EXPERIMENTS AND NUMERICAL SIMULATION OF PING-PONG BALL AVALANCHES

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ABSTRACT : Snow avalanche experiments at a ski jump have been carried out since 1995. Instead of snow, we used up to 550,000 ping-pong balls to simulate three-dimensional granular flows along the inclined plane. A laser radar system revealed the distribution of the flow thickness; a head with about 0.8m long and 0.5m high was clearly recognized for 200,000 ping-pong balls flow and the oval lateral cross-section with 13m long and 0.1-0.2m high was found for 20,000 balls flow. After the head, particle concentration became low and the specific structure like "eyes" appeared in the flow. Video camera positioned above gave us not only the distance of a single ball but also its velocities. Obtained results revealed that the vertical and outward (horizontal) activities are rather high around the head. A new device, that is composed of 4 pipes with open ends pointing up, down, left and right and connected to 4 pressure difference sensors through a 20m long tube was also developed to investigate the three-dimensional air flow structures. The movement of balls and the surrounding air obtained suggest a strong interaction each other. Computer simulation with the DEM (Discrete Element Method) shows reasonable results for small avalanches. However, the air drag will be a crucial factor for the larger flows in which specific structures like head and eddies are observed in the experiments.

KEYWORDS : Snow avalanche, Ping-pong ball, Ski jump, Particle and air interaction

1. INTRODUCTION

We have carried out the systematic snow avalanche observations in the Shiai-dani valley, Kurobe Canyon since 1989. The results obtained in this decade revealed the velocity distribution in the dense flowing part and the powder snow cloud part in the snow avalanche (Kawada et al., 1989; Nishimura et al., 1989, 1993; Nishimura and Ito, 1997). However, our knowledge of the dynamics and internal structures of the snow avalanche are still far from satisfactory to describe and simulate the avalanche motion properly.

The avalanche dynamics can also be investigated in the laboratory with granular flows on inclined chutes since snow avalanches are made up of granular materials. These experiments have the advantage that they can be repeated many times and studied under the same conditions. However, most of these experiments were carried out on the short inclined chute, thus the question whether the flow reached the steady state was still remaining. In order to solve above problems, the large scale experiment to obtain steady state flow and to investigate the flow mechanics in detail were required.

On the other hand, the progress of the numerical simulation for granular material may apply it to snow avalanche simulation. In recent years, two-dimensional DEM (Discrete Element Method) simulations have increased the understanding of granular flows including two-phase flows. However, as yet these simulations do not accurately deal with particles strongly coupled to fluids nor do they deal with three dimensional and/or anisotropic flows. In addition, these simulations should be checked with experimental or observational results, however, those results which include strong particle-air interaction have never been produced in laboratory experiments.

In 1995, we have started the snow avalanche experiments at a ski jump using up to 550,000 ping-pong balls. Since the effect of the air drag on the ping-pong ball is fairly large, the flow velocities arrived at a steady state within a short distance. Flow characteristics and internal structures have been investigated (Nishimura et al., 1997, Keller et al., 1998). This paper reports the structures of the ping-pong balls flow and the velocity distribution of the surrounding air. Preliminary results of the numerical simulation are also shown.

2. EXPERIMENTS AND MEASUREMENTS

Experiments were made at Miyanomori ski jump in Sapporo. The whole slope (landing bahn) which is more than 150m long is covered with the artificial grass. All the ping-pong balls with a diameter of 37.7mm and a weight of 2.48g were put into a large container at a position of 30m (Figure 1, 2). After the balls were released simultaneously with opening the front gate of the container, the flow accelerated and reached steady state at the steepest part, 40 to 60m from the start point and slope angle of 36°. (Figure 1). More information about the experiment procedure is given by Nishimura et al. (1997).

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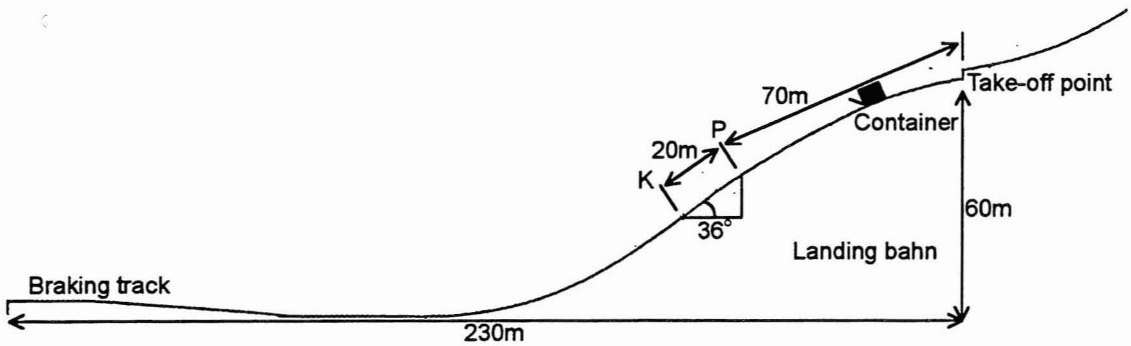

Figure 1 : Cross section of the Miyanomori ski jump.

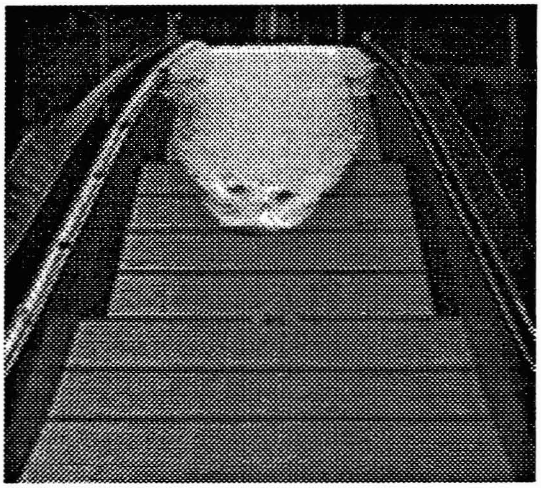

Figure 2 : Ping-pong ball avalanche with 250,000 balls on the ski jump. Interval of the horizontal line is 5m and the lowest one is 100m from the take-off point.

In this paper we introduce the results obtained with 20,000, 30,000 and 200,000 ping-pong balls. Measurement devices were set at positions of 100, 115, and 130m in Figure 1. The position at 100m was steep enough to maintain the high (steady) velocity, while it was almost flat at 130m. Combination of results obtained at three positions is expected to give us the insight of deceleration process of the flow. Debris distribution was also measured as a function of position.

Flow structures and ball velocities

A laser radar system (SICK optic electronic, Proximity Laser Scanner LMS 200) was utilized to reveal the flow structure. It calculates the distance to the flow using the length of time between sending and receiving the beam of light (infrared laser beam). A mirror set inside rotates in a semicircle at 40ms which can sense the positions of moving objects. The system was set at 0.8m high and 1m left from the center of the flow.

The velocity distribution in the ping-pong ball avalanche was measured with video cameras which looked down the flow (Figure 3). The velocity measurement of the ping-pong balls is based on a uniform ball size; i.e. the balls closer to the video camera appear bigger than other balls. The location of the ball, including the distance from the camera, can be calculated with the visible diameter of a ball in the video picture. If the same ball is tracked within two subsequent pictures, the three-dimensional velocity vector can be obtained. In the calculation, different corrections have to be made, such as the distortion of the wide-conversion lens and rotation from the perpendicular line to the ground (Keller et al., 1998). Video camera was set at 2.4m left-hand side from the flow center.

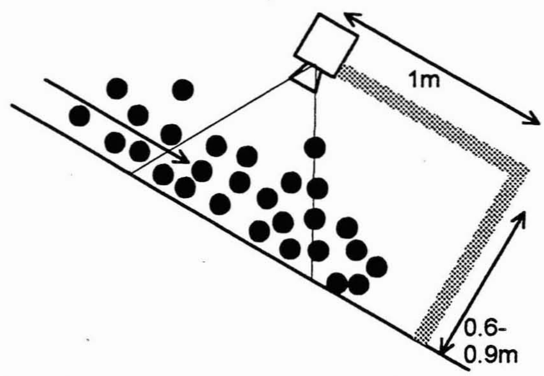

Figure 3 : Setup of the video camera at the measurement of the ball velocity.

Air flow measurements with static pressure depression

The measurement of the air flow velocity in the snow avalanche has been difficult with an ordinary meteorological anemometer, since its destructivity and a disturbance by a large amount of suspending snow particles. Nishimura et al. (1997) and Nishimura and Ito (1997) developed a new air flow measurement device based on the static pressure depression in the avalanche and proofed its reliability by comparing its results with video picture or impact pressure data. The measuring setup is very simple; a tube connected to a pressure difference sensor is set in the flow as its open end points downward and is perpendicular to the main flow direction. Basic equation to calculate the velocity is below,

$$\Delta P = \frac{1}{2}\rho u^2 .$$

Where ΔP is the static pressure depression, ρ is the density of the air and u is the air flow velocity.
However, this equation is valid when the air blows perpendicular to the tube. Since the air flow direction in the avalanches including our ping-pong balls flow are conjectured to be never uniform due to the turbulence inside, precise structures with only one tube becomes hard to obtain. To overcome this limitation, we renewed the device, that is a combination of 4 pipes with open ends pointing up, down, left and right as shown in Figure 4. Each pipe is connected to 4 pressure difference sensors through a 20m long tube. Three-dimensional air flow structures can be obtained according to the following procedures;

(1) The pressure depression was measured in different wind velocities and angles for each pipe in a wind tunnel (Figure 5). As indicated in Figure 6, the angle the wind blows into the pipe directly was set as 0°, the wind blows from the root to open ends (nozzles) as 180°.
(2) The calculation of the air flow velocity and direction was done as follows. Here, for the simplicity, we consider only vertical component, as illustrated in Figure 6, a combination of the output from the up-and-downward pointing nozzles are taken into account. When the air flow involves upward component as shown in Figure 6, the output connected to the upward nozzle (x) is supposed to be larger than the one connected to the downward nozzle (y). The air flow in Figure 6 corresponds to (90+θ)° for A, while (90-θ)° for B. Thus, referencing the calibration curves obtained in Figure 5, the wind velocity, for which the difference of angles from 90° to both outputs (x and y) become equal can be found. This is the wind speed and the direction θ we wanted to obtain. Likewise lateral component are shown with the right-and-leftward pointing nozzles and then we can obtain the wind velocity in a 3-dimensional space.

This measurement system was set at a height of 15cm on the measuring tower.

3. RESULTS AND DISCUSSIONS

Flow structures and ball flow velocities

Figure 7 shows longitudinal height distribution of 200,000 ping-pong ball flow measured with the laser radar. A head with about 0.8m long and 0.5m high was clearly recognized. After the head, vacant space was shown, which probably corresponds to the reduction of particle concentration. It is also recognized in Figure 2 like "eyes" in the flow. Keller et al. (1998) revealed that the ratios of maximum ball velocity to the front velocity, u_{max} / u_f, was almost 1.4.

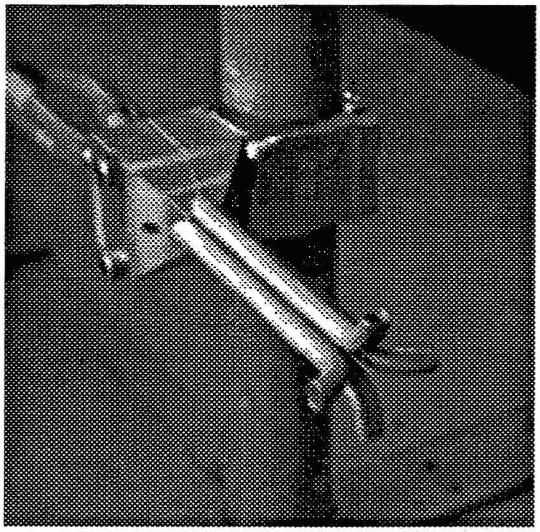

Figure 4 : Air velocity measurement device. It is composed of four pipes and each pipes are connected to the pressure sensor through 20m long tube.

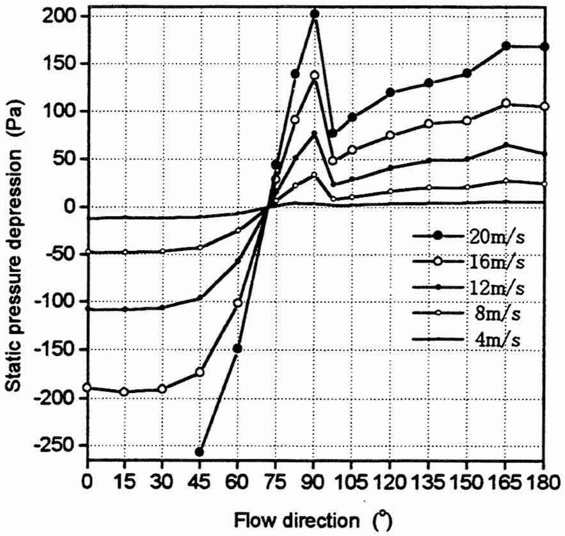

Figure 5 : Calibration curve obtained in a wind tunnel. The pressure depression changes with wind direction as well as velocity.

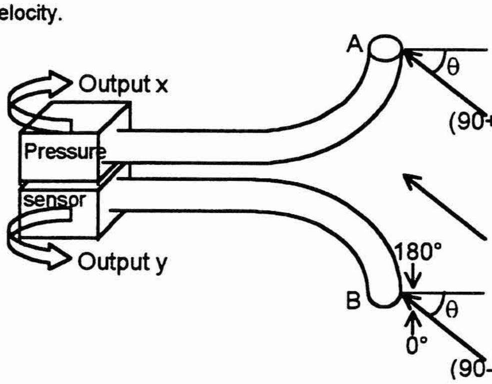

Figure 6 : Schematic picture showing the air velocity measurement device.

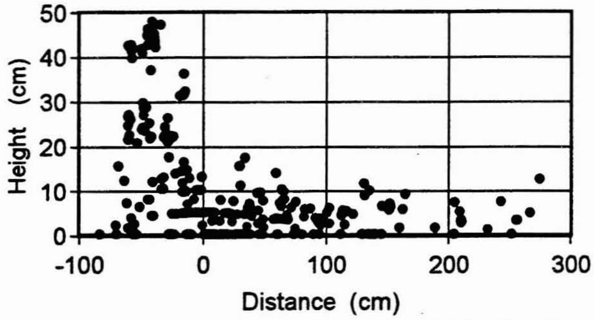

Figure 7 : Longitudinal height distribution of 200,000 ping-pong ball flow measured with the laser radar.

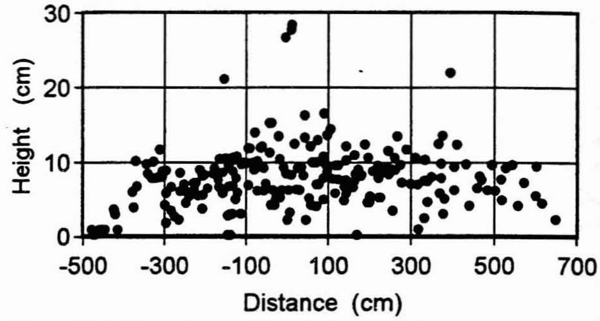

Figure 8 : Lateral shape of the 20,000 balls flow.

That is the balls at the front were reduced the velocity by the air drag and they change the position to the side or are overridden by the following balls. The eddy, therefore, was created vertically and horizontally. This alternate appearance of dense and low particle concentration part (waves) are also observed behind the head successively.

Figure 8 gives the lateral shape of the 20,000 balls flow observed with laser radar as well. Although we don't know the exact position along the flow (perhaps just after the head), we can see at least that the flow have clear oval cross-section which is around 13m long and 0.1-0.2m high.

Figure 9 shows the vertical and lateral profiles in the head of avalanche with 200,000 balls. The time interval of one profile is 17ms. It can be seen that vertical activity is high; the balls are jumping up and down, particularly, after the front head. The lateral profiles show a strong outwards movement during the first 50 ms (corresponding to a length of about 0.7 m), away from the center of the flow; as anticipated above discussion. After this first part in the head, there is no more specific lateral movement.

In 1997 and 1998 we have set six video cameras across flow width at positions of 100, 115 and 130 m. Analysis now in progress is expected to give us the detailed structures, including the velocity distributions, of the three-dimensional granular flows.

Air flow velocity

Figure 10 shows the output from two pressure sensors connected to up and downward nozzles and the impact pressure sensor at 10cm high. From 0.05 to 0.15s (just after the front) the static pressure depression was negative, which implies that the static pressure in the flow was larger than in the atmospheric pressure. This phenomenon was also observed both in the natural snow avalanche at Kurobe Canyon and snow flow experiments at ski jump (Nishimura and Ito, 1997). Two possibilities which may cause to increase the static pressure are assumed; one is the air compression near the front, and the other process is the existence of vertical air flow. Since measurements with a ultrasonic anemometer showed the rising current not only just before the avalanche front but also in the following flow (Nishimura et al., 1993), the latter process looked plausible. However, this scenario becomes skeptical in the ping-pong ball flow since the static pressure increase was observed from not only upward sensor but also downward sensor; upward current increases the output from the downward sensor only as shown in

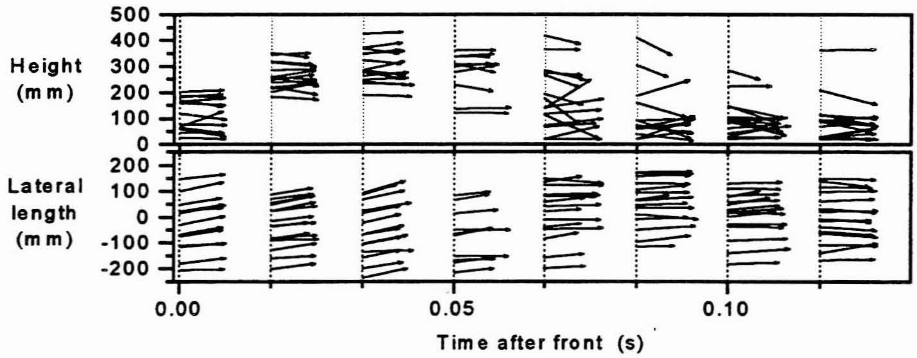

Figure 9 : Vertical (above) and lateral (below) profiles in the head of avalanche with 200,000 balls obtained with video camera. Each line shows the vector of ball motion. The camera position (0 in the lateral length) is 2.4m left from the center of ski jump.

Figure 5. On the other hand, the comparison of the static pressure with the impact pressure in Figure 10 implies that the static pressure tends to be negative when the balls hit an impact pressure sensor. It suggests that the negative value appears when the ball concentration is high, thus the mass of balls suspended in air may cause the static pressure increase. The increase in the static pressure ΔP can be expressed as

$$\Delta P = \delta \rho_b g h$$

where g is the gravitational acceleration, h is the height of the layer of balls, $\delta\rho_b$ is the density difference between the ball and the air (about 100kg/m^3). The maximum static pressure increase (100Pa at 0.15s) in Figure 10 is equivalent to the flow of 0.1m thick with $\delta\rho_b$; it corresponds to the weight of three ping-pong balls. Since the output was combination of the depression by the air flow and the increase by the suspended balls, we cannot estimate precise contribution of latter at this stage. However, three ping-pong ball layers above the static pressure sensor are plausible according to the video picture. To avoid the effects of the balls above described, the air flow velocity and flow direction were calculated from 0.15 to 0.3s and from 0.5 to 0.7s. The air flow projected on the vertical plane are shown in Figure 11. First result, showing the flow just after the front, indicates large velocity fluctuation. The average velocity within 0.15s is about 14m/s, that is almost the same as the front

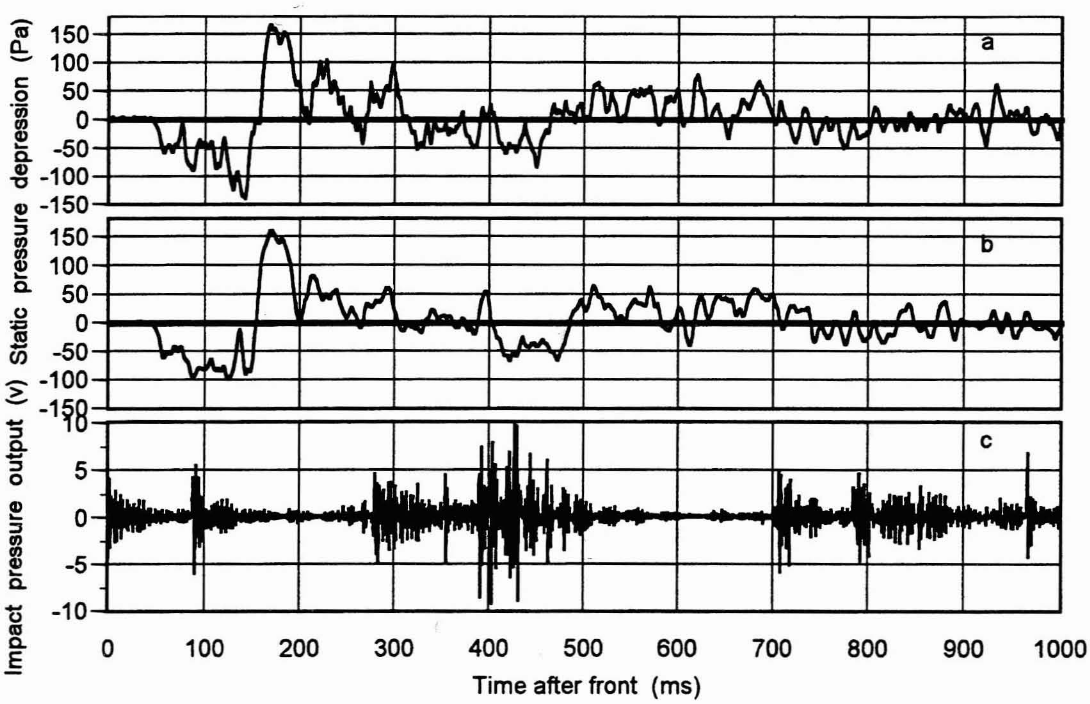

Figure 10 : Static pressure depression obtained with upward (a) and downward (b) sensors and the impact pressure at 10cm high (c).

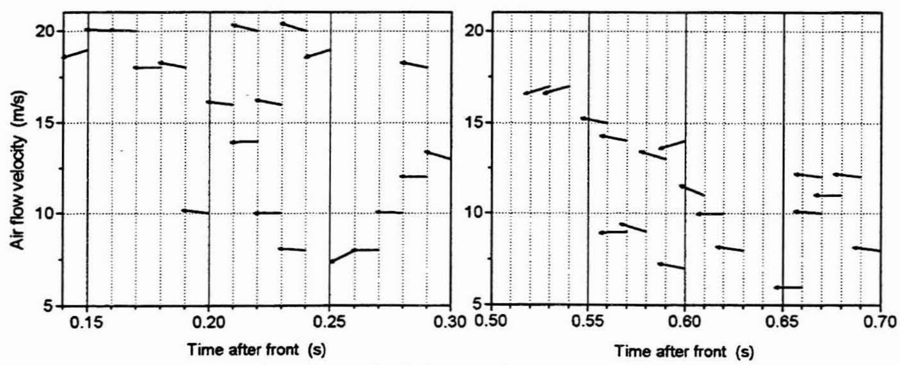

Figure 11 : The air flow variation projected on the vertical plane, when 30,000 ping-pong ball were released. Left one is 0.15-0.3s from the avalanche front and right 0.5-0.7s. The origin of the arrow indicates air flow velocity and the angle indicates flow direction. Two arrows in the same time division mean two possible solutions were calculated.

velocity obtained from video picture analysis. From 0.5 to 0.7s the air flow velocities shows a monotonous decrease.

The flow direction is nearly parallel to the bed (downstream component is dominant) but a little upward and downward components are also involved. The downward current existed just after the dense flow part where impact pressure was observed in Figure 10. Taking into consideration the flow structures in Figures 9 and 11, we can reasonably conclude that the downward flow after the head was derived by the vigorous ball movements; the balls and the surrounding air interacts tightly.

In order to increase the information around the head, the effective contribution of the balls suspended in the air is planned to measure with setting a pressure sensor on the bed floor.

Numerical simulation

The final stage of our simulation will predict snow avalanche motion, considering mechanical properties of snow in the two-phase flow. However, at the first stage of the project, we limit the system design to simple with well understood particles (ping-pong ball) and test the theoretical predictions.

The discrete element method (DEM) is an approach to modeling systems, in which the equations of motion are integrated for each individual particle. The system is specified by the particles, the geometry, the particle-particle and particle-geometry interactions and the body forces. We choose a very simple model of a damped spring with Coulomb friction for all interactions. The spring constant and the damping coefficient are calculated from the coefficient of restitution and the stiffness of the ping-pong balls. However, the effect of air drag has not been included yet. Figure 12 shows the four snapshots of the simulation of 1000 balls flow from start to its deposition. The simulation results are reasonably accurate for small avalanches (up to 1,000 balls). However, flows rapidly spread to one ball thick and no interaction between the balls was found. In addition, no specific structures, such as head, tail and eyes in Figures 2, 7, and 9 are formed, which suggests the air drag is a crucial factor in the simulation of ping-pong ball flow.

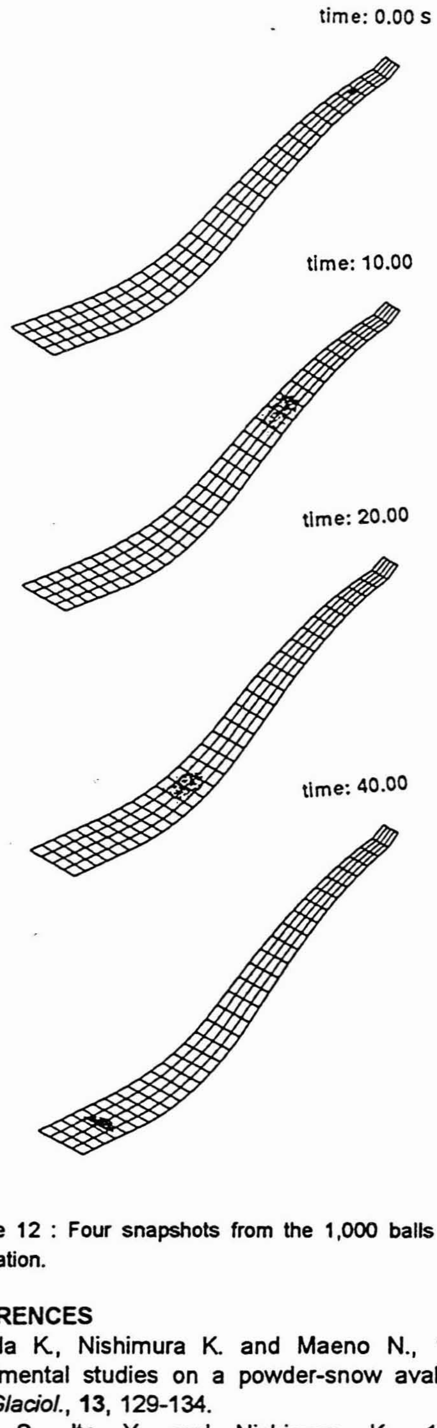

Figure 12 : Four snapshots from the 1,000 balls flow simulation.

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REFERENCES

Kawada K., Nishimura K. and Maeno N., 1989 : Experimental studies on a powder-snow avalanche. *Ann. Glaciol.*, **13**, 129-134.

Keller S., Ito Y. and Nishimura K., 1998 : Measurements of the velocity distribution in ping-pong-ball avalanches. *Ann. Glaciol.*, **26**, 259-264.

Nishimura K., Narita H., Maeno N. and Kawada K., 1989 : The internal structure of powder-snow avalanches. *Ann. Glaciol.*, **13**, 207-210.

Nishimura K., Maeno N., Kawada K. and Izumi K., 1993 : Structures of snow cloud in dry-snow

avalanches. *Ann. Glaciol.*, **18**, 173-178.
Nishimura K., Nohguchi Y., Ito Y., Kosugi K. and Izumi K., 1997 : Snow avalanche experiments at ski jump. *Proceedings of the International Snow Science Workshop, 1996, Banff, Canada*, 244-251.
Nishimura K. and Ito Y., 1997 : Velocity distribution in snow avalanches. *J. Geophys. Res.*, **102** (B12), 27297-27303.
Nohguchi, Y., 1996 : Avalanche experiments with styrene foam particles. *Proceedings of the Third International Conference on Snow Engineering (ICSE-3), 1996, Sendai, Japan*, 63-68.