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: Hákónardóttir, 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; Hákónardóttir 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 kg m⁻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 m s⁻¹, while the depth of its mobile dense part is typically 1 m, leading to a
the upstream face as the relative height of the dam increased and the flow became fully deflected (i.e., $\beta \rightarrow \alpha$ as $d/h \rightarrow \infty$). Figure 4 shows the variation of the measured value of $\beta$ 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 ($\alpha = 30^\circ$ and $45^\circ$), the launch angle attained the angle of the upstream dam face for relatively small values of $d/h$, while the steeper dams ($\alpha = 60^\circ$ and $\alpha = 75^\circ$) needed to be higher for the jet to be fully turned by the interaction. The experimental results for $\alpha = 90^\circ$ are plotted in Figure 4 (iii) with independent experimental results for a rapid freesurface 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, $\beta$, is key for determining the range of the jet following lift off from the barrier.

### 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 $\beta$ may be expressed implicitly in terms of the inclination of the upstream face of the dam $\alpha$ and the depth of the dam relative to the depth of the flow, $d/h$. Denoting $\alpha = \pi n/m$, this expression is given by

$$
\frac{d}{h} = \frac{1}{\pi} \sum_{m=0}^{n-1} \left( \exp(-i(2\pi\alpha + \beta))) \ln \left[ 1 - \exp \left( \frac{i(\alpha - 2\pi\alpha - \beta)}{n} \right) \right] \right)
+ \left[ \exp(-i(2\pi\alpha - \beta)) \ln \left[ 1 - \exp \left( \frac{i(\alpha - 2\pi\alpha + \beta)}{n} \right) \right] \right] - 2 \exp(-i2\pi\alpha) \ln \left[ 1 - \exp \left( \frac{i(\alpha - 2\pi\alpha)}{n} \right) \right] \right) \}
$$

Figure 4 also shows this theoretical relationship (solid lines) between the launch angle, $\beta$, 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 $\alpha = 30^\circ$, $45^\circ$, $60^\circ$ and $75^\circ$. For
5.3 (+)).

the angle of deflection avalanches relative to that of the obstacle, the range of the forces. Thus for a given flow speed and depth of the region, these granular currents are not affected by resistive flow of a fluid jet. This implies that within the deflection similar to that predicted for an inviscid, two-dimensional vertical deflection of the momentum flux by the barrier is of fluid and granular flows, our experiments show that the though different physical interactions control the dynamics airborne and follows a coherent ballistic trajectory. Even a shallow granular flow of high Froude number becomes negligible role for these trajectories. For example, our jet, on the assumption that air resistance plays only a 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].

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 3. The vertical height of the jet trajectories above the dam as a function of horizontal distance downstream, for experimental series i with \( \alpha = 90° \). 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 (+)).

Figure 4. The launch angle, \( \beta \), 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) \( \alpha = 30° \) (x) and \( \alpha = 60° \) (○); (ii) \( \alpha = 45° \) (x) and \( \alpha = 75° \) (○); and (iii) \( \alpha = 90° \). 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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References


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