

Submerged planar granular column collapse: Fluid fluxes at the collapsing granular front

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Abstract

Understanding of particle-fluid interactions in a kinematic system is of great importance in the assessment and mitigation of natural mass flows (i.e., debris flows, submarine landslides, pyroclastic density currents). Previous research has pointed on the crucial role of the solid packing fraction in the motion of saturated and submerged granular systems. However, issues in understanding the role and dominance of particle-fluid interactions in transitional granular flows remain a work in progress. The granular column collapse allows a simplification of the complex dynamics observed in those systems, in which a granular assembly is organized with a given aspect ratio, between its initial height and initial width ($a=H_0/R_0$), and let to collapse by self-weight onto a horizontal surface. This work presents a new approach to study submerged granular columns through the use of a modified planar model, incorporating a novel gate mechanism that does not interact with the surrounding fluid nor the granular media. Dye fluid is added to visualize the behaviour of the fluid enclosing the granular mass. Experimental results allow the formulation of an interaction mechanism between the particles and the surrounding fluid, identifying the fluid inflow into the column at release, followed by an recirculating outflow during the column spreading. These fluxes between the mobile mass and the fluid result in vortices next to the surface, entraining particles and mixing the surrounding fluids. The insights and conclusions gained in this research can be applied to the development and validation of analytical and numerical models studying the motion of immersed granular flows.

Keywords: Granular column; granular flows; physical modeling; submarine landslides

1. Introduction

Submarine landslides can generate tsunamis (Ivanova et al., 2018), damage submarine infrastructure (Harbitz et al., 2013) and even induce coastal geomorphological changes (Dawson, 1994). Recent studies have found that the coupled motion of submarine landslides has a strong link with the initial volume packing fraction (Rondon et al., 2011), presenting a dilatant behaviour when densely packed and a contractant behaviour when loosely packed. However, it is yet not clear the mechanism controlling the momentum exchange between the particulate media and surrounding fluid during failure. In this paper, we address the momentum exchange originated in a submerged granular column collapse.

The granular column collapse is an ideal model to reproduce transitional granular flows on a small scale (both in dry and submerged conditions), where a granular column is quickly released over a horizontal surface and led to collapse by self-weight (Lajeunesse et al., 2004; Lube et al., 2004). In the current paper, a submerged granular system with the addition of dyed fluid is studied in a planar 2D model. The granular mass is characterized by its initial height H_0 and horizontal length R_0 , related by the aspect ratio $a=H_0/R_0$. Two aspect ratios ($a=0.85$ and $a=2.63$) are used to analyze the behaviour of the surrounding fluid during collapse.

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2. Planar granular column setup

A dry planar model, similar to a Hele-Shaw cell, is introduced by Lacaze et al. (2008) with a thickness varying from 1.2 to 1.8 particle diameters. This configuration provides an easy measurement of the internal deformation and kinematic field during collapse. In their configuration, a top-swinging gate is employed as the opening mechanism. However, if such a mechanism is to be employed in submerged conditions, the gate motion will generate secondary fluxes that would interact with the overall collapse dynamics. This paper presents a similar setup adapted to the submerged case condition with an alternative opening mechanism. In this model, the top-swinging gate is replaced by a sliding gate moving in a plane perpendicular to the particles plane of motion, guaranteeing that all particles are released simultaneously and that no additional fluxes are generated (see Fig. 1).

Figure 1 presents a sketch of the experimental setup. The experimental setup is composed of two Plexiglass (PMMA) square windows of 450 mm side and 10 mm thick. A cell gap of 2.4 mm lies between them and a 2 mm thick PMMA hollow square with an inner length of 390 mm. To limit leakages in the model perimeter, pieces of paperboard are added in between the PMMA windows and the hollow square. The paperboard pieces are moistened to diminish their potential absorption and prevent leakages. The opening mechanism is operated by a 4 bar linear pneumatic actuator. A high-intensity LED panel of 4000 lm backlights the model. A Mikrotron MotionBLITZ Cube 4 camera records the granular column collapse at a frame rate of 800 fps and with a resolution of 720 px by 530 px.

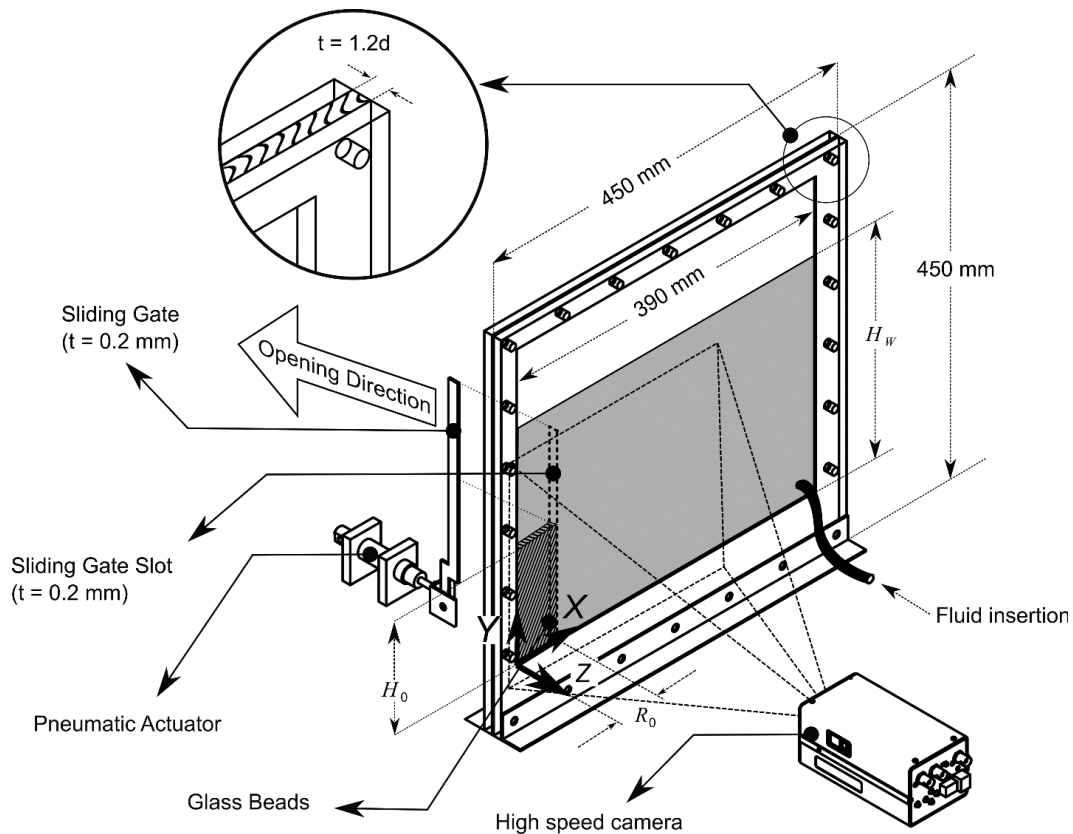


Fig. 1. Sketch of the granular column setup

Experiments are performed with 2 mm diameter ceramic beads with a particle density of $\rho_p = 3600 \text{ kg/m}^3$, manufactured by Sigmund-Lindner GmbH. The particles present a repose angle of $28.15^\circ \pm 0.75^\circ$, measured inside the experimental setup by releasing the particles in free-fall and under dry conditions. To prevent leaks in the sliding gate slot, petroleum-jelly seal is applied in the sliding gate, taking care that none of it gets inside the slot. The granular column is build up to a desired initial height H_0 and the fluid is injected into the model. A slow fluid injection is performed, ensuring that no air bubbles remain trapped inside the granular body. The fluid used in this work is

composed of a mixture of deionized water with regular soap in a volume ratio of 40:1. Fluid is added until it reaches a height of 50 mm above the granular column. The sliding gate is connected to the pneumatic actuator and the illumination system is turned on, along with the camera and pressure system. At this point a dye is added using a needle through a compartment in the upper part of the experimental setup (see Fig. 2). The dye solution is made of 100 ml of whole milk and 10 ml of rubbing alcohol. Once the dye reaches the bottom of the model and stabilize, the opening mechanism is activated and the camera records the movement of the granular mass. In this paper, we explore the collapse dynamics of short and tall columns at aspect ratios of $a=0.85$ and $a=2.63$, respectively. The following sections present the main results on the interaction of the granular column collapse and the surrounding fluid.

3. Results and discussion

The submerged granular column is released evenly and quickly through its height with the occurrence of minimal droppings at the gate slice. The column collapse starts with the release of single particles on the column's vertical free-face and the formation of a curved wedge at its bottom-right corner. For the aspect ratio of $a=0.85$, the wedge crosses the granular column and emerges at near its surface-mid-width, transitioning into a shallow flow over the collapsed material, up to five particles thick, and deposits into a trapezoidal shape (see Fig. 2 (a-e)). For the aspect ratio of $a=2.63$, the wedge extends through the full column width curving up to the column's top-left corner, releasing groups of free falling particles (see Fig. 2(g)) and transitioning into a slightly thicker flow over the collapsed material, up to ten particles thick, and deposits into a triangular shape (see Fig. 2 (f-j)). The single particles ejected from the collapsing mass decelerate and swirl, in a counterclockwise motion, until returning to the moving mass at a position behind from their release point (Topin et al., 2011).

Following the work of Courrech du Pont et al. (2003) the Stokes number St (Eq. 1) and the fluid-grain density ratio χ (Eq. 2) can be used in the classification of a mass flow within three main flow regimes: free-fall regime, viscous regime, and inertial regime. Considering the particle parameters described above and assuming a fluid density of $\rho_f=1000 \text{ kg/m}^3$ and fluid viscosity of $\mu_f=0.001 \text{ Pa}\cdot\text{s}$, the current set of experiments result in $St \approx 17.9$ and $\chi \approx 1.9$, falling into the inertial regime. Mass flows in the inertial regime are understood to be controlled by gravity and fluid drag, approaching a limit velocity when the equilibrium between these two quantities is reached.

$$St = \frac{1}{18\sqrt{2}} \frac{(\rho_p \Delta \rho g d^3)^{1/2}}{\mu_f} \quad (1)$$

$$\chi = \left(\frac{\rho_p}{\rho_f} \right)^{1/2} \quad (2)$$

Figure 3 presents the propagation of the granular front in time for the two aspect ratios being studied. On it, the collapse dynamics can be divided into three phases: first, an acceleration phase initiates after the column is released; then, the front propagation reaches a constant-velocity phase; and finally, a deceleration phase transits the column motion until deposition. The instantaneous front position (R_i) is measured directly from the digital images and the time collapsing time (t_f) is taken as the time lasted until the column reached its final front position (R_f). Unlike dry granular flows, the front spreads as an interconnected mass (see Fig. 2), without releasing particles during its spreading (Pinzon and Cabrera, 2018). The collapsing time t_f is 0.8 s and 1.7 s for the short and tall columns, respectively.

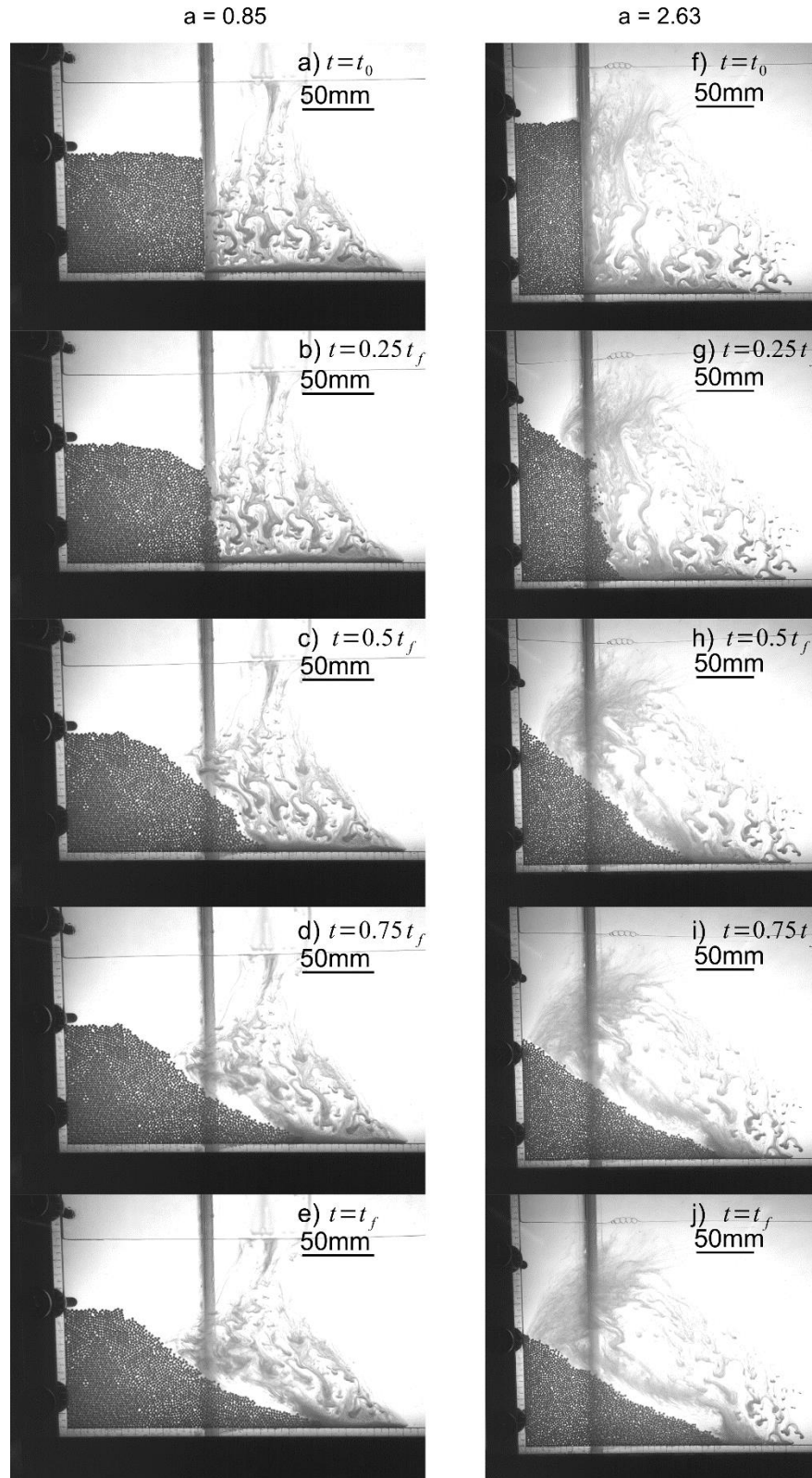


Fig. 2. Snapshots of the submerged column collapse. (a) to (e) short column with initial aspect ratio $a = 0.85$; (f) to (j) tall column with initial aspect ratio $a = 2.63$.

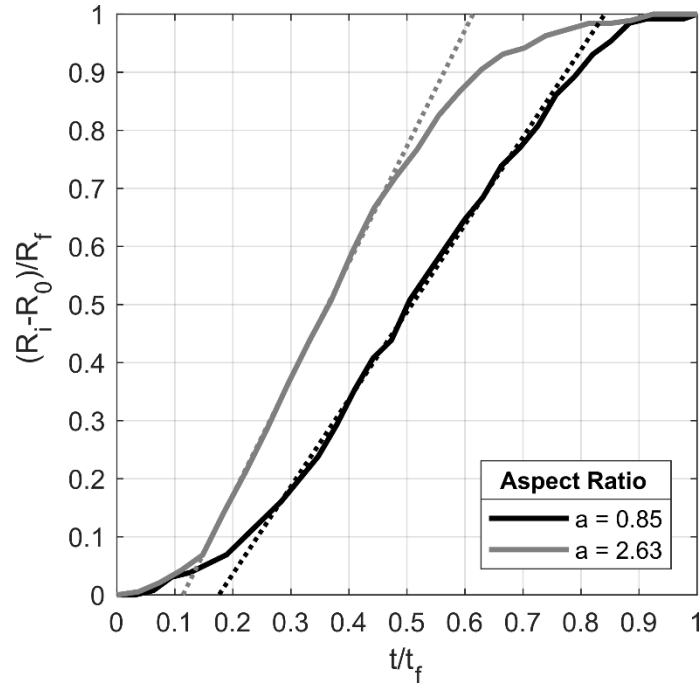


Fig. 3 Normalized lateral displacement of the granular front vs time. The dashed line marks the zone where the front presents a steady lateral propagation.

Figure 3 shows that the short column accelerates for a longer period of its total collapsing time, while the deceleration phase starts earlier on the tall column. However, the duration of the acceleration phase is on both cases close to 0.25 s, being in agreement with the observations of Bouguin and Lacaze (2018) for submerged columns in water. Moreover, the constant-velocity phase occurs in an equivalent time fraction of $0.4 t_f$ on both cases but relates to different durations. In this region, the front propagation velocity is 0.35 m/s and 0.42 m/s for short and tall columns, respectively.

After the column release, the water free-surface above the column is dragged-down, up to 4 mm and 10 mm for the short and tall columns, respectively, and waves sideways. Thanks to the dyed fluid, it is possible to visualize the flow patterns generated from the interaction of the granular column collapse with the surrounding fluid. Note that no secondary flows being induced by the gate opening are observed, being one of the main advantages of the current experimental setup.

Rondon et al. (2011) found that the deposit morphology of a submerged granular column is mainly controlled by the initial volume packing fraction, resulting in short runout (R_f) for initially dense columns and viceversa. In their analysis, dense columns would dilate at the column release, inducing an inflow of fluid into the newly form voids and then reaching an equilibrium between the system dilation speed and viscous drag. For the current experimental setup, a rather dense assembly is obtained, being controlled by the cell gap and the system configuration alignment (Lévy et al., 2018). In our experiments, the momentum exchange mechanism between particles and fluid can be identified at the same three phases described in Fig. 3.

Figure 4 presents the mean velocities of the fluid next to the granular column at release and within the acceleration phase. These flow velocities are computed with the particle image velocimetry (PIV) technique implemented in PIVlab (Thielicke and Stamhuis, 2014) and correspond to the mean velocities along the x-axis of the bottom-half and top-half of the initial column height (hollow and filled markers, respectively). Mean negative velocities, within the coloured region, represent fluid motion pointing into the granular column. The short column presents fluid motion predominantly in the collapse direction at release and transits into a slight inflow at its bottom marked up by the hollow markers errorbars (see Fig. 4(a)). The tall column presents an oscillating inflow through the column height,

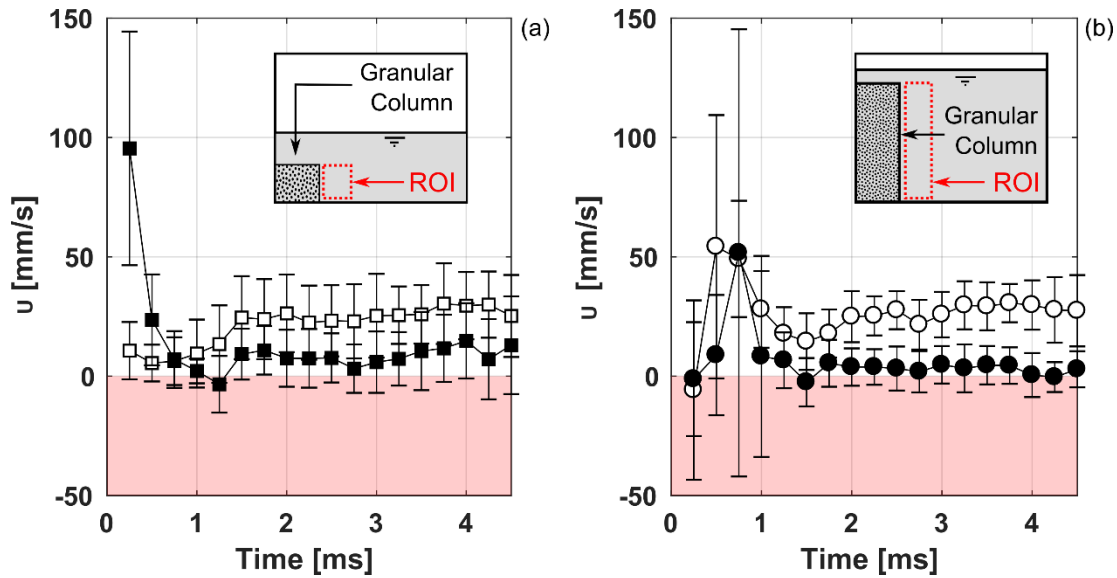


Fig. 4. Mean fluid front velocity at release and within the region of interest (ROI) marked in the inset for (a) $a=0.85$; (b) $a=2.63$. Hollow and filled markers represent the mean velocities along the x-axis of the bottom-half and top-half of the initial column height, respectively

immediately after release, and then dissipates moving predominantly in the collapse direction on top and presenting fluid inflow next to the column's bottom.

At the constant-velocity phase, three simultaneous movements occur: the fluid next to the granular column front i) fills the moving particles at its base, ii) is pushed upwards at its mid-height, and iii) moves against the collapse direction at its top. This motion pattern results in vortices that spin the ejected particles in a counterclockwise direction and explain the formation of the dye-free zone parallel to the granular surface (observed in Fig. 2(c) and 2(h)). The generation of this zone is formed from the fluid that is dragged from within the column and then flows out the granular assembly at this phase.

At the decelerating phase, some dye reached the deposit top and starts to settle while being moved by the remaining inertia from the momentum transfer described in the previous phase. Note that at this phase most of the dye is mixed and diffuse during the collapse.

4. Conclusions

The collapse of a submerged granular column is studied in a planar configuration, testing short and tall columns made of densely packed ceramic beads, immersed in a solution of deionized water and regular soap. The fluid motion next to the column is visualized with the addition of a dye solution.

Our experiments agree on the deposition patterns between short and tall columns (i.e., trapezoidal and triangular deposits, respectively) and can be classified as submerged granular flows within the inertial regime. In this regime, the collapse phases (e.g., acceleration, constant-velocity, and deceleration) are clearly identified from the motion of the granular column spreading, and are linked with the interaction mechanism between grains and surrounding fluid. This mechanism is observed on both column's aspect ratios, starting with an inflow of fluid next to the column's free-vertical face associated with the dilation of the granular assembly. This inflow is overcome by the moving granular media, entraining fluid at its base and pushing fluid out at its surface. These fluxes between the collapsing granular media and the surrounding fluid result in vortices next to the surface, entraining particles and mixing the surrounding and interstitial fluids. This mechanism complements the current understanding of mass flows in submerged conditions and provides an opportunity for analytical and numerical verification.

Further work would extend on this visualization advantages, studying the coupling between particles and fluid as a function of the column aspect ratio, fluid viscosity, and level of saturation. These extensions would set the validation case for the development of numerical approaches studying the motion of immersed granular flows.

Acknowledgements

We are grateful to Daniel Osorio for his assistance in the execution of the experiments. This research was funded by the Early-stage Researcher fund (FAPA) under the Grant No. PR.3.2016.3667.

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