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Collapse of a granular column under rotation

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ABSTRACT

Experimental results for the collapse of granular columns on a rotating table are presented. In the non-rotating case two flow regimes are exhibited dependent on the aspect ratio $a = h_0/r_0$, where h_0 is the initial height and r_0 is the initial column radius. Scaling relations for the characteristic geometrical properties of the collapsed column under varying rotation rates are obtained. As the rotation rate increases, material is lost from the main pile and travels to the edge of the rotating table. This results in a decrease in the final radius of the main collapsed pile, as material is lost during this secondary, rotation-induced spreading phase. The degree of mass ejection in the secondary spread increases with rotation frequency for a given initial aspect ratio. Analysis of the flow characteristics including time evolution and final pile height are also described.

1. Introduction

The study of granular flows is important to gaining an understanding of environmental particulate movements. Insight into natural deluges such as avalanches and pyroclastic flows and sediment transport processes has been developed through experimental, theoretical and numerical studies of idealised granular flows [1–4]. Many industrial processes involve the transportation of grains and powders, which can be optimised with improved understanding of the underlying granular dynamics.

Static granular flows are important to civil engineering projects, predominantly in the storage of grains and powders in silos and geotechnical retaining walls. Failure of these containers is analogous to a ‘dam break’ investigated by several previous authors [5,6]. A description of these flows has been offered by interpretation of experiments on the collapse of a granular column [7–11] and the failure of a granular step [5,12–16]. The simplified geometry provides data with traceable boundary conditions for testing theories, thus linking the theoretical models with the dam break itself.

An agricultural application where granular flows are utilised is the distribution of fertilisers and seeds. This is achieved by a continuous injection of granular material via a hopper, which falls onto a centrifuging disc of a prescribed frequency to ensure the even spreading of the material. This has been a recent subject of investigation, both experimentally and computationally [17–20].

Granular flows display properties of a solid (stationary), liquid (avalanching flows) and a gas (saltation of grains), often simultaneously as in the case of granular column collapse. Theoretical models of this arrangement derived from hydrodynamic approximations [2,21–24], while on the whole describe the flow regime well, can occasionally diverge from the true flow precisely due to this nature when verified against experimental results. Any model which extends this case to include rotation requires similar experimental data to validate the theoretical framework given its potential to deviate from reality.

The current investigation incorporates rotation with the collapse of a granular column. A cylinder filled with granular material was placed centrally on a rotating table of prescribed frequency. The cylinder was then quickly removed and the resulting flow observed. The granular column slumped to form a pile similar to the non-rotating case, but rotation caused mass to continue to be extruded from this pile in a secondary rotation-induced spreading regime. The purpose of this study is to discover how rotation frequency affects the scaling laws describing the pile for non-rotating granular column collapse as expressed by previous authors [7–9], and to find the onset and degree of granular spreading. Some parallels can be drawn with the arrangements for spreading of seeds and fertilisers, but is still more akin to a dam break situation. The derived empirical relations could find future application in the testing of new granular rheologies in different flow regimes.

A description of the experimental procedure is given in Section 2. Qualitative investigations into collapse dynamics are detailed in Section 3. Results on the relations between experimental parameters are presented in Section 4. Scaling laws are given for final runout and height and how these parameters advance with time, found to be dependent upon the initial column setup and the frequency of the rotating table. When the rotation rate is high enough the secondary rotation-induced spreading regime envelopes leading to material ejection which is described and quantified. Discussion and an overview of this research are presented in Section 5.

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2. Experimental setup

2.1. Apparatus

A cylinder of radius r_0 was aligned centrally on a rotating turntable and filled with granular material to a specified height h_0 as shown in Fig. 1. The table was then set into rotation at a frequency f, and the column of material allowed to enter solid body rotation. The cylinder was mechanically removed vertically via a system of pulleys directly above the tank and the granular material allowed to collapse. Its removal time, $t_r = h_0/v$, is required to be small compared to the time for the mass to be set into motion, approximately calculated as $t_m = \sqrt{2h_0/g}$. The average removal speed of $v = 2.5\text{ms}^{-1}$ used was sufficient for this to hold up to the tallest column $h_0 = 63\text{mm}$ where $t_r = 0.03\text{s}$ and $t_m = 0.11\text{s}$.

Cylinders of inner radius $r_0 = 20$ mm, 25 mm, 30 mm, 36 mm were used. For each cylinder radius, the initial height of the column of granular material, h_0, and frequency, f, were varied systematically. The aspect ratio of the initial column is defined by $a = h_0/r_0$, determined by the initial mass of granular material m_0. The aspect ratio was varied in the range 0.28–1.75, and frequency in the range 0.0–1.7 Hz.

A calcium carbonate granular material of bulk density ≈ 1.6 g/cm^3 and particle size $d = 0.6$–0.8 mm was used throughout these experiments. The particulate had an internal friction angle $\theta_\mu \approx 39^\circ$ and an angle of repose $\theta_r \approx 30^\circ$. The material was dried in an oven to evaporate any residual moisture, minimising cohesive effects between particles. The initial column was prepared by funneling the granular material into the cylinder, and the top was flattened to ensure uniform height of the column, accurate to ± 1 mm. The method of preparation showed good repeatability with a mean packing density, $\phi = m_0/(\pi r_0^2 h_0 \rho)$, between 0.78 and 0.82 across all prepared columns.

2.2. Measurement and accuracy

Time evolution of the resultant flow was studied by recording the collapse within the rotating frame of reference using a high speed digital camera fixed to the spinning table with a frame rate of 240 fps. This enabled data capture of the radial runout as a function of time, $r(t)$, and was also used to determine the collapse duration, t_f. Interpreting the video with image processing software allowed a spatial resolution of 0.5 mm when recording radial values. The resultant accuracy was of the order ± 3 mm due to the uneven periphery observed, increasing to ± 5 mm for the higher frequencies.

After the collapse occurs several dimensional values were measured from the resultant deposit. The final pile radius, r_f, was recorded using an alignment sheet fixed to the surface with radial markings of 10 mm in conjunction with a horizontal vernier scale accurate to ± 0.2 mm. The final height, h_f, was recorded with similar accuracy using a vernier height gauge. In the case where granular material was lost from the main pile and thrown to the edge of the tank the final mass of the resultant pile, m_f, was recorded by sweeping up the granular material, but resulted in some particles being lost in transit. The method was trialled with known masses of granular material, and was found to be accurate to ± 1.5 g.

A known source of error in recording the final pile radius r_f is the uneven periphery. Experiments have shown that in the case of no rotation this is approximately 3–4 particle diameters for the range of aspect ratios trialled, with the effect becoming more pronounced for increased values of rotation reaching up to 6–7 particle diameters. This uncertainty was considered during repeatability testing performed across various aspect ratios and frequencies. If was found that r_f, h_f and m_f varied by ± 3.0 mm, ± 1.0 mm and ± 2.0 g respectively.

3. Collapse dynamics

3.1. Flow description

The collapse in the non-rotating case is well reported by previous authors [7,8]. The collapse begins with the periphery of the column starting to crumble and avalanche. This causes a frontal flow to develop at the foot of the column, which propagates radially outwards eventually defining the final pile radius. Simultaneously there is a discontinuity that separates the frontal flow and the central static summittal region, which propagates inwards and is eventually consumed by the avalanche. The propagation of the discontinuity may continue for a proportionally short phase after the column has ceased to spread, acting only to alter the profile of the deposit which can only sustain material at an angle less than the angle of repose. With the introduction of rotation a second set of dynamics envelopes as can be seen in Fig. 2 and further shown by the video in the journal online.

The avalanching begins in the same way as described above but the rotation of the table actuates a non-zero azimuthal component of the front flow at the foot of the pile as can be seen in Fig. 2. The photos in Fig. 2 are taken from the camera mounted on the tank rotating in an anticlockwise (negative azimuthal) direction. It is observed that, due to Coriolis effects, the particulate moves in a positive azimuthal direction within the rotating frame of reference while flowing radially outwards, resulting in curvature of the runout (for video see supplementary material online). Rotation induces higher avalanche front speeds than in the non-rotating collapse, causing greater radial spread of granular material and results in a faster propagation rate of the discontinuity between central static and avalanching regions. The result is a greater final deposit radius, r_f, up to a given frequency f_{crit}. It appears that as the frequency increases, the discontinuity disappears before the spreading phase is over in contrast to the static case. It is difficult to pinpoint where this occurs given that this profile altering stage was extremely short, even in the static case, but it was observed that after the discontinuity disappears the avalanching flow continues to feed the front until the spreading ceases.

Where f_{crit} is passed for a particular cylinder size and aspect ratio there is a secondary rotation-induced spreading phase as described in Fig. 3. The first stage of the collapse results in the pile spreading to a radius r_{max}. If $f < f_{crit}$ then this radius is exactly r_f. If $f > f_{crit}$ then some material at the edge of the pile is lost and moves to the edge of the table. This rotation-induced spreading phase results in a retraction of the radius of the resultant pile to a value r_{crit} where the process of material ejection ceases and the radius stagnates. This is then the final pile radius r_f. The reason for this is that the centripetal force is great enough to

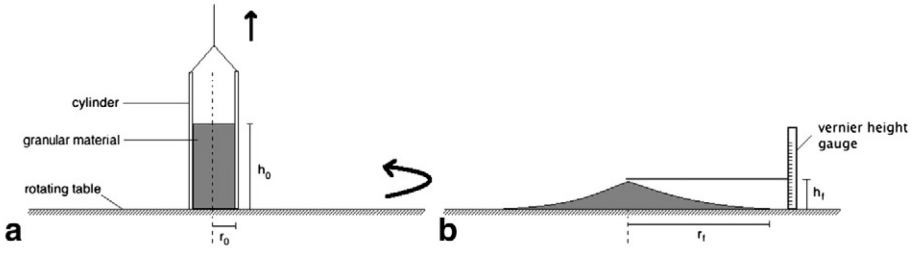

Fig. 1. Experimental setup. **a** Initial setup of granular column on rotating table. **b** After collapse.