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Experimental study of volume effects in geophysical flows

Etude expérimentale des effets de taille dans les écoulements géophysiques

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ABSTRACT: For large-scale geophysical flows, such as debris flows and submarine landslides, one striking issue is the increase of runout distance with increase of the source volume of the initial mass. Dry and underwater granular column collapses of different sizes (with the initial column length L_i of 3 cm, 5 cm and 10 cm) were carried out in the laboratory to study the effect of flow volume on geophysical flow mobility. We confirm that the larger the flow volume, the larger the mobility of the granular flows and the effect is more pronounced in underwater cases than their dry counterparts. The enhanced size effect in underwater condition is due to the fact that a stronger eddy with high inertia is induced in the large case, which penetrates through the flowing layer of the granular phase and pushes the particles forward to reach a longer runout distance.

RÉSUMÉ : Pour les écoulements géophysiques à grande échelle, tels que les coulées de débris et les glissements de terre sous-marins, un problème frappant est l'augmentation de la distance parcourue par l'écoulement avec l'augmentation du volume source de la masse initiale. Des effondrements de colonnes granulaires de différentes tailles (avec une longueur initiale de colonne Li de 3 cm, 5 cm et 10 cm) ont été réalisés en laboratoire pour étudier l'effet du volume initial sur la mobilité géophysique des écoulements en conditions sèches et immergées. Nous confirmons que plus le volume d'écoulement est important, plus la mobilité des écoulements granulaires est grande et l'effet est plus prononcé dans les cas immergés que dans les cas secs. L'effet de taille est dû au fait qu'un tourbillon avec une inertie élevée est induit dans le cas de la plus grande colonne, qui pénètre à travers la couche d'écoulement de la phase granulaire et pousse les particules, tout en faisant qu'elles atteindent une distance parcourue plus longue.

KEYWORDS: Granular column collapse, Volume effect, Geophysical flow.

1 INTRODUCTION

In the study of geophysical flows, such as landslides, avalanches, debris flows, mudflows, and lava flows, one striking issue is the increase of flow mobility (or the reduction of apparent friction) with the increase of the total volume of the flow. Different theories have been proposed to explain this volume-induced lubrication, for instance, local melting near the gliding surface due to high energy concentration (Erismann, 1979), acoustic fluidization caused by strong acoustic waves (Melosh, 1979), lubrication by a layer of trapped and compressed air (Kent, 1966; Shreve, 1968), and hydroplaning due to a pressurized layer of water in a submarine environment (Mohrig et al., 1998).

Early granular collapse experiments in air showed that the final runout distance L_f normalized by the initial column length Li is nearly independent on the column size, within the limits of experimental error (Lajeunesse et al., 2005; Lube et al., 2005). However, a more recent study has demonstrated a clear increase of normalized runout distance with the increasing column size, benefiting from the improved accuracy of experimental measurements by using three-dimensional laser scanning (Warnett et al., 2014). In experiments of steady granular flows down rough inclined slopes, a similar granular behavior of strength weakening as the flow thickness increases was observed (Pouliquen, 1999).

The current study is inspired by this size-dependent granular flow mobility problem. We perform dry and underwater granular collapse experiments with different column sizes, considering a range of small initial aspect ratios ($a \leq 2$) to avoid non-trivial effects of free-fall dynamics at higher aspect ratios (Jing et al., 2018). The collapse dynamics and the runout behavior are discussed in detail with particular focus on the important role of ambient fluid as the column size changes.

This paper is organized as follows. The experimental setup and measurements are presented in Section 2. Section 3 provides the experimental evidence for the column size effects and discusses the underlying mechanisms. Conclusions are drawn in Section 4.

2 LABORATORY EXPERIMENTS

2.1 *Experimental setup*

Figure 1(a) presents the experimental setup for dry and underwater granular collapses. It consists of a transparent Perspex tank with dimensions 50 cm, 30 cm and 20 cm in the *x*, *y* and *z* directions, respectively. An 80 Cw grit size sandpaper is glued to the bottom wall to make the base rough. A vertically positioned 1.8 mm thick aluminum gate (facing the x-direction) is constrained by a pair of slots on the side walls, forming a reservoir behind the gate for constructing the granular columns with the initial length and height denoted by L_i and H_i, respectively. There are three pairs of slots on the side walls at different locations, so that we can have a variable L_i = 3 cm, 5 cm and 10 cm. The gate is connected to a pulley system, which can be used to rapidly lift the gate up by releasing the dead weight to mimic a dam-break scenario. The particles used in this study are glass beads. The final deposit of granular collapse is sketched in Fig. 1(b). The final runout distance and the residual height of the particles are denoted by L_f and H_f, respectively.

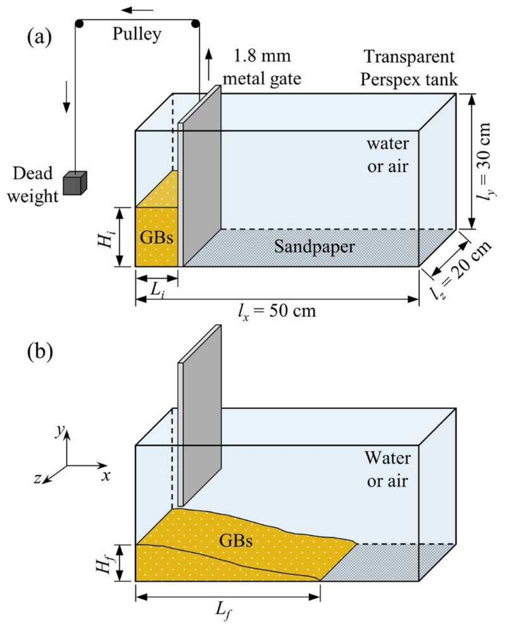

Figure 1. Sketch of the experimental setup for dry and underwater collapses of granular columns composed of glass beads (GBs): (a) initial condition, (b) final deposit.

2.2 *Test procedures*

The experimental procedures are as follows. In underwater cases, the tank is filled with water to a high enough level, while no fluid filling process is conducted for dry cases (i.e., the ambient fluid is air). After that, the metal gate is placed at a desired position such that granular columns with different initial lengths can be created. The total dry mass of glass beads used in each test is first estimated based on a presumed initial packing density (i.e., 0.62) and the target column size. The total mass is later used for calculating the actual initial packing density. The glass beads are then gently poured into the reservoir enclosed by the gate and the tank walls. The packing density is strictly controlled in our experiments by tapping the side walls continuously to adjust the height (and hence the volume) of the granular column to a target value. The top surface of the granular columns remains flat during tapping. The resulting packing density averaged among all test cases is 0.621 ± 0.013. Once the granular column and the fluid (if there is) in the reservoir are quiescent, the metal gate is lifted up rapidly by releasing the dead weight [see Fig. 1(a)]. Once the gate is removed, the granular column collapses onto the horizontal bottom plane and the grains propagate forward in the x-direction.

Experiments of underwater granular collapses with the initial lengths L_i = 3 cm (S: small case), L_i = 5 cm (M: medium case) and L_i = 10 cm (L: large case) are conducted. The aspect ratios ($a = H_i/L_i$) tested are 0.5, 0.65, 0.8, 1, 1.5 and 2. Experiments with a = 0.3 are carried out when L_i = 5 cm and 10 cm, and another experiment with a = 0.2 is performed when L_i = 10 cm. In total, there are 21 sets of experiments, each of which is carried out twice to ensure repeatability. Three granular collapse experiments in dry condition are carried out for comparison.

2.3 *Data acquisition*

The glass beads are illuminated by an LED lamp. In the experiments, we ignore the small variations of the measured properties in the spanwise (z) direction and consider that the granular collapse is essentially two-dimensional. That means we can mainly focus on the collapse dynamics from a side view. A camera is carefully aligned in the horizontal direction and records the whole granular collapse with a resolution of 3840 by 2160 pixels at 60 frames per second. After that, the free surface of the glass beads during the collapse at each frame is extracted, which enables the measurements of the instantaneous front position x_{ft} and column height, including the final values (i.e., L_f and H_f).

3. EXPERIMENTAL RESULTS

3.1 *Experimental observations*

Experiments of dry granular collapses with various geometries have been reported in the literature (Lajeunesse et al., 2005; Lube et al., 2005). There are also a few experimental studies on immersed granular collapses (Rondon et al., 2011, Bougouin & Lacaze, 2018), but the column size effects have not yet been thoroughly investigated. To visualize the effects of the column size in underwater granular collapses, snapshots of the small, medium and large granular columns with the aspect ratio a = 0.5, 1, and 2 during the collapses are presented in Fig. 2. For each case, three snapshots are extracted at three typical time instants $t = t_{95}/3$, $2t_{95}/3$ and t_{95}, where t_{95} is the time instant corresponding to 95% of the normalized final runout distance $(L_f - L_i)/L_i$.

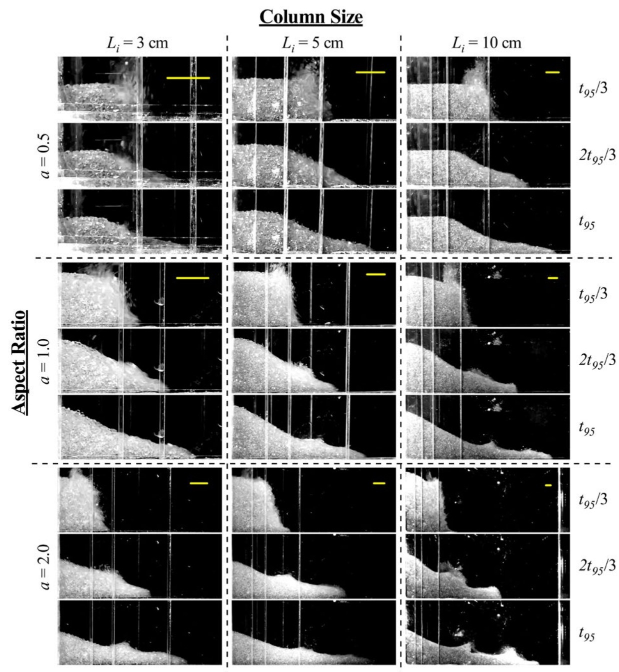

Figure 2. Underwater granular collapses in experiments. The three columns and rows correspond to three different column sizes (small, medium and large) and aspect ratios (a = 0.5, 1, 2), respectively. Snapshots at three time instants, namely t_{95} =3, t_{95} = 2 and t_{95}, for each case are shown. The yellows bars are the scales indicating a fixed length equal to 1.5 cm.

During underwater granular collapses, it is the movement of particles that sets the surrounding water into motion via hydrodynamic interactions. The water flow in turn exerts a drag force on the particles as a feedback. When both the column size and the aspect ratio are small, i.e., the top-left corner of Fig. 2, there is a small grain inertia developed during the collapse. A weak eddy is induced in the fluid field, which can barely alter the particle motion. In this case, the surrounding water mainly poses a resisting force on the particles in the form of viscous drag. Besides, the surface of the final deposit appears to be quite smooth.

However, as the column size and the aspect ratio increase, the particles can gain a much higher kinetic energy during the collapse, and their faster motion induces a much stronger eddy that carries higher fluid inertia. The high-intensity eddy is powerful enough to erode the particles close to the granular free surface and put them into suspension (see the case with L_i = 10 cm and a = 2 in Fig. 2). This phenomenon has been reported in previous CFD-DEM simulations with aspect ratios of 4 and beyond (Jing et al., 2018). Our experimental data show that the erosion of granular free surface can also take place at a smaller aspect ratio as long as the column size is large enough. When the fluid energy is gradually dissipated due to the viscous effect, the suspended particles settle down slowly, forming a wavy surface of the final deposit. The complex fluid-particle interactions have a great influence on the flow mobility.

3.2 *Column size effects on runout*

The front position normalized by the initial column length, $\tilde{x}_{ft} = (x_{ft} - L_i)/L_i$, is plotted against time in Fig. 3 for a = 1. The large case with L_i = 10 cm is first shown for a typical description of the collapse sequence, which can be divided into three stages: triggering, propagation and deposition. The following approach has been applied consistently through-out all experimental cases to delimit the three stages. A straight line is drawn though the points characterizing the period with a nearly constant propagation velocity. This straight line intercepts the horizontal axis at t_{trig}, which separates the triggering and propagation stages. Another time instant (t_{95}) is used to delimit the propagation and deposition stages, when 95% of the normalized final runout distance is reached.

The inset of Fig. 3 compares the runout evolution between underwater granular collapses with three different column sizes at a = 1. It is found that the triggering time t_{trig} increases as the column size increases, which is probably due to the enhanced frictional resistance by the induced negative excess pore pressure caused by the dilation of the dense granular column (Izard et al., 2018; Rondon et al., 2011; Yang et al., 2020). Furthermore, the negative excess pore pressure takes longer time to dissipate due to the longer drainage paths in the larger case. Interestingly, the final runout distance in the large case is significantly longer than that in the small case, indicating a size-dependent granular flow mobility. Note that the runout distance presented in these results has already been normalized by the column size (L_i).

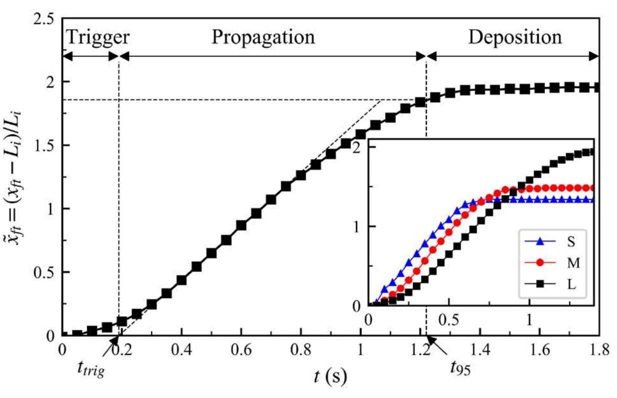

Figure 3. Experimental results of the normalized front position $\tilde{x}_{ft}$ plotted against time t when a = 1 for the large case with L_i = 10 cm. The inset compares the runout evolution between the small (S), medium (M) and large (L) cases.

As the effect of column size on the runout distance of underwater granular collapses is evident, it is interesting to investigate if similar effects exist in their dry counterparts. Figure 4 compares the dry and underwater granular collapses regarding the column size effects on the normalized final runout distance. For the range of column sizes considered in this study, the normalized runout distance is generally longer in the dry condition, because additional energy is dissipated through fluid-particle interactions in the underwater cases (Jing et al., 2018). Nevertheless, the normalized runout distance increases at a faster rate in the underwater condition as the column size becomes larger, showing a more significant column size effect due to the presence of the interstitial fluid. It has also been demonstrated that the interstitial fluid is capable of enhancing the flow during the spreading stage (Jing et al., 2018; Topin et al., 2012). Our result qualitatively agrees with a recent study on the size effects on the runout behavior of immersed granular collapses via two-dimensional numerical simulations (Wang et al., 2021). According to Wang et al. (2021), the runout distance of underwater granular collapses could exceed the value observed in the dry counterpart as long as the column size becomes large enough, despite the inhibiting effect of the fluid drag force.

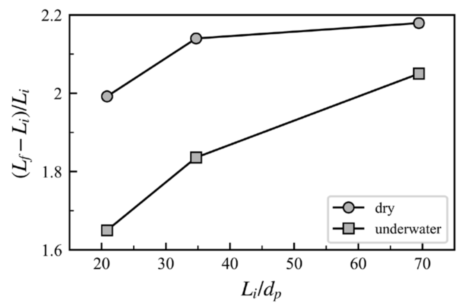

Figure 4. Plot of the normalized final runout distance $(L_f - L_i)/L_i$ against the normalized column size L_i/d_p for dry and underwater granular collapses.

3.3 *Runout scaling for underwater granular collapses*

In the study of granular collapses, one of the most important previous findings is the scaling of normalized final runout distance $\tilde{L}_f = (L_f - L_i)/L_i$ with the initial aspect ratio a. To further show the influence of column size on the flow mobility, the measured experimental data ($\tilde{L}_f$) are grouped according to the column size and plotted against a in Fig. 5. For the range of aspect ratios ($a \leq 2$) considered in this study, there is a positive linear relationship between $\tilde{L}_f$ and a, i.e. $\tilde{L}_f = \lambda a$, where λ is the coefficient of proportionality. This result agrees with a previous study on immersed granular collapses in fluids with different viscosities (Bougouin & Lacaze, 2018). Linear fitting of the experimental data shows that the value of λ increases from 1.71 to 2.03 as the initial column length increases from 3 cm to 10 cm.

Immersed granular flows can be classified into three different regimes: grain inertial, fluid inertial and viscous regimes (Courrech du Pont et al., 2003). According to Bougouin and Lacaze (2018), the value of λ is bounded by the two limits 1.4 and 3.0 belonging to the viscous and grain inertial regimes, respectively. Figure 5 shows that our experimental data are well bounded by the two limits proposed by Bougouin and Lacaze (2018). Since the fluid used in our experiments is water and the particle-to-fluid density ratio is about 2.5 (which also remains constant as the column size changes), the flow regime of the underwater granular collapses may belong to the fluid inertial and viscous regimes based on the phase diagram proposed by

Courrech du Pont et al. (2003). Note that the specific value of λ in the fluid inertial regime was not reported by Bougouin and Lacaze (2018), but its value should lie slightly below the upper limit (i.e., λ = 3.0) of the grain inertial regime. Therefore, the increase of λ with L_i might be associated with the increase of fluid inertia as the column size increases, indicating a potential transition of flow regimes from viscous drag to inertia as the dominant mechanism governing the fluid-particle interactions in underwater granular collapses.

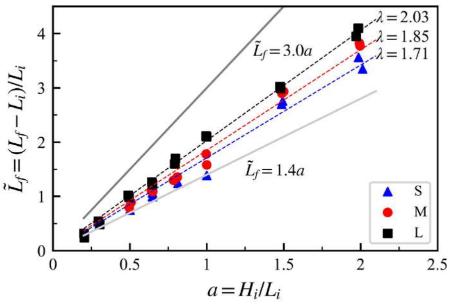

Figure 5. Plots of the normalized final runout distance $(L_f - L_i)/L_i$ against the aspect ratio a for small, medium and large granular column collapses. The dashed lines are the linear fit of the experimental and numerical data with the color matching the data points. The dark gray and the light gray solid lines set the two limits characterized by the free-fall regime and the viscous regime, respectively.

4 CONCLUSIONS

In this paper, we report an experimental study on the role of column size in dry and underwater granular collapses, with a major focus on the latter case, where complex feedbacks between the column size and the ambient fluid are present. In experiments the column size varies with the initial column length L_i = 3 cm, 5 cm, 10 cm and a variable aspect ratio up to 2 has been adopted.

Snapshots of underwater granular collapses in experiments are extracted, showing fluid eddies carrying particles into suspension at large column sizes and aspect ratios, which is responsible for the wavy granular free surface of the final deposit. Within the range of aspect ratios considered in this study, it is found that the normalized runout distance $\tilde{L}_f$ of underwater granular collapses scales linearly with the initial aspect ratio a, i.e., $\tilde{L}_f = \lambda a$, indicating a significant increase of granular flow mobility as the column size becomes larger. Compared to dry granular collapses, the size effect in underwater cases is more pronounced, which is probably due to the enhanced and forward-acting fluid drag force as the column size increases

The current study focuses on a limited range of column size in experiments, due to the lack of laboratory space. The laboratory test data will be used to validate one-to-one numerical simulations using the coupled lattice Boltzmann and discrete element method (LBM-DEM) which can provide detailed hydrodynamic forces and energy dissipation between the fluid and the particles to explain the volume effect. The numerical simulations will also provide flow velocity, stress and pressure fields to establish emerging constitutive laws in a continuum framework to extend our findings in larger scales. Ideally, the constitutive model shall be able to capture all the complex interparticle and fluid-particle interactions at the grain scale, which automatically converges to the correct macroscopic flow behavior at any system size. The results presented in this study can be useful to validate such size-dependent continuum models and their establishment will be our next focus for bridging the micromechanics and the macroscopic flow behaviors.

5 ACKNOWLEDGEMENTS

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