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Gravity-driven granular flows in pipes: teaching experimental skills in the context of granular flows

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Abstract

Granular flows appear frequently in the natural world and in civil engineering applications. These flows can exhibit features which are surprising and counter-intuitive and are often used to test the limits of the classical continuum approximation for modelling of fluid flows. An important sub-class of the granular flows are the gravity-driven granular flows, which include the granular column collapse and the flow of granular material down through a vertical pipe. In this article, quantitative analysis is performed of the flow using video analysis software. The utility and relevance of the experiment for development of experimental skills in physics students and modelling of unexpected phenomena is discussed.

Keywords: granular flows, fluid flows, gravity-driven flows

1. Introduction

A material is said to be granular if is formed from a collection of individual macroscopic particles. A familiar example is given by beach sand, which is formed from a large number of sand grains. Although granular flows behave as if they were fluid flows in certain regimes, the behaviour of granular flows can differ significantly from that of fluid flows and can exhibit many surprising and counter-intuitive features [1]. The concept of a granular flow might seem rather academic, but in fact they are present in a large number of applications. Natural deluges such as avalanches, landslides and pyroclastic flows have been well-modelled as granular flows [2–4]. Granular flows are also important in civil engineering, primarily in storages of grains in silos. Besides this, man-made granular flows are often initiated by deposition from a hopper. These grains are typically deposited onto a centrifuging disc to facilitate spreading of seeds and fertilisers on fields. This process has been successfully modelled both on the experimental and the computational side using the theory of granular flows [5–8].

A key illustrative example of a granular flow is the granular column collapse. In this flow, a cylindrical tube with a flattened top is filled with granular material from a funnel. To initiate collapse, the cylinder is then quickly raised such that the time to raise the cylinder is much smaller than the time needed for the mass of granular material to be set into motion. This flow is frequently used in experiments and simulations to learn more about gravity-driven granular flows [9–18]. A related, well-motived example is the flow or collapse of a mass of granular material down an incline. As mentioned already, a key question is whether these flows can be modelled using some combination of models from continuum mechanics, where the continuum approximation assumes that materials under flow can always be modelled as a continuous mass rather than a collection of discrete particles. It follows that these simple collapsing granular flows offer an important test of the limits of the continuum approximation for modelling of flows.

One common approach to the flow down a slope is to treat the system using a shallow water model [19–21]. Another study has found that the vertical column collapse can be modelled in part with the Navier–Stokes equations from fluid dynamics [22]. There is, however, no universally agreed-upon set of equations which could be used to model granular flows in any situation, because granular materials can behave as a gas, a liquid, or a solid depending on the circumstances [23]. For this reason, most of the major studies of the granular collapse and other archetypal granular flows tend to be experimental in nature. In this article, we propose to carry out some simple pedagogical experiments for another gravity-driven granular flow: flow of granular material down through a vertical tube. Careful experimental measurements have previously been carried out for this flow. These measurements mostly focus on the density variations which occur as the flow moves down the pipe (known as 'density waves'), which are both interesting and surprising [24–26]. More specifically, we argue that this experiment can potentially be adapted so that it targets introductory physics lab instructors looking for activities that go beyond merely verifying textbook physics principles and instead focus on developing experimental skills and modelling of unexpected phenomena.

An experiment with gravity-driven granular flows is proposed which is ideal in this sense. It is relatively unusual or little-known as ex experiment, but it can be carried out with simple equipment. It follows that the student will not have a preconceived idea of what will happen and is unlikely to have seen the experiment previously. Students will probably make an intuitive guess as to what will happen based on elementary knowledge of fluid dynamics and then be surprised by what actually happens in practice, realising that real experimental physics involves the ability to model phenomena which are unexpected or surprising. In section 2, simple quantitative analysis of the experiment is carried out using Vernier video analysis software. This software is very user-friendly, so the experiment should be accessible to all students. In section 3, we discuss how our results fit in with the related literature on gravity-driven granular flows through pipes and briefly discuss the pedagogical utility of the experiment. In section 4, we conclude by summarising our findings and suggesting ways in which the work could be taken further.

2. Results

Three possible regimes can be observed when a granular material falls downwards through the pipe, depending on the ratio of the diameter of the pipe to the size of the particles [24]. The first regime occurs when this ratio is larger than 30 and corresponds to free fall. As usual, the free fall equation for a falling grain is

$$v = \sqrt{2gh}, \tag{1}$$

where g is the value for acceleration under gravity and h is the height difference between the initial and final end points of the trajectory of a grain. This makes intuitive sense, since one expects if the tube diameter were very large and the grains very small that they should just fall straight through the tube under gravity with no significant interactions with the walls. Secondly, if this ratio is below 6, the flowing grains are highly compact.

Again, this should make intuitive sense, since if the tube is very narrow and the grains very large, the grains will clog up the pipe due to friction with the wall and with each other, possibly even stopping altogether.

However, students will probably not be able to guess what happens in the intermediate regime between these values and importantly, they will not have studied theory which tells them what to expect so that the demonstration does not become a mere verification exercise. In this third regime, the flow is characterized by so-called density waves. Each density wave has a dense, compact section (referred to as a clog in the literature) and an air pocket with a much lower particle density and higher velocity. To begin, it can be demonstrated that the intermediate regime is qualitatively observable with a high-speed camera. The experimental set-up will consist of a vertical glass tube with length 1.3 m and internal diameter 3 mm. It should be possible to obtain such a tube from a commercial glassblower or a glassblower at a university chemistry department. In figure 1, a sample of small glass spheres with diameter between 100 and 200 μm is fed into the top of the tube using a funnel so that the material falls and collects at the bottom. The tube is then kept sealed by hand and turned upside down so that the material goes to the top and falls downwards under gravity.

Note that the ratio of the tube diameter to particle size is between 6 and 30, so that one expects the flow to fall according to the intermediate regime. However, the bottom of the granular plug at the top of the tube has to drop under free fall. To show that this occurs, we capture images of the flow using a Photron FASTCAM SA-X2 high-speed video camera at frame rate of 12 500 fps. Backlighting is provided by a single light source of luminance 178 256 cd m^2 and uniformity 99.44%. The left-hand image of figure 1 shows the bottom of the plug falling under free fall and the middle and right-hand images of figure 1 show the appearance of a clog alternating with an air pocket typical of the density wave regime. Note that the falling grains in the lower section drag air with them by the equation by the standard equation for the drag force

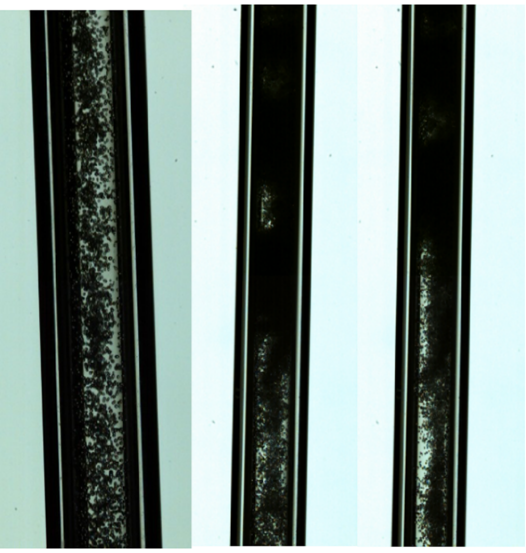


Figure 1. Freely falling granular material (left) and appearance of density waves (middle and right).

$$F_{\mathrm{D}} = \frac{1}{2} C A \rho v^2, \qquad (2)$$

where C is the drag coefficient, A is the cross-sectional area, ρ is the gas density, and v is the speed of the object. This induces suction, which causes air to flow through the granular material in the upper section of the clog.

It is reassuring that one can obtain good images of the different types of particle flow using a high-speed video camera, but such a device is extremely expensive and would not be available at a high school or undergraduate laboratory. For the experiment to be useful for students, it must be shown that the density waves and air pockets are clearly visible at 400 fps (capture rate for a typical smartphone) and that students can use the experiment to perform quantitative analysis using a regular smartphone and video analysis software. To begin, a glass tube with internal diameter 1.1 cm is held vertical. A conical funnel of angle 60° is placed on top of the tube and the glass spheres are poured into the funnel where they enter the tube. As expected both from formula (1) and basic physical intuition about flow of a fine sand through a wide pipe, the flow falls freely through the pipe. One can see from figure 2

Figure 2. Gravity-driven granular flow through a pipe using particles with diameter between 100 and 200 μm and pipe with diameter 1.1 cm.

that the tube turns pure white much as it would with a regular continuous fluid with no air gaps or pockets as the granular material leaves the funnel and falls through the pipe. However, at this stage one should not introduce ratio (1) to the students before the demonstration as there is then a temptation to seek to verify this formula.

Things become more interesting when we revert back to the more narrow tube with internal diameter 3 mm and ask students to observe what happens. Note that at this point no theory has been introduced beyond elementary fluid dynamics ideas. From our classroom tests of the experiment with undergraduate students, the students generally do not have a preconceived theoretical prejudice about what will happen in these circumstances. The quantitative analysis which we describe here is more limited than that used in [24], where the density variations were quantified by analysing time variations of the intensity of light transmitted through the pipe. More specifically, in this simple classroom set-up there is no easy way of determining the mass flow rate as a function of the time (this is done in [24] by using electronic computer controlled scales beneath the pipe outlet). The mass flow rate is generally defined to be

$$\Phi = \rho Q, \tag{3}$$

where ρ is the mass density of the fluid and Q is the volume flow rate. If the mass flow rate of grains in a frame moving at the velocity of a clog v_l is denoted by $\Phi_{v,g}$ then the total mass flow rate Φ in the lab frame is

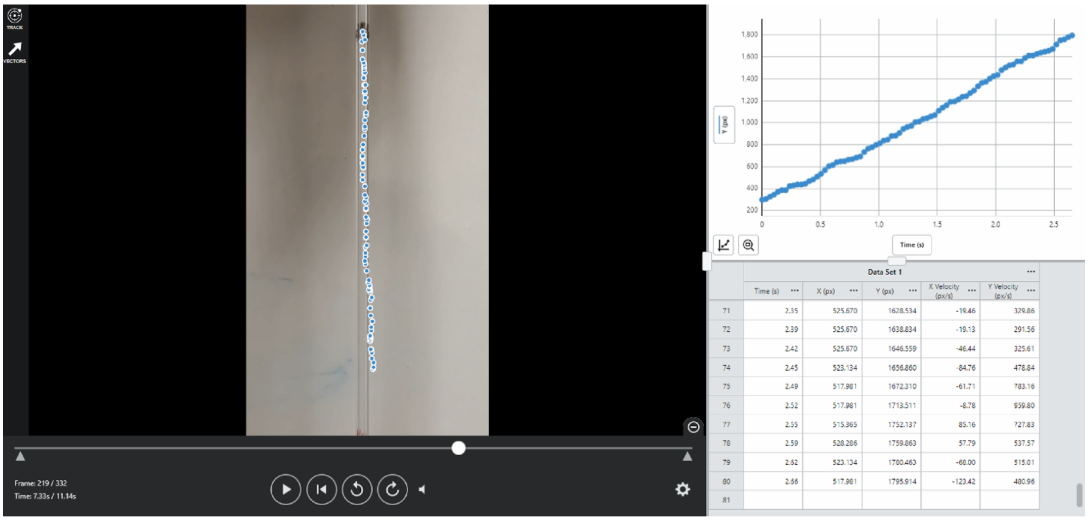
$$\Phi = \Phi_{v,g} + \Phi_{v,l}, \tag{4}$$

where

$$\Phi_{v,l} = v_l \frac{m_x + m_l}{x + l} \tag{5}$$

for m_x the mean mass of the granular material in a bubble, m_l the mean mass of the granular material in a clog, x the average length of a bubble, and l the characteristic length of a clog. Lengths of clogs do not depend on the total mass flow rate, but lengths of bubbles do.

Since measurements of the mass flow rate are not easy, the experiment proposed here is restricted to other measurements which can be performed with software such as Vernier video analysis software, which allows one to plot physical trajectories of objects frame by frame. It is impossible to get clear images using the whole pipe, so a section with length 19 cm is magnified (between the red and black marks on the pipe). In figure 3, we use Vernier video analysis software to plot the trajectory of a granular plug which moves upwards in the frame of the observer with respect to the pipe. The deviation of the x-coordinate is due to the pipe moving slightly where it is not being held perfectly steady by hand. One sees in the associated plot that the velocity of the clog as it moves upwards is approximately constant. The distance covered by the plug when we track



Data Set 1

	Time (s)	X (px)	Y (px)	X Velocity (px/s)	Y Velocity (px/s)
71	2.35	525.670	1628.534	-19.46	329.86
72	2.39	525.670	1638.834	-19.13	291.56
73	2.42	525.670	1646.559	-46.44	325.61
74	2.45	523.134	1656.860	-84.76	478.84
75	2.49	517.981	1672.310	-61.71	783.16
76	2.52	517.981	1713.511	-8.78	959.80
77	2.55	515.365	1752.137	85.16	727.83
78	2.59	528.286	1759.863	57.79	537.57
79	2.62	523.134	1780.463	-68.00	515.01
80	2.66	517.981	1795.914	-123.42	480.96
81					

Figure 3. Plot of the velocity of a clog along the pipe as a function of the time.

it with blue dots is 0.165 m and the time scale is around 2.6 s. Dividing the distance travelled by the time elapsed, we find that the speed of the clog is 0.06 ms^{-1}.

Secondly, in figure 4, camera images are able to show with reasonably clarity the almost constancy of the structure of clogs and air bubbles as it moves up the pipe over a time period of 1.2 s. The length distribution for lengths of clogs and air bubbles was also reported to be an invariant in [24]. As we have said, this fact is found using sophisticated methods in [24] so it is quite surprising that it can be seen with a camera on a regular smartphone. Finally, it was confirmed that the pockets where there are no grains are due to air bubbles by pulling a vacuum in the pipe to evacuate air from it. It was found as expected that gaps in the granular material did not occur and that the material dropped in one continuous piece. A vacuum can be pulled with a cheap vacuum pump so it should in theory be possible to check this in a high school laboratory although one must not be careful to suck the glass beads into the pump, as this can damage the pump internally.

3. Discussion

The experiment described here has been proposed mainly for its pedagogical utility. Nevertheless, it is reassuring that the quantitative analysis which we have carried out with limited equipment does not contradict results reported in the related literature on granular flows in pipes, although as we have emphasised several times, students should not be introduced to the entirety of this theory before the experiment so that they can be encouraged to try to build models themselves. The result in figure 3 matches the clog velocities reported in figure 5 of [24]. These range between 0.05 and 0.32 ms^{-1}, where 0.06 ms^{-1} corresponds to a low mass flow rate. The finding that the velocity v_l is approximately constant is in good agreement with the assumption of constant v_l in [24]. This assumption was based on the empirical observation that a measurement of the clog velocity is independent of the measurement height h.

Secondly, the near-stationarity of the structure of density waves over a short section of pipe does not contradict the assertion in [24] that the length distribution of clogs and bubbles is an invariant (or almost invariant) over the length of the pipe. On the other hand, the relative lengths of the clogs and bubbles in figure 4 does not seem to match the prediction in figure 6 of [24] that characteristic lengths of air bubbles should generally be between 1.5 and 3 times longer than the clog lengths. This is attributed to the fact that figure 6 of [24] uses mass flow rates which are fairly high (starting at 1.4 gs^{-1}), whereas as confirmed in figure 3, the mass flow rate which we use is

Figure 4. Almost stationary structure of density waves over a time period of 1.2 s.

lower than this. Bubble lengths increase with Φ and in this experiment, the mass flow rate is sufficiently low that bubble lengths are smaller than clog lengths when bubbles and clogs alternate.

An objection to our experiment might be that the majority of students have not given much thought to granular flows, or that they will not even know what a granular flow is at all. However, we are arguing here that this actually makes the experiment suitable for the type of alternative demonstration which we are proposing, since students are not bringing theoretical prejudices to the demonstration. As discussed in the Introduction, alternative lab outcomes are of great interest in the physics education community because the necessity of teaching a large amount of theory to students has started to create a pernicious impression that the purpose of a laboratory demonstration is effectively to verify a piece of theory which has been learned during the course [27].

4. Conclusion

In conclusion, an experiment in gravity-driven granular flows through pipes has been proposed which only requires simple equipment and a standard smartphone. The experiment develops lab skills and use of simple video analysis software. As explained in section 3, although the experiment does provide some non-trivial checks on claims in the granular flows literature which were asserted using much more sophisticated equipment, it is argued that the main utility of the experiment is to meet some alternative lab outcomes which are typically neglected in standard lab practical work, which is often unfortunately based on confirming or verifying some well-known physical law and does not encourage students to actively design their own models.

The phenomena which we describe with density waves in pipes during gravity-driven granular flows have been studied intensively both from the numerical and experimental side. However, these simulations and experiments are typically sophisticated and involve equipment which would not be available in a normal high school or undergraduate teaching laboratory. It has been shown here both that the phenomenon can be observed with basic equipment and importantly, that some quantitative analysis can also be performed using this equipment. A next step in our analysis for those who like to study granular flows further would likely be to consider if there is available equipment which would enable calculations of mass flow rates. This would strengthen the quantitative analysis. There are also many other simple experiments which can be performed with granular flows (the granular column collapse, for example) which can be carried out by students which have counterintuitive or surprising results which likely cannot be predicted from theory on the elementary physics curriculum. It is anticipated that this will further help motivated students to overhaul their understanding of the aims of experimental science, to stop practices such as error bar inflation in their lab work and to start developing and testing their own models which build upon basic material which they have learned.

Data availability statement

No new data were created or analysed in this study.

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