Snow Avalanche Experiments at Ski Jump

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ABSTRACT

In 1995, we have started the experiments at a ski jump to investigate the avalanche dynamics and internal structures in detail. In winter, natural snow 300 kg in weight at maximum was released and flow velocities, impact pressures, induced wind velocities, and dynamic friction coefficients were measured. The observation setup is almost the same as the one installed in Kurobe Canyon where a systematic investigation of natural snow avalanche is under way since 1989. Instead of snow itself, in summer, we have used 300,000 ping-pong balls. They were stored in a container set on the top of the inclined plane and were released simultaneously. Movements of the individual balls and flow behaviors were recorded with several video cameras. Since the air drag gave a large effect on the ping-pong movement, the flow arrived at a steady state within a relatively short distance. The front velocities strongly depended on the number of released balls. In addition, the flow formed a distinct head and tail structure, which had been often observed not only the snow avalanche but also other large-scale geophysical flows in nature.

INTRODUCTION

The authors have carried out the systematic snow avalanche observations in the Shiai-dani valley, Kurobe Canyon since 1989 (Kawada et al., 1989; Nishimura et al., 1989; Nishimura et al., 1993) and recently succeeded in obtaining some sets of valuable data. (Nishimura et al., 1995). However, our knowledge of the dynamics and internal structures of the snow avalanche itself are still far from satisfactory. In order to define the flowing system and make an appropriate model which describes the avalanche motion, at least we need to know the velocities and densities as a function of time and space. However, mainly due to its formidable characteristics, even the simplest measurements have been difficult to perform in nature. Thus, in 1995, we have started the snow avalanche experiments at a ski jump so as to investigate the avalanche dynamics and its detailed structures. In winter, natural snow 300 kg at maximum was used. In summer, on the other hand, we have released from 2 to 300,000 ping-pong balls to simulate the three dimensional granular flows. This paper reports the above experimental procedures and gives some results of the preliminary analysis.

MEASUREMENTS

Experiments were made at the Miyanomori ski jump field in Sapporo, which has been used for the normal-hill ski jump competition; Olympic games were held in 1972 there. Figure 1 shows the cross section of slope. Snow flow experiments in winter were carried out along the approach and ping-pong ball experiments in summer on the landing bahn. Both flows descended the slopes, the steepest part of which was 36 deg., and came to rest near the kante or on the braking truck.

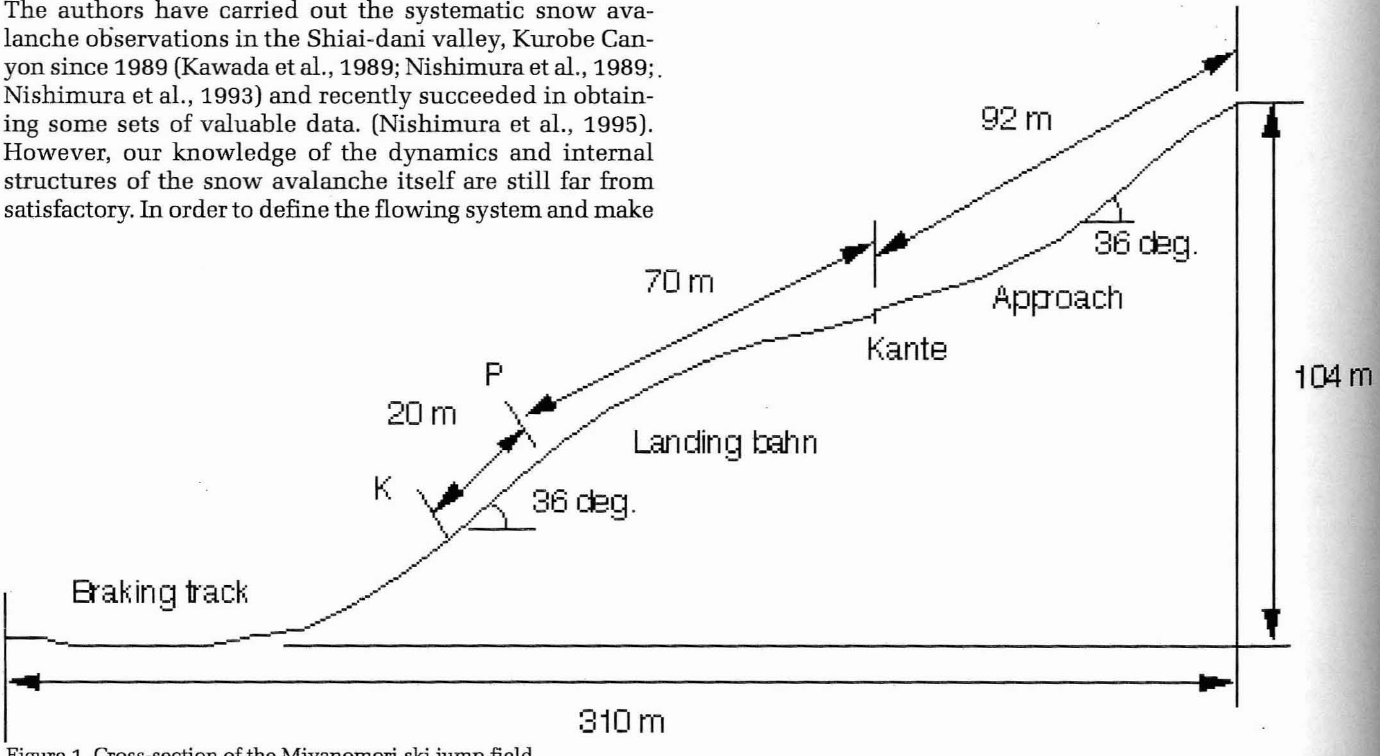


Figure 1. Cross-section of the Miyanomori ski jump field.

SNOW FLOW EXPERIMENTS

In these experiments, weights of natural snow up to 300 kg were released at the top of the approach. A container set on top of the approach was filled with the snow chunks, density and temperature of which were 290 kg/m³ and -10 °C respectively, and all the snow was released by opening the sliding gate. Upon release, the snow accelerated down in a rectangular cross-section track, which is 0.8 m wide, 0.3 m deep and 70 m long. The track was covered with a polyethylene sheet to reduce the friction and to achieve maximum flow velocities. The flow eventually reached more than 10 m/s and then with approaching the Kante in Figure 1 decelerated. Above flow behaviors including the leading edge position as a function of time were recorded with several sets of video cameras. During the experiments it was overcast and the ambient temperature was -2 °C.

Figure 2 shows the measuring apparatus set up on the snow flow track. The observation point was 55m away from the gate. Most equipment was installed in two sets of steel towers which consisted of cylinders 0.05 m in diameter and 1.2 m in height. The distance between two towers was 0.87 m. Impact forces were measured with strain-gauge-type load cells, KYOWA LUB20KB, attached to 10 cm diameter pressure plate. Three load cells were cited on each tower, at height of 0.14, 0.24 and 0.34 m above the track surface. The air velocity induced by the snow flow was recorded with an ultra-sonic anemometer, Kaijodenki WA-200, which has been installed in Kurobe canyon to observe the natural snow avalanche and revealed the snow cloud structure of one powder snow avalanche once(Nishimura et al. 1995). However, there are a couple disadvantages in this method. Firstly it costs fairly high although large avalanches sometimes take away the sensor. Secondly it often gives the abnormal signal when the density of the snow cloud is relatively high. In this study, thus, we measured the static pressure depression in the flow at the same time and tried to transfer the obtained value into the air velocity. In general, we can expect the flow velocity u is related to the static pressure depression ΔP as follows,

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

where ρ is the density of the air. However, since the diameter and the length of tube give substantial effects on the above relation, we obtained the correction factor with the wind-tunnel in advance. In the experiments two sets of tube, inner diameter of which is 0.01 m, were set as each cut ends looked downward. Besides a drag meter newly designed was set at the end of the track. It consisted essentially of a plate, which was 0.3 m x 0.2 m in size and was covered with snow, and a strain-gauge-type load cell, KYOWA LSM-20KBS, which could sense the three components of stresses. This equipment was utilized to investigate both the shear and normal stresses acting on the snow surface during the snow flow passing by.

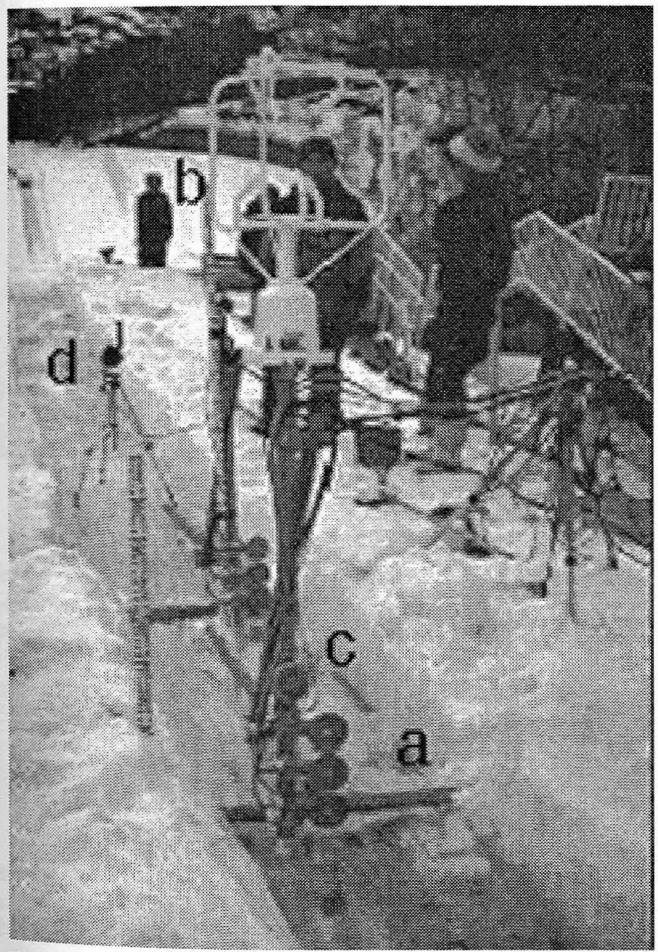


Figure 2. The measuring apparatus set in the snow flow path. a: impact pressure sensors, b: ultra-sonic anemometer, c: tubes for measuring the static pressure depressions, d: video camera.

Ping-pong ball experiments

Snow avalanches are made up of granular materials. Upon breaking out the dry snow avalanche, the snow blocks are broken into smaller lumps or even ice particles. On the other hand, after stopping the wet snow avalanche we can find a number of snow balls in the debris. Hence, some of the results studied in the granular flow can be applicable in the snow avalanche modeling (e.g., Savage, 1983), but unfortunately most of theories and numerical simulations developed so far look too simplified and not enough to formulate the snow avalanche motion at this stage. Before much progress can be made in this area, more data sets should be compiled in order to check the models.

Nishimura et al. (1991) carried out inclined chute experiments with ice spheres in a cold laboratory and obtained the profiles of density and velocity as functions of inclination and temperature. However, the question whether the flow reached the steady-state in the 5.4 m long chute was remained.

In this study, we have used a ping-pong ball with 37.7 mm in diameter and 2.48 g in weight. Since the effect of the air drag on the ping-pong ball was fairly large, the flow velocities are expected to arrive at steady state within a short distance. In fact, Nohguchi et al. (1996) found in their 22 m long chute experiments that the front velocity of ping-pong ball flow became nearly constant at 10m downstream of the starting point. Furthermore, Nohguchi.

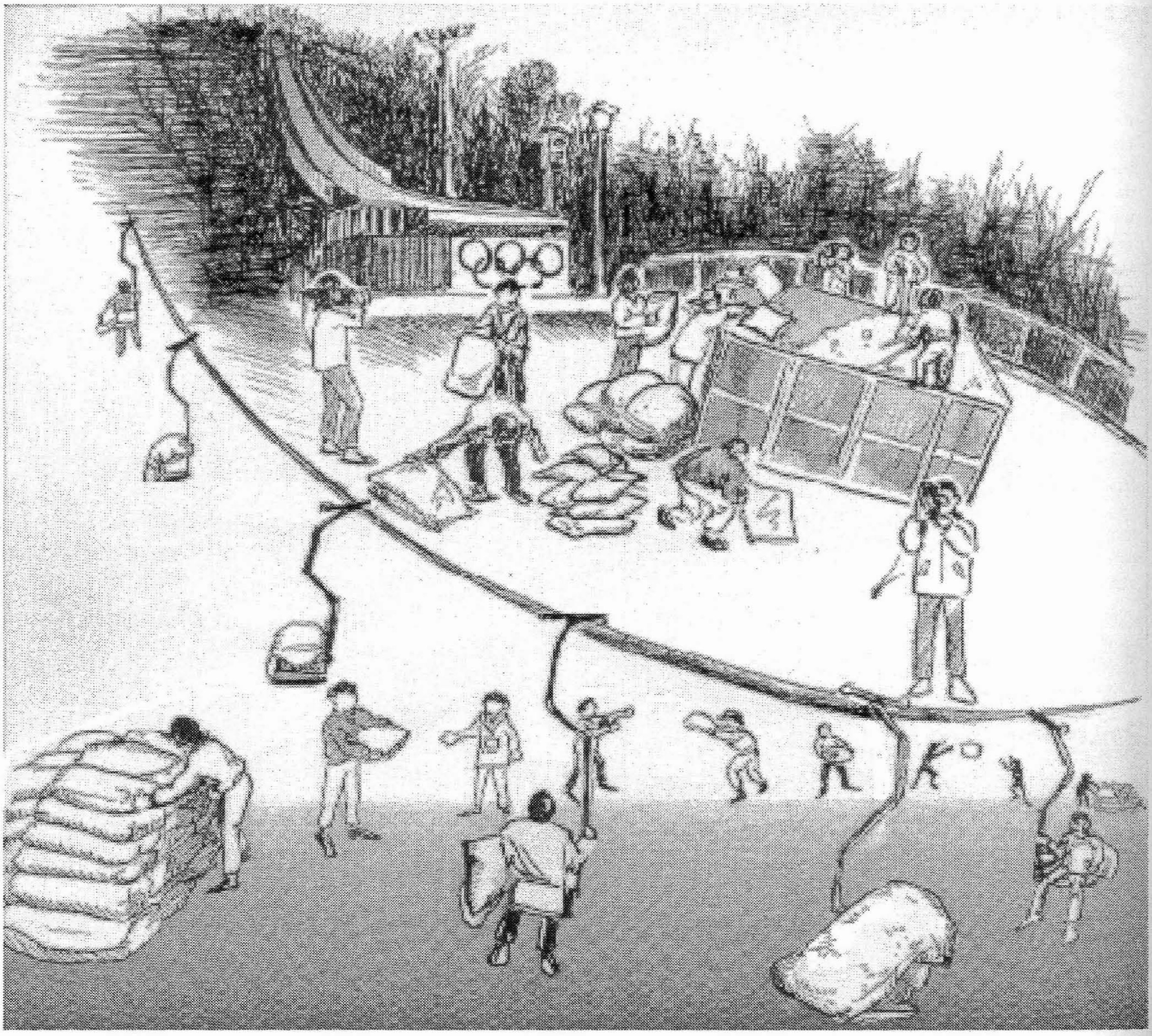


Figure 3. Preparation of the ping-pong ball experiment.

(1996) concluded with his similarity analysis that the ping-pong flow on the 100 m long slope corresponded to the natural powder snow avalanches which run down for a few kilometer distance.

In the experiments, 300,000 balls at the maximum were stored in a large container set on top of the landing-bahn (landing path). Experiment preparation are shown schematically in Figure 3. Ping-pong balls were released simultaneously with opening the front gate of the container. Then the flow accelerated down on the inclined plane which is more than 150m long and 30 m wide. The floor was made with the artificial lawn and its inclination amounted to 36 deg. from K to P point in Figure 1. After passing the steepest part, the flow decelerated and stopped on the braking track. Individual movements of the balls and flow behaviors were recorded with several video cameras. In addition, upon coming to rest, the debris distribution was measured as a function of position. Four towers were set 10 m down from the K-point to investigate the structures of these three dimensional granular flows. The tower structures and measuring devices mounted on it were almost as same as those used in the snow flow experiments except the height of tower was 60 cm.

RESULTS AND DISCUSSIONS

Snow flow experiments

Each experimental run was recorded with several sets of video cameras. Analysis of pictures are utilized to obtain the position of the leading edge (front) as a function of time. As shown in Figure 4 the snow flow increased the velocity linearly with distance and reached about 12 m/s after flowing down 35 m from the starting point. As the

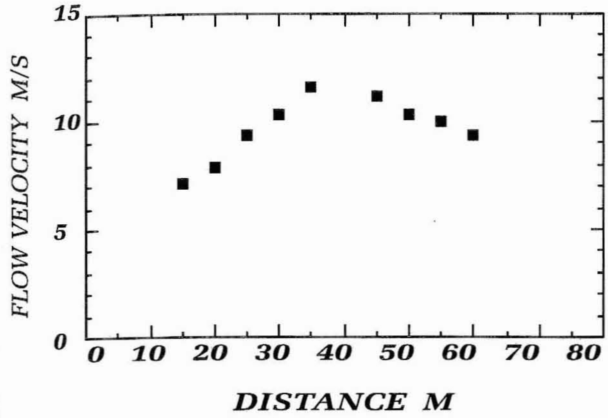


Figure 4. The leading edge velocity of snow flow.

flow reached about 7 m/s, a powder cloud was observed to form and obscured the denser flow (Figure 5). Afterwards, it reduced the velocity gradually with the decrease in the inclination. The velocity at the position of the measuring tower was about 10 m/s.

Figure 6 presents the recordings of air velocities at 0.17 m and 0.42 m above the floor, both of which are calculated from the static pressure depression. Taking into the consideration of the impact pressure data at 0.14 m listed in Figure 6 and the video recordings viewed from the side, it is reasonable to see that the lower sensor shows the air movement in the dense flow and the higher one in the snow cloud. Hence, Figure 6 indicates that air movement in the upper snow cloud was less than half of the one in the dense flow. Both velocities increased rapidly just after the front and then decreased gradually. Such trend in Figure 6 is very analogous to the real avalanche one reported in Nishimura et al. (1993). In addition, since at the measuring tower the leading edge velocity in Figure 4 agrees roughly with the velocity appeared in Figure 6, we see that the system introduced here is a reliable and useful tool for the two-phase flow in nature, such as the snow avalanches and the drifting snow. Impact pressure and the air flow at 0.17 m do appear to resemble each other, which suggests a close interaction between the snow and the ambient air in the dense flow.

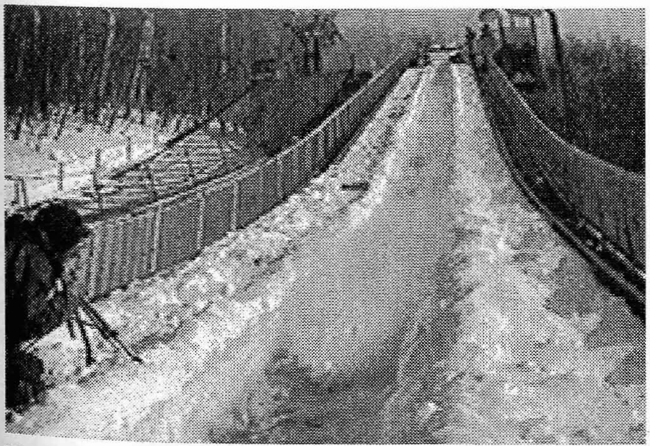


Figure 5. Snow flow with the powder cloud.

Figure 7 shows the normal stress and the shear stress measured with the drag meter when 70 kg snow was released. The normal stress increased rapidly when the flow front has arrived. It came up to about 400 Pa. In the following 1.5 sec., it declined gradually. Since the normal stress directly represents the snow mass passing on the drag plate, we can say that most of the mass was involved in the first 0.5 sec. The variation of the shear stress, on the other hand, was rather small comparing to the normal stress. Figure 7 also indicates the time variation of the dynamic friction coefficient which is expressed as the ratio of the shear stress to the normal stress. It is interesting note that the dynamic friction was kept roughly constant around 0.4 for the first one sec., but in the rear part of the flow it showed a gradual increase with decreasing the normal stress, in other words, with decreasing the snow flow mass. Izumi (1985) pointed out that very large snow avalanches, involving more than about 10^5 m^3 of snow, exhibit anomalously low friction coefficients. Consequently they traveled much further than conventional criteria prediction. Namely, increase in the volume (mass) of the flow leads the decrease in dynamic friction. This is also known in some other types of geophysical flows, such as turbidity currents on the ground of oceans or lakes, pyroclastic flows emerging from volcanoes, rock avalanches and debris flows. Although a number of attempts to explain this behavior have been tried, little is known so far. Obviously the results shown in Figure 7 correspond to the direct measurement of the above phenomena, thus our approach is expected to give a clue to the solution.

Ping-pong flow experiments

As mentioned in the previous section, a variety of instruments were mounted on the towers to measure the ping-pong flow characteristics. However, in this paper we just describe the flow behavior and introduce some distinctive evidence found in these experiments.

As running down the slope the flow was observed to spread out laterally and longitudinally in general (Figure 9). After passing the steepest part, the flow decelerated and stopped on the braking track. Figure 8 shows the leading edge velocities as a function of runout distance when 250,000 ping-pong balls were released from a point of 15 m. The flow accelerated linearly with the distance on the inclined artificial grass floor and its velocity eventually amounted to 15 m/s after 65 m down from the starting point. Then the flow kept the velocity almost constant for 30m until the inclination changed to decrease; a steady granular flow was formed.

The flow velocities and run out distance strongly depended on the number of released balls. The leading edge velocities measured from K to P point are given in Figure 10 as a function of released ball numbers. The velocity showed a remarkable growth from 2.8 to 15 m/s with increasing the amount of ping-pong balls. Generally not only a air drag but also a particle-particle and particle-floor collision act to reduce the velocity. In fact, when two balls were released the velocity was only 2.8 m/s; each ball ran down individually without interaction. It is much less than

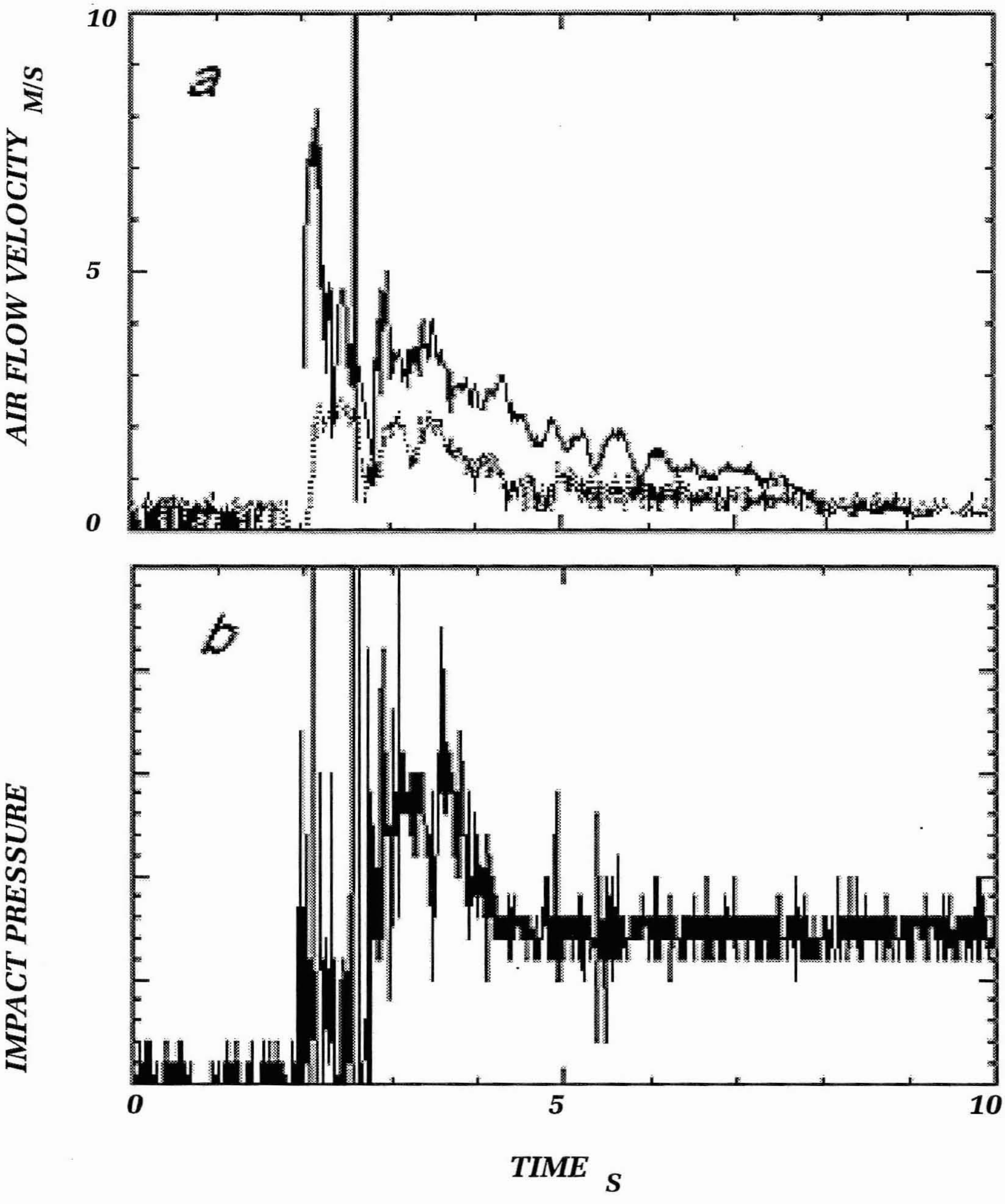


Figure 6. Recordings of the snow flow experiment. a: air flow velocities measured with the static pressure depression at 0.17 m and 0.42 m in height; solid line shows the former and dotted line latter.b: Impact pressure at 0.14 m.

the terminal velocity of a ping-pong ball U_t = 9.5 m/s, which can be calculated with the following expression.

$$U_t=\sqrt{\frac{3g\,(\rho_S-\rho_F)D}{P_F}}$$

where ρ_S, ρ_F and d are the particle density, fluid (air) density and particle diameter respectively. However, with increasing numbers it gained the velocity and it eventually arrived at 15 m/s which is even 1.5 times larger than the terminal velocity. Nohguchi (1996) assumed that the flow velocity *Ve* arrived at the steady state is proportional to N^a where N shows the particle number. Then he derived with his similarity analysis that the coefficient a is 1/6 for three dimensional systems; it fit his avalanche experiments with the styrene foam particles (1.5-2.0 mm in diameter). Figure 10 proves clearly that the above theory gives good account for these ping-pong ball flows as well.

In the experiments, with increasing the number of balls, we could recognize a head and tail structure more and more clearly. Figure 11 gives a picture of head when 250,000 balls were released. Here the thickness of the head

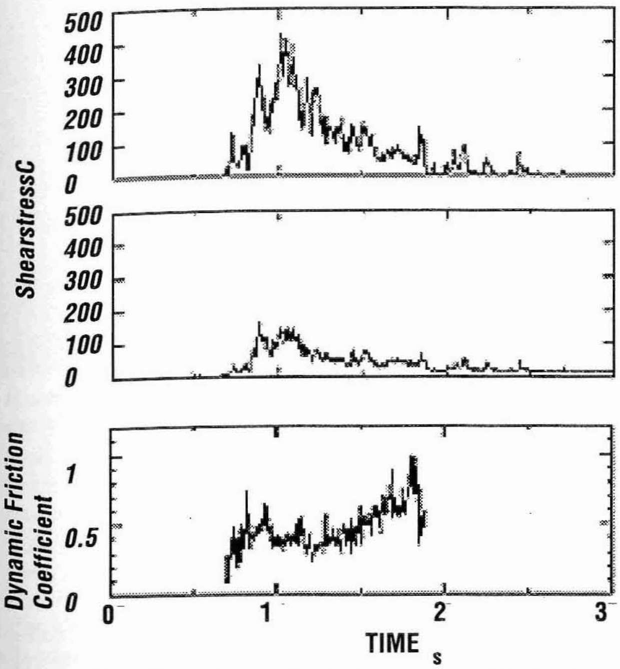


Figure 7. Recordings of normal and shear stresses with the drag meter and the dynamic friction coefficient calculated with the above two stresses.

was higher than 60 cm which corresponded to about 40 particles diameter. Although the individual ball changed the mutual position rapidly, the leading edge looked to flow down like a consolidated body. Hence, it is reasonable to say that the size of the head gives a strong effect on the flow velocity change listed in Figure 10. In addition, it should be noteworthy that the head and tail structure shown this experiments had been often observed not only the snow avalanche but also other large-scale natural geophysical flows in nature.

CONCLUSIONS

We have started the avalanche experiments with the ski jump, because it seems the longest inclined plane we are available under the controlled condition. In winter, natural snow 300 kg in weight at maximum was released and flow velocities, impact pressures, induced wind velocities, and dynamic friction coefficients were measured. Instead of snow itself, in summer, we have used up to 300,000 ping-pong balls. Although some measurements like in snow experiments were carried out as well, in this paper we have just concentrated on introducing the leading edge velocity as functions of the runout distance and the number of ping-pong balls. As mentioned earlier, a number of theories and their numerical simulation have been carried out to describe the granular flow. However, all of them are still too simplified to draw even the figure of the ping-pong ball flow in this study. At least the model should be extended to three-dimension and the air drag effect has to be included. Computer simulations including above effects are currently in progress.

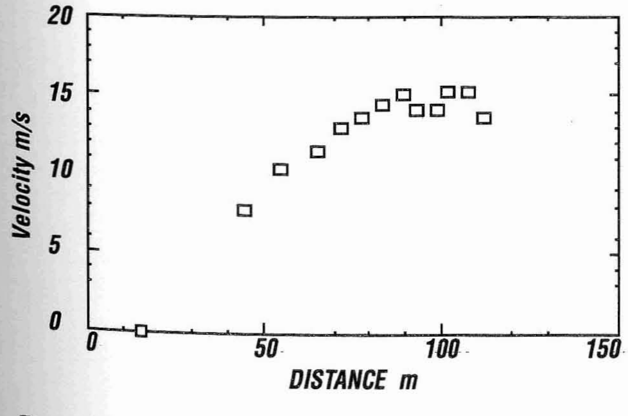
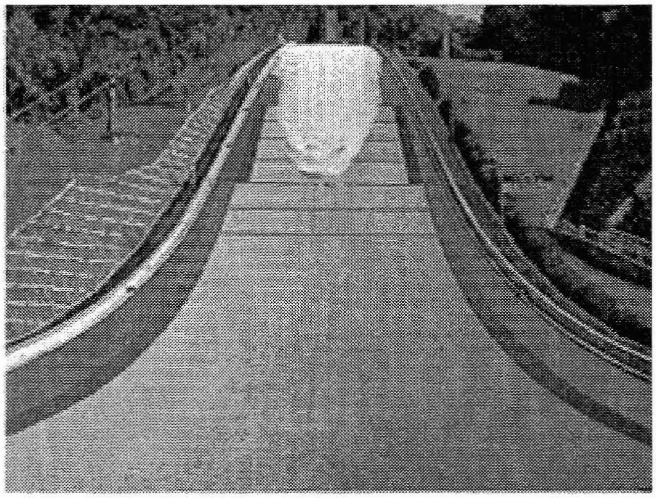


Figure 8. The leading edge velocity of the ping-pong ball flow. Here 250,000 balls were released from the point of 15 m.



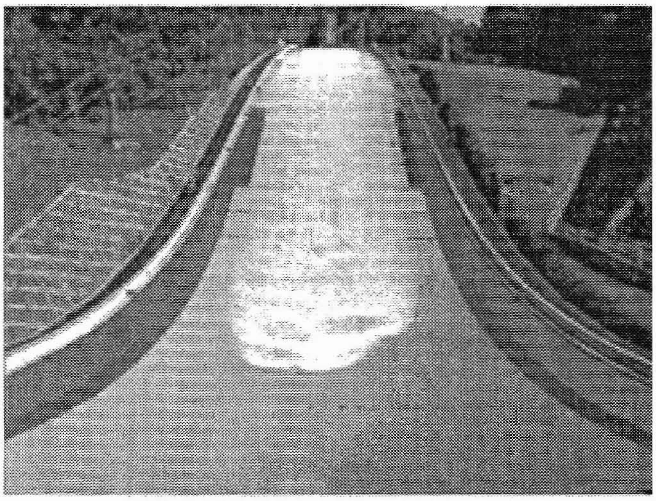


Figure 9. 250,000 ping-pong ball flow along the ski jump.

Our snow experiments proved that the measurement of static depression was the reliable and useful tool to investigate the air movement in the snow avalanche. At Kurobe Canyon where a systematic investigation of natural powder snow avalanche is under way since 1989, an ultra-sonic anemometer has been utilized, but so far we could obtain the air movement data for one small avalanche once (Nishimura et al., 1993); others showed just the abnormal signals due to the fairly large snow concentrations. Securing the foothold in this study, in the winter

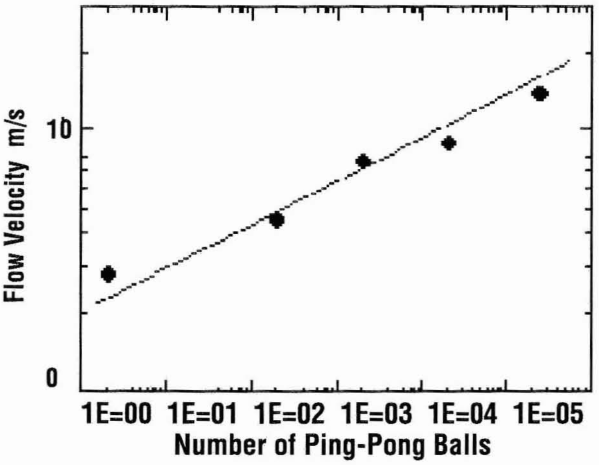


Figure 10. The leading edge velocities from K to P point as a function of released ball numbers. The line was derived theoretically by Nohguchi (1996).

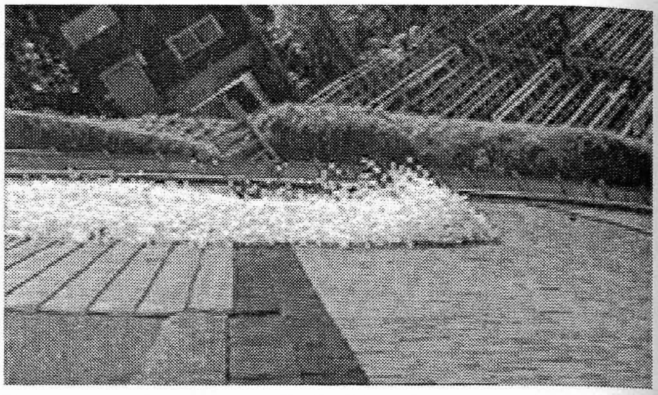


Figure 11. Distinct head found at leading edge of ping-pong flow.

from 1995 to 1996 we installed the tube measuring the static pressure depression. During the observation period we had larger amount of snow accumulation than average and several snow avalanches passed by the station. Figure 12 gives the data of snow avalanche broke out at 1337 on 29 January 1996. It is certain that air movement in the snow cloud has never been revealed for such a large powder snow avalanche, velocity of which amounted to more than 50 m/s. Since we can estimate the velocity of dense part with analyzing the impact pressure data and seismic signals, the comparison with the data in Figure 12 promises to give a new insight about the internal structure of the powder snow avalanches.

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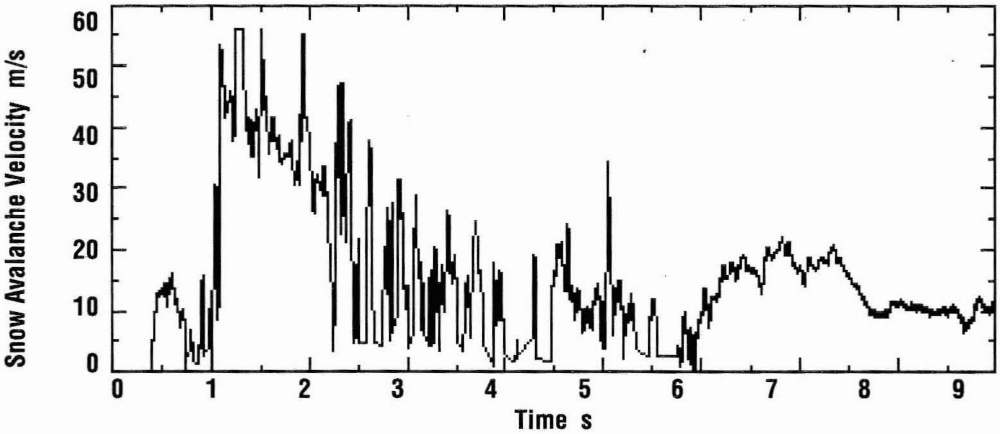

Figure 12. Air velocity in the snow cloud. This avalanche broke out at Shiai-dani, Kurobe Canyon, at 1337 on 29 January 1996.

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