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Pattern formation in granular avalanches

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Three new experiments are described which exhibit strong pattern formation in the deposits left by successive granular avalanches. At low flow rates continuous deposition, erosion or rotation gives rise to intermittent avalanche release. Once in motion kinetic sieving of a bi-disperse granular mixture creates a two-layer shear band in which the larger particles overlie the smaller particles. When this is brought abruptly to rest by the upslope propagation of a shock wave a pair of stripes is "frozen" into the deposited material. Successive releases create a large scale pattern, which strongly reflects the history of the granular flow. At faster deposition, erosion and rotation rates a new flow regime is entered in which intermittency and shock formation ceases, and the associated patterns change.

1 Introduction

Granular avalanches are shallow gravity driven free surface flows of weakly cohesive solid particles or grains, which occur when a surface layer of granular material becomes unstable. They are abundant in our everyday environment as well as in food manufacturing, industrial processes and in geophysical flows such as landslides, rock-falls and snow (slab) avalanches. Here we describe three mechanisms for avalanche initiation, which in conjunction with particle size segregation within the flowing avalanche [1], [2] and the occurrence of dispersed shock waves that bring the avalanche quickly to rest, lead to pattern formation within the deposited material.

2 Shock waves and particle size segregation

It is well known that avalanches act as a *kinetic sieve* [1], [2], which sorts the granular material by grain size. A typical *roll wave* configuration on an inclined slope is shown in the schematic diagram in Fig. 1. As the grains are sheared gaps between the particles are continually being created and annihilated. Under the action of gravity the smaller particles are more likely to fall into gaps that open up beneath them than the large grains, because they are more likely to fit into the space available. An *inverse-grading* of the particles rapidly develops in which the larger particles overlie the smaller particles. For the experiments presented here this means that the white particles overlie the dark particles forming a two-layered shear band or stripe. In addition, since the surface of the avalanche moves faster than the base, the larger grains are transported to the front whilst the smaller grains concentrate at the rear of the avalanche as shown in Fig. 1.

A further important component of pattern formation in granular avalanches is the presence of dispersed shock waves, which bring the granular material rapidly to rest. These are initiated when the avalanche front reaches the base of the slope, or a solid wall, and propagate rapidly upslope *freezing* the particle

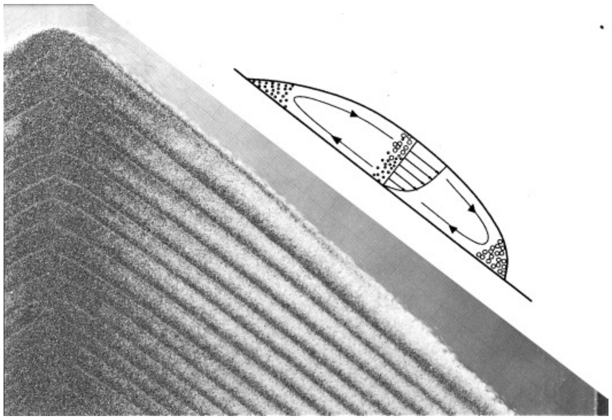

Fig. 1. Photograph and schematic diagram of a granular avalanche in a typical roll wave configuration. An inverse-graded particle size distribution rapidly develops in which the large (white) particles overlie the small (dark) particles forming a stripe. Velocity shear through the avalanche thickness then transports the larger (white) particles to the front

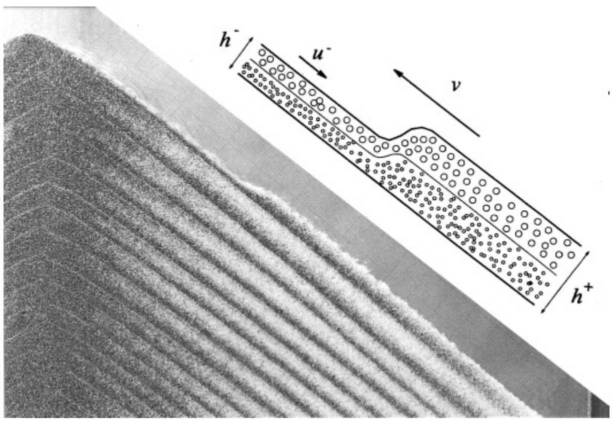

Fig. 2. Photograph and schematic diagram of the upwards propagating dispersed shock wave. The material below the shock is at or near rest, whilst the grains above the shock are flowing rapidly downslope

size distribution into the deposited granular material and thereby preserving the pattern formed during the avalanche motion.

The shocks are travelling waves that form a hump on the free surface of the granular material, which is thicker on the downslope side (Fig. 2). A simple mass jump condition [3] for the Savage-Hutter avalanche theory [4], [5] requires that $h^+(u^+ - v) = h^-(u^- - v)$, where h^+, h^- is the avalanche thickness ahead of and behind the shock, u^+, u^- is the depth averaged avalanche velocity ahead of and behind the shock and v is the shock speed. If there is no motion on the downslope side, $u^+ = 0$, then the front speed $v = -u^-h^-/(h^+-h^-)$. For downslope velocity $u^- > 0$ and thicknesses $h^+ > h^- > 0$ the front speed v is negative and propagates upslope as observed (Fig. 2).

3 Experiments

Three experiments are described in which deposition, erosion and rotation are used to produce intermittent avalanche release. All the experiments take place between parallel plates with a spacing of 3 mm, which prevent lateral spreading of the avalanche and exert an additional wall friction that slows the avalanche to easily observable speeds. A mixture of (white) sugar crystals and (dark) spherical iron powder with mean grain diameters of 0.5 mm and 0.34 mm, respectively, is used with a mixing ratio by volume of 1:1.

3.1 Parallel plates

In the first experiment the granular mixture is poured into a thin silo (70 cm high by 34 cm wide) from a point source at the top-centre and a triangular pile of granular material is formed. Although material is continuously deposited at the top of the pile, it does not flow immediately down the faces because of the

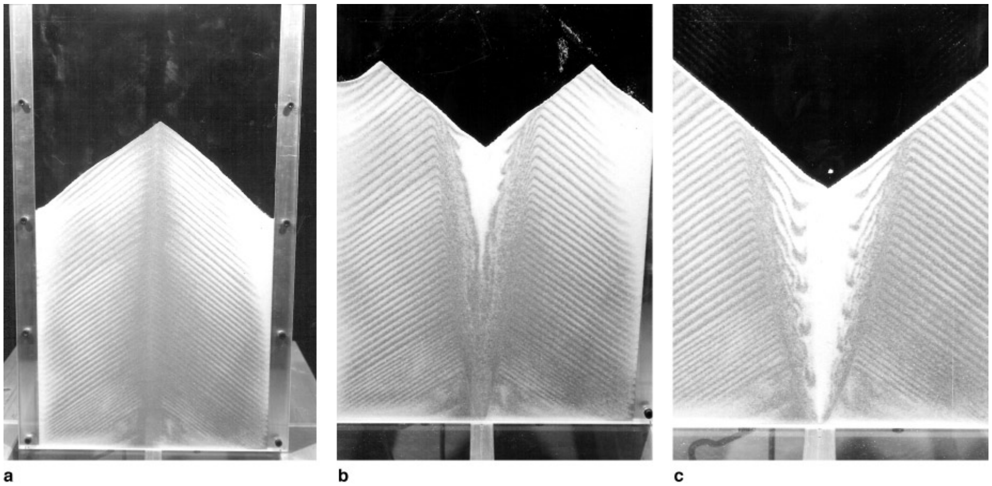

Fig. 3. A pine tree effect is built up through successive stripe formation and burial (a). When a small hole is opened at the base a core flow develops (b) with the large (white) particles at the centre and the small (dark) at the side. At low flow rates intermittent granular avalanches penetrate into the central core leaving a straight stripe on the free surface that acts as a tracer in the flow (c)

difference between the static and dynamic internal friction angles [6], [7]. Once the static friction angle is exceeded the avalanche flows down the face of the pile and forms a roll-wave, as shown in Fig. 1, in which kinetic sieving takes place. As the avalanche reaches either the base, or the wall, of the silo it is rapidly brought to rest by the upslope propagating shock wave, as shown in Fig. 2, and the inverse grading pattern is frozen into the deposit. Successive and alternating avalanche releases on both faces of the triangular pile build up a sequence of such layers giving rise to a *pine tree* pattern as shown in Fig. 3a. It is also interesting to note that there is a tendency for the upslope propagating shock wave to destabilize the granular material on the opposite face of the pile, as it reaches the centre, so that avalanches tend to form first on one side and then on the other.

3.2 Silos and sand clocks

If a small hole (diameter 5 mm) is opened at the centre of the silo base the granular material develops an internal core flow and a vee-shaped rat-hole is quickly formed, as shown in Fig. 3b. The granular material on either side of the core is at rest and the pine tree pattern is preserved there. Material is fed to the core by a sequence of intermittent avalanches that flow down the faces of the rat-hole and are initiated by erosion at the base of the avalanche slope. Kinetic sieving takes place within the avalanche and the larger particles concentrate in the centre of the core whilst the smaller particles are drawn into a dark shear band on either side of the white core. At low flow rates avalanches are also able to penetrate into the centre of the core and come to rest when they hit the opposite side of the rat-hole by upslope shock wave propagation. They leave behind an initially straight white and dark stripe at the surface of the white core, which then acts as a tracer in the internal flow. Fig. 3c shows how a series of initially straight stripes have been sheared and deformed.

The processes of erosion and deposition both occur in a *sand clock* as illustrated in Fig. 4. This provides a useful demonstration tool to illustrate the core flow of experiment two and the successive build up of layers in experiment one.

3.3 Thin rotating disk

In the final experiment the granular mixture is contained within a closed vertical disk (diameter 25 cm) with a free surface that lies above the centre as shown in Fig. 5a. To emphasise the pattern formation the disk is laid horizontally and gently shaken so that all the small particles fall to the bottom. Once returned to the vertical one side of the disk is completely white, whilst the other is completely dark. When the disk is

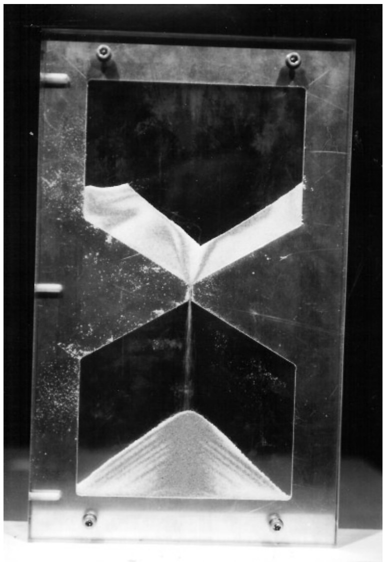

Fig. 4. A sand clock exhibits both deposition in the lower half and erosion in the upper half of the clock

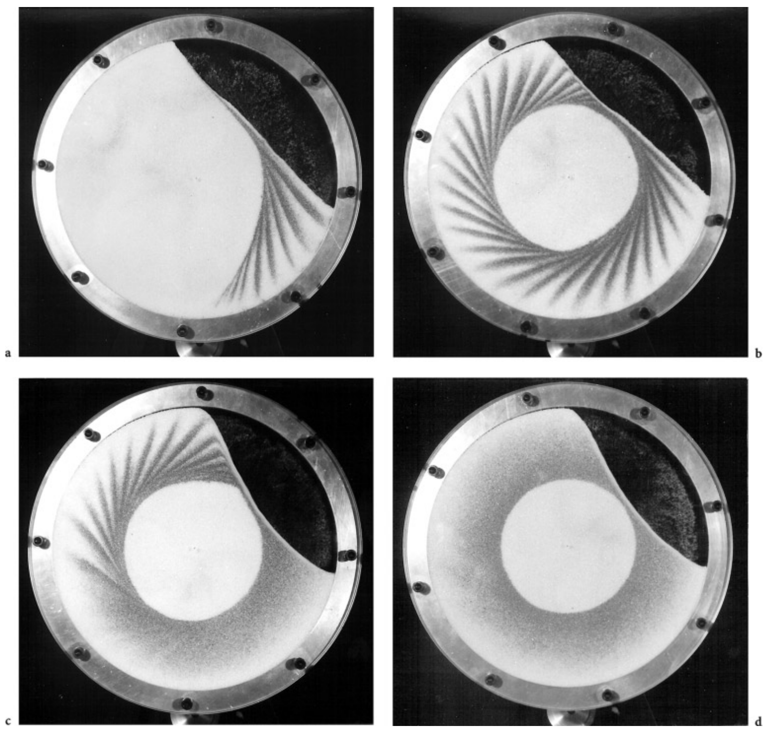

Fig. 5. At low rotation rates intermittent avalanche release in a thin rotating disk filled with a granular mixture leads to the formation of stripes tangent to the free surface (a), which are then rotated and buried to form a Catherine wheel effect (b). At faster rotation rates a quasi-steady flow develops (c) in which the free surface is fixed in space and there is a continuous distribution of particle sizes outside the central core (d)

rotated at a constant rate (110 seconds per revolution) intermittent avalanches are formed at the free surface. The intermittency again stems from the difference between static and dynamic internal friction angles. The central circular core of material remains completely undisturbed by slow rotation of the drum [8], [9]. Each avalanche release sorts the material, forming a stripe, which is frozen into the deposit by the shock wave and subsequently rotated and buried in the undisturbed material below the free surface. Subsequent releases create a sequence of stripes (Fig. 5a) tangent to the central core, which create a *Catherine wheel* effect (Fig. 5b).

At faster rotation rates (< 20 seconds per revolution) the intermittency of the avalanche release, the shock waves and the stripes disappear and a steady-state flow regime dominates Fig. 5c. The material is continuously released on the upper side and continuously deposited on the lower side of the concave free surface and is transported between the two positions by a quasi-steady avalanche in which kinetic sieving takes place. Since the smaller particles are concentrated at the bottom of the avalanche they are the first to get deposited on the lower half of the free surface and a new pattern develops in which the central core is undisturbed, and there is a continuous distribution of grain sizes outside the central core, starting with a high concentration of small particles near the core and ending with a high concentration of large particles near the outer wall as shown in Fig. 5d.

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