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Sensitivity of granular surface flows to preparation

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Abstract. – The transient surface granular flow occurring when a cylindrical pile of granular media supported by a disc crumbles to form a cone is investigated. The experiments show that this flow depends strongly on the way the granular material was prepared. We found a clear dependence on the density of the packing, leading from a deep bulk flow for low densities to an erosive surface flow for high ones. But the flow is also sensitive to possible asymmetries of the internal structure of the material.

Introduction. – Although granular flow has attracted interest in the past years, it is surprising to see that there is not yet a general description of this phenomenon. The situation is thus far from that of fluids, where governing equations have been established and confirmed since a long time. Even the possibility of a fluid-like description of granular flow is debated [1].

A particularity of granular media is their ability to remain stable up to a limiting slope, called the static angle [2]. When this angle is exceeded, the pile starts to flow, and this flow has the property of being a surface flow on a pile remaining static. The depth of the flow and the characteristics of the flowing layer for instance are not yet known. This article presents a simple experiment which shows that this surface flow depends on the way the pile has been prepared.

Experiments. – The experimental set-up consists of a disc with a chamfered edge which supports a vertical cylinder. The whole system is placed on top of a balance. The disk and the cylinder form a container which is filled with sand or polydisperse glass beads (250–425 μm) in different ways. Then we remove carefully the sand in excess, so that the cylinder be exactly filled to the top. From its weight m, knowing the volume of the cylinder V and the density of

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the grains ρ_0, we deduce the mean density of the packing $\nu = m/\rho_0 V$, which is the ratio of the volume occupied by the grains over the total volume.

We then abruptly pull up the cylinder and record, using a CCD-camera, the flow by which the sand pile reduces finally to a cone resting on the disc. The video film is digitalised frame by frame (at 50 Hz). Each frame is then analysed to find the profile. The film has been slightly over-exposed so that the pile appears white on a black background. Although the pictures have a precision limited by the size of a pixel (typically 0.3 mm), the pixel value is a spatial average which at the pile boundary leads to a gray value. A simple fit on these gray levels gives us the position of the boundary with sub-pixel precision (1/10 pi). From the profile obtained this way, or directly from the picture using a 2D fit, the local slope is measured along the profile. When a region is straight enough, we measure the slope angle on the whole interval. The first profiles (shown in dashed lines in fig. 1), are not taken into account, and no angles are measured when we cannot make out straight slopes.

For the preparation of the sample three simple methods are used:

a). The sand is poured out of a container directly, swiftly and from a small height at the centre of the cylinder.

b). The sand is poured via a funnel onto two sieves, superposed at a distance of 15 cm. The grains bounce, resulting in a homogeneous downfall of grains with a high velocity and a small rate.

c). The sand is poured into the cylinder, and the whole system is then vibrated vertically for about 10 minutes.

The first method a) is very crude and probably not homogeneous. However, because the grains are just slightly diluted and their velocity is small, the energy is dissipated very quickly by internal collisions. This leads to very low densities ($\nu \approx 0.58$). On the contrary, the "rainfall method" b) can lead to high densities of $\nu \approx 0.65$ (which is the value for the dense random packing limit of monodisperse spheres), as the grains fall nearly independently with a large velocity. But decreasing this velocity, by tuning the various distances between the funnel, the grids and the sand layer, allows to decrease continuously the density [3]. The third method c) was long used to compact granular piles [4], but we chose it here because of another, convective, effect.

Results. – The typical evolution of the overall profile in the three cases is shown in fig. 1. In a) the transient obtained for a low initial compactness (method a)) is shown. Upon removal of the outer wall, part of the material falls off the pile almost freely. A tenth of a second later (roughly the time for a gravitational free fall over the height of the pile $\sqrt{2h/g}$) we are left with a cone whose angle will then simply relax exponentially towards a constant value. This relaxation has again a characteristic time of the order of the free fall time (see fig. 4a) in the following). The interesting point is that the top is blunt from the very beginning. This means that the summit of the pile starts to flow instantly. The large radius of curvature of the top, and the rapid decrease in height are both strong indications of a great depth of the flow in this loose case. Some profiles in fig. 1a) have been omitted, in order to show that the late evolution of the profile is such that the straight slope becomes slightly convex in the bottom part of the pile.

For a high initial compactness (obtained through method b), we observe a very different flow (see fig. 1b)). As in the loose case there is a rapid fall of the "corners", but it can now be more precisely interpreted as an active Coulomb-yielding of the material: the latter yields to the stress by breaking at an angle which is determined by the internal friction angle.

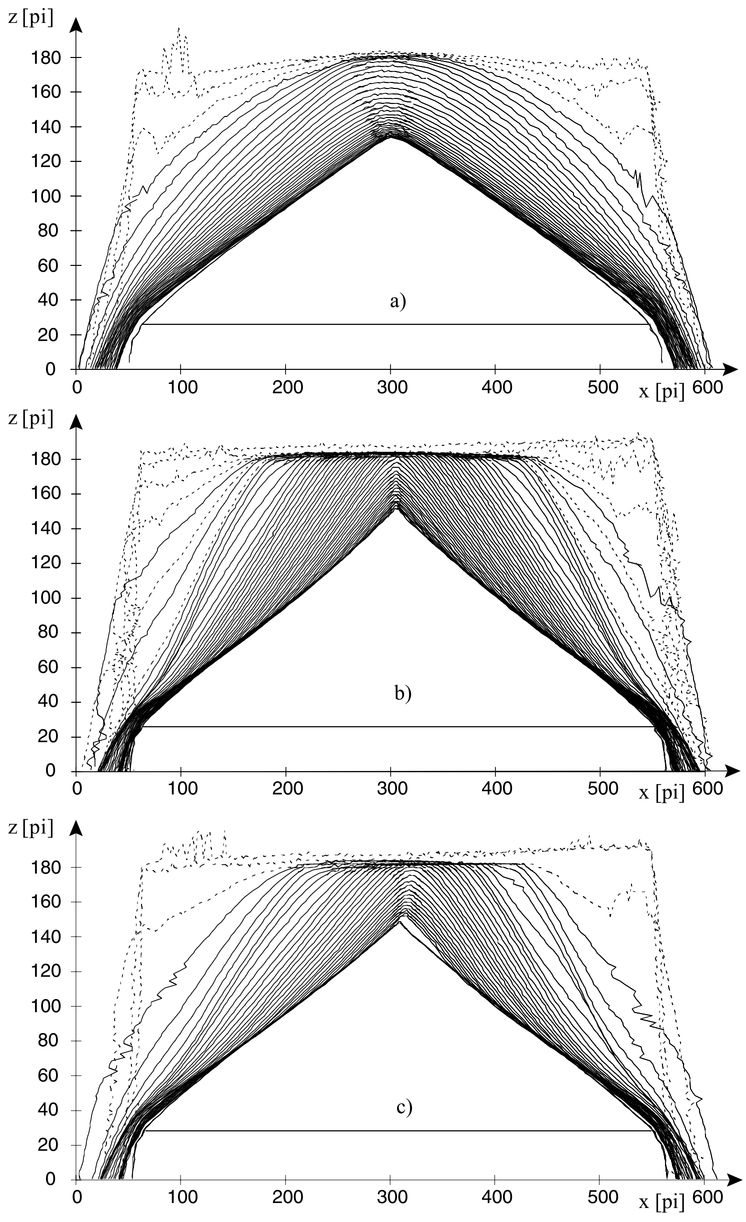

Fig. 1. – Series of profiles for glass beads. The initial height is 46 mm and the diameter of the support (horizontal line) is 142 mm. The time lapse between consecutive profiles is 0.02 s in a) and 0.04 s in b) and c). The three experiments differ only by their preparation (see text a)-c)). a) Loose case ($\nu = 0.58$): Fast relaxation towards the final cone, with a tip rounded from the very beginning. b) Dense case ($\nu = 0.65$): A fracture takes the corners down; the flow is characterised by the existence of an upper steep region slowly moving inwards and a left lower region at the angle of the final pile. As opposed to a), the centre region does not move before being reached by the steep front. c) Asymmetrical dense case ($\nu = 0.63$): The flow basically resembles b), but it exhibits a strong right-left asymmetry.

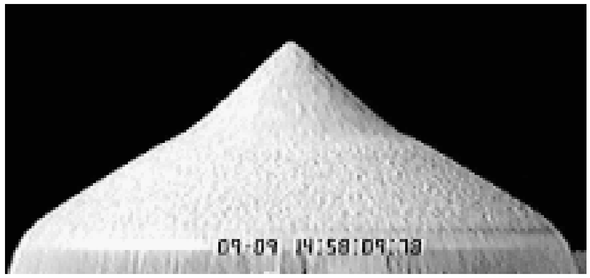

Fig. 2. – Snapshot of the flow for sand with coloured grains in the dense case. The exposure time of 1/50 s allows to distinguish the grain velocities. The two regions, at a large angle with accelerating particles and at the small final angle with slow particles, are clearly visible.

In addition, there appears to be a second fracture a few moments later. Its origin is still unclear, and a possible effect of the bottom [5] is actually under investigation. But the main difference to the "loose" case lies in the flow regime after the second fracture: the profile can present three different regions. The upper central region remains perfectly still until the flowing region reaches it. This flowing region presents a large angle (typically 40°). During its inwards propagation it leaves behind a cone with a much shallower slope, close to the final one (see fig. 4b)). The flow depth is small, as can be inferred from the large flow duration and the stability of the upper central region before it is reached by the flowing front.

The use of sand with grains of various colours reveals that the grains in the upper part of the flowing region accelerate almost freely on their way down, reaching quickly a large velocity. On the final cone region, in contrast, their velocity is small and roughly constant (fig. 2). The abrupt change in the flow regime induces the formation of a "hydraulic jump" (see fig. 3), the accelerated flow being very thin compared to the slow flow region by mass conservation. The difference between the two regions tells us that in the upper region, the flow seems to be only limited by erosion or the ability of the beads to unlock from their tight packing. Once moving, the flowing grains seem to hardly interact with the underlying grains (nearly free fall). When they reach the lower part, the grains flow at a smaller angle on the motionless particles of the final pile. They thus experience a large friction which leads to a small velocity.

The time evolution of the slope angles in the two distinct regions is shown in fig. 4b). Contrary to the loose case, the flowing slope is well defined much earlier after the cylinder removal, and starts from a much larger angle. It then decreases only slowly and during its decrease, the final cone appears in the lower part.

Contrary to the transient angles, this final cone is much closer to the loose case (angle difference of $\approx 2.5°$). Moreover, the slope is always better defined during the flow than in the final state, because in all cases the bottom part becomes convex in the end (some profiles close to the end of the flow have been omitted in fig. 1a), c) in order to point out the ultimate changes). These similar convex bottom parts and close final profiles can be understood as a result of an annealing process. In the loose case a), the flow occurs deep in the pile, and the final evolution of the profile can be seen as a freezing of the deep flow. By its motion, the frozen layer has forgotten the density of the pile. There is the same effect in the dense case: even though the flowing layer is much thinner in the eroding part, it enlarges on the final cone. So it is natural for the final profiles to be similar. The rounded bottom part can be explained because the freezing layer is not supported at the limit of the disc. It will therefore continue flowing, and erode up to a larger angle where it is locally stable (see fig. 1a)). This interpretation in terms of annealing also explains why the tip, which is much sharper in fig. 1b)

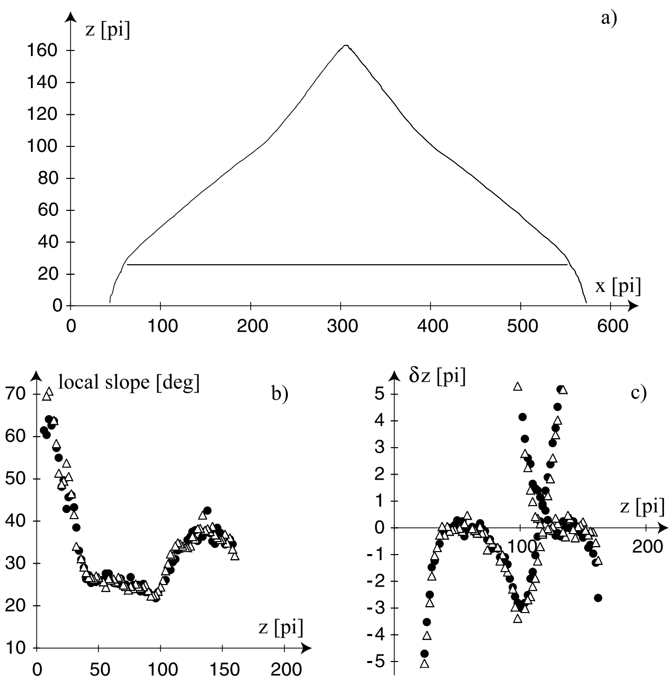

Fig. 3. – a) presents an intermediate profile from fig. 4b). b) shows the local slope measured from this profile, as a function of the height, for both the left (black circles) and the right (triangles) sides. It shows the simultaneous presence of two regions of nearly constant slope. c) The deviations from the two linear fits derived from the two plateaux. The dip at the transition ($z \approx 100$) is a hydraulic jump from a thin high-velocity (accelerated) layer to a thick small-velocity flow.

than in the loose case 1a), seems to keep a memory of the density: it has not been annealed because it emerges at vanishing flow and is thus not covered by a frozen layer.

When method c) is used to prepare the sample, above a given acceleration the free surface of the sand tilts spontaneously and the material accumulates on one side of the container. This is due to an inner motion in which the grains form a convective roll: the material comes up close to one side wall and flows down the tilted free surface. This was the case for fig. 1c) and 4c), where the tip of the convective cone was on the left (in the preparation of the experiment, a second cylinder was placed on top of the first one with more material, so that the proper experimental cylinder was filled entirely in spite of the tilted surface). With this convective motion, the density measured, once removed the second cylinder and the excess material of the cone, was high.

The main result is the strong asymmetry observed in the profiles (see fig. 1c)): the right part is roughly 10° steeper than the left part (see fig. 4c)). To understand this asymmetry, we can recall the one observed in ref. [6]. Half a pile was prepared by pouring sand on one side of a cell. Then by opening an outlet in the cell floor, two different angles were measured, depending on whether the grains had to flow in the same direction than during the pile formation or in the opposite. A first interpretation could be that there are density variations, which appear whenever the material has accumulated through avalanches, and which are merely a memory of the latter (as was seen using X-rays [7]).

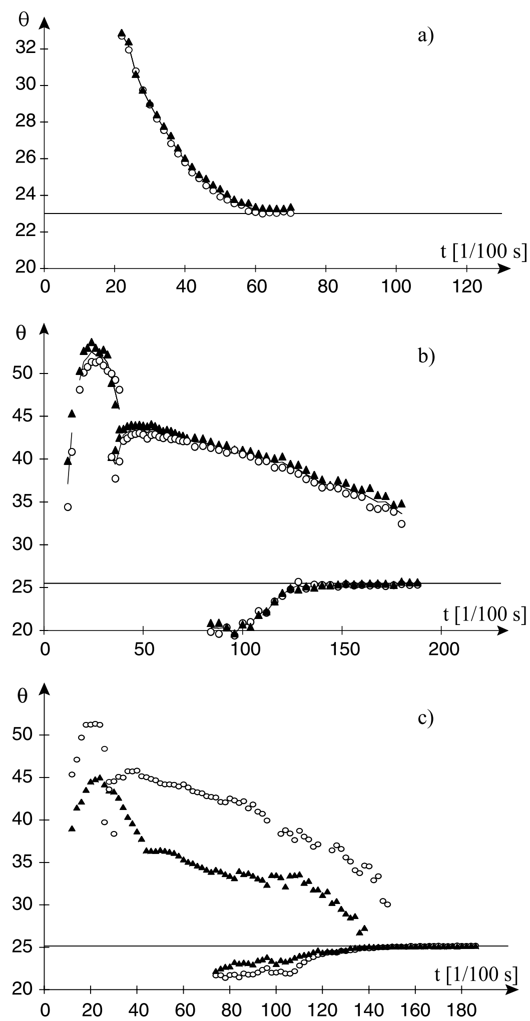

Fig. 4. – Time evolution of the slopes. Triangles and circles describe the right and left sides, respectively. The time origin is the cylinder removal, and the last time is approximately that of the last grain dropping from the pile. a) Exponential relaxation for loose packings. b) Dense case: The upper set of points corresponds to the steep region, and the lower ones to the shallow outer region. The first fracture leads to angles of $\sim 52^\circ$, and is followed closely by a second fracture at $t \approx 0.35\,\mathrm{s}$ at an angle of 43°. The decrease is much slower than in a). c) Asymmetrical case: The right and left high upper slopes differ by about 10°, whereas the final slopes are identical.

In the convective motion, avalanche flow recalls the model proposed in ref. [8] for the convective motion. It is based on the formation, during the collision of the pile with the bottom plate, of an internal avalanche flow going down to the centre of the heap, and propagating from the lower side to the top of the convective cone. However, the avalanches are not discrete inside the convective roll, so that the asymmetry cannot be ascribed to density variations, but only to an anisotropic structure on the level of grain contacts. This anisotropy in the distributions of contacts between grains is known to arise particularly in sheared layers [9], what avalanche flows are, and to influence mechanical properties [10]. In our experiment, this explains why the smaller slope is on the left: the internal flow at each shaking period was directed downwards below the summit, so towards the lower-left side.

The fact that the final profile is symmetrical (except near the tip) (see fig. 1c) and fig. 4c)), although the transient is not, corresponds to the annealing process due to a freezing flowing layer described above. In the dense transient, there is even another possible mechanism: when the high velocity/angle flow hits the underneath and hereafter fixed grains of the final cone, there can be a local destruction of the original pile structure. The final cone has thus a surface which is a mixing of a frozen flow and a reorganised layer.

Conclusion. – The importance of the density has been recognised in the static (yield) properties of granular material [11]. Some experiments have also shown the dependence of static and repose angle on the pile preparation [6, 12]. This experiment shows that the free surface flow is also sensitive to the density and internal structure, in particular to contact anisotropy. As we observed these phenomena for very different granular material such as sorted glass beads and rough polydisperse sand, we believe them to be general. This shows that internal parameters have to be taken into account in any model, in order to reproduce the transition from static to flowing granular media in a realistic way.

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