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On the run-out distance of geophysical gravitational flows: Insight from fluidized granular collapse experiments

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ABSTRACT

We present the results of laboratory experiments on the emplacement of gravitational granular flows generated from axisymmetrical release of columns of fine (~75 μm) or coarse (~330 μm) particles initially fluidized with air. Internal friction is first negligible in the granular columns and then increases as pore pressure diffuses within the propagating flows, which are thus characterized by a mean friction lower than that of dry (i.e., non fluidized) flows. For columns of height-to-radius ratios $a \approx 0.2$–30, we identify the modes of flow propagation and the scaling laws that characterize the morphology of the resulting deposits. Here we show that the normalized run-out distance of the initially fluidized flows scales as a power law of a (i.e., λa^n), thus demonstrating that this scaling law is not only typical of dry granular flows, as claimed in the literature. Fluidization reduces contacts between the grains and thus effective energy dissipation. Its effect increases the coefficient λ compared to dry flows but it has no influence on the exponent n that decreases from 1 to 1/2 at increasing a, mainly due to axisymmetrical spreading as shown by earlier works on dry coarse particles, except for the initially dry flows of fine particles at $a > \sim 2$ as it decreases to ~2/3. In this latter case the flows could experience (partial) auto fluidization as their normalized flow run-out is equal to that of their initially fluidized counterparts at $a > \sim 4$. The auto fluidization mechanism, supported by other recent experimental works, is particularly appealing to account for the long run-out distance of natural dense gas–particle mixtures such as pyroclastic flows. At high a, fluidization also affects the generation of surface waves with clear signatures on the deposits. We compare our experimental results with published data on Valles Marineris landslides (Mars) whose emplacement mechanisms are controversial. These natural events are characterized by values of λ higher than that of the laboratory flows, including those with low friction. This shows that some mechanism and/or scale effects promoted energy dissipation for the VM landslides that was significantly smaller than for typical dry frictional granular materials, as suggested by Lucas and Mangeney (2007).

1. Introduction

Gravity driven granular flows are common events at the surfaces of the Earth and of other planets. They consist of solid particles commonly mixed with an interstitial lighter fluid (liquid or gas) that may interact with the grains and decrease the intensity of their contacts, thus reducing energy dissipation and favoring propagation. Examples include subaerial or subaqueous rock avalanches (i.e., landslides), snow avalanches, debris flows, and volcanic phenomena such as pyroclastic flows and debris avalanches. Their volumes are up to $\sim 10^{11}$ m^3 in terrestrial subaerial environments and up to $\sim 10^{13}$ m^3 for submarine and extraterrestrial events (see references in Legros, 2002). These granular flows can travel distances up to several kilometers, so that subaerial flows on Earth represent important natural hazards. As discussed extensively in literature, long flow run-out distance can have various causes, including a lubrication layer generated by an air cushion (Shreve, 1968) or basal melting (De Blasio and Elverhøi, 2008; Goren and Aharonov, 2007), fluidization by a fluid of internal or external source (Hungr and Evans, 2004), acoustic fluidization (Collins and Melosh, 2003), destabilization of a loose granular substrate (Iverson et al., 2011; Mangeney, 2011; Mangeney et al., 2007, 2010), or friction reduction caused by segregation effects (Linares-Guerrero et al., 2007; Phillips et al., 2006; Roche et al., 2005). Predicting the run-out distance of geophysical granular flows is crucial for hazards assessment and requires identifying the control parameters, which represents a challenging issue.

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Several methods are proposed in literature to describe quantitatively the run-out distance of gravitational granular flows and to assess the degree of energy dissipation. The ratio of the run-out distance over the vertical fall height, known as the Heim coefficient, has been long assumed to represent the inverse of a mean effective friction coefficient (i.e., representative of the mean energy dissipation during the flow if a simple Coulomb frictional behavior is assumed). This ratio, however, increases with the volume of the deposit (e.g., Hayashi and Self, 1992; Legros, 2002; McEwen, 1989), as confirmed by analytical and numerical modeling of granular collapse (see Eq. (5) of Lucas and Mangeney, 2007; Staron, 2008; Staron and Lajeunesse, 2009), and hence is not appropriate to describe the mean effective friction. Instead, Lucas and Mangeney (2007) propose to use the ratio of the run-out distance over the initial thickness of the released mass, which eliminates the artificial volume dependence and therefore reflects more accurately the inverse of the mean energy dissipation during the flow. The high values of this ratio (typically ~10) that characterize many large natural landslides suggest an effective friction significantly smaller than what would be expected from purely dry granular flows, as confirmed by back analyses of natural landslides (e.g., Kuo et al., 2009; Lucas and Mangeney, 2007; Pirulli and Mangeney, 2008).

Recent experimental works on flows generated from dry granular column collapse offer a straightforward and powerful way to quantify, under controlled conditions, the run-out as a function of the geometrical characteristics of the mobilized granular mass. They reveal that the flows have a run-out distance that obey a well-defined unique scaling law independently of the volume of the material and primarily depends on the height-to-radius ratio of the columns (e.g., Balmforth and Kerswell, 2005; Lajeunesse et al., 2004; Lube et al., 2004). Analytical and numerical simulations of these experiments, typically at ratios ~1, allow relating the parameters involved in the scaling laws to the frictional properties of the granular media and to the experimental configuration (channel or axisymmetrical collapse) (e.g., Kerswell, 2005; Mangeney-Castelnau et al., 2005; Staron and Hinch, 2005; Zenit, 2005). One of the key questions in prospect of using these scaling laws for interpretation of natural events is as to whether they are a typical signature of dry granular flow processes, as claimed in the literature (e.g., Lajeunesse et al., 2006; Staron, 2008), or if they could also characterize flows with much less energy dissipation.

In order to address this issue, we carried out new experiments on axisymmetrical granular column collapse. In this paper, we investigate the scaling laws of the run-out distance of flows generated from fluidized columns and whose mean effective friction during emplacement is significantly smaller than that of typical dry granular materials. The geometrical configuration applies well to large-scale granular flows generated, for instance, from cliff collapse and that propagate over a rather flat and laterally unconfined topography. We stress that low effective friction is obtained through initial fluidization but could be achieved in nature by other means as mentioned above (e.g., lubrication layer, acoustic fluidization, substrate destabilization, segregation effects). After analysis of the experimental flow dynamics and deposits, experimental results are compared with natural data of some Martian landslides whose emplacement mechanisms are controversial. Then, we follow the method of Lucas and Mangeney (2007) to discuss the dynamics of these landslides (for which the original height-to-radius ratio is <1) in terms of effective friction in the context of thin layer (i.e., depth-averaged) models.

2. Scaling laws of dry granular column collapse

2.1. Earlier experimental studies

The experimental investigations of Lajeunesse et al. (2004) and Lube et al. (2004), involving dry and relatively coarse particles of typical grain size of a few hundreds of microns to a few millimeters, show that the deposit characteristics of flows generated from column collapse on a horizontal plane in the axisymmetrical configuration (hereafter called 3D for convenience) are controlled primarily by the column aspect ratio

$$a = \frac{h_i}{r_i}, \tag{1}$$

where h_i and r_i are the height and radius of the column, respectively (Fig. 1). Three deposit morphologies are identified at increasing a, that is, truncated-cone generated by flank avalanches, and cone or cone with a bulge ("Mexican-hat" of Lajeunesse et al., 2004) as the whole column collapses (Fig. 1). These works reveal scaling laws that characterize the geometrical parameters of the deposits for a~0.5–30. The final deposit length, r_f, and height, h_f, (see Fig. 1) are used to define the normalized run-out distance

$$r^* = \frac{r_f - r_i}{r_i}, \tag{2}$$

and the normalized deposit height

$$h^* = \frac{h_f}{r_i}, \tag{3}$$

which helps to identify scaling laws of the form

$$r^*, h^* = \lambda a^n, \tag{4}$$

where the coefficient λ and the exponent n are determined by fitting the experimental data (Table S1, supplementary material). As mentioned by the authors, $r_f - r_i$ and h_f could be normalized by h_i instead of r_i, and we note that in that case r^*, $h^* = \lambda a^{n-1}$. A notable result concerning r^* is that $n = 1$ at $a < 1.5$–3 whereas $n = 1/2$ at $a > 1.5$–3. This transition may reflect influence of the axisymmetrical spreading of the granular mass at increasing a as shown by Lajeunesse et al. (2004) from a heuristic model. This is supported by experiments on flows in channels (hereafter called 2D for convenience, see Table S1) for which material spreading is unidirectional. From the compilation we present in Table S1, we note that at high a, the exponent n is different in the various studies but it approaches one as the channel width increases so that side effects become less important (Balmforth and Kerswell, 2005; Lacaze et al., 2008; Lajeunesse et al., 2005; Lube et al., 2005; Mériaux, 2006). The study of Lube et al. (2004) suggests that these scaling laws are not influenced by the particle shape (spherical, angular) or the nature of the substrate (smooth, rough, erodible). In contrast, the 2D experiments of Balmforth and Kerswell (2005) show that the coefficient λ is dependent on the type of granular material. Concerning the normalized height in 3D experiments, $h^* = a$ (that is $h_f = h_i$) at low aspect ratios as the deposits are truncated cones, whereas at higher aspect ratios h^* is either constant (Lajeunesse et al., 2004) or shows a weak variation with a (Lube et al., 2004; Table S1). Other experimental works in 2D explore the influence of the interstitial fluid phase and/or of the polydispersity of the granular material (Girolami et al., 2008, 2010; Meruane et al., 2010; Phillips et al., 2006; Roche et al., 2002, 2005, 2008; Thompson and Huppert, 2007). However, they consider a limited range of column aspect ratio (a~1–3) and do not offer the opportunity to identify scaling laws as described above.

2.2. Insights from analytical and numerical studies

Discrete and continuum simulations at low a reproduce quantitatively the values of the exponent n of the experimental scaling laws (e.g., Kerswell, 2005; Mangeney-Castelnau et al., 2005; Staron and Hinch, 2005; Zenit, 2005). Discrete element models, however, reveal contrasting results as some of them significantly overestimate the run-out distance compared to laboratory experiments (i.e., higher λ values) when considering an intergranular friction coefficient typical of the experimental material (Staron and Hinch, 2005; Zenit, 2005)