Planar granular column collapse: an experimental proxy for the study of transitional granular flows

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Abstract

Mass flows are common geohazards associated with the mobilization of an initially stable mass that deforms and flows until reaching deposition. Current constitutive models challenge with the description of a fully transient phenomenon, limiting their predictions to either one or two of the mass flowing stages of initiation, mobilization or deposition. This paper presents a planar setup for the study of the collapse of a granular column, simplifying the complex dynamics of transitional granular flows and allowing the systematic evaluation of particle and fluid parameters. In this system, an initially static granular column is set to collapse by self-weight over a horizontal surface, with a width slightly larger than one particle diameter. This paper aims to present the capabilities of the granular column in a planar configuration, exploring several flow scenarios in dry and wet conditions while making use of a singular aspect ratio of $a \sim 1.5$*. These scenarios review the influence of an ambient fluid in the collapse dynamics providing a look into the dynamics of the particles during collapse; examine the particle-fluid interaction by visualizing the fluid movement on a submerged collapse; and present a novel approach for the study of partially-saturated granular columns.*

1 INTRODUCTION

Mass flows are common natural hazards like landslides, debris flows, rock avalanches, or pyroclastic flows, among others. Mass flows are characterized by the transition of an initially static mass that after reaching an instability condition mobilizes and travels as a function of its particle and fluid content and is constrained by the local topographic setting (e.g., channel cross-section, terrain slope, presence of obstacles). Current constitutive models challenge with the description of a fully transient phenomenon, limiting their predictions to either one or two of the mass flowing stages of initiation, mobilization or deposition. These challenges demand validation in a controlled environment for further advancements in the models' predictive capabilities.

The planar granular column collapse is currently acknowledged as a benchmark case, simplifying the complex dynamics of transitional granular flows and allowing the systematic evaluation of particle and fluid parameters. In this system, an initially static granular column is set to collapse by self-weight over a horizontal surface. Each column is characterized by its initial height H_0 and initial width L_0, yielding an aspect ratio $a = H_0/L_0$. Due to the setup simplicity and the facility of visualizing its macroscopic flow features (e.g., runout geometry, repose angle), the planar granular column collapse has been established as a proxy to study transitional granular flows. As a result, the granular column collapse is commonly used as a reference for the validation of numerical and analytical models, as well as a tool for studying the mobility of mass flows (Lube 2006, Roche et al. 2010, Rondon et al. 2011).

This paper aims to present the capabilities of the granular column in a planar configuration, exploring several flow scenarios in dry and wet conditions while making use of a singular aspect ratio of $a \sim 1.5$. The paper is organized as follows: Sec. 2 presents the planar granular column collapse setup; Sec. 3 reviews the influence of an ambient fluid in the collapse dynamics providing a look into the dynamics of the particles during collapse; Sec. 4 examines the particle-fluid interaction by visualizing the fluid movement on a submerged collapse; and Sec. 5 presents a novel approach for the study of partially-saturated granular columns. Finally, Sec. 6 summarizes and presents the main conclusions from this work.

2 EXPERIMENTAL SETUP

The current research presents a planar configuration, similar to a Hele-Shaw cell, where the internal kinematics during collapse is easily measured (Lacaze et al. 2008, Pinzon and Cabrera 2018). The experimental set-up consists of two Plexiglass (PMMA) square windows of 450 mm side and 10 mm thick with a PMMA hollow frame between them. The frame is 450 mm side with an inner square of 390 mm. The frame thickness can be varied between , with a 0.2 mm thick moistened paperboard seals on the sides, creating an inner gap of $1.2d$, where d is the bead diameter varied between 1 mm and 2 mm, The gap between the PMMA windows provides the simulation space for the particles to move in a nearly two-dimensional plane of motion. The column is assembled next to one of the frame-corners, collapsing towards its free side. The opening mechanism consists of a sliding gate moving in a plane perpendicular to the plane of the particles-motion, guaranteeing that all particles are released simultaneously. The gate is operated by a 4 bar linear pneumatic actuator, and a 4000 lm high-intensity led panel backlights the model. A Mikrotron MotionBLITZ Cube 4 camera records the collapse at a frame rate of 800 fps and a resolution of 720 px$\times$ 530 px (see Fig. 1).

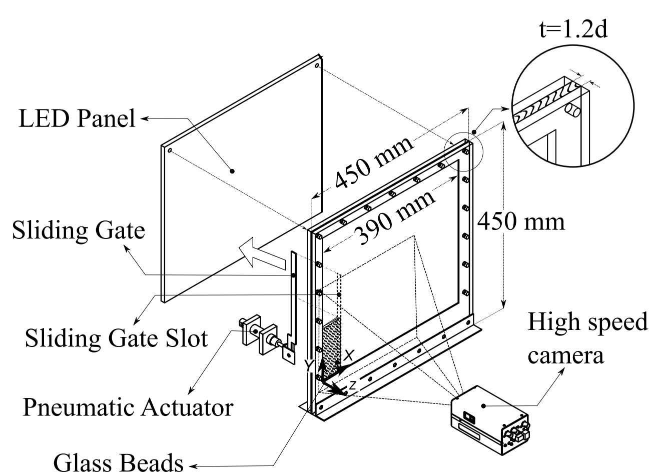


Figure 1: Planar granular column collapse setup.

The granular column is made of ceramic beads of 2 mm and 1 mm in diameter (the latter are only used in the dry scenario) with a density of $\rho_p = 3600$ kg/cm^3, manufactured by Sigmund-Linder GmbH. The beads have a repose angle of $\varphi = 27.85°$, measured inside the planar setup under dry conditions as the heap repose angle after a free-fall release. Due to the experimental set-up constraints and the use of monodisperse particles, the column solid fraction is limited to $\phi \sim 0.50 \pm 0.01$, agreeing with the results on frustrated packings in crystalline systems (Oğuz et al. 2012). The fluid used in the submerged scenario consists of a solution of deionized water and regular soap, in a volume ratio of 40:1, reducing the surface tension and inhibiting the creation of trapped air bubbles inside the granular column. In the submerged experiments, the fluid level raises up to 5 cm above H_0.

For each scenario, the velocity field is computed through a Particle Image Velocimetry (PIV) analysis (Thielicke and Stamhuis 2014). Additionally, the particle tracking or direct measurement of the particle front or fluid surface is possible by digital image analysis, providing a detailed insight into the full collapse sequence.

The following sections summarize the capabilities of the planar setup for the study of dry, submerged, and partially-saturated granular columns.

3 A LOOK ON PARTICLE MOTION

The ambient fluid plays a dominant role in the dynamics of a granular column, controlling the system mobility as a result of a pore pressure feedback (Cassar et al. 2005, Rondon et al. 2011). The current setup provides the alternative of injecting a fluid and submerging the full column, allowing the comparison in the collapse dynamics of dry and submerged columns, while providing an internal view to the particle dynamics. Figure 2 presents the velocity magnitude fields at different instants of a dry and a submerged collapse. In both scenarios, the mobilized area (i.e., the region that presents a velocity magnitude V greater than 0) increases as the collapse advances (Fig. 2 a-b & d-e), and then decreases until only a superficial layer remains in motion (Fig. 2 b-c & e-f). The fluid viscosity abates the maximum velocity during collapse, reducing the maximum velocity of $V_{max} = 0.78$ m/s in the dry test to $V_{max} = 0.55$ m/s in the submerged test. This influence results from greater drag forces developed during the submerged collapse, being a function of the fluid viscosity and the beads inertia as discussed in Pinzon and Cabrera (2019). Moreover, the column mobility is defined as $L^* = (L_f - L_0)/L_f$, where L_f is the deposit horizontal runout. L^* decreases when the collapse takes place under submerged conditions, reducing from $L^* = 2.6$ to $L^* = 1.87$.

A third difference between the dry and submerged scenarios is on the extension of the mobilized region during collapse. For the first instants of collapse (Fig. 2 a & d), the mobilized region is greater in the dry scenario. In the submerged scenario, the fluid viscosity is observed to slow the collapsing sequence, diminishing the retrogressive propagation of the mobilized region while augmenting the overall collapse time (see Fig. 2 c & f). This effect can be explained by the initially dense configuration that dilates after release, dissipating and augmenting the overall drag on the moving region.

4 A LOOK INTO THE FLUID

In addition to the insight gained from the study of the motion of the particles, the planar configuration can be used to study the particle-fluid interaction with ease. For example, it provides the opportunity of tracking the fluid motion in a fully-submerged scenario with the addition of a dye. Figure 3 presents the PIV results of a submerged collapse of both the granular mass and the ambient fluid. The velocity field in each domain was obtained from separated PIV analysis, and the velocity field over the fluid was captured after applying a dye to the fluid (Pinzón and Cabrera 2019). Moreover, the PIV analysis was performed on an early stage of collapse, when the granular mass is starting to spread horizontally and reaches a steady propagation. Note that the velocity field is presented along with the contour of the velocity magnitude, allowing the visualization of the mobilized area and the direction of the velocity field.

The maximum velocity registered in the granular column is $V_{max,g} = 0.60$ m/s, similar to the one observed in the previous section, and is located near the column mid-height. The velocity field reveals that the upper region of the granular column moves predominantly in the vertical direction, while at its base the motion is in a horizontal spreading. For the surrounding fluid, the velocity field registers a maximum velocity of $V_{max,f} = 0.29$ m/s, being half of the observed in the granular mass, and is located on the top corner of the moving wedge. Additionally, the streamlines reveal that the fluid in the lower region is pushed away by the front collapse, while the fluid in the upper region is dragged into the column. This pattern allows the visualization of a convection cell generated in submerged mass flows, where the fluid enters the granular mass on the surface of the moving wedge and outflows on its base. The occurrence of the convection cell has been observed in numerical simulations (Lee et al. 2018), and these results offer an experimental validation of this phenomenon.

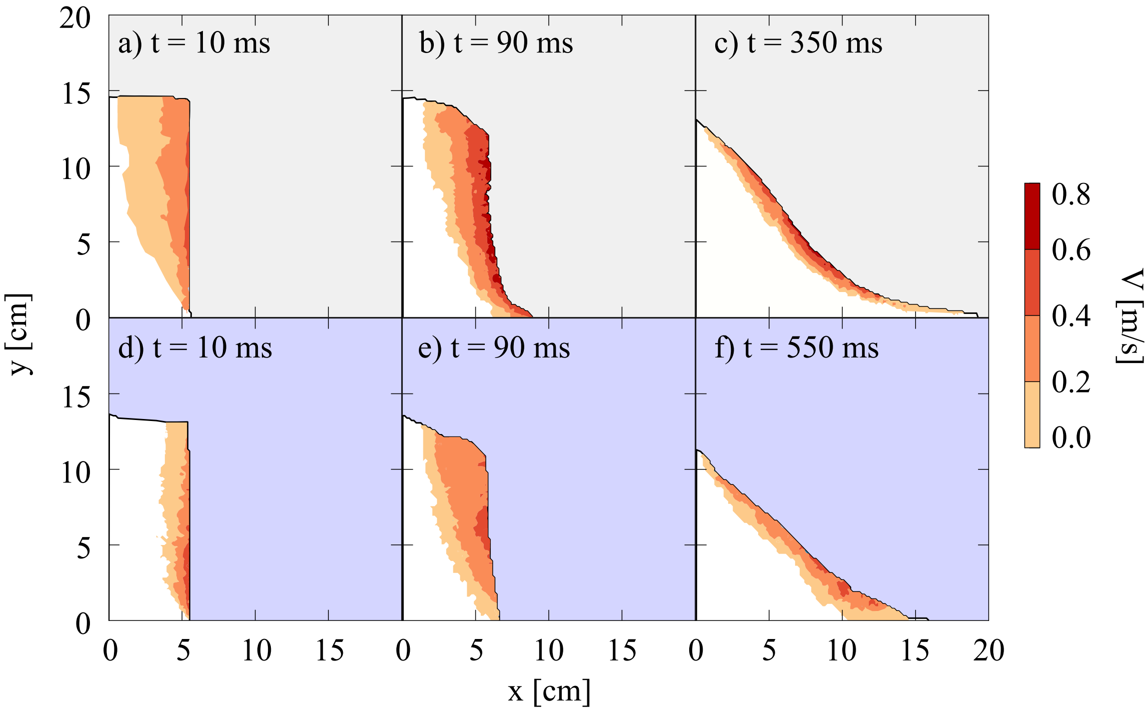


Figure 2: Velocity fields for a dry collapse (a-c) and a submerged collapse (d-f) at different instants of collapse. The last frame in each scenario (c & f) corresponds to the instant when the granular mass reaches its final runout (L_f) while maintaining a shallow layer of particles moving on its surface.

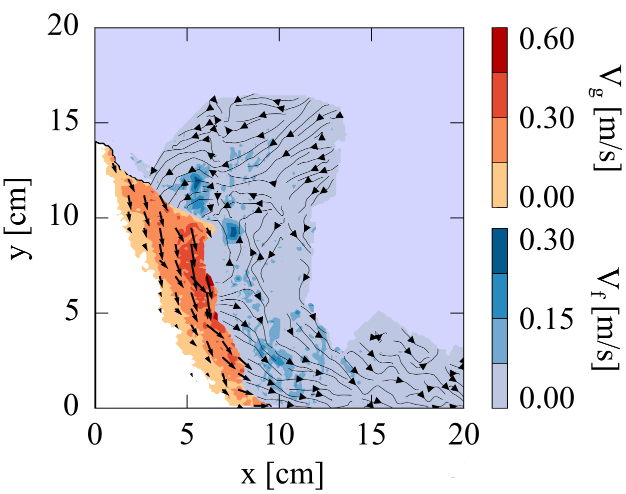


Figure 3: Velocity fields of a submerged collapse over the granular mass and the surrounding fluid. The fluid motion is captured by applying a liquid dye (Pinzón and Cabrera, 2019).

The results obtained through the planar setup offer a unique insight into the momentum transfer between the collapsing mass and the surrounding fluid and provide the potential for the validation of numerical models of submerged mass flows. Ongoing work explores an alternative scenario, where the fluid level relative to the column height is varied, exploring the generation of waves by means of the momentum transfer from the column collapse.

5 A LOOK INTO THE PORES

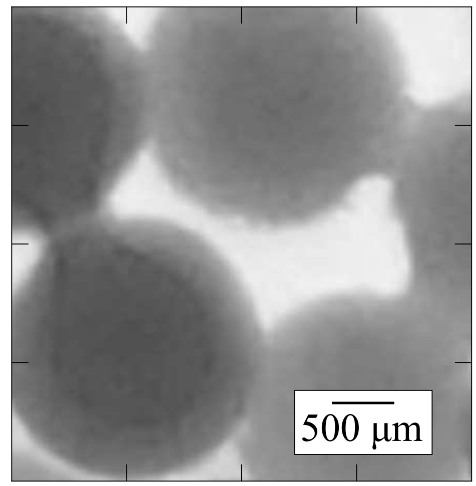
Partial-saturation in granular media has been proved to impact the material's strength, involving additional resisting and triggering forces and being of great relevance for the study of slope stability and landslide mobility (Badetti et al. 2018). Recent advances in partially saturated porous media deal with the challenging simulation of partially-saturated granular flows, displaying enormous challenges when controlling the main variables (e.g., degree of saturation, suction, fluid tension) of the problem while keeping a relative control into boundary conditions (Morse et al. 2014, Bougouin et al. 2019, Ceccato et al. 2017).

The planar setup offers a unique opportunity to study transitional granular flows under partially-saturated conditions, allowing the identification of the water meniscus and their impact on the column stability and flow properties. In order to obtain the partial-saturation conditions in the granular column, the system is fully saturated with deionized water and then drained. The surface tension of the water is high enough to create water menisci during the system drainage. Figure 4a presents a photograph taken after the de-saturation of the granular column, where the water meniscus can be easily identified. Two different types of water meniscus are observed: (a) interparticle meniscus, like the ones located in the upper-right region of the image; and (b) wall-particle meniscus, corresponding to the dark area in the bottom-left region. The presence of wall-particle menisci could be interpreted as an equivalent of the interparticle menisci in a three-dimensional system.

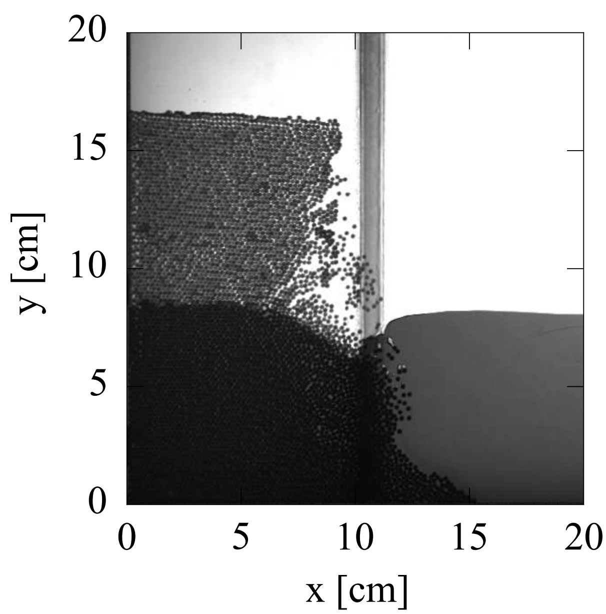
To explore the setup capabilities under partially-saturated conditions, the granular column is saturated and drained up to the middle section of the column, creating two different regions inside the system: a submerged inferior region and a partially-saturated upper region. Figure 4b presents a snapshot of the collapse at $t = 230$ ms after release. The overall collapse sequence differs completely from the dry and submerged scenarios. On the partially-saturated region, well-defined clumps of particles are observed to fall from the main granular mass. Additionally, in the lower part of the partially-saturated region, the collapse creates cavities inside the granular body, exhibiting outer angles greater than $180°$. The instantaneous stability of the partially-saturated region, along with the falling of particle clumps, evidence the effects of the water meniscus over the collapse behaviour, adding additional resistance to the propagation of a discontinuous and interrupted shear band that diffuses the formation of a moving wedge. In the submerged region, the column collapses as observed in the previous sections, dragging down the water level as it spreads horizontally.

The transition between both mechanisms is then followed by a common triangular deposit also observed in the previous scenarios. The column mobility measured in this scenario presents a value of $L^* = 1.1$, lower than the observed in the dry and submerged scenarios.

Ongoing work deals with the characterization of the partially-saturated column and scaling of the collapse sequence. Among these challenges is the description of the partially-saturated scenario, aiming at a characterization of the column degree of saturation S_r locally and in space. This can be performed by using high-resolution images of the sat-



(a) Close-up to the menisci between beads after the column desaturation and prior to collapse.



(b) Colum collapse at $t = 230$ ms under partially-saturated conditions

Figure 4: Partially-saturated scenario in a planar configuration, allowing the study of the role of (a) menisci prior to collapse and (b) its effect during collapse.

uration and de-saturation process, as Fig. 4a, allowing the segmentation of particles, voids, and meniscus. The morphological features of the water meniscus, like size, shape, and location, can also be tracked through the collapse, offering an exceptional opportunity to study partially-saturated granular flows. On the other hand, modifying the fluid surface tension might provide the opportunity for exploring alternative scenarios of the water bridge strength and overall column stability.

6 CONCLUSIONS

This paper presented a planar set-up for the study of transitional granular flows, focusing on the model capabilities and the wide variety of scenarios that can be studied. This work presented the collapse of a granular column as a proxy of the mobility of mass flows. The planar set-up allows the measurement of the column kinematics and mobility by the use of digital image analysis as a direct and continuous measurement tool. Three main capabilities were presented: *i*) a look in the motion of the particles during collapse; *ii*) a look into the fluid motion resultant from the particle-fluid interactions; and *iii*) a look into the pores as an alternative for the study of partial-saturated granular flows.

From the vantage point the planar setup, the column mobility is found to be slower and shortened when in a submerged scenario, involving a lesser portion of the column in the motion and delaying the whole collapse sequence. With the use of a fluid dye, the motion patterns during collapse provide evidence of a convection cell driven by the column collapse and its dilation after release. In summary, the planar setup provides a valuable opportunity for the validation of numerical methods, studying the mobility and runout of mass flows.

Finally, a novel scenario is presented, exploring the behaviour of transitional granular flows under partial-saturation. The planar set-up enables the creation of fluid menisci and captures the increase of strength due to their presence. The water menisci can be identified and measured, and further work focuses on the characterization and evolution of size and localization of this partially saturated system and its effect on the overall column mobility.

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