Flying avalanches

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[1] Rapidly flowing avalanches are highly destructive natural phenomena, especially when they interact with buildings or other man-made structures. Here we report a new experimental study of the interaction of a rapid granular flow with a solid barrier, which is of a comparable height to the flow depth. Our experiments show that the flow detaches from the top of the obstacle as a coherent granular jet, the motion of which is well described by theory for an inviscid jet of fluid. As well as giving fundamental new insights into the behaviour of granular flows, the results have important practical consequences for the design of dams used to provide protection from snow avalanches. *INDEX TERMS:* 1863 Hydrology: Snow and ice (1827); 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 5104 Physical Properties of Rocks: Fracture and flow; 5499 Planetology: Solid Surface Planets: General or miscellaneous; 9810 General or Miscellaneous: New fields (not classifiable under other headings). **Citation:** Hákonardóttir, K. M., A. J. Hogg, J. Batey, and A. W. Woods, Flying avalanches, *Geophys. Res. Lett.*, *30*(23), 2191, doi:10.1029/2003GL018172, 2003.

1. Introduction

[2] A complete dynamical description of granular materials is currently a matter of extensive research, because unlike many other materials, individual flows readily undergo transitions between static and mobile states, within which there are different forces that dominate the interactions between the constituent particles. For example, static piles of grains are often very close to conditions for collapse, while rapid energy dissipation in fast-moving granular flows may cause an abrupt arrest of the motion [*Campbell*, 1990; *Behringer et al.*, 1999]. There is a pressing need to improve our understanding of these flows, stimulated by industrial concerns, such as the flow of grains through a silo [*Samadani et al.*, 2002], or by hazards associated with natural phenomena such as rock and snow avalanches [*Hopfinger*, 1983; *Dade and Huppert*, 1998; *Issler*, 2003]. For example during the winter of 1999, Switzerland and Austria endured the greatest number of avalanches in over 50 years, with the most devastating avalanche in Galtür, Austria causing 38 fatalities [*Bartelt and Buser*, 2001]. There have also been several accidents in Iceland during the last decade, which have led to the development of a series of structures designed to defend against the effects of the oncoming granular flows by its deflection or arrest [*Tómasson et al.*, 1998a, 1998b]. However the fundamental dynamics of the interactions between the granular flows and the defence structures remain poorly understood and there are no accepted guidelines for their design [*McClung and Schaerer*, 1993; *Hákonardóttir et al.*, 2003]. Here we present some analyses of laboratory experiments that investigate the collision between rapid shallow flows of a granular material and solid obstacles. In this study we have examined how the flow overtops the obstacles; this supplements preceding studies of the runup on barriers [*Chu et al.*, 1995]. This work is also relevant for the interaction of atmospheric pyroclastic flows and oceanic turbidity currents with natural topography [*Woods et al.*, 1998; *Bursik and Woods*, 2000; *Calder et al.*, 1999; *Yamamoto et al.*, 1993; *Druitt*, 1996]; and rock avalanches with buildings [*Sparks et al.*, 2002].

2. Laboratory Experiments

[3] We conducted a series of small-scale, laboratory experiments, in which small glass particles were instantaneously released down an inclined chute to form a rapid granular flow, which interacted with a barrier obstacle at the end of the chute (Figure 1, Table 1). The barriers had a planar upstream face, which was inclined at an angle α to the chute (see Figures 1 and 2), spanned the width of the chute and were of varying heights. The particles were approximately spherical with mean diameter 100 μm and density 2500 kgm^{-3}. The thickness of these laboratory flows was therefore approximately 100 particle diameters. The volume fraction of particles in the flow is difficult to measure directly; rather by measuring bulk characteristics of the steady flows, namely the speed and depth of each run, we estimate that the volume fraction lies in the range 0.3–0.5. Experiments were conducted for a range of dam heights relative to flow depths, d/h, between 0.5 and 5 and with upstream faces at angles to the chute between 30° and 90°.

[4] In each experiment a measured quantity of particles was released from the top of the chute and the progression down the chute and interaction with the obstacle were recorded using a video camera, which recorded at 50 frames per second. The velocity field was measured by tracking tracer particles. The experiments were designed so that the particulate current had a Froude number, close to that estimated for natural snow avalanches. In this context, the Froude number, Fr, is defined in terms of the flow velocity, u, the depth of the flow, h, and gravitational acceleration, g, and is given by Fr = u/[gh]$^{1/2}$. A typical flow speed of dense snow avalanches is 30 ms^{-1}, while the depth of its mobile dense part is typically 1 m, leading to a

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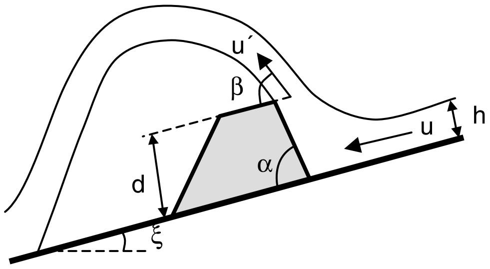

Figure 1. Side view of the interaction between the granular flow and the obstacle. The granular material flows down the chute, inclined at an angle ξ to the horizontal. The chute is of length 3 m and width 30 cm in experimental series (i) and (ii), but of length 1.5 m and width 20 cm in series (iii). The velocity and depth of the flow are denoted u & h, respectively. The flow interacts with a stationary obstacle that spans the chute. The obstacle is of height d and its upstream face is inclined at an angle α to the chute. The granular flow forms a coherent jet of velocity u′ from the top of the dam and is initially projected at angle β to the chute.

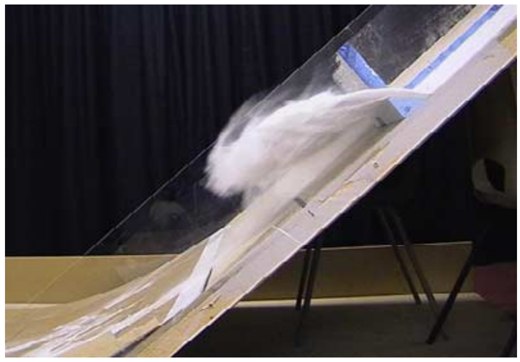

Figure 2. Photograph of the granular jet as it detaches from the top of the obstacle. In this photograph, the chute is inclined at 40° to the horizontal and the upstream face of the obstacle is at 45° to the chute.

Froude number equal to approximately 10 [*Hopfinger*, 1983]. In each of the experiments the flows rapidly accelerated to a constant speed such that the Froude number was approximately independent of the mass of particles released (Table 1).

[5] In all of the experiments it was observed that on reaching the dam, the stream of particles was projected from the top of the dam and formed a coherent jet. During the first few seconds of the interaction, the airborne jet established a quasi-steady shape that persisted while the bulk of the flow passed over the barrier until the source of particles from the chute waned (Figures 2 and 3). Images captured from video recordings of the experiments showed that the airborne jets followed parabolic paths with constant horizontal speed (Figure 3). This is consistent with a ballistic trajectory in which the airborne jet is subject solely to gravitational forces with negligible air resistance. The photographic images of the experiments indicate that there is some entrainment of air into the jet-like motion. However this appears not to influence significantly the ballistic trajectories.

[6] The angle at which the jet detached from the obstacle relative to the chute, β, and the speed u′, were evaluated by fitting parabolas to jet trajectories using least-squares regression. We observed that β was less than the angle of the upstream face of the dams for small dam heights relative to the flow depth. However, β asymptoted towards the angle of the upstream face as the relative height of the dam increased and the flow became fully deflected (i.e., $\beta \to \alpha$ as $d/h \to \infty$). Figure 4 shows the variation of the measured value of β with height of the barrier relative to the depth of the oncoming flow. Curves are given for several values of the upstream angle of the barrier. For the less steep dams (α = 30° and 45°), the launch angle attained the angle of the upstream dam face for relatively small values of d/h, while the steeper dams (α = 60° and α = 75°) needed to be higher for the jet to be fully turned by the interaction. The experimental results for α = 90° are plotted in Figure 4 (iii) with independent experimental results for a rapid free-surface flow of a fluid jet [*Yih*, 1979]. We note that the trajectories of the granular and fluid jets are similar. Prediction of this launch angle, β, is key for determining the range of the jet following lift off from the barrier.

Table 1. Experimental Conditions and Average Flow Speeds, Flow Depths and Froude Numbers

Experimental series	Chute Inclination (degrees)	Mass of particles (kg)	Average speed (ms^{-1})	Depth of flow (cm)	Average Froude number
i	41	6	3.1 ± 0.2	0.8 ± 0.2	11
ii	37[a]	6	2.8 ± 0.1	1.0 ± 0.1	9
iii	43	2	2.7 ± 0.2	0.6 ± 0.1	11

[a]Obstacles were situated on a metal sheet of inclination 30° connecting the chute to a runout zone of lower inclination.

3. Discussion

[7] Since the granular jets are of high Froude number, it is of interest to compare our experimental results with the predictions for the two-dimensional irrotational flow of an inviscid fluid over a dam. *Yih* [1979] has shown that in the absence of gravity, the launch angle β may be expressed implicitly in terms of the inclination of the upstream face of the dam α and the depth of the dam relative to the depth of the flow, d/h. Denoting α = πn/m, this expression is given by

$$\begin{aligned}\frac{d}{h} = \mathrm{Im}\Bigg\{\frac{1}{\pi}\sum_{r=0}^{m-1}&\left(\exp(-\mathrm{i}(2r\alpha+\beta))\ln\left[1-\exp\left(\frac{\mathrm{i}(\alpha-2r\alpha-\beta)}{n}\right)\right]\right.\\ &+\exp(-\mathrm{i}(2r\alpha-\beta))\ln\left[1-\exp\left(\frac{\mathrm{i}(\alpha-2r\alpha+\beta)}{n}\right)\right]\\ &\left.-2\exp(-\mathrm{i}2r\alpha)\ln\left[1-\exp\left(\frac{\mathrm{i}(\alpha-2r\alpha)}{n}\right)\right]\right)\Bigg\}. \qquad (1)\end{aligned}$$

Figure 4 also shows this theoretical relationship (solid lines) between the launch angle, β, and the height of the dam relative to the depth of the flow for various inclinations of the upstream face. There is generally reasonably close agreement between the experimental results and theoretical predictions for the dams with α = 30°, 45°, 60° and 75°. For

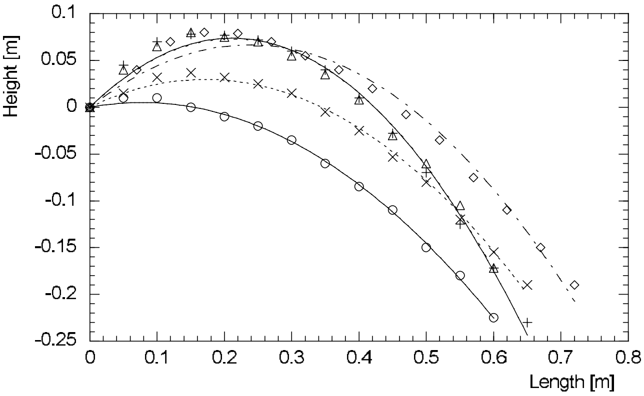

Figure 3. The vertical height of the jet trajectories above the dam as a function of horizontal distance downstream, for experimental series i with α = 90°. The datapoints are experimental observations; the lines denote the parabola fitted using least squares regression. Each data series corresponds to a different height of obstacle relative to depth of the flow. (d/h = 0.6 (○); 1.2 (x); 2.4 (◇); 3.8 (Δ); 5.3 (+)).

the dams with an upstream face inclined at 90° agreement is reasonable for small relative heights. However, for larger relative heights, β asymptotes to an angle of approximately 75° instead of 90°. A possible explanation for this effect in the context of these granular flows is that a wedge of particles is deposited on the upstream face of the obstacles, thereby lowering the effective inclination of the face. Some investigators refer to this effect as self-ramping [*Chu et al.*, 1995]. After each experimental run we found particles deposited in this location and we hypothesise that this occurs during the interaction with the obstacle so that the quasi-steady jet is not deflected at the full angle of the upstream face of the obstacle. This residue of particles is evident for all barrier inclinations, but it is most pronounced when the barrier is at 90° to the chute. Some of these particles were deposited at the end of the flow as the velocity wanes; they would have little effect on the deflection of the jet. Instead it is those trapped during the earlier phases that may alter the observed deflection.

[8] This study has shown that on colliding with a barrier, a shallow granular flow of high Froude number becomes airborne and follows a coherent ballistic trajectory. Even though different physical interactions control the dynamics of fluid and granular flows, our experiments show that the vertical deflection of the momentum flux by the barrier is similar to that predicted for an inviscid, two-dimensional flow of a fluid jet. This implies that within the deflection region, these granular currents are not affected by resistive forces. Thus for a given flow speed and depth of the avalanche relative to that of the obstacle, the range of the airborne jet can be estimated by combining the prediction of the angle of deflection β with the parabolic trajectory of the jet, on the assumption that air resistance plays only a negligible role for these trajectories. For example, our results imply that for an obstacle of height 5 m, situated on a slope of 10° with an upstream face inclined at 90° to the slope, an avalanche with flow speed 30 ms^{-1} and depth 1 m would travel though the air a distance of 33 m, while an avalanche with flow speed 50 ms^{-1} and depth 5 m would travel 307 m. Such predictions provide valuable quantitative information for the design of avalanche protection schemes; for example with multiple rows of barriers it is important to ensure that the distance between obstacles is sufficient so that the avalanches do not jump over successive rows [*Tómasson et al.*, 1998a; *Hákonardóttir et al.*, 2003].

[9] Further research is ongoing to investigate the interaction with obstacles that do not span the chute so that the flow may be deflected laterally in addition to forming a coherent jet. Also, experimental studies at larger scales are planned using different material (including natural snow); preliminary results indicate that the same phenomena are observed.

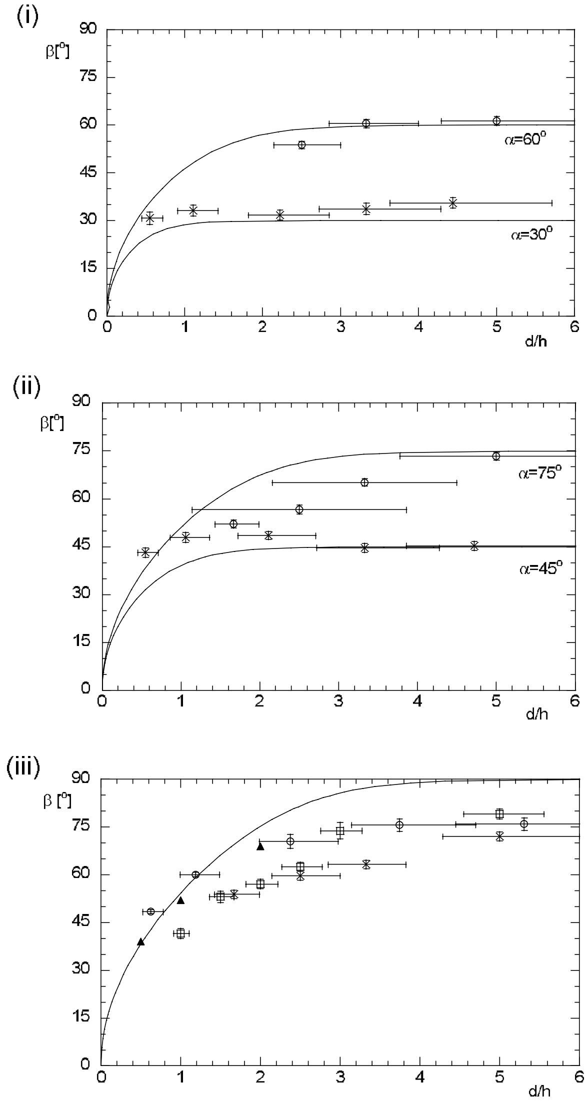

Figure 4. The launch angle, β, of the jet as a function of the height of the dam relative to the depth of the flow, for varying inclinations of the upstream face of the dam: (i) α = 30° (x) and α = 60° (○); (ii) α = 45° (x) and α = 75° (○); and (iii) α = 90°. The theoretical predictions are plotted as solid lines and the experimental data are plotted as data points: Series i (○); Series ii (□); Series iii (x); and Fluid jet (▲) [data from *Yih* [1979]].

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