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A question of scaling in immersed granular collapses

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ABSTRACT

Immersed granular collapse is a common benchmark case for numerical modeling of fluid-particle interactions and large deformation of fluid-particle mixtures. Here we study the effects of column size in immersed granular collapses with laboratory experiments and numerical simulations. With controlled initial aspect ratio, packing density, and the same particles (glass beads) and fluid (water), the increase of column size leads to distinct collapse characteristics of longer normalized runout distance and a "granular jump" behind the surge front. Companion CFD-DEM simulations show an unscaled fluid inertia effect as the column size increases, which may underlie the observed column size effect. It suggests that the dynamics of immersed granular collapse is heavily dependent on the scale of the problem if the fluid inertia plays a sufficient role.

KEY WORDS: Granular collapse; column size; fluid inertia, scaling; CFD-DEM.

INTRODUCTION

Large-scale geophysical flow is a ubiquitous phenomenon in nature that plays a crucial role in shaping the landscape and sometimes brings enormous losses to human life and property. Such mass movements are usually composed of granular materials (soils and rocks) surrounded by an ambient fluid. Understanding the dynamics of such hydro-granular flows still remains a challenge due to the complex fluid-particle interactions.

Down-scaled granular column collapse, which involves the initiation, runout and deposition of a granular mass, has been extensively studied in the literature. In the dry case, where the interstitial fluid (air) plays a negligible role, the deposition morphology is found to be mainly controlled by the initial aspect ratio (AR) of the granular column (Lajeunesse et al., 2005; Lube et al., 2005; Balmforth and Kerswell, 2005). A simple piece-wise power law has been proposed to relate the residual height (H_f) and the final runout distance (L_f) to AR, independent on the material properties and the initial packing density (ϕ_i). As AR increase, the runout distance increases rapidly when AR < 2.5 and the growth rate is attenuated at higher AR. It is because a large portion of the particle kinetic energy is lost due to the severe particle collisions during vertical fall (Jing et al., 2018).

However, in the case of granular column collapse in a viscous fluid, although AR remains to be a relevant parameter (Rondon et al., 2011; Bougouin and Lacaze, 2018), the collapsing dynamics can be significantly affected by the packing density, particle density (r_p) and size (d), as well as the fluid density (ρ_f) and viscosity (μ_f). Considering the large variety of collapsing behaviors affected by different parameters, a phase diagram in the (St, r) plane has been proposed to characterize the granular flow within three regimes: free-fall, fluid inertial and viscous regimes (Bougouin and Lacaze, 2018), with St and r referring to the Stokes number and the particle-to-fluid density ratio, respectively. It shall be noted that both St and r are derived based on an ideal scenario that a single particle falling in a viscous fluid, in which the characteristic length is taken as the particle diameter d.

The immersed granular column collapse problem has also served as a popular benchmark case for the numerical modeling of multi-phase fluid flows. The successful numerical schemes can be mainly classified into two categories. One is first to develop constitutive models that is capable of describing the behavior of the fluid-particle mixture within a continuum framework, for instance, the mixture theory (Iverson and Denlinger, 2001). The governing equations are then solved by a numerical method, which is usually a meshless approach that allows large deformations, such as the Smoothed Particle Hydrodynamics (SPH) (Wang et al., 2017) and the Material

Point Method (MPM) (Soga et al., 2016; Baumgarten and Kamrin, 2018). The other refers to the coupling numerical schemes, in which the Discrete Element Method (DEM) is normally applied to solve the particle motion and the fluid dynamics is usually solved by the Computational Fluid Dynamics (CFD) (Jing et al., 2018) or the Lattice Boltzmann Method (LBM) (Kumar et al., 2017; Yang et al., 2017, 2018).

When applying the knowledge of particle physics obtained at the laboratory scale (centimeters) to the field scale (kilometers), one question often asked is whether and how scaling can be done. In the current context, it is essential to understand how column size plays a role in the dynamics of immersed granular flows. Therefore, we carry out immersed granular collapse tests to study the effect of the column size, which has not yet been clearly discussed in literature. In particular, granular column collapses with two different column sizes are presented, while other column parameters (AR and ϕ_i) and particle and fluid properties (ρ_p, d, ρ_f, and μ_f) are controlled to be roughly the same. In order to better visualize the fluid field and to study the fluid-particle interactions, corresponding CFD-DEM simulations are also conducted for comparison.

EXPERIMENTS ON IMMERSED GRANULAR COLLAPSE

Experimental setup

Figure 1 shows the experimental setup for the collapse of granular columns in water. It consists of a transparent Perspex tank with dimensions: 50 cm, 30 cm and 20 cm in the x, y and z directions. An 80 Cw grit size sandpaper is glued to the bottom wall to make the base rough. A vertically positioned 1.8 mm thick aluminium gate is constrained by two slots on the side walls (facing z-direction), which can be rapidly removed by releasing the dead weight to mimic a dam break scenario.

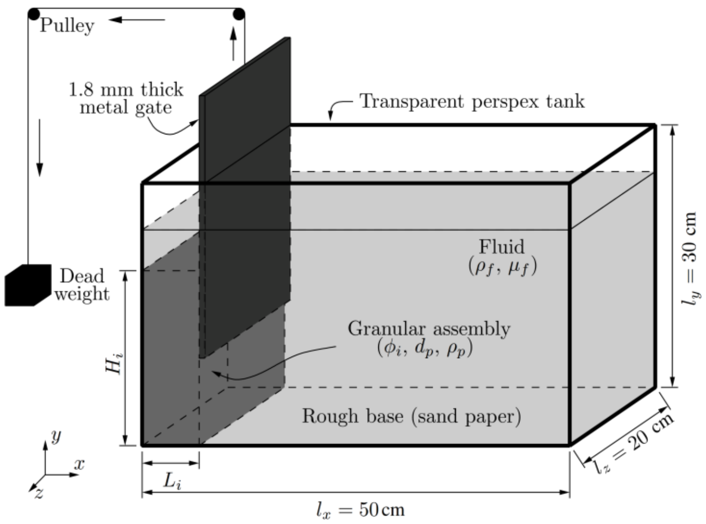

Figure 1 Experimental setup for the collapse of granular columns in water. L_i and H_i are the initial length and height of the granular columns

Material properties

The particles used in this study are glass beads (GB), as shown in Figure 2(a). QICPIC analysis has been carried out on three individual batches of samples. The particle size distribution (PSD) curves are presented in Figure 2(b). It can be seen that three PSD curves almost overlap with each other, showing a consistent statistical result. The averaged median diameter is 1.436 mm, which is denoted as d_{50}. Besides, the GBs are quite spherical with a sphericity as high as 0.94. The density of the GBs is measured to be 2468 kg/m^3, with a repose angle of 21.3 degrees. The GBs are immersed in water, which has a density and a viscosity equal to 998.2 kg/m^3 and 0.001 Pa·s, respectively, at a room temperature of 20 Celsius degree.

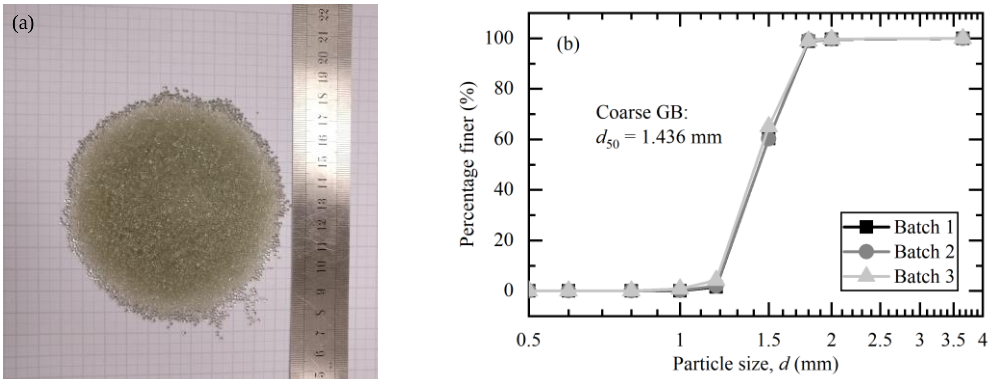

Figure 2 (a) GBs used to build the granular columns; (b) Particle size distribution curves of three individual batches from QICPIC analysis. The averaged d_{50} is 1.436 mm

Test procedures

The experimental procedures are as follows. After filling the tank with enough water, the metal gate was positioned at the desire location: L_i = 3 cm for the small column and L_i = 5 cm for the large column. In each test, the dry mass of used GBs was recorded for the calculation of initial packing density later. The GBs mixed with water were then gently poured into the reservoir delimited by the metal gate and the tank walls. The GBs were then stirred vigorously by moving a spatula back and forth to remove some air bubbles potentially trapped inside the pores during the pouring process. Once the stirring process was stopped, all GBs were well settled within a few seconds. As a result, a relatively loose packing was obtained. Then the top surface of the granular column was carefully flattened by the spatula with a minimum amount of compaction. For the small and large granular columns presented in this study, continuous tapping on the side walls was conducted to obtain uniform and dense packings (ϕ_i > 0.58). It should be noted that the effect of the packing density is expected to be small compared to that observed by Rondon et al. (2011) due to the much larger particle size and the smaller fluid viscosity.

Once the granular column was prepared, the metal gate was lifted rapidly by releasing the dead weight. Then the granular column collapsed onto the horizontal bottom plane and propagated forward in the x-direction. There was no noticeable variation observed in the spanwise (z) direction in terms of the granular collapsing behavior, indicating negligible side wall effects and the granular flow was essentially two-dimensional. That means we can mainly focus on the collapsing dynamics from a side view only, which was recorded by a video camera with a resolution 1920 by 1080 pixels at 30 frames per second. The height and length were measured at five different locations uniformly spread in the z-direction, which were further averaged to minimize the measurement errors. Table 1 summarizes the parameters of the small and the large column collapse cases.

Table 1 Properties of the small and the large granular columns

Property	Small column	Large column
Initial height, H_i	3.14 cm	5.21 cm
Initial length, L_i	3.0 cm	5.0 cm
Aspect ratio, AR = H_i/L_i	1.05	1.04
Mass of GBs, M	290.1 g	800.6 g
Initial packing density, ϕ_i	0.621	0.620
Final height, H_f	2.76 cm	4.32 cm
Final runout, L_f	7.60 cm	14.19 cm

RESULTS AND DISCUSSION

Figures 3(a) and 3(b) present the final depositions of the large and small columns from experiments. The x and y dimensions are both normalized by L_i. We observe that after normalization, the runout distance of the large column is significantly larger than that of the small column, indicating that the runout behavior is not scaled linearly with the increase of column size.

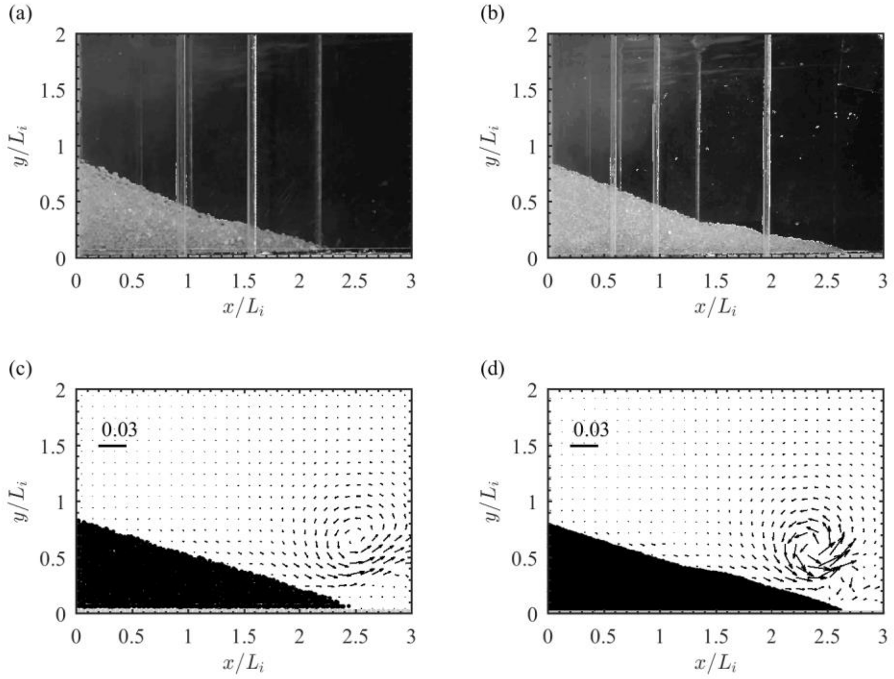

Figure 3 Final depositions from experiments and CFD-DEM simulations. (a) Experiment with L_i = 3 cm; (b) Experiment with L_i = 5 cm; (c) Simulation with L_i = 3 cm; (d) Simulation with L_i = 5 cm. The bars in (c) and (d) are scales for fluid velocity, which is normalized by a velocity scale, $(gH_i)^{1/2}$

Moreover, a major difference is observed from the surface morphology, which exhibits a small change of slope at around x/L_i = 1.5 for the small column (Figure 3(a)), but a more significant non-monotonic transition (also known as "granular jump") between x/L_i = 1.5 and 2 for the large column (Figure 3(b)). The complex morphology in the latter case stems from a secondary transport of particles on the deposit surface, which seems to be eroded by the fluid flow after deposition. Such a surface erosion effect is not observed in the small column case.

In order to better characterize the fluid flow and to understand the unscaled collapsing behavior, we perform CFD-DEM simulations (see Jing et al. 2016 for details of the numerical method) for the small and large columns, which reproduce the distinct deposition morphology and provide more detailed information of fluid velocity (Figure 3(c) and 3(d)). The fluid vectors are normalized by a velocity scale, $(gH_i)^{1/2}$. It can be observed that the velocity vectors in the large column case are much larger than those in the small column case after normalization, meaning that the velocity does not scale with $(gH_i)^{1/2}$ as it would do in dry situations. More quantitatively, the maximum magnitude of velocity of the fluid eddy induced by column collapse increases by a factor of 2.92, when the sample height increases by 1.67 (or the square root of height increases by 1.29). With the knowledge that the behavior of dry column collapses scales with column height due to the scaled potential energy, it becomes reasonable to propose that it is the unscaled fluid inertia in immersed column collapses that underlies the distinct characteristics of larger columns (i.e. longer runout and more complicated deposit surface).

Apart from the unscaled fluid inertia effect, the distinct collapse dynamics may also be caused by the stress-dependent behavior of the granular materials. Unlike fluids, granular particles have a higher resistance to shearing under a higher stress condition, which in our case is caused by the increase of the column size. In addition, the grain inertia shall increase monotonically as the column size increases (Bougouin and Lacaze, 2018). Therefore, more particle-particle collisions are expected in the large column case. As a result, it leads to a scaling problem about the dissipation of particle kinetic energy via inter-particle friction and collision.

For the simulation of large-scale geophysical flows, a continuum approach is usually adopted for its high computational efficiency. Ideally, the constitutive model used to describe the granular behaviors and the drag model used to capture the fluid-particle interactions should be able to adapt themselves to the various fluid inertia effects, stress levels, grain inertia effects and energy dissipation mechanisms at different scales. However, it is quite challenging to incorporate these particle-scale physics into a continuum framework even for a very simple problem, for instance, the MPM simulation of a granular collapse in the dry condition at the laboratory scale (Sołowski and Sloan, 2015). In this regard, our coupled fluid-particle numerical simulations can provide more detailed data (e.g., particle velocity, contact forces, particle concentration), which might promote constitutive relations with excellent scaling performance.

CONCLUSIONS

This paper presents the experimental results for the underwater granular collapse case with two different column sizes. Unlike the granular collapse in air, in which the role of ambient fluid can be neglected, the collapsing behavior and deposition morphology can be significantly altered by the fluid in the underwater cases. The distinct feature of longer normalized runout distance and a "granular jump" behind the surge front in the large column case can be reproduced by a CFD-DEM model, showing the role of fluid inertia beyond a simple linear scaling law as the column size increases. In addition, the test results are also very useful for the benchmark of numerical models, especially for the coupled fluid-particle techniques, in which the number of particles and the fluid domain are small enough for an affordable computational cost. Although the coupled fluid-particle simulations are generally computationally prohibitive for large-scale geophysical problems, they offer extensive particle-scale information that is useful for the derivation of constitutive laws to describe the material behaviors within a continuum framework. The technique to bridge micro-mechanics to macroscopic phenomena will be our future focus.

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