \( u \) sont respectivement, la densité et la vitesse de l'écoulement de neige.

1. Introduction

Mixed-phase snow flows have the following two distinct characteristics compared with other mixed-phase flows such as mud
flows and alluvial streams (Maeno et al., 1985):

1. Snow and ice particles are adhesive especially near the melting of ice, so that they may interact strongly in the flow.

2. Shapes of the particles are usually complex and their densities are relatively low, so that the interaction between particles and fluid is also strong.

It is suspected that the above characteristics influence structures and physical properties of the mixed-phase snow flows significantly.

A snow-avalanche is a typical example of such flows, which is usually composed of snow particles and air. So far dynamics and structures of snow avalanches could not be investigated in detail mainly because natural avalanches break out accidentally and precise data are usually very difficult to obtain.

We have constructed a mini-avalanche system in a cold laboratory and carried out the following measurements: flow velocities and particle motions; impact forces; bulk densities; induced wind speed; static pressure; sizes and shapes of snow particles, etc. Results obtained in the measurements in an inclined chute were already reported elsewhere (Nishimura et al., 1985); in this paper we present new results obtained on a non-slip horizontal floor and discuss structures of the snow flow.

2. Experimental system and method

![Diagram of experimental apparatus](image)

**FIG. 1** Schematic diagram showing the experimental set-up.

FIG.1 shows the experimental apparatus schematically. Sieved snow, 20-35 kg in weight, was fluidized with a modified snow removal machine and allowed to flow down in an inclined chute, which is 7.2 to 9 m long and 0.1 m wide. Although the angle of inclination could be varied between 10° and 35°, most experiments were carried out at 30°. The floor of the chute was covered with a polyethylene film to minimize friction and achieve higher velocities.

The snow flow accelerated down the chute and flew into another horizontal chute (2.8 m long) of the same width as the inclined chute. The maximum velocities attained were 6-7 m/s. The floor of the horizontal chute was covered with rough cloth or sifted snow except the nearest part 0.5 m to the inclined chute. In the horizontal chute, the snow flow decelerated and finally came to rest. All the measurements were made at a temperature of -10°C.

Snow used in the experiments was pure and natural, which was
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collected from snow covers in the suburb of Sapporo city and kept in a cold room at -20°C for one month. The average diameter of snow particles was 0.3 mm.

The movement of a snow flow was recorded with a high-speed video system (NAC HSV-200), viewed from side or up of the chute. Analyses of each picture taken every 1/200 second gave various dynamic behaviors of the overall flow and individual snow particles.

The density of a snow flow was measured with an electric capacitance-method, the description of which is given in Maeno (1986). Three sets of parallel electrodes (2 cm x 5 cm) were fixed in the horizontal chute at heights of 1 cm, 3.5 cm and 6 cm above the floor. Hence the densities obtained represent average values from 0 cm to 2 cm, 2.5 cm to 4.5 cm, and 5 cm to 7 cm.

Impact force was measured with a strain-gauge-type pressure-transducer; its form is a disk of 6 mm in diameter and 0.6 mm in thickness. The pressure-transducer was mounted on a rigid pipe at a height of 1.5 cm above the floor, and data were recorded on a magnetic tape.

The speed of wind induced by the snow flow was measured with a hot-wire anemometer (KANOMAX MODEL6200). Its sensor was set at 15 cm height at the end of the horizontal chute.

3. Results

A photograph of a snow flow running in the horizontal non-slip chute is shown in FIG. 2 which was taken under a screened stroboscopic light lasting 25μs. It is clear from this picture that the snow flow consists of two layers, namely the upper snow-dust and lower flowing layers. The height of the latter was roughly 2~3 cm.

![FIG.2 Photograph of a snow flow running in the horizontal chute.](image)

3.1 Velocities of flows and particles

FIG.3 shows a profile of the front velocity across a snow flow, which was measured at x=100 cm, where x is the distance from the edge of cloth-covering in the horizontal chute (see FIG.1). Effects of wall-friction are noted at both the sides (one wall is glass and the other wood); but they are usually small, less than
10% of the center velocity.

Typical velocity profiles of individual snow particles in a non-slip horizontal chute are shown in FIG. 4. Velocities at given heights decrease with increasing x, and diminish around x=200 to 250 cm. In the profile at x=50 cm, there exists a strong velocity gradient roughly below h=1 cm where h is the height from the floor. In the region h=1~2 cm the velocity is almost constant. It was confirmed by more detailed video analyses that the height 2 cm corresponds to the thickness of the flowing layer mentioned above. Above 2 cm, that is, in the snow-dust layer, particle velocities showed larger scatter.

FIG. 4 Velocity profiles of individual snow particles. (1) x=50 cm, (2) x=100 cm, (3) x=150 cm.

3.2 Bulk densities of flows

FIG.5 shows bulk densities of a snow flow. As mentioned before the average thickness of a flowing layer was 2 cm; the density measured by the lowest electrodes (at 1 cm height) corresponds to the mean value in the flowing layer and other two to those in a snow-dust layer. As shown in FIG.5 the difference in the density amounts to about 200 kg/m³ between the flowing and snow dust layers, but less
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FIG. 5 Vertical profiles of densities of snow flows.

than 20 kg/m$^3$ between the lower and higher parts of snow-dust layer.
The density of the snow flow increased gradually with increasing \( x \); for example, 265 kg/m$^3$ at \( x=20 \) cm and 340 kg/m$^3$ at \( x=150 \) cm in the flowing layer. At \( x=150 \) cm, the density at \( h=2.5\sim4.5 \) cm is as high as that in the flowing layer. This is because the electrodes were buried in a debris.

3.3 Impact forces

FIG.6 shows a typical example of impact force measured at \( h=1.5 \) cm; the force is actually a mean in an area between \( h=1.2 \) and 1.8 cm. The impact force showed high-frequency oscillations in the magnitude from 0 to 11.2 kPa. Maximum value was 11.2 kPa and average was 2.3 kPa, which was estimated from data at every 2 ms within 7 seconds of the measurement. The magnitude of impact force is small compared with that of natural avalanches (1/10~1/100), but overall forms of its time variation seem to resemble each other.

More detailed analyses by digitizing the data and showing them in a wider time scale made it clear that each of the oscillations in FIG.6 consists of a rapid rise and slow relaxation phenomenon, which seems to correspond to a collision of a snow particle.

The impact force \( P \) in avalanches is usually expressed as

\[
P = k \rho u^2, \tag{1}
\]

where \( \rho \) and \( u \) is the density and velocity of avalanche, and \( k \) is a numerical constant. If we assume that an avalanche is an incompressible fluid, \( k \) is equal to 1/2. The conservation of
momentum suggests that $k$ is unity. Actually in the engineering fields $k$ is put to be 1 to 2.

On the other hand, if we suppose that a plastic wave propagates in the compressed snow when the snow flow impacts the pressure transducer, the conservation of mass and momentum at the plastic wave front gives

$$P = \rho_1 (1 + \frac{\rho_1}{\rho_2 - \rho_1}) u^2,$$

where $\rho_1(=\rho)$ and $\rho_2$ are the densities before and after the impact and $U_0$ is the velocity of the plastic wave. In case of $u \gg U_0$ Eq.(2) corresponds to Eq.(1) when $k=1$. In practice densities usually increase after impact, thus $k$ should be greater than unity.

FIG.7 presents maximum impact force in each experiment as a function of observed impact velocity. In this figure impact forces calculated from Eq.(1) when $k = 1/2$ and 1, and Eq.(2) are also shown as regions. Data used in the calculation are as follows;

$\rho(=\rho_1) = 265$–$340$ kg/m$^3$ (see FIG. 5)

$\rho_2 = 550$ kg/m$^3$ (the value of maximum mechanical packing)

As shown in FIG.7, Eq.(1) when $k = 1$ represents the experimental data best.

3.4 Wind speeds

TABLE 1 lists speeds of wind at $x=220$ cm and $h=15$ cm. Many measurements were made but precise data were rather difficult to obtain because of the impacting of snow particles on the sensor. However Table 1 shows that observed speeds of wind induced by a snow flow ranged from 0.7 to 4.5 m/s. The wind was also observed even when a snow flow itself stopped before reaching the sensor. Thus the aerodynamic interaction between snow particles and air should cause significant air flows, which seem to be related to avalanche winds or blasts often reported in large-scale powder avalanches.
TABLE 1  Speeds of wind measured at x=220 cm and h=15 cm

<table>
<thead>
<tr>
<th>No.</th>
<th>#132</th>
<th>#133</th>
<th>#134</th>
<th>#139</th>
<th>#142</th>
<th>#143</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{air}$ (m/s)</td>
<td>2.9-4.5</td>
<td>0.7-1.4</td>
<td>0.8-1.9</td>
<td>1.9-2.4</td>
<td>2.8-4.0</td>
<td>3.4-3.8</td>
</tr>
</tbody>
</table>

4. Discussions

Various models have been proposed so far to describe the motion of snow avalanches (Mellor, 1978; Perla, 1980), which may be divided into two groups: fluid models and rigid-body models. In the following we regard a snow-avalanche as a fluid and examine four fluid-models by comparing theoretical velocity profiles with those observed in our measurements.

(1) Newtonian fluid model

If we assume that the fluidized snow flow is a 2-dimensional Newtonian fluid and flows only in an x-direction with velocity $u$, the Navier-Stokes equation to describe the flows is

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial y^2} \right)$$

(3)

where $\rho$ is the density of the flowing snow, $p$ is the hydrostatic pressure and $\nu$ is the kinematic viscosity coefficient of the snow flow ($= \frac{\mu}{\rho}$; $\mu$: viscosity coefficient).

Assuming a steady and nonaccelerating flow ($\frac{\partial}{\partial t} = \frac{\partial}{\partial x} = 0$) and integrating Eq.(3) with $u = 0$ and $U$ at $y = 0$ and $h$ respectively, we obtain

$$u = \frac{\alpha}{2\nu} (h - y)y + \frac{U}{h}y.$$  

(4)

where $\alpha$ is a constant pressure gradient ($-\frac{\partial p}{\partial x}$).

The steady-state assumption made above is only satisfied in a narrow range in our experiment. Flow velocity data measured at x=15, 20, and 50 cm are plotted in FIG.8. It is clear that the velocity profiles do not change much in this region of x; hence we may assume the steady state and nonacceleration.

The shear stress $\tau$ of Newtonian fluid is expressed as

$$\tau = \mu \frac{\partial u}{\partial y}.$$  

(5)

By substituting Eq.(4) into Eq.(5) and putting $\tau = 0$ at the free surface ($y=h$), we obtain the velocity as a function of $U$ and $h$ only:

$$u = U \frac{y}{h} \left( 2 - \frac{y}{h} \right)$$  

(6)

By substituting experimental values ($U = 4.5$ m/s, $h = 2.5 \times 10^{-2}$ m, see FIG. 8 ) in Eq.(6), we get a theoretical velocity profile in the flowing layer. The result is shown in FIG.9.

(2) Bingham body model

A Bingham body remains rigid and no flow takes place when the shear stress is smaller than a yield stress $\tau_y$; it flows like a Newtonian fluid when the shear stress exceeds $\tau_y$. Dent and Lang (1983) have simulated avalanches numerically with a modified Bingham model.
In the Bingham body model the shear stress is defined as
\[ \tau = \tau_0 + \mu \frac{du}{dy}. \]  
By substituting Eq.(4) into Eq.(7) and assuming \( \tau = 0 \) at \( y = h \) and \( \tau = \tau_0 \) at \( y = H \), a theoretical velocity profile is obtained as
\[ u = \frac{\tau_0 y - 2H - y}{2\mu} \left( \frac{2H - y}{h - H} \right). \]

(3) Dilatant flow model
Bagnold (1954) introduced a dilatant flow model from his experimental and theoretical investigations of motion of sand particles. This model has been applied to other granular flows (Savage, 1970), mud and debris flows (Takahashi, 1980).

The shear stress in the dilatant model is expressed as follows:
\[ \tau \propto \rho_p (d\lambda)^2 \left( \frac{du}{dy} \right)^2, \]
where \( \rho_p \) is the density of particles, \( d \) is a particle diameter and \( \lambda \) represents a linear particle-concentration. Applying this model to a steady-state channel flow, we get the velocity as a function of \( h \) and \( U \):
\[ \frac{U - u}{u} = \left( \frac{h - y}{h} \right)^2. \]

(4) Turbulent flow model
According to our measurements the density of the flowing layer was about 250–350 kg/m\(^3\) (FIG.5); we know that the kinematic viscosity coefficient of fluidized snow in this density range is \( 10^{-4} \sim 10^{-5} \) m\(^2\)/s (Nishimura & Maeno, 1986). By use of the above data the apparent Reynolds number of the snow flow is calculated as
\[ Re = \frac{Lu}{\nu} \approx 1.5 \times 10^3 \sim 10^4. \]
Here we put the length scale \( L \) as the depth of flowing layer (=3 cm)
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and the representative flow velocity \( u = 5 \) m/s. This large value of \( Re \) suggests that the snow flow may be treated as a turbulent flow.

According to the theory of turbulent flows the shear stress is expressed as

\[
\tau = \rho l \left( \frac{du}{dy} \right)^2 ,
\]

where \( l \) is the Prandtl mixing length; the velocity profile on a rough surface is

\[
\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y}{y_0} ,
\]

where \( u_* \) is the friction velocity \( \left( = \sqrt{\frac{\tau}{\rho}} \right) \), \( \kappa \) is the Karman constant \( (\kappa = 0.4) \) and \( y_0 \) is the surface roughness. \( Ar \) is a constant, which is 8.5 according to the experiment by J. Nikuradse (Schlichting, 1955). A velocity profile was drawn in FIG.9 using Eq.(12); in the calculation adequate values of \( y_0 \) and \( u_* \) were chosen to be 2.5 cm and 4.5 m/s respectively.

The comparison of the four curves with experimental data in FIG.9 shows that the Bingham body model seems to fit best. Then the value \( \tau_0/\mu \) is estimated as \( 13.5 \times 10^2 \) s\(^{-1}\). The density of the flowing layer at \( x = 25-50 \) cm is \( 250-350 \) kg/m\(^3\), then \( \nu \) is in a range \( 10^{-4}-10^{-3} \) m\(^2\)/s (Nishimura & Maeno, 1986). Consequently the yield stress of a snow flow in the assumption of the Bingham body model is about 40-100 N/m\(^2\).

Lang and Dent (1981) measured friction resistance of hard sintered snow in a velocity range from 0.1 to 0.25 m/s and got the yield stress of magnitudes of 540-1000 N/m\(^2\). Their values are roughly by an order of magnitudes larger than ours; This difference is considered to be caused by the degree of fluidization and velocity. On the other hand, the shear strength of bonded snow is in a range \( 1 \times 10^3 - 3 \times 10^4 \) N/m\(^2\) at \( \rho = 250-350 \) kg/m\(^3\) (Mellor, 1974). It is reasonable that the yield stress of fluidized snow is about two orders of magnitudes smaller than that of bonded snow.

FIG.9 Measured and calculated velocity profiles in the flowing layer.
The above discussion is based on an assumption of non-slip situation, that is \( u = 0 \) at the surface. It is also likely, however, that snow particles at the surface are movable and even have some definite slip-velocities since the surface of the horizontal chute was observed to be covered by successive snow particles and the surface or height zero is only defined vaguely or relatively.

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