Report
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Remarks on the design of avalanche braking mounds based on experiments in 3, 6, 9 and 34 m long chutes

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1 Introduction

Braking mounds (or retarding mounds) are widely used for protection against dense, wet snow avalanches, but they are often thought to have little effect against rapidly moving, dry snow avalanches (see for example Norem, 1994; McClung and Schaerer, 1993). The design of such mounds is in most cases based on the subjective judgement of avalanche experts as there exist no accepted design guidelines for braking mounds for retarding snow avalanches. There are, furthermore, no accepted methods for estimating the retarding effect of avalanche mounds in a quantitative way. The retarding effect is particularly badly known for dry snow avalanches.

A number of chute experiments at different scales and with different types of granular materials have recently been performed in order to shed light on the dynamics of avalanche flow over and around braking mounds and catching dams and to estimate the retarding effect of the mounds (Woods and Hogg, 1998, 1999; Hákonardóttir and others, 2001, 2003, in press/a,b; Faug and others, in press). Some of these experiments were carried out as a part of the design of avalanche protection measures for the town of Neskaupstaður in eastern Iceland (Figs. 1 and 2) (Tómasson and others, 1998a,b). A review of available hydro-engineering studies of retarding structures for high speed water flow was also carried out as a part of the design (Tómasson, 1998b; this review is summarised in the Appendix). The experiments were designed for dry, supercritical, granular flow in order to analyse the retarding effect of mounds against rapid, dry snow avalanches.

This report summarises the main results of the abovementioned studies. Several general recommendations for the practical design of braking mounds are given with references to technical articles and reports that contain more detailed descriptions of the experimental results on which the recommendations are based.

There remain open questions regarding the applicability of the experimental results to natural avalanches due to the very different scales. An insignificant braking effect at the scales of the experiments would suggest that this effect would also be small for natural snow avalanches. On the other hand, a result indicating a substantial braking effect does not necessarily apply to natural avalanches due to the different physics and scales of the flows, such as compression of the snow in the impact with the mounds and the effect of air resistance on the flow over the mounds. Nevertheless, the experiments may be used to identify certain types of behaviour, which does not strongly depend on scale or material properties, and which may be exploited in the design of avalanche protection measures. The experiments, thus, provide useful indications for designers of retarding structures for snow avalanches in the absence of data from experiments at larger scales and measurements of natural avalanches.

2 Background

Dry, natural snow avalanches often consist of a powder cloud and a denser core. The dense core is commonly modelled as a shallow, free-surface, granular gravity current (*cf.* Eglit,

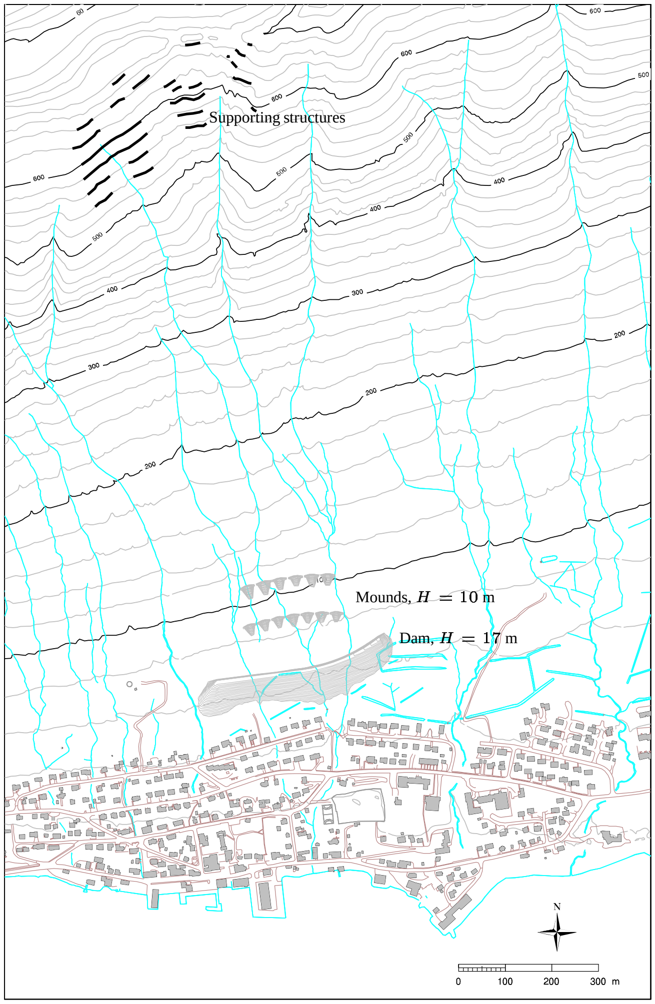


Figure 1: Plan view of the protection measures in the Drangagil area in Neskaupstaður, eastern Iceland. The map shows the position of the supporting structures in the starting zone, two rows of braking mounds beneath the gully and a dam just above the uppermost houses.

1983). The Froude number of the flow can be defined as

$$Fr = \frac{u}{\sqrt{g \cos(\psi) h}},$$

where u is the speed of the flow, g is the gravitational acceleration, ψ is the inclination of the terrain and h is the flow depth. This dimensionless number is commonly used to characterise free surface fluid flows. A typical Froude number of the dense core of rapid, dry snow avalanches is on the order of 10. The design of the chute experiments was based on the

Figure 2: A photograph of the braking mounds in Neskaupstaður and the catching dam behind them. Each mound is 10 m high and the catching dam is 17 m high.

conjecture that if the Froude numbers were on the same order of magnitude, dynamical similarity between natural snow avalanches and the smaller-scale experimental avalanches would be maintained (see Hákonardóttir and others (in press/a) for a further discussion). The Froude number of the smaller scale experiments in the 3, 6 and 9 m long chutes in Reykjavík, Bristol and Davos was $Fr \approx 10$. The Froude number in the snow experiments in the 34 m long chute at Weissfluhjoch was in the range 3–6, varying with each experimental run, depending on the condition of the snow. This was the highest Froude number that the experimental setup allowed for, and it was somewhat lower than would have been preferable.

Although there exist no generally accepted guidelines for the design of avalanche mounds, Salm (1987) has formulated an estimate for the reduction in the speed of an avalanche that hits several obstacles, such as buildings, that are spread over the run-out area of the avalanche and assumed to cover a certain fraction, c, of the cross-sectional area of the path. According to this expression, the speed of the avalanche is reduced by the ratio $c/2$, assuming that the obstacles are sufficiently strong and are not swept away by the avalanche. If, for example, $c = 1/2$, this expression predicts that the speed is reduced by 25%, indicating a substantial effect of the obstructions on the speed of the avalanche. Voellmy (1955) proposes a similar expression for the reduction in the speed of an avalanche that hits several rows of trees. These expressions are not derived from a conceptual model of the flow around obstacles and it is not clear whether they may be expected to apply to a rapidly moving dry snow avalanche.

Braking mounds designed to retard rapidly moving dry snow avalanches will in most cases be of a height that is only a small fraction of the height-scale corresponding to the kinetic energy of the avalanche, which is defined as $u^2/(2g)$, where u is the speed of the flow and g is the gravitational acceleration. One might expect that having flowed up the mounds, the avalanche could regain the kinetic energy spent when it descends down the backside of the mounds. Salm's expression nevertheless suggests that 44% of the kinetic energy of an avalanche is dissipated by one row of mounds covering 50% of the cross-sectional area of the path and Voellmy's expression leads to a similar conclusion. This energy dissipation must, if the mounds are in fact as effective as assumed, be brought about by irregularities and mixing introduced by the deviation of the avalanche flow over and around the mounds. Such an effect may be expected to depend to a high degree on various details in the layout and geometry of the mounds, making the lack of established guidelines for the design of avalanche mounds particularly acute. One may also note that the volume of the avalanche will typically be so large that only a small fraction of the snow near the front of the avalanche is needed to fill the space upstream of the mounds so that they become effectively buried and the bulk of the avalanche easily overflows the mounds. For braking mounds to be effective while the avalanche passes over them, they must not become buried by the avalanche.

Experiments to study the effect of braking mounds on snow avalanches have not been performed until recently. Similar structures have, however, been studied extensively for supercritical, free-surface water flow in dam spillways and bottom outlets where they are used to dissipate the kinetic energy of water before it enters the downstream channel (in this context they are termed baffle blocks and baffle piers). The original experiments are described by the US Bureau of Reclamation (Peterka, 1984; U.S.B.R., 1987) and they are summarised in many text books on hydraulic engineering, for example Roberson and others (1997). These studies complement the braking mound experiments with granular materials in an important way because the scale of the hydraulic structures is much larger than the scale of the experimental chutes and therefore closer to the scale of natural avalanches. The speed of the water flow in the spillways is sometimes more than an order of magnitude higher than the speed of the granular materials in the experiments in the 3, 6, and 9 m long chutes.

A general result from these hydraulic experiments is that the Froude number of the flow upstream of the dissipating structures is an important dimensionless parameter that characterises the interaction of the flow with the structures and the energy loss due to the baffle piers and other dissipating elements. Baffle piers of the same relative geometry were found to behave identically for the same Froude number for widely different scales and speeds of the flow. For so-called type II basins (*cf.* Fig. 8 in the Appendix), available data from full-scale spillways span maximum discharges in the range 34–13000 m^3s^{-1}, upstream flow depths in the range 0.2–2.7 m, upstream flow speeds in the range 12–33 ms^{-1} and upstream Froude numbers in the range 4–22 (Peterka, 1984). For Froude numbers on the order of 10, the interaction of the flow with the baffle piers may be crudely estimated to lead to a dissipation of between 25% and 50% of the kinetic energy of the flow, corresponding to a speed reduction of between 15% to 30%. This is similar to the numbers that can be derived from Salm's and Voellmy's expressions for the speed reduction of snow avalanches that hit obstructions (see the Appendix for a further description of these hydraulic experiments).

The fluid experiments that have been carried out to find an effective geometry for baffle piers to optimise the rate of dissipation (Peterka, 1984), indicate that effective piers should have a height approximately 2–2.5 times the upstream flow depth for a flow with Froude numbers in the range 8–12. The transverse width of the piers and the spacing between them should be 0.75 times their height. It was further found that a steep upstream face, perpendicular to the bottom of the stilling basin, with relatively sharp corners, was important, whereas, the geometry of the downstream part of the piers was of little importance. The width and spacing of the blocks may be varied, but it was recommended that the total width of spaces in the transverse direction should be equal to the total width of blocks.

The energy dissipation that is induced by baffle piers in dam spillways and bottom outlets is principally a shallow-layer flow phenomenon and does not depend on the frictional properties of the fluid in question. The dense core of rapidly moving snow avalanches is commonly modelled as a shallow-layer, gravity-driven flow. Energy dissipation by inelastic granular collisions could play a similar role in avalanche flow around and over dissipating structures as turbulent dissipation by fluid friction in ordinary fluid flow. This suggests that existing results from hydraulic experiments may give valuable insight to the interaction of avalanche flows with retarding structures. Indeed, the work discussed above includes ranges of discharges, flow depths, flow speeds and Froude numbers in full-scale dam spillways which are similar to rapidly-moving, natural dry snow avalanches. The results of the hydraulic experiments and their implications in the context of snow avalanches, including the importance of the Froude number in both cases, are discussed further by Hákonardóttir and others (in press/b).

3 Interaction of a supercritical granular avalanche with mounds

The experiments showed that a collision of a supercritical granular avalanche with a row of mounds leads to the formation of a jump or a jet, whereby a large fraction of the flow is launched from the top of the mounds and subsequently lands back on the chute (Figs. 3 and 4). For steep obstacles, particles are initially launched from the top of the obstacle at an angle close to its upstream angle, α. The jet rapidly adjusts to a new angle due to the formation of a wedge behind the upstream face of the mound. This angle is termed the throw angle and is denoted by β. The bulk of the current then passes over the barrier as a coherent, quasi-steady jet (Figs. 3 and 4). This part of the jet lands furthest away from the mounds.

Energy dissipation takes place in the impact of the avalanche with the mounds and also in the interaction of jets from adjacent mounds. Energy dissipation, furthermore, takes place in the landing of the jets on the chute and the subsequent mixing with material flowing in between the mounds.

The airborne jet that is formed by the collision of the flow with the mounds has important practical consequences for the use of multiple rows of mounds or combinations of rows of

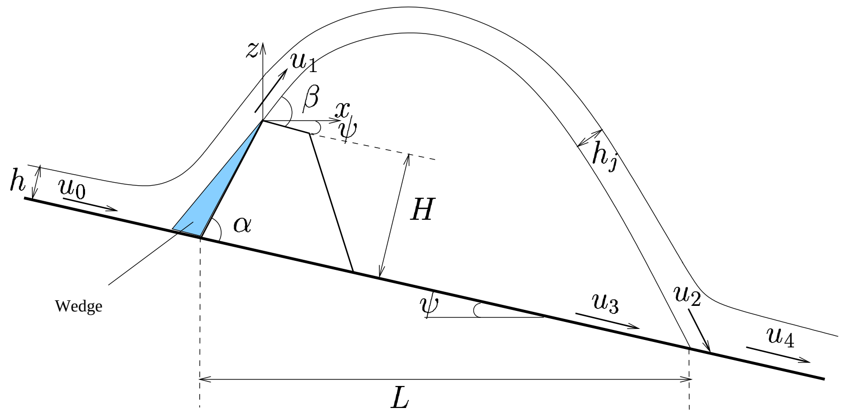


Figure 3: A schematic diagram of a jet of length L with upstream flow thickness h and jet thickness h_j. The jet is deflected at an angle β over a mound or a dam of height H positioned in a terrain with inclination ψ. The upstream mound face is inclined at an angle α with respect to the slope. u_0, u_1, u_2, u_3 and u_4 are the speed at different locations in the path.

mounds and a catching dam. The spacing between the rows must be chosen sufficiently long so that the material launched from the mounds does not jump over structures farther down the slope.

The trajectory of the jet launched directly over the mounds can be approximated as a projectile motion in two dimensions (Fig. 3). Conservation of momentum leads to the equation

$$\mathbf{F} = m\mathbf{g} - m(f/h_j)\dot{\mathbf{x}}|\dot{\mathbf{x}}| \,, \tag{1}$$

where $\mathbf{F}$ is the force exerted on the mass, m, $\mathbf{g}$ is the gravitational acceleration, f is a dimensionless constant representing turbulent drag caused by air resistance, h_j is the thickness of the core of the jet, $\mathbf{x} = (x, z)$ is the location of the particle in horizontal and vertical directions, respectively, with the origin at the top of the mound, and a dot denotes a time derivative. Equation (1) can be written as

$$\ddot{x} = -(f/h_j)\dot{x}\sqrt{\dot{x}^2 + \dot{z}^2} \tag{2}$$

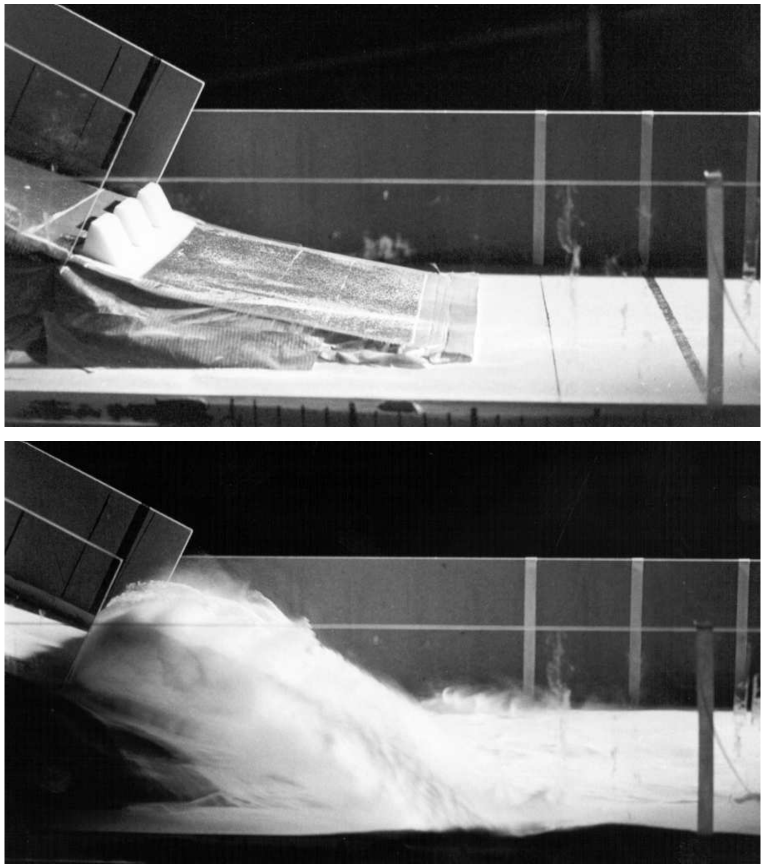
$$\ddot{z} = -g - (f/h_j)\dot{z}\sqrt{\dot{x}^2 + \dot{z}^2} \,. \tag{3}$$

The initial conditions at $t = 0$ are

$$x = z = 0 \qquad \text{at} \qquad t = 0$$

and

$$\dot{x}(0) = u_1 \cos(\beta - \psi) \qquad \text{and} \qquad \dot{z}(0) = u_1 \sin(\beta - \psi),$$



(a)

(b)

Figure 4: Photographs of (a) the datum mound configuration and (b) the jet in a quasi-steady state on the 6 m long experimental chute in Bristol (Hákonardóttir and others, in press/b).

where β is the throw angle and ψ is the slope in which the mounds are situated. The horizontal length of the jump, L (Fig. 3), can be found by solving the two equations given appropriate values of u_1, β and f/h_j. Recommended values for these parameters for natural snow avalanches are discussed below.

$\mathbf{u_1}$ The throw speed u_1 may be expressed as

$$u_1 = k\sqrt{u_0^2 - 2gH\cos\psi},$$

where u_0 is the incoming speed, H is the height of the mounds and k is a dimensionless constant representing the energy dissipation involved in the impact of the avalanche with the mounds. The value $k = 1$ corresponds to no energy loss in the impact. The experimental results indicate that k is in the range 0.5–0.8 for mound and dam heights 2–3 times the flow depth (Hákonardóttir and others, 2001 (Fig. 38), 2003 (Fig. 7), in

Figure 5: A photograph of the snow hitting a 60 cm high catching dam in the 34 m long chute at Weissfluhjoch. A part of the dam broke during this experiment as seen on the photograph.

press/b (Fig. 10)), with most of the values falling in the range 0.6–0.7. For natural snow avalanches, it is recommended that the throw length is computed for the three values $k = 0.7$, 0.8 and 0.9 and that the result for $k = 0.8$ be used to calculate the minimum distance between a row of mounds and retarding or retaining structures below.

β Figure 6 shows theoretical curves for the inviscid, irrotational flow of a fluid over an obstacle where gravity effects are neglected (Yih, 1979). The experimental results indicate that the theory gives an upper bound for the throw angle, β. For mounds with $H/h \approx$ 2–3 and $\alpha = 90°$, the theoretical β should be reduced by 20–25°, for $\alpha = 75°$, β should be reduced by 10–20° and for $\alpha = 60°$, it should be reduced by 0°–10°. It is recommended that the throw angle β be chosen based on these considerations.

$\mathbf{\frac{f}{h_j}}$ The turbulent drag on the jet, caused by air resistance, is represented by the dimensionless constant f, and depends on the jet thickness, h_j, and the speed of the airborne flow (Eqs. (2) and (3)). Air resistance does not affect the flow on the small scale of the granular experiments (including the snow experiments) and the experimental trajectories are therefore well reproduced by using $f = 0$ in equations (2) and (3). On the other hand, full scale experiments with water jets suggest that between 0% to 30% of the initial kinetic energy of the jet may be lost during the jump (see Hager, 1995; Novak and others, 1989; U.S.B.R., 1987). The dense core of an avalanche is less dense (density in the range 100–400 kgm^{-3}) than water (density of 1000 kgm^{-3}). Therefore, it is reasonable to assume that an avalanche jet will be affected by air resistance at least to the same

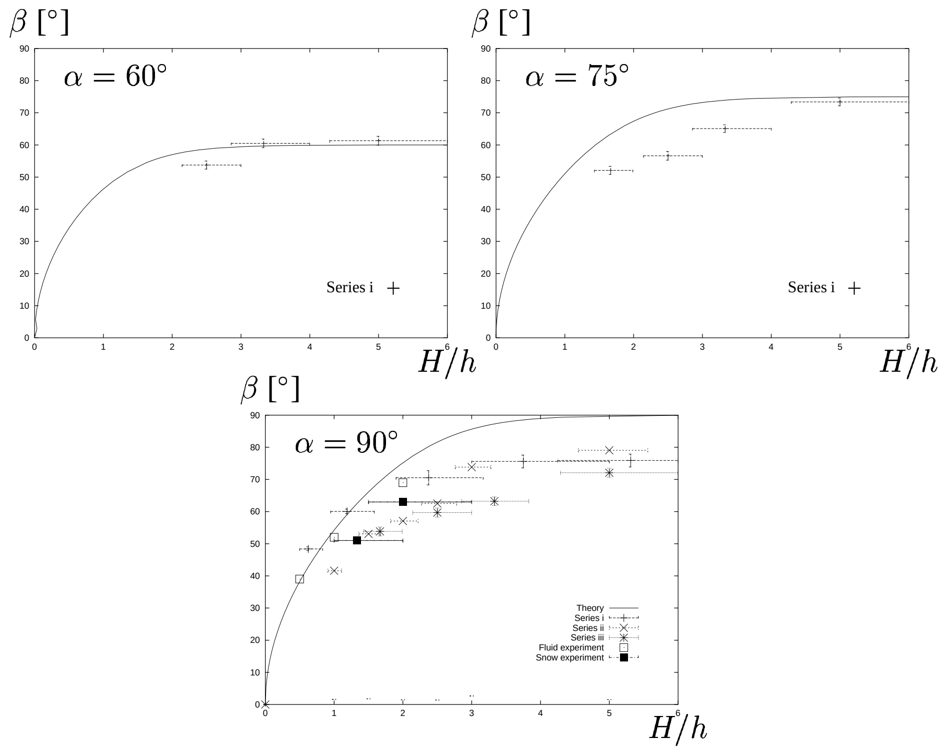


Figure 6: The throw angle, β, plotted against the non-dimensional mound height, H/h, for different angles between the upstream faces of the mounds and the slope, α. The points denote experimental results and the solid lines are theoretical predictions. 'Series i, ii and iii' are results from experiments using glass particles on 3, 6 and 9 m long experimental chutes. 'Snow experiments' denotes experiments with snow on the 34 m long experimental chute at Weissfluhjoch and 'Fluid experiment' denotes an experiment described by Yih (1979).

extent as a jet of water, leading to a shortening of the jet. By taking $f \approx 0.01$ and $h_j \approx$ 2–4 m we obtain $f/h_j =$ 0.0025–0.005 m^{-1}. In order to reduce the kinetic energy of a fluid jet flowing with a speed of 40 ms^{-1} by 30%, as given in (Novak and others, 1989), f/h_j needs to be given a value of $f/h_j \approx$ 0.004 m^{-1} which fits into the range given above. Here it is recommended that the value $f/h_j =$ 0.004 m^{-1} is adopted in computations of the throw length.

Given the above recommended values of u_1, β and f/h_j, the ordinary differential equations (2) and (3) may be solved numerically with commonly available algorithms in order to obtain the throw length for determining the minimum longitudinal spacing of retarding and retaining structures in the design of breaking mounds.

4 Recommendations regarding the geometry and layout of the mounds

The chute experiments with granular materials lead to the following recommendations for the geometry of avalanche braking mounds.

1. The height of the mounds, H, above the snow cover should be 2–3 times the thickness of the dense core of the avalanche. Increasing the height of the mounds beyond this, for a fixed width of the mounds, does not significantly reduce the run-out according to the experiments.

2. The upstream face of the mounds should be steep. For the chute experiments with glass beads (ballotini), $\alpha \approx 60°$ was sufficient since a steeper upstream face only marginally improved the energy dissipation. This result may not be appropriate for natural snow avalanches because of the different physical properties of the materials.

3. The aspect ratio of the mounds above snow cover, H/B, should be chosen close to 1.

4. The mounds should be placed close together with steep side faces, so that jets launched sideways from adjacent mounds will interact. Many short mounds were found to be more effective than fewer and wider mounds for the same area of the flow path covered by mounds.

If there is sufficient space in the terrain for a second row, it should be staggered with respect to the first row (Fig. 7). As discussed in the next section, the retarding effect of the second row may be expected to be somewhat less than the effect of the first row although this is not well constrained by the available experiments (Hákonardóttir and others, 2001).

5 Retarding effect

The goal of the chute experiments with granular materials that have been carried out during and after the design of the mounds in Neskaupstaður was, in addition to finding an optimum layout and geometry of the mounds, to obtain a quantitative estimate of the energy dissipation of braking mounds for granular materials that would provide an indication of the retarding effect of the mounds for natural snow avalanches.

There are many technical difficulties associated with direct measurements of the flow speed of the granular material in the chute experiments, in particular for measurements of the speed of the flow downstream of the landing point of the jet. In most of the experiments, the speed reduction was not directly measured. Rather, the effect of the mounds for reducing the run-out distance of the material beyond the location of the mounds was measured, both

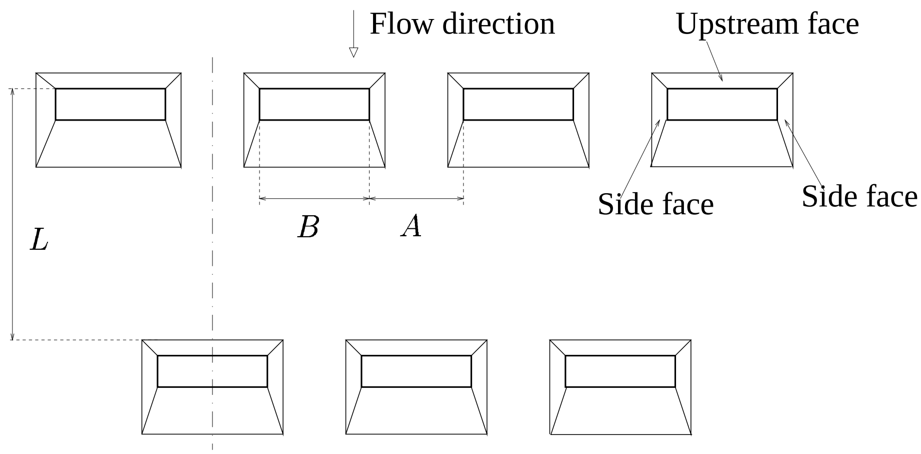


Figure 7: Planview of two staggered rows of braking mounds. The minimum horizontal distance between the two rows, L, is found according to the procedures outlined in §3. Recommendations regarding the geometry and layout of the mounds are given in §4. B is the top breadth of a mound and A is the distance between the tops of two mounds. A should be similar to or shorter than B and B should be similar to the height of the mounds H (above the snow cover).

the reduction in the maximum run-out and the reduction in the run-out corresponding to the centre of mass.

The most effective single row mound configurations with mound height 2–3 times the flow thickness in the 3, 6 and 9 m long chutes were found to shorten the maximum run-out beyond the mounds by about 30% in the experiments with small glass beads (ballotini) and by a similar amount for sand in the 9 m long chute (Hákonardóttir and others, 2001). The reduction in the run-out corresponding to the centre of mass was greater, *i.e.* 40–50%. The reduction in the maximum run-out for two staggered rows of mounds was found to be in the approximate range 40–50% for experiments in the 3 and 9 m long chutes, and the reduction in the run-out corresponding to the centre of mass was greater than 50%.

The relative run-out reduction may be crudely interpreted as a relative reduction in the kinetic energy of the granular material by assuming that the slowing down of the avalanche in the run-out zone is brought about by frictional forces between the bed and the moving material that are approximately proportional to the weight of the material (Coulomb friction). A relative run-out reduction of about 30% (the maximum run-out) to 40–50% (the centre of mass run-out) then corresponds to a reduction in the speed of an avalanche by about 15–30% by one row of mounds. For two mound rows, a run-out reduction by 40–50% or more corresponds to a speed reduction of 20–30% or more. This interpretation of run-out reduction in terms of speed reduction is so crude that it is not possible to say whether it is more appropriate to use the relative reduction in the maximum run-out or in the run-out corresponding to the centre of mass.

The velocity of the avalanche was measured in the experiments with snow in the 34 m long chute at Weissfluhjoch (Hákonardóttir and others, 2003), both the velocity just upstream from the mounds (u_0) and the velocity after the landing of the jet (u_4) (*cf.* Fig. 3). The velocity of the control avalanche in the absence of mounds at the landing location of the jet (u_{cont}) could furthermore be estimated. There is considerable uncertainty in the measurements of both the velocity and the flow thickness in the Weissfluhjoch experiments, but the results indicate that the ratio $u_4/u_{\mathrm{cont}} \approx 0.8$ for mounds that are about 1.3 times higher than the flow thickness.

Although the available results are open to different interpretations, they indicate that braking mounds have a substantial retarding effect on supercritical granular flows. Furthermore, the retarding effect does not seem to vary much with the scale of the chutes over the range of scales, velocities and experimental materials covered by the experiments (lengths of the chutes in the range 3–34 m and flow speeds upstream of the obstacles in the range 2.6–7.5 ms^{-1}). Here it is recommended that *the relative velocity reduction corresponding to one row of mounds that is designed according to the recommendations given above is estimated as 20%*. It is not possible to specify in detail how the energy dissipation caused by the mounds is divided between the initial impact, the interaction between adjacent jets, air resistance and energy lost in the landing of the jet and mixing with material that flows between the mounds. This will among other things be dependent on the slope and shape of the terrain where the mounds are located. For simplicity, it is recommended that the assumed speed reduction is applied at the location of the upper face of the mounds in a model computation of the flow of the avalanche down the terrain in the absence of the mounds. This assumption should only be used for mounds that are located in the run-out zone of the avalanches. It will not provide reasonable results higher up in the path of the avalanche where the terrain is steeper, but this is not an important restriction since mounds are not likely to be located outside the run-out zone.

It appears from the experimental results that the second row of mounds has less relative effect on the flow velocity than the initial row. This is also indicated by the hydraulic experiments with baffle piers in dam spillways and bottom outlets (Peterka, 1984). Here it is recommended that *a second row of mounds is assumed to reduce the velocity of the avalanche by 10%* in addition to the 20% reduction provided by the first row.

It needs to be stressed that the above recommendations are based on an incomplete understanding of the complex dynamics of granular avalanches that hit obstructions. Nevertheless, we believe that the chute experiments and the above recommendations that are derived from them, provide useful indications for designers of retarding structures for snow avalanches in the absence of data from experiments at larger scales and measurements of natural avalanches.

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A Appendix: Experimental results for hydraulic energy dissipators

Experiments for studying the effect of braking mounds on snow avalanches and other granular flows have not been performed until recently. Similar structures have, however, been studied extensively for supercritical, free-surface water flow in dam spillways and bottom outlets where they are used to dissipate the kinetic energy of water before it enters the downstream channel (in this context they are termed baffle blocks and baffle piers). The original experiments are described by the US Bureau of Reclamation (Peterka, 1984; U.S.B.R., 1987) and they are summarized in many text books on hydraulic engineering, for example Roberson and others (1997). These experiments complement the laboratory experiments with granular materials that are described in the main text of this document in an important way because the scale of the hydraulic structures is much larger than the scale of the laboratory chutes and the speed of the water flow in the spillways is sometimes more than an order of magnitude higher than the speed of the granular material in the laboratory experiments. Therefore a number of the results of the hydraulic experiments are described here in some detail and the implications of these studies are discussed in the context of snow avalanches.

Stilling basins dissipate energy by introducing a stationary hydraulic jump across which the flow depth is abruptly increased and the speed of the water is reduced. According to the classical analysis of stationary hydraulic jumps (see, *e.g.* Whitham, 1999) the mass flux and momentum flux in the flow are conserved, but a part of the kinetic energy is dissipated. The depth of the flow downstream of the jump, h_2, is given as a function of the depth of the flow upstream, h_1, and the upstream Froude number ($Fr = u_1/(gh_1)^{1/2}$, where u_1 denotes the upstream velocity, and g denotes gravitational acceleration) by

$$\frac{h_2}{h_1} = \frac{1}{2}\left(\sqrt{1+8Fr^2}-1\right). \tag{4}$$

Furthermore, the ratio of the downstream to upstream velocity is given by

$$\left(\frac{u_2}{u_1}\right)^2 = \frac{1+4Fr^2+\sqrt{1+8Fr^2}}{8Fr^4}, \tag{5}$$

while the rate at which energy per unit width is dissipated is given by

$$\frac{(h_2-h_1)^3\rho g q}{4h_2h_1}, \tag{6}$$

where $q = u_1h_1 = u_2h_2$ denotes the volume flux of fluid per unit width. From (5) we note that for flows at high upstream Froude numbers the velocity downstream is small. For example if $Fr > 8$, then $u_2/u_1 < 0.1$. Furthermore from (6) the rate of energy dissipation across the hydraulic jump increases with increasing upstream Froude number and when the upstream Froude number is high, a large proportion of the energy flux can be dissipated across the transition. Using (4) and (5) we find that if $Fr > 8$ then over 66% of the energy flux is dissipated across the hydraulic jump and the kinetic energy of the flow is reduced by over 99%. Introducing a hydraulic jump into the flow is therefore an effective means of reducing the speed of the flow.

The transition from the upstream to the downstream state does not occur abruptly, but rather occurs over a finite length, throughout which energy is dissipated by turbulent fluid motion. In the context of hydraulic engineering, and specifically dam spillways, obstacles are constructed in the flow which have two consequences on the motion. First the flow exerts a force on the obstacle leading to a slight reduction in the flux of momentum per unit width. However, more importantly these obstacles induce disturbances to the fluid motion which enhance the rate of dissipation and consequently shorten the length of the hydraulic jump.

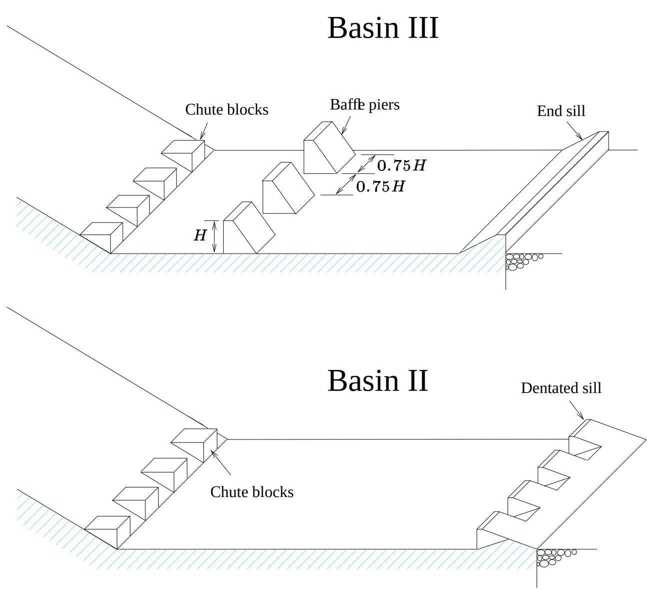

Figure 8: Stilling basins of types III and II for $Fr > 4.5$.

Stilling basins with baffle piers, termed as type III basins (see Fig. 8), provide an efficient means for dissipating energy and have been shown to shorten the length of hydraulic jumps by 50–60% (U.S.B.R., 1987). Similar basins without piers, which are termed type II basins (Fig. 8), are about 25% less effective than the type III basins (Petrarka, 1984; U.S.B.R., 1987). Thus the presence of the piers alone leads to dissipation by introducing disturbances into the flow. The reduction in the speed of the flow due to the interaction with the baffle piers may be estimated as follows: if the structures dissipate between 25% and 50% of the kinetic energy of the flow, then the speed is reduced by between 15% to 30%. This is similar to the numbers that can be derived from Salm's and Voellmy's expressions for the speed reduction of snow avalanches that hit obstructions that are described in the introduction.

A series of experiments have been carried out to find an effective geometry for the baffle piers in type III stilling basins to optimise the rate of dissipation (Peterka, 1984). It was found that effective piers had a height approximately 2–2.5 times the upstream flow depth for a flow with Froude numbers in the range 8–12. The transverse width of the piers and the spacing between them was 0.75 times their height (Fig. 8). It was found that a steep upstream face, perpendicular to the bottom of the stilling basin, with relatively sharp corners, was important for effective dissipation whereas, the geometry of the downstream part of the piers was of little importance. Some experiments with baffle piers as energy dissipators in hydraulic spillways have been carried out in which a forced hydraulic jump is not present (Gerodetti, 1985). The jets that form in these experiments show striking resemblance to the jets formed by granular flow hitting braking mounds in small scale laboratory experiments with granular materials.

A general result from these hydraulic experiments is that the Froude number of the upstream flow is an important dimensionless parameter, the magnitude of which determines the characteristics of the hydraulic jump and the energy loss due to the baffle piers and other dissipating elements. Baffle piers of the same relative geometry were found to behave identically for the same Froude number for widely different scales and speeds of the flow. Furthermore, the experimental results are complemented by data from full-scale spillways. For type II basins (Fig. 8), the data spans maximum discharges in the range 34–13000 m^3s^{-1}, upstream flow depths in the range 0.2–2.7 m and upstream flow speeds in the range 12–33 ms^{-1} and upstream Froude numbers in the range 4–22 (Peterka, 1984). Corresponding data about existing type III basins are not available.

A hydraulic jump is principally a shallow-layer flow phenomenon. It does not depend on the frictional properties of the fluid in question and is simply a transition between two flow states. The dense core of rapidly moving snow avalanches is commonly modelled as a shallow-layer, gravity-driven flow, indicating that physical characteristics such as flow depth and speed discontinuities should be important for understanding avalanche flow by analogy with ordinary fluid flow (Jóhannesson, 2001; Tai and others, 2001). Energy dissipation by inelastic granular collisions would then play a similar role in discontinuities in avalanche flow as turbulent dissipation by fluid friction in ordinary fluid flow. This suggests that existing results from hydraulic experiments as described above may give valuable insight to the interaction of avalanche flows with retarding structures. Indeed, the work discussed above includes ranges of discharges, flow depths, flow speeds and Froude numbers in full-scale dam spillways which are similar to rapidly-moving, natural dry snow avalanches.