ENERGY DISSIPATION STUDIES ON MODEL CONTROL STRUCTURES USING AN AVALANCHE CHUTE

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ABSTRACT: Design of avalanche control structures in middle and runout zones of an avalanche requires a careful study of the flow-structure and its interaction with the defence mechanisms. To investigate the interaction of the flowing snow mass with the obstacles (friction blocks) of different geometries, a series of experiments were conducted in a 61m long snow chute. 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. The intelligent design of the upper chute part, which widens immediately after the release of snow mass allows lateral spreading and this step ensures this highly desirable flow behavior generally observed in the natural avalanches.

In this study, we report a series of experiments on model control structures in the form of mounds, a blunt body of similar projection area which are of a comparable height to the flow depth and a catch dam. 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 center of mass of the final debris deposited. The experimental results can be helpful in predicting the behavior of flow around the obstacles. 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 traveling in the upstream direction. The effect of several arrangements in the layout of the mounds on their retarding effects was examined. 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 very 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 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 very useful in determining the effective distance between rows of retarding barriers.

KEY-WORDS: - avalanche-like flows, dynamic similarity, Froude number, large – scale snow experiments, energy dissipation ratio

1. NOMENCLATURE:-

Fr	Froude number, ratio of internal kinetic energy and potential energy or of the flow velocity and speed of long wave length surface gravity waves
	coefficient of dynamic friction
ξ	coefficient of turbulent friction ***(ms^{-2})***
H	Obstacle height ***(m)***
h	particle diameter ***(m)***
d	Release depth/fracture depth in hopper ***(m)***
u	mean velocity of the moving snow mass ***(ms^{-1})***
u_0	terminal/steady state velocity in the accelerating part chute***(ms^{-1})***
u_1	velocity after interaction with obstacle ***(ms^{-1})***
θ	Inclination of the chute where obstacles interaction is being investigated ***(°)***
Δx	Run-out shortening with obstacle in the flow path ***(m)***

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x	Run-out distance ***(m)***
V	Fracture volume/volume of the released mass in hopper ***(m^3)***
v	kinematic viscosity of the interstitial fluid ***(m^2s^{-1})***
φ	Internal friction angle***(º)***
δ	Bed friction angle***(º)***
D	Energy dissipation ratio***,*** $D = u_1 / \sqrt{u_0^2 - 2gH\cos 12\square}$
D_{mound}	Energy dissipated by the mound in the flow path
D_{plate}	Energy dissipated by the blunt body in the flow path

2. INTRODUCTION

Snow avalanches are a common phenomenon every year in the snow bound Himalayan region along the northern Indian boundary. The volume of snow mobilized by this phenomenon is highly variable and can seriously strike human settlements, causing huge economic loss as well as the loss in precious human lives. For planning any avalanche control scheme, assessment of the hazard becomes necessary, and the estimation of the dynamic parameters, like velocity and impact forces are vital inputs 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 barriers on the real avalanches becomes difficult, and therefore scaled experiments are required to be carried out to investigate the avalanche-obstacle interaction. Its dynamics is poorly understood because of the complexity of moving snow mass and inaccurate descriptions of constitutive equations into currently available mathematical models. 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.

The scientists at Snow & Avalanche Study Establishment, SASE are working for 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 is obtained from the Experimental vessel i.e., Snow chute that generates an avalanche like flow akin to the 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 [Lang (1980) & Hákonardóttir, (2003)]. Some studies on the numerical modeling of granular flow in an inclined plane have also been reported [Savage (1979), Norem (1986), and Savage (1989)]. 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 jump or a jet thereof. A large fraction of the flow is launched from the experimental Chute which subsequently lands back on the chute and these flows are accompanied by the shocks induced by the presence of the obstacles.

3. EXPERIMENTAL SETUP AND DESIGN

3.1 Experimental Facility

A snow chute of 61 m length, 2 m width and 1 m deep having 30° slope in top 22 m and 12° for next 8 m length is designed and constructed at Dhundhi (3000 m asl) 20 Km from Manali, H.P(India) to generate avalanche like flows under reproducible conditions (Figure 1). It has a hydraulic operated 6 m long snow-feeding platform to release snow mass in the chute and a 12 m long and 4 m wide horizontal testing platform. The testing platform has facility to change its slope from 0° to –15° using a pair of hydraulic system. Using natural snow of different densities, avalanche waves up to 18.0 m^3 volume having velocity of 8.0 ± 0.5 m/s to 18.0 ± 0.5 m/s can be generated in the chute experiments. The avalanche flow is viewed and recorded by CCD cameras connected to a digital video recorder. The results of the experiments conducted in the snow chute are used to verify the existing avalanche flow models and friction laws. It is also observed that these experiments help to study the effect of Coulomb friction and turbulent friction by measuring the run out distances for varying slopes in run out zone [Verma (2004)].

3.2 Experimental design

3.2.1 Law of Similitude:

Dynamic Similarity of the Flow

Flow conditions for a model test are completely similar if all the relevant dimensionless parameters have the same corresponding values for the model and prototype. The physical parameters that describe the dynamic processes in the granular flow and snow avalanches are: i) g, acceleration due to gravity, ii) u, the mean velocity of the avalanche, iii) d, the avalanche depth, iv) h, the particle diameter, v) ν, the kinematic viscosity of the interstitial fluid, vi) φ, the internal friction angle of the material and vii) 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.

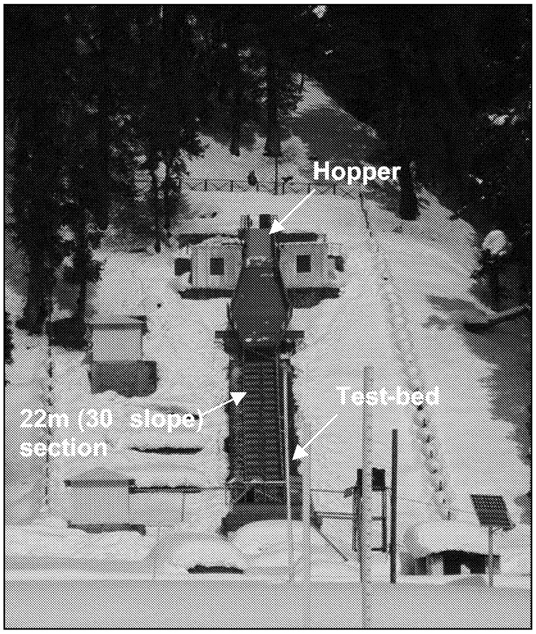


Fig1: - Snow Chute, 61m long at Dhundhi, Manali

The phenomenon of snow avalanches is gravity driven; the 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 dimensionless quantities φ and δ must also be kept invariant in transformations from the prototype to the laboratory scale. The aspect ratio h/d and the Reynolds number $\mathrm{Re} = \frac{uh}{\nu}$ need not necessarily be same, because the particle size is very small, and the interstitial fluid (air for dry and dense snow avalanche) has a very small mass in comparison to the granules, which can in most cases be ignored. The Froude numbers exhibited by the flow are lying 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.

3.2.2 Experimental Details and obstacle configurations

The 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 is recorded using four CCD Cameras covering the entire length of the chute. The flow speed and depth at different locations upstream and downstream of the obstacles was also recorded.

The experiments were carried out for the variable fracture depth from 0.2 m to 1.0 m in the temperature range of -4° to 0° C using wet snow having density between 300 kg/m^3 to 550 kg/m^3. Velocity and run-out distance have been measured in the snow chute experiments and compared with the simulated values obtained from Voellmy-Salm model [Bartelt (1999)] and SASE numerical model. For Voellmy-Salm model the run-out distance is calculated by taking measured velocity at end of 12□slope and measured snow depth at test bed. The details of the experiments conducted in the avalanche chute at Dhundhi in 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 Table 1 and 2 respectively. The effect of an obstacle on the avalanche strongly depends on its geometry [Naaim (2004)]; as a result different configurations were tested for the obstacles (Table 2). A continuous dam was also used and the evolution of possible shock wave in the upstream direction while the flow went past the catch dam at the end of 12° slopes was investigated and the results of this study are given in Figure 6.

Table 1:- Flow depth & terminal velocity in different set-ups

Flow depth (m)	V-terminal (m/s)	No of Expts.
0.30	8.0 -10 ± 1.0	03
0.60	10.0 - 12 ± 0.5	09
1.0	12.0 - 18 ± 0.5	08

Table 2:- Different obstacles used for energy dissipation studies

Type of Structure	No of Expts.	Remarks
Mound at 30° end	02	Energy dissipation studies
Blunt body at 30° end	02	Energy dissipation studies
Mound at 12° end	03	Energy dissipation studies
Catch dam 45° inclination at test bed	03	Evolution of shock behind the dam
Catch dam 90° inclination at test bed	04	Evolution of shock behind the dam
Catch dam 90° inclination at 1m from 12° slope	03	Evolution of shock behind the dam and mapping of the trajectory of flowing mass.

<u>3.3 Instrumentation</u>

To visualize and capture the motion of moving snow mass in snow chute, four CCD cameras were mounted along the chute channel at fixed intervals. These cameras are connected with the digital video recorder (DVR) which has the facility to analyze 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 time taken to cross these intervals is taken from DVR, and is used for determination of average velocity of moving snow mass.

<u>3.4 Measurements</u>

The various parameters that were measured during the large scale experimentation in snow chute in 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 of centre of mass with the obstacle on testing platform, stopping distance, lateral spread with and without structure

Using this information, the following quantities were derived to be used in analysis of the experiments:-

(a) Average initial velocity at the exit of 2^{nd} Hopper- It is the ratio of length of snow mass in the snow feeding platform to the time taken to discharge the snow at exit of the snow feeding platform.

(b) Discharge at 2^{nd} hopper exit estimated from the time required to pass the entire mass from the said section.

(c) Velocity at intermediate stages along 30° slope and 12° slope respectively, from the time elapsed in passing a specified distance on the said section.

(d) Friction coefficients as fit parameters to fit the model behavior using Voellmy Salm model [Mears (1992)] to compute velocities and runout lengths under similar conditions as in chute experimentation.

4. RESULTS AND DISCUSSION

The experiments were performed in the supercritical regime and close to avalanche flows, characterized by a non-dimensional internal Froude number, $Fr = \frac{u}{\sqrt{g\cos(\xi)d}}$. This type of experiments consisted in releasing snow mass or the granular material in an accelerating zone and studying the deposit in the runout zone with the presence of obstacles (mounds, blunt body and catch dams) in comparison with control experiments (without obstacle). 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 gravity current travelled with the shape of a parabolic cap, with a quasi-steady maximum flow depth of 30.0 cm, corresponding to an Froude number of approximately 8….10. It was verified that the collision of the flow with retarding barriers (mounds/blunt geometries) lead 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 measurements of the velocity and runout length of the flow along with the geometry of the jet with the help of CCD Cameras mounted at the 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 a height two times the flow depth, can lead to a 30-40% reduction of the runout length of the flow.The retardation of the flow caused by the impact with the mound and dams found from the experiments with snow in the 61.0 m long chute at Dhundhi is on a similar order of magnitude as previously found in experiments in 3, 6 and 9 m long chutes using other materials[3] (the shortening of the runout is broadly similar for the ballotini experiments at the three scales and the maximum reported run-out shortening is about 40%) and 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 and the velocity was reduced by about 50% for a non dimensional height close to 4.4).

4.1 Energy Dissipation

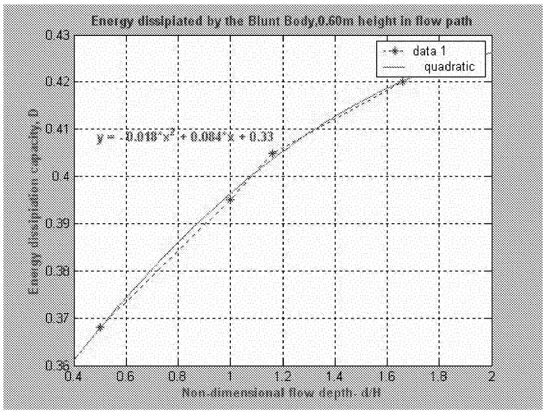
If the mechanical energy of the flow is conserved in the collision, simple energy conservation gives

$$\frac{1}{2}u_1^2 = \frac{1}{2}u_0^2 - gH' \quad \text{.................................(1)}$$

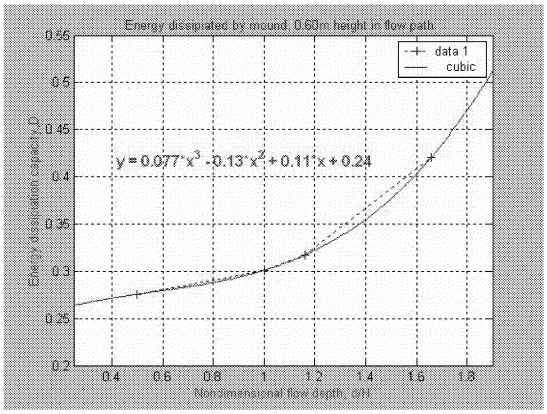
where H' is the vertical rise of the flow when it passes over the obstacles (H' =H cos12°, since the structures were positioned on a slope of 12°). Hence, no energy loss during the impact with the obstacles leads to the expression

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

The ratio $D = u_1 \Big/ \sqrt{u_0^2 - 2gH'}$ 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. The energy dissipation ratio, D represents the 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 slightly inaccurate (too high) since the velocity used after impact was captured by the digital camera with the use of 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 is somewhat lower when the current hits the mounds since it has travelled on the less steep lower section of the chute for 1.5m. While evaluating the energy dissipation capacity of the structure, a non–dimensional flow depth is plotted against the energy dissipation ratio, D for the blunt body (Fig 3a) as well as the mound (Fig 3b), and from the figure it is quite evident that at non-dimensional height close to 0.55, the energy dissipation ratio for 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 very close to the bed slope, therefore most of the dissipation is due to the spreading of flow in different directions and the associated turbulence.



3a) 0.60m Blunt body in the flow path



3b) 0.60m Mound in the flow path

Fig 3: - The energy dissipation ratio, $D = u_1 \Big/ \sqrt{u_0^2 - 2gH'}$ *plotted as a function of non - dimensional height,* d/H *for the geometries in the flow path.*

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 2. However, the dynamics of the impact of the flow with barriers such as dams and mound do not depend on details in the rheology [Kern (2004)] of the material, but are primarily dependent on the large-scale flow.

Fig 2:- Flowing mass approaching the blunt body

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

The 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 shown in Figure 3 showing the equations fitting the experimental variables. Runout shortening as a result of the obstruction in the flow path was also evaluated and the change in pattern of debris deposition on the test-bed was also evaluated.

Table 3: $\mathbf{D}_{plate}$ & $\mathbf{D}_{mound}$ Vs d/H

Fracture Volume	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

Table 4: Δx/x Vs d/H

Fracture Volume	d/H	$\Delta x/x\,\vert plate$	$\Delta x/x\,\vert mound$
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

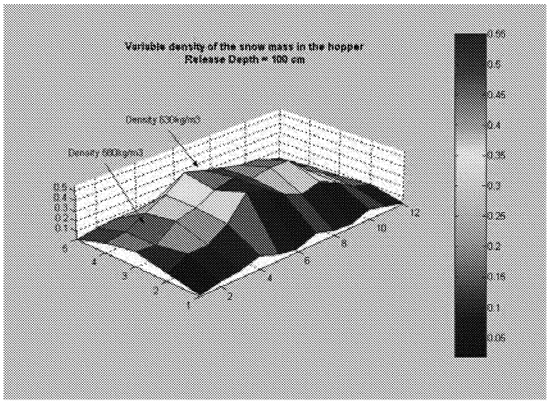


Fig 4a:- Spread on the test-bed without obstruction

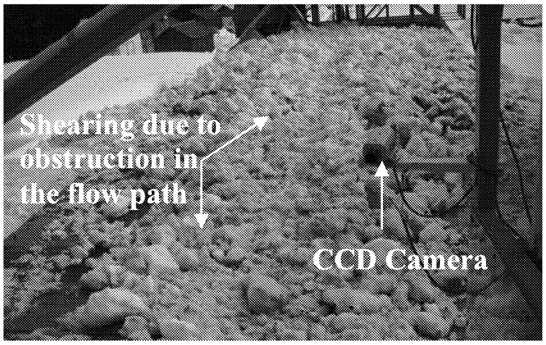


Fig 4b:- Spread on test bed with obstruction

The change in the spread of the deposited pattern is shown in Figure 4 and the run-out reduction with the barriers is compared in table 4 for mound as well as the blunt body, and the results are represented graphically in Figure 5 with the equations connecting the experimental variables. It is evident from the figure that at non-dimensional height close to 0.50, the runout reduction is about 33 % for blunt body whereas the it is just around 15% for a mound of similar projection, but as obstacle height increases the run-out reduction decreases for blunt body as a function of $\left(d/H \right)^{3}$ whereas it increases for mound as function of the $\left(d/H \right)^{3}$.

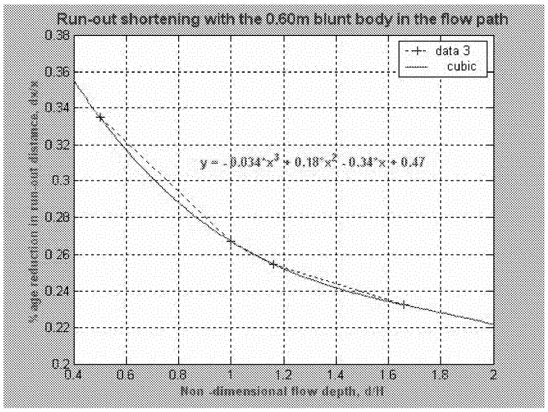
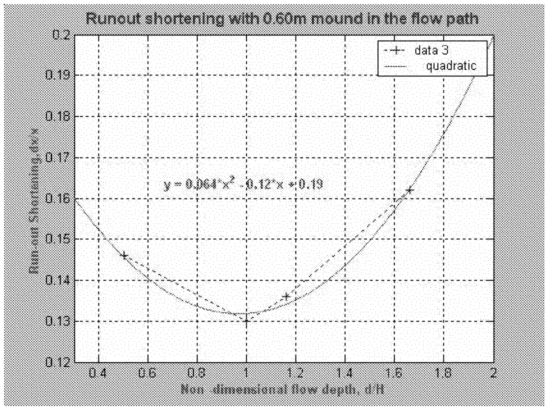


Fig 5a:- 0.60m Blunt body in the flow path



5b) 0.60m Mound in the flow path

Fig 5: - The run-out reduction factor, $\Delta x/x$ plotted as a function of non-dimensional height, d/H for the geometries in the flow path.

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 flow path.

5. CONCLUSIONS

The effect of varying the snow mass on the Froude number of the flow on a 30 ^{0} slope of the snow chute was investigated for flow with and without barriers in the flow path. The Froude number, once the flow had reached a quasi-steady state on the upper section of the chute, was found to be relatively independent of the amount of material released. The speed of the flow front varied from about 8.0±0.5m/s for 3.3m^3 of snow to about 12.0±0.5m/s for 11.0 m^3 and the maximum flow depth of about 40 cm for the release mass of 11.0 m^3. 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, the proportion of the cross sectional area of the impact zone covered by the mounds was examined in this study. The experiments verify that the mounds have a considerable retarding effect on high 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 12° slope with the non-dimensional obstacle height up to 4.0 has almost the same retarding effect as row of appropriately designed mounds, where the jet launched from the top traverses the longitudinal distance of about 3.0m (Fig. 6) before coming to rest.

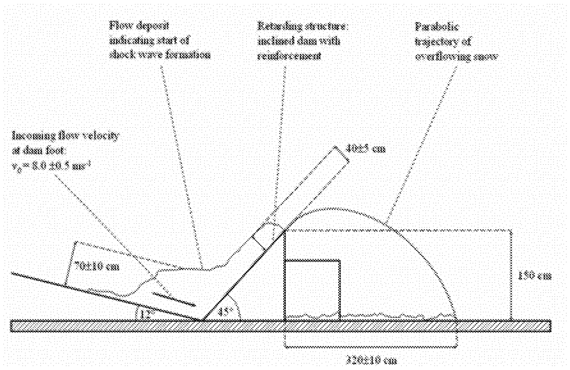


Fig 6:- Flow past a 1.50m high Catch dam at the end of 12^{0} slope

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 parabolic jet from the top of barriers has practical implications while choosing spacing between the retarding barriers in the run-out path of the avalanche. The spacing between the rows has to judiciously chosen to accommodate the detached mass, and, hence have a full retardation effect.

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