Interaction of retarding structures with simulated avalanches in snow chute

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A series of experiments were conducted in a 61-m long snow chute to investigate the interaction of the flowing snow mass with obstacles (friction blocks) of different geometries. The flows generated are approximated as avalanche-like flows as they show typical features such as a steady velocity along the track, longitudinal spreading and almost fluidized flowing characteristics, despite the smooth chute surface. In this study, we report a series of experiments on model control structures in the form of mounds and a blunt body of similar projection area which are of a comparable height to the flow depth. The retarding effects were investigated by a direct measurement of the velocity of flow at various sections using CCD cameras, its run-out length and location of centre of mass of the final debris deposited. The experiments show that the avalanche currents generated in the snow chute detach from the top of the obstacles in the form of a jet and a granular jump is created, which results in a sufficient dissipation of the energy and a possibility of a shock wave travelling in the upstream direction. It was observed that mounds with height more than two times the flow depth, can lead to a significant reduction in the runout length. However, at low flow depths the effectiveness of the blunt body is more because the avalanching snow splits into different segments and the flow profile is close to the bed slope. On the contrary, when the flow depth is of the same order of magnitude as the obstacle height, the mound becomes more effective as the flow detaches from the top of the blunt body and travels a much larger distance at high velocity, while as in case of mounds a jet is formed both in horizontal and vertical directions, and travels a comparatively less distance. The study of the jet traverse in the vertical direction becomes useful in determining the effective distance between rows of retarding structures.

Keywords: Avalanche-like flows, dynamic similarity, energy dissipation ratio, show chute.

THE volume of snow mobilized by avalanches is highly variable and can seriously strike human settlements, causing huge economic loss as well as the loss of human lives. For planning any avalanche control scheme, assessment of the hazard becomes necessary, and estimation of the dynamic parameters, like velocity and impact forces is vital for designing the control measures. Due to uncertainty of the avalanche flow parameters under variable initial and boundary conditions, the study of interaction of the retarding structures on the real avalanches becomes difficult, and therefore scaled experiments are required to be carried out to investigate the avalanche–obstacle interaction. An insight into the complex dynamics of the moving snow mass is a sine-qua-non for correct estimation of avalanche forces, velocities and run-out distances by suitable theoretical formulation or mathematical models based on some basic assumptions and snow-chute experimentation. At present, numerical models based on hydrodynamic theory considering Voellmy fluid require a careful selection of friction parameters to determine avalanche flow parameters and run-out distances.

Scientists at the Snow and Avalanche Study Establishment (SASE) Chandigarh are working on the development of a reliable model for avalanche flow suitable for Himalayan terrain conditions through computer simulation for transient flow and model study of friction parameters. For this, the data were obtained from the experimental vessel, i.e. snow chute that generates an avalanche-like flow akin to observations from the natural avalanche occurrences. Investigations have been carried out in the past to predict the snow–avalanche impact on structures both in the real scale as well as on the laboratory scale[1,2]. Some studies on the numerical modelling of granular flow in an inclined plane have also been reported[3–5]. In this study, we present a large-scale experimental set-up, which allows the generation of avalanche-like gravity currents of snow under reproducible experimental conditions. We have studied the interaction of flow with obstacles in the flow path and the formation of a jump or a jet thereof. A large fraction of the flow was launched from the experimental chute, which subsequently lands back on the chute and these flows were accompanied by shocks induced by the presence of the obstacles.

A snow chute of 61 m length, 2 m width and 1 m depth having 5.5 m long snow-feeding platform (hopper) inclined at 35°, convergent–divergent section of 13 m (30°) for fluidization of flow was designed and constructed at Dhundhi (3000 m asl), 20 km from Manali, Himachal Pradesh, to generate avalanche-like flows under reproducible conditions (Figure 1). After fluidization of flow, the flowing mass enters the main observation channel having a slope of 30° for 22 m and 12° for the next 8 m length, and a 12 m long and 4 m wide horizontal testing platform. The testing platform has the facility to change its slope from 0° to –15° using a hydraulic system pair. Using natural snow of different densities, avalanche waves up to 18.0 cubic m volume and having velocity of 8.0 ± 0.5 to 18.0 ± 0.5 m/s can be generated in the chute experiments. The avalanche flow was viewed and recorded by CCD cameras connected to a digital video-recorder. The results of the experiments conducted in the

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snow chute were used to verify the existing avalanche flow models and friction laws. It was also observed that these experiments helped to study the effect of Coulomb friction and turbulent friction by measuring the run-out distances for varying slopes in the run-out zone[6].

The physical parameters that describe the dynamic processes in the granular flow and snow avalanches are: g, the acceleration due to gravity; u, the mean velocity of the avalanche; d, the avalanche depth; h, the particle diameter; v, the kinematic viscosity of the interstitial fluid; φ, the internal friction angle of the material, and δ, the bed surface friction angle. The internal friction angle of the material describes a Coulomb-type plastic yield between the moving particles. Similarly, the bed friction angle is a measure of the Coulomb-type friction between the particles and the bed.

The phenomenon of snow avalanches is gravity-driven; dimensional analysis indicates that the law of similitude requires the Froude number

$$Fr = \frac{u}{\sqrt{gd}},$$

of the flow to be invariant under transformations to the laboratory scale. The Froude numbers exhibited by the flow lie in the range of Fr = 6–12, which is almost overlapping with the range of Froude numbers exhibited by real-scale avalanches, and thereby ensures a dynamic similarity between the experimental runs and the natural snow avalanches.

Snow collected from the mountainside and the loading platform was dumped into the chute hopper, behind the gate (manually operated gate). Obstacles such as a blunt body and mounds of similar projection were placed in the flow path of the avalanche, perpendicular to the experimental chute and the progression of the avalanche mass down the chute was recorded using four CCD cameras covering the entire length of the chute. Flow speed and depth at different locations upstream and downstream of the obstacles were also recorded.

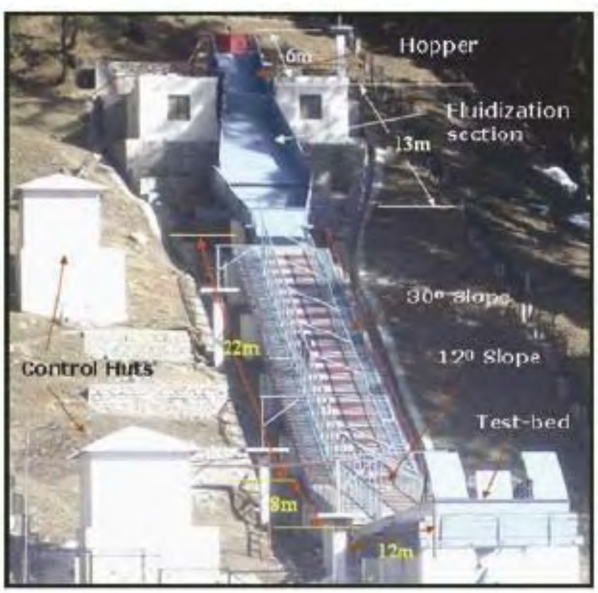

Figure 1. Snow chute, 61-m long at Dhundhi.

The experiments were carried out for variable fracture depth from 0.2 to 1.0 m in the temperature range –4–0°C using wet snow having density between 300 and 550 kg/cubic m. Velocity and run-out distance were measured in the snow-chute experiments to ascertain the run-out shortening and velocity reduction with the retarding barriers. Details of the experiments conducted in the avalanche chute at Dhundhi during winter 2005 and 2006 respectively, for studies pertaining to energy dissipation by barriers and investigation of the shock in the upstream direction on interaction with the barriers are given in Tables 1 and 2 respectively. The effect of an obstacle on the avalanche strongly depends on its geometry[7] and accordingly, different configurations of obstacles were tested (Table 2).

To visualize and capture the motion of the moving snow mass in the snow chute, four CCD cameras were mounted along the chute channel at fixed intervals. These cameras were connected with a digital video recorder (DVR) which has the facility to analyse the picture captured by the camera frame by frame, to study the flow parameters. The chute surface was marked at fixed intervals of 50 cm and the time taken to cross these intervals was taken from the DVR, and used to determine the average velocity of moving snow mass.

The various parameters that were measured during the large-scale experimentation in the snow chute during winter 2005 and 2006 respectively, with natural snow include ambient temperature and snow-surface temperature, type of snow, type of grains, density of snow in different layers, geometry of released snow mass, depth of deposited snow/shift in the centre of mass with the obstacle on the testing platform, stopping distance, and lateral spread with and without structure. Using this information, the following quantities were derived to be used in the analysis of the experiments: (a) Average initial velocity at the exit of the second hopper. (b) Discharge at the second hopper exit estimated from the time required to pass the entire mass from the said section. (c) Velocity at intermediate stages along 30° and 12° slope respectively, from the time elapsed in passing a specified distance on the

Table 1. Flow depth and terminal velocity in different set-ups

Flow depth (m)	Terminal velocity (m/s)	No. of experiments
0.30	8.0–10 ± 1.0	3
0.60	10.0–12 ± 0.5	9
1.0	12.0–18 ± 0.5	8

Table 2. Different obstacles used for energy-dissipation studies

Type of structure	No. of experiments	Remarks
Mound at 30° end	2	Energy dissipation studies
Blunt body at 30° end	2	Energy dissipation studies
Mound at 12° end	3	Energy dissipation studies
Catch dam 45° inclination at test bed	3	Evolution of shock behind the dam
Catch dam 90° inclination at test bed	4	Evolution of shock behind the dam
Catch dam 90° inclination at 1 m from 12° slope	3	Evolution of shock behind the dam and mapping of the trajectory of flowing mass

said section. (d) Friction coefficients as fit parameters to fit the model behaviour using Voellmy Salm model[8] to compute velocities and run-out lengths under similar conditions as in chute experimentation.

The experiments were performed in the supercritical regime and close to avalanche flows, characterized by a non-dimensional internal Froude number,

$$Fr = \frac{u}{\sqrt{gd\cos(\theta)}}.$$

Here u is the velocity, d the depth and θ the inclination. This type of experiment consisted in releasing snow mass or granular material in an accelerating zone and studying the deposit in the run-out zone with the presence of obstacles (mounds, blunt body and catch dams) in comparison with control experiments (without obstacles). The released snow mass, travelling down the upper section of the chute (30° slope), reached a terminal speed close to 12.0 ± 1.0 m/s, which remained constant until the slope angle changed to 12°. The released snow mass travelled with the shape of a parabolic cap, with a quasi-steady maximum flow depth of 30.0 cm, corresponding to a Froude number of approximately 8–10. As this avalanche wave descends downwards, due to change in slope and subsequent debris deposition, velocity continuously falls till the avalanche wave stops in the test-bed. To add to this argument, we must understand that for avalanche formation and initiation, weather, terrain and slope are important factors. Weather and terrain for a particular series of experiments are dormant and therefore slope angle plays a vital role in the acceleration and deceleration of flow. It has been verified that the collision of the flow with retarding barriers (mounds/blunt geometries) leads to the formation of a jump or a jet, whereby a large fraction of the flow is launched from the experimental chute and subsequently lands back on the chute. The retarding effect of the mounds/blunt body was investigated quantitatively by direct measurement of the velocity and run-out length of the flow along with the geometry of the jet, using CCD cameras mounted at fixed locations on the chute axis and a digital camera focused to capture the geometry of the jet flowing past the barrier. It was observed that mounds with height two times the flow depth, lead to a 30–40% reduction of the run-out length of the flow. Retardation of the flow caused by impact with the mound and dams found from the experiments with snow in the 61.0 m long chute at Dhundhi, was of similar order of magnitude as previously found in experiments in 3, 6 and 9 m long chutes using other materials (shortening of the run-out is broadly similar for the ballotini experiments at the three scales and maximum reported run-out shortening is about 40%) and the 34.0 m long Weissfluhjoch chute at SLF (around 20% for a non-dimensional dam height of 1.0 and further increase in the dam height leads to lowering of the velocity; the velocity was reduced by about 50% for a non dimensional height close to 4.4).

If the mechanical energy of the flow is conserved in the collision, simple energy conservation gives

$$\frac{1}{2}u_1^2 = \frac{1}{2}u_0^2 - gH', \qquad (1)$$

where H' is the vertical rise of the flow when it passes over the obstacles ($H' = H\cos 12°$, since the structures were positioned on a slope of 12°). Hence, no energy loss during impact with the obstacles leads to the expression

$$u_1/\sqrt{u_0^2 - 2gH'} = 1. \qquad (2)$$

The energy dissipation ratio $D = u_1/\sqrt{u_0^2 - 2gH'}$ provides an estimate of the amount of energy dissipated in the turning process, since if the kinetic energy is solely converted into gravitational potential energy, this ratio should be unity. D represents energy dissipation in the impact with the mounds and the process of turning the flow, illustrates that a substantial fraction of the energy was dissipated in the impact. The velocity was lowered by around 42% for a non-dimensional dam height close to 1.66. This reduction might be inaccurate (too high), since the velocity used after impact was captured by the digital camera using the CCD camera looking backwards to the direction of the main flow. The semi-steady speed on the upper section of the chute was 12.0 ± 1.0 m/s, and it was somewhat lower when the current hit the mound, since it travelled on the less steep lower section of the chute for 1.5 m. While evaluating the energy dissipation capacity of the structure, a non-dimensional flow depth was plotted

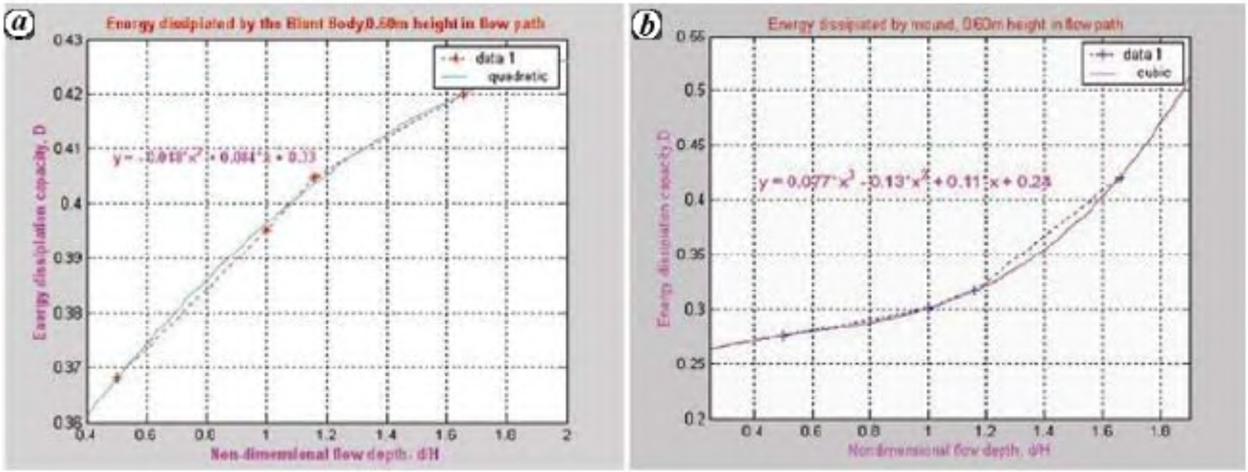

Figure 2. Energy dissipation ratio, plotted as a function of non-dimensional height, for geometries in the flow path. ***a***, Blunt body (0.60 m) and ***b***, Mound (0.60 m).

Figure 3. Flowing mass approaching the blunt body.

Table 3. Comparison of velocity reduction as a result of flow–structure interaction for both mound and blunt body

Fracture volume (m^3)	d/H	D_{plate}	D_{mound}
3.3	0.50	0.368	0.2755
6.6	1.00	0.395	0.301
7.7	1.16	0.405	0.317
11.0	1.66	0.420	0.421

D_{mound}, Energy dissipated by the mound in the flow path. D_{plate}, Energy dissipated by the plate in the flow path.

against the energy dissipation ratio, D for the blunt body (Figure 2 *a*) as well as the mound (Figure 2 *b*). From Figure 2 it is evident that at non-dimensional height close to 0.55, the energy dissipation ratio for the mound is 27.55% as against 36.80% for the blunt body, whereas at a non-dimensional height close to 1.5, the energy dissipation ratio for the mound is 42%. At low flow depths the effectiveness of the blunt body is more because the avalanching snow splits into different segments and the flow profile is close to the bed slope. Therefore most of the dissipation is due to the spreading of flow in different directions and the associated turbulence.

On the contrary, when the flow depth is of the same order of magnitude as the obstacle height, the mound becomes more effective as the flow detaches from the top of the blunt body and travels a much larger distance at high velocity, while as in case of the mound, a jet is formed both in horizontal and vertical directions, and travels a comparatively less distance.

The flow pattern of the released mass past a mound and a blunt body of similar projection area is shown in Figure 3. However, the dynamics of the impact of the flow with barriers such as dams and mound does not depend on the rheology of the material[9], but is primarily dependent on the large-scale flow.

The experiments indicate that the Fr is the most important dimensionless number describing the nature of the interaction of the flow with the obstructions.

Velocity reduction as a result of the flow–structure interaction for both mound as well as a blunt body is compared in Table 3 and graphically represented in Figure 2, with the equations fitting the experimental variables. Run-out shortening as a result of obstruction in the flow path and the change in pattern of debris deposition on the test-bed were also evaluated.

The change in the spread of the deposited pattern is shown in MATLAB plots of Figure 4. The run-out reduction with barriers is compared in Table 4 for the mound as well as the blunt body, and the results are represented graphically in Figure 5, with the equations connecting the experimental variables.

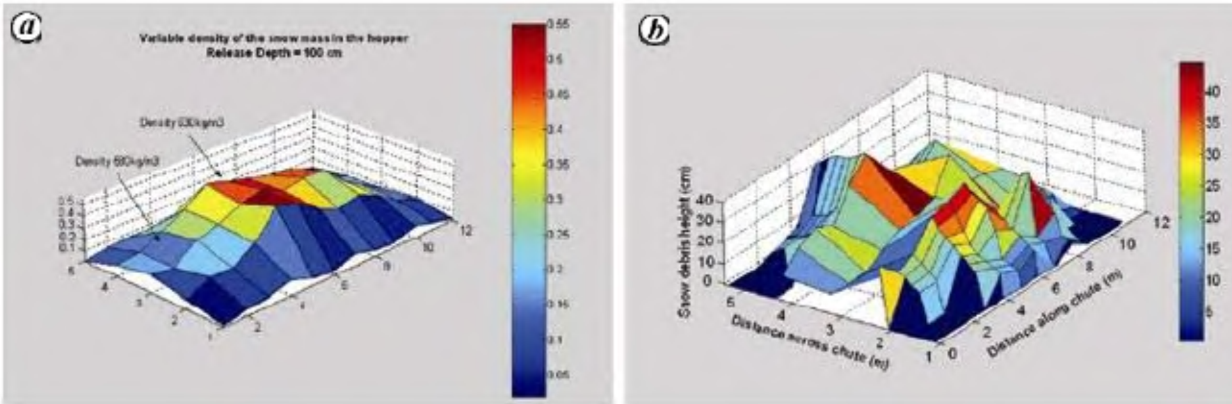

Figure 4. Spread on the test-bed (***a***) without obstruction and (***b***) with obstruction.

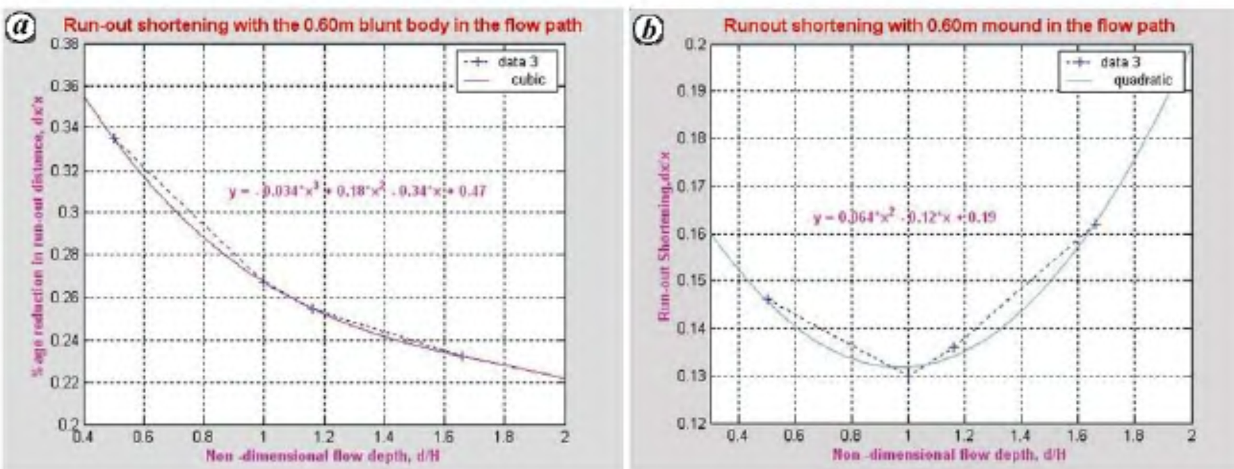

Figure 5. Run-out reduction factor, plotted as a function of non-dimensional height, for the geometries in the flow path. ***a***, Blunt body (0.60 m) and ***b***, Mound (0.60 m).

Table 4. Comparison of run-out reduction with barriers

Fracture volume (m^3)	d/H	$\Delta x/x$ plate	$\Delta x/x$ mound
3.3	1.25	0.335	0.146
5.5	1.42	0.267	0.132
7.7	1.66	0.2546	0.137
11	2.5	0.2322	0.162

x, Run-out distance; Δx, Run-out shortening with obstacle in the flow path.

It is evident from Figure 5 that at non-dimensional height close to 0.50, the runout reduction is about 33% for blunt body, whereas it is just around 15% for a mound of similar projection. However, as obstacle height increases the run-out reduction decreases for the blunt body as a function of $(d/H)^2$, whereas it increases for mound as a function of the $(d/H)^3$. This can be explained by the fact that at higher velocities the snow mass detaches from the horizontal as well as the vertical faces of the obstacle and travels a much larger distance with the blunt body in the flow path.

The effect of varying snow mass on the Froude number of the flow on a 30° slope of the snow chute was investigated for flow with and without barriers in the flow path. Once the flow had reached a quasi-steady state on the upper section of the chute, the Froude number, was found to be relatively independent of the amount of material released. The speed of the flow front varied from about 8.0 ± 0.5 m/s for 3.3 cubic m of snow to about 12.0 ± 0.5 m/s for 11.0 cubic m, with maximum flow depth of about 40 cm for the release mass of 11.0 cubic m. The energy dissipation depends on several aspects in the layout of the retarding structures. The influence of the height of the mounds/blunt body relative to the depth of the incoming flow stream and the proportion of the cross-sectional area of the impact zone covered by the mounds were examined in this study. The experiments verify that the mounds have a considerable retarding effect on high

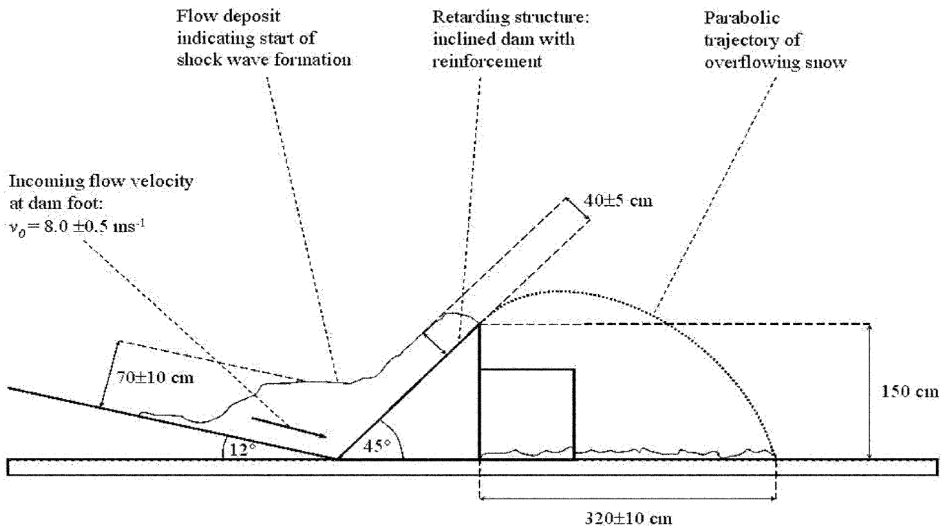

Figure 6. Flow past a 1.50 m high catch dam at the end of 12° slope.

Froude number granular currents, and about 40% reduction in velocity occurs at non-dimensional obstacle height close to 2. A substantial fraction of the kinetic energy of the incoming flow is dissipated in the interaction of the flow with the mounds, including the launching of the jet and the subsequent landing of the jet and mixing with material flowing along the chute.

Furthermore, a continuous dam at the end of the 12° slope with the non-dimensional obstacle height up to 4.0 has almost the same retarding effect as a row of appropriately designed mounds, where the jet launched from the top traverses a longitudinal distance of about 3.0 m (Figure 6) before coming to rest.

For quantitative examination of the possible shock wave travelling in the upstream direction during the interaction with the catch dam, further experiments need to be carried out. The jump created as a result of interaction with mounds/blunt body or the detachment of the parabolic jet from the top of the barriers has practical implications while choosing the spacing between the retarding barriers in the run-out path of the avalanche. The spacing between the rows has to be judiciously chosen to accommodate the detached mass, and hence has a full retardation effect.

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ACKNOWLEDGEMENTS. We are grateful to Dr R. N. Sarwade, Director, SASE, Chandigarh for guidance and encouragement. We also thank Mr Martin Kern, Schnee- und Lawinenforschung, Davos, for valuable suggestions.

Received 10 October 2006; revised accepted 5 February 2008