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The planar setup: a window through the complex interactions in granular flows

Miguel Cabrera[1,2*], *Laura* Cote[1], and *Santiago* Caro[1]

[1]Department of Civil and Environmental Engineering, Universidad de los Andes, 111711, Bogotá, Colombia
[2]Department of Geoscience & Engineering, TU Delft, 5048, Stevinweg 1, Delft, The Netherlands

Abstract. Granular flows are a complex process, involving a wide range of grain sizes, materials, varied viscous fluids, among others. For this reason, the simulation of granular flows requires a certain level of simplification, allowing the isolated study of its governing variables and extending the global observations to field events. Here, we present the planar setup as an alternative for studying simplified processes associated to granular flows. The planar setup consists of two windows separated by a thin gap and enclosing a granular assembly. We present two examples where the planar setup is adapted for the study of the competing action of segregation and disaggregation in a fractured grain under shear flow, and for the study of the stability scenarios of a flow impacting a permeable obstacle. The close visualization of the kinematics at the particle scale provides an ideal opportunity for describing the mechanisms behind the grain disaggregation or controlling the obstacle stability. Both examples highlight the advantages of the planar setup for the study of granular flows.

1 The power of simplification

Granular flows like debris flows, mudflows, and hyperconcentrated flows pose a latent thread to mountain communities, interacting with its infrastructure and eventually causing fatalities [1-2]. Such granular flows are complex processes, involving a wide range of grain sizes, materials with fluctuating viscosity and varying density, erosion and deposition processes changing the channel geometry, and transitional flow regimes from initiation to deposition [3-5]. In consequence, simplification has been key in understanding and simulating granular flows for natural hazard assessments and in the design of mitigation systems, among others. Numerical simplifications range from continuum constitutive models describing the flow motion and runout [3-6] to micro-mechanical models providing insights into the particle-fluid interactions [7-8]. Experimental simplifications range from large configurations aiming at matching some features of field scale events [9-11] to small laboratory scale models isolating some of the governing processes in a granular flow [12-15].

The similarity between field processes and numerical and experimental models is explored at different levels of abstraction (i.e., geometry, loading, materials) and chosen out of convenience of the process under study [16]. Geometrical similarities come from the simplification of the macroscopic characteristics (e.g., channel cross section, channel slope) and microscopic features (e.g., grain shape, bed roughness) [17]; loading similarities aim at reproducing the associated stresses and stress ratios of large field events (e.g., pore-pressure feedback) [16]; and material similarities intend to reproduce closely the rheological behavior of the materials involved in field events [18]. However, the introduction of these simplifications sets a distance with a detailed description of a particular field event, requiring a careful consideration of the advantages and disadvantages at each point of the model design and simplification.

One example of intense simplification in experimental models is the planar setup, similar to the Hele-Shaw cell in fluid mechanics. A planar setup is a nearly two-dimensional configuration, consisting of two windows that enclose a granular assembly in a gap slightly thicker than one particle diameter [19-23]. This setup allows clear visualization of the granular assembly, its kinematics, and ambient fluid motion [24], while reducing the complexity of boundary and initial conditions to the interaction between the grains and the model walls. Moreover, the richness of information extracted from the visualization of the kinematics at the particle scale overcomes in some instances the limitations of studying monodisperse systems. The visualization is obtained by a simple camera setup and recent advances in open-source digital image analysis tools (e.g., scikit-image, imageJ, napari) points to a cost-effective strategy for the study of granular flows.

In this work, we present two examples where the planar setup is adapted for the study of processes that might remain hidden in a three-dimensional configuration. The first example studies the competing action of segregation and disaggregation in a fractured

* Corresponding author: miguel.cabrera.geo@gmail.com

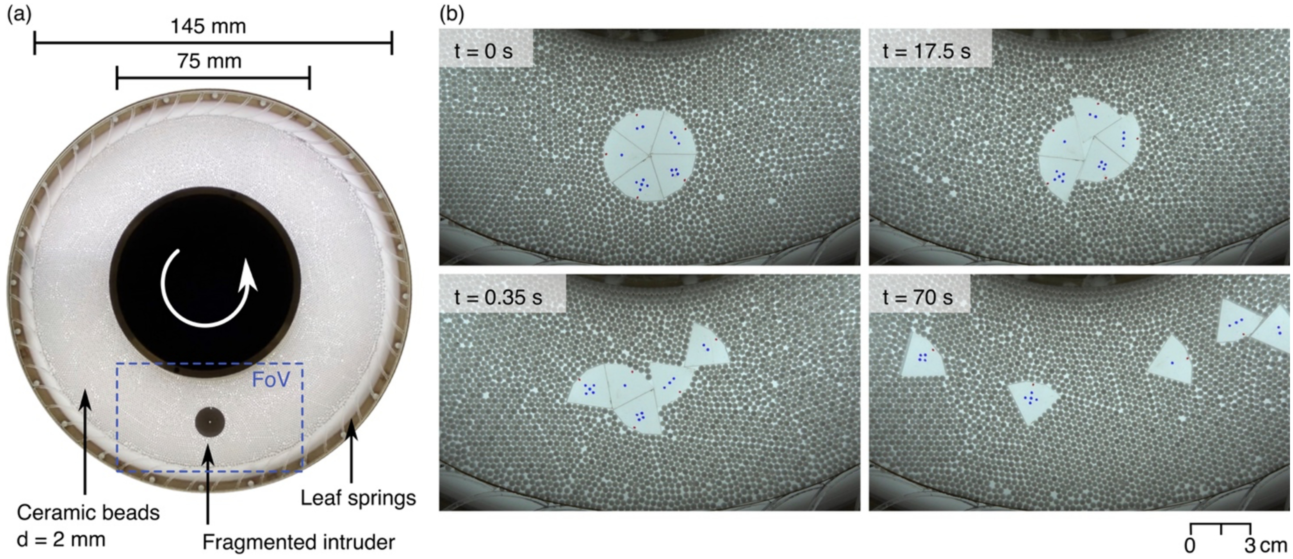

Fig. 1. (a) Planar Couette cell top view; and (b) snapshots of the disaggregation and segregation of a fragmented disk.

grain under shear flow [25], and the second example studies the stability scenarios of a flow impacting a permeable obstacle [26]. Finally, the last section summarizes and proposes a forecast on the alternatives to be explored in a planar setup in future works.

2 A look into a fractured grain

Highly fractured boulders, also known as Jigsaw-fit blocks, are often found in volcanic debris avalanche deposits with little separation between its fragments [27]. Despite the avalanche long runout and agitated motion, jigsaw-fit blocks appear to evade the expected disaggregation within a gravity-driven shear flow. The mechanisms behind the fragments frustrated disaggregation are explored in a planar Couette cell, focusing on the interactions frustrating the disaggregation of a fragmented grain in a steady state shear flow. In this configuration, two horizontal annular windows enclose a granular assembly of 2 mm ceramic beads and 2 mm thick PMMA laser-cut plates of 30 mm diameter (see Fig. 1(a)). The PMMA plates are cut in a simplified pattern of a jigsaw fit block, assuming that cracks found on the outer-surface concentrate at the block center. The shear flow within the two annular windows is driven by the rotation of the inner cylinder and the basal plate. The bottom annular window is backlighted by a led panel and the beads and fragments motion is monitored by a top high-speed camera (see Fig. 1(b)). The test is driven by a steady angular velocity and lasts until complete disaggregation is reached.

After initiation, the fragmented plate starts spinning in a clockwise direction around its axis until a relative displacement between fragments generates a void at its center and the exposed edges are dragged apart by the moving beads. The asymmetrical distribution of normal forces on the fragments and the equivalent volume fraction gradient on the surrounding grains, creates a lift force that sets a gradual disaggregation until no fragments are left in contact with each other. Remarkably, the fragments disaggregation does not initiate at the test start, but it is eventually triggered by the shear flow agitation (see Fig. 1(c-d)). Further work focuses on the role of the fragment pattern and on the formulation of a generalized model for fragments disaggregation.

3 A look into a flow impacting a permeable obstacle

Open mitigation structures like filter barriers and baffles allow flow through a series of openings, resulting in a decrease of the mass flow kinematics [28-29]. Among these, baffles are a cost-effective alternative, requiring less materials and of easier construction and replacement. However, the basal fixture and single stability of these elements is among their main challenges. Here, the stability against impact of a permeable obstacle is simplified into a two-dimensional planar setup. The obstacle is made of a lattice of 6 mm perforated beads connected through their orifices with a nylon thread. The planar setup consists of a 1.5 m long channel, connected upstream to a 15 l tank that fills a 0.28 m wide reservoir and impacts the obstacle at 0.56 m from the reservoir outlet (see Fig. 2(a)). The flow kinematics and obstacle motion are monitored by a side high-sped camera, recording a back-lighted region. We explore the obstacle stability as a function of the ratio between its height H and width B.

After the water flow impacts the permeable obstacle, three main scenarios are observed: (i) the obstacle overturns once the flow upstream is just above $0.5H$ (see Fig. 2(b)); (ii) the obstacle slides before the flow upstream is about H (see Fig. 2(c)); and (iii) the obstacle remains in place when the flow upstream is at H (see Fig. 2(d)). The occurrence of each scenario is conditioned by the obstacle width and upstream filling time, resulting in stable outcomes for all obstacles with a ratio of $H/B \leq 0.75$. Ongoing work aims at providing a simplified analytical model for describing the stability of permeable obstacles and guide the design of such mitigation structures.

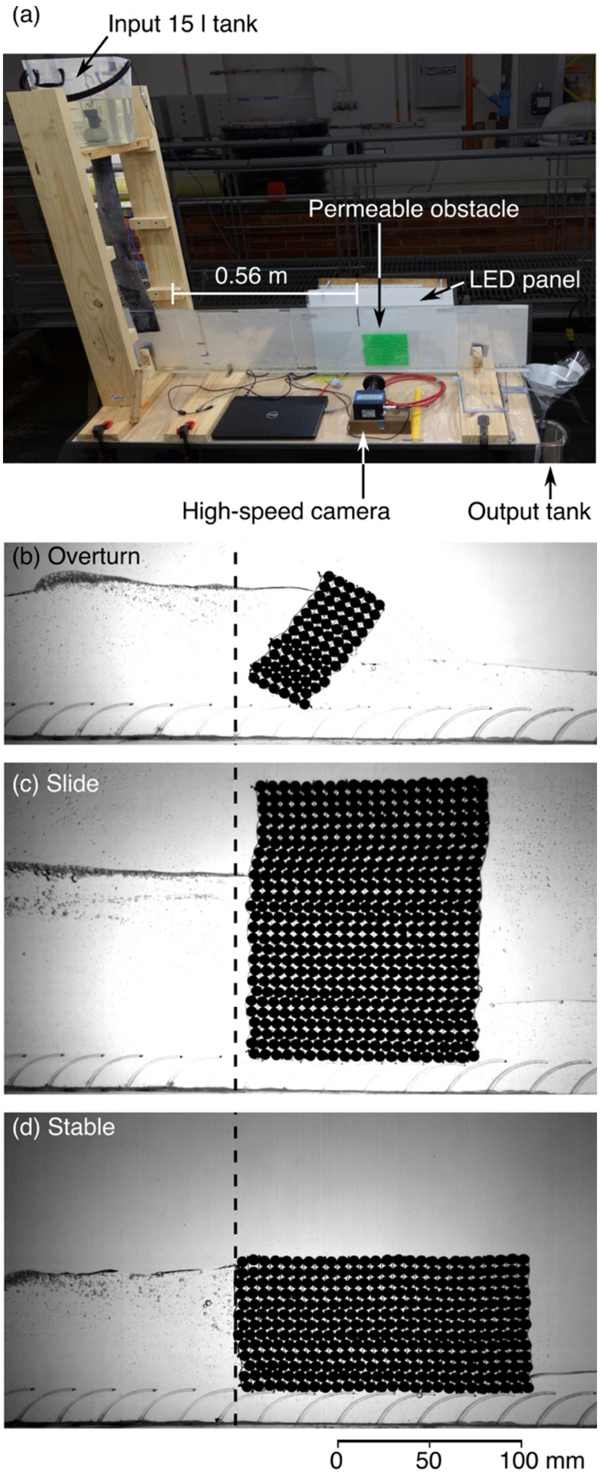

Fig. 2. Flow impact against a permeable obstacle. (a) Planar setup, and (b-d) observed impact scenarios, with the dashed line marking the obstacle initial position.

4 Perspectives and futures challenges

The simplification of the complex interactions in granular flows poses the challenging task of identifying the dominant variables of a given process and isolating them in a controlled system. This task is non-trivial and demands a clear link between the abstraction and the idealized field event. In this work, we present two examples of such simplification, exploiting the advantages of a planar setup in the visualization of the internal kinematics of a disaggregating fractured grain and studying the flow impact against a permeable obstacle. In both instances, the richness of information collected through digital image analysis, provides a comprehensive collection of information for describing in detail the process under study. It is important to highlight, that these simplified systems are a first order approach, aimed at setting a benchmark scenario for the validation of more complex tools.

Future works could aim at validating the observed behaviours in a planar setup with three-dimensional models instrumented with a visualization of its inner kinematics (e.g., Planar laser-induced fluorescence [30]), or compare the observed patterns with field-scale instrumented cases. Moreover, the advantages and disadvantages of the planar setup require further idealizations for including the study of polydisperse systems, the role of non-Newtonian viscous fluids, and the scaling of flexible mitigation structures. In this sense, it should be highlighted that the cost-effective alternative of a planar setup should be tempting enough for driving more research and stablishing it as a common tool for the study of granular flows.

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