Influence of release mechanisms on flow velocity and depth in dry granular flows: an experimental investigation

Influence of release mechanisms on flow velocity and depth in dry granular flows: an experimental investigation

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ABSTRACT: Debris flows are an extremely rapid and unpredictable phenomena with a dynamic that remains poorly understood. Further complicating the problem, human settlements are often located in regions prone to debris flows. Despite the acknowledged hazard, comprehending the intricate behaviour of debris flows remains a challenging task. Laboratory experiments serve as a crucial tool, enabling the simplification of complex channel geometries and facilitating detailed observations. However, the often-overlooked influence of release mechanisms on resulting flows presents a significant gap in current practices. This paper addresses the simplification of release mechanisms, commonly reduced to dam break schemes or, less frequently, double gate systems regulating flow discharge. To isolate this issue, focus is placed on the influence of different release mechanisms only on dry dense granular flows. Flume experiments are carried out and recorded with a high-speed camera. The videos are analysed using the Particle Image Velocimetry (PIV) technique, providing insightful results on flow velocity, depth, and velocity profiles. The findings highlight the role played by the release mechanism in influencing both flow depth and velocity. This factor has the potential to modify outcomes when studying the interaction of debris flows with mitigation structures. This highlights the need to consider the release mechanisms in the study of granular flows, particularly when proposing new criteria for the design of structures or estimating the forces acting on them.

1 INTRODUCTION

Debris flows rank among the most hazardous landslide phenomena. They are constituted by poorly sorted materials saturated with water, quickly flowing on channelized paths under the influence of gravity (Iverson, 1997). These flows are distinguished by the absence of premonitory signals and by exceptionally high speed, often surpassing 5 m/s (Hungr et al., 2014). Frequently, human settlements are situated in regions susceptible to debris flows. The absence of warning signals and the extraordinarily high speed pose challenges to evacuating the local population, thereby rendering debris flows hazardous events.

The inherent risks associated with debris flows necessitate the implementation of effective mitigation measures. Installing mitigation structures, like barriers, is a common practice to address the risk. These structures are strategically placed in the flow paths to dissipate flow energy and retain the largest boulders. Despite the hazards posed by debris flows, the design of mitigation structures relies on empirical or simplified approaches (Iverson, 2003). To enhance the understanding of debris flow dynamics and, consequently, improve mitigation strategies, it is imperative to gain a deeper insight into the behaviour of these events. For this, laboratory experiments are a valuable tool (Choi et al., 2015; Faug et al., 2015; Moriguchi et al., 2009; Yang & Cheng, 2017). They simplify complex geometries, like channels in mountain valleys. Moreover, these experiments enable detailed observations of the flows, capturing aspects that are challenging to observe at the site scale. Data collection is relatively straightforward, and their interpretation is more accessible than at the site scale (Leonardi & Pirulli, 2020). Cuomo et al., (2014) studied the influence of the rheology using numerical models.

Notwithstanding the fact that the laboratory scale offers valuable advantages, the release mechanisms of flows are often overlooked. Some studies assume that a stationary flow exists, and that Froude similarity holds (Choi et al., 2015; Ng et al., 2019, 2021, 2022; Primus et al., 2004). Typically, these mechanisms are simplified to either a dam break scheme, corresponding to a debris flow surge or, less commonly, to a double gate system regulating flow discharge into the domain. Despite their common usage, little attention has been given to understanding the influence of the release mechanism on the resulting flow, and especially on whether stationary actually occurs, and for which portion of the flow. Specifically, it is crucial to comprehend if and how the release mechanism affects flow depth and velocity.

In this paper, the influence of the release mechanism on dry dense granular flows is discussed in detail. To accomplish this, experiments in a flume are conducted. Specifically, a series of releases is carried out and recorded with a high-speed camera. Subsequently, the videos are analysed using the Particle Image Velocimetry (PIV) technique, yielding results regarding flow velocity in depth.

The paper is structured as follows: Section 2 provides a description of the flume and the experimental devices employed. In Section 3, preliminary results are presented. Finally, Section 4 draws conclusions on the importance of the release mechanisms.

2 EXPERIMENTAL DETAILS

The study utilises the small-scale flume available in the Geotechnics laboratory at the University of Sheffield, and depicted in Figure 2. A comprehensive description of the flume can be found in Zhao et al., (2024).The flume has dimensions of 1.2 m in length and 0.1 m in width, with an inclination of 30°. The base of the flume is made rough by glueing a layer of particles onto it, following a similar approach adopted in other experimental setups (Pouliquen, 1999). At the summit of the flume, a tank is positioned for storing granular materials. The inclusion of two plates at the tank facilitates the testing of two distinct release mechanisms: (i) the dam break and (ii) the double gate system. In the case of the dam break mechanism, the tank is initially filled with material, and upon removal of the plate, the material is released to flow. The double-gate system is tested with the second plate in place, allowing for the regulation of flow height and, consequently, the discharge into the flume. The first plate remains fixed at the desired flow height, while the second plate, initially fully lowered, is suddenly removed to initiate the flow. This setup provides precise control over the flow discharge and enables the accurate adjustment of the inlet flow height. Figure 1 depicts the differences between dam break and double gate system.

Table 1. Experiments conducted with various release mechanisms. Mass in kg.

Test Number	Release mechanism	Mass	H/d
1	Dam break	12	-
2	Double gate	12	17
3	Double gate	12	20
4	Double gate	12	25

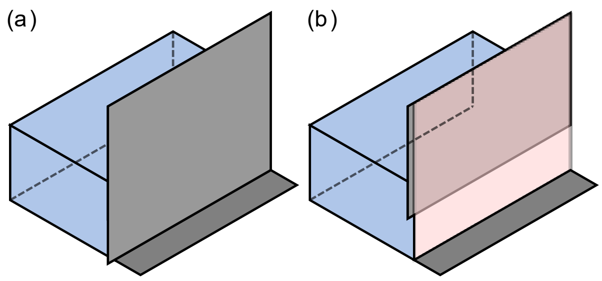

Figure 1 (a) Dam break setup: In this setup, a single plate (grey area) is removed suddenly to initiate the flow. (b) Double gate setup: In this system, the grey plate remains fixed to control the flow height, while the red plate is completely and suddenly removed to initiate the flow.

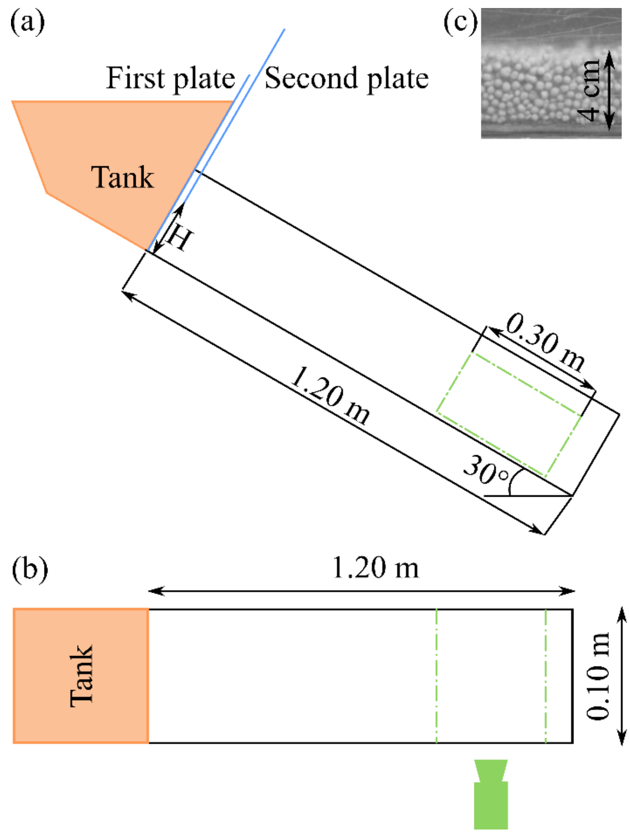

Figure 2. (a) Side view of the experimental setup indicating the recorded area. (b) Top view illustrating the position of the high-speed camera. (c) Runtime image of the Denstone used in the experiments.

The granular flow experiments utilise Denstone® 2000 Support Media, ceramic pseudo-spheres with an average grain size of $d = 3.85$ mm. Detailed characteristics of the material can be found in Zhao et al., (2024). The mass used in the tests is 12 kg, sufficient for ensuring flow development and, if achievable, a steady state. This material is suitable for multiple tests runs due to its hardness, ensuring consistent particle characteristics in successive experiments. Its clear distinguishability in videos, avoiding excessive homogeneity, facilitates straightforward analysis using the Particle Image

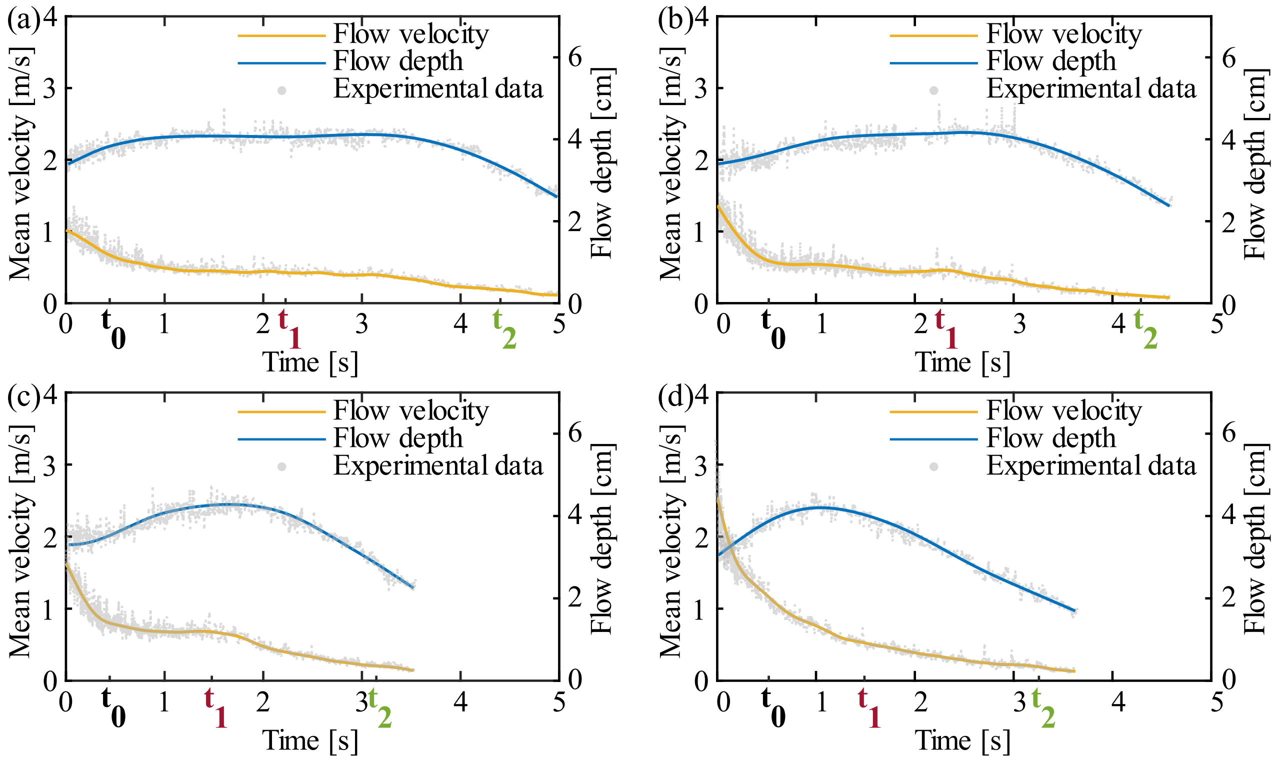

Figure 3. Variation of flow velocity (left axis) and flow depth (right axis) over time for different H/d ratios and dam break scenarios: (a) H/d=17, (b) H/d=20, (c) H/d=25, and (d) dam break. The solid blue and yellow lines depict spline interpolations derived from the PIV results, whereas the grey series illustrates experimental data acquired from the PIV analysis for both flow velocity and height.

Velocimetry (PIV) technique. A Phantom Miro 310 high-speed camera is positioned at one side of the flume, as depicted in Figure 1(b). This camera captures a planar side view of the flow, recording high-speed images at a rate of 1200 frames per second (fps) and a resolution of 1280×800 pixels throughout all conducted tests.

Table 1 presents the details of each conducted test. The release is carried out through a different mechanism, and each experiment is repeated three times to ensure repeatability and eliminate anomalous results. In the case of the double-gate system, the ratio of gate opening to material diameter (H/d) is specifically defined. This ratio is chosen in accordance with established literature (Faug et al., 2015), to attain a flow that conforms to continuum theory rather than a collisional regime (Midi, 2004).

3 RESULTS

This study investigates the mean flow velocity and flow depth observed in laboratory-scale experiments. Furthermore, the PIV technique was employed to derive velocity profiles from high-speed videos. The PIV software utilised in this research is static mesh GeoPIV, developed by White et al. (2003) and Bryant et al., (2015) The flows are assumed as a continuum in this work, adhering to the mass conservation hypothesis:

$$\nabla \cdot \boldsymbol{u} = 0 \qquad (1)$$

Where $\boldsymbol{u}$ represents the vector describing the velocity.

Figure 3 shows the variations in flow depth and mean velocity during the experiments conducted for different release mechanisms. The choice of the release mechanism significantly influences both the mean velocity and flow depth. For the double-gate release ($H/d = 17$) shown in Figure 3a, the flow depth exhibits three distinct phases. In the initial moments of the test, the flow depth increases because the front is reaching the recorded area. Later, the flow stabilises at an approximately constant height, around 4 cm. This suggests the attainment of a steady-state or quasi-steady-state condition, maintained for extended periods during the experiment. Within this presumably steady-state condition, the flow would conform to the analytical solutions proposed in the literature for dense granular flows (Jop, 2015; Midi, 2004; Pouliquen, 1999). The subsequent decrease in

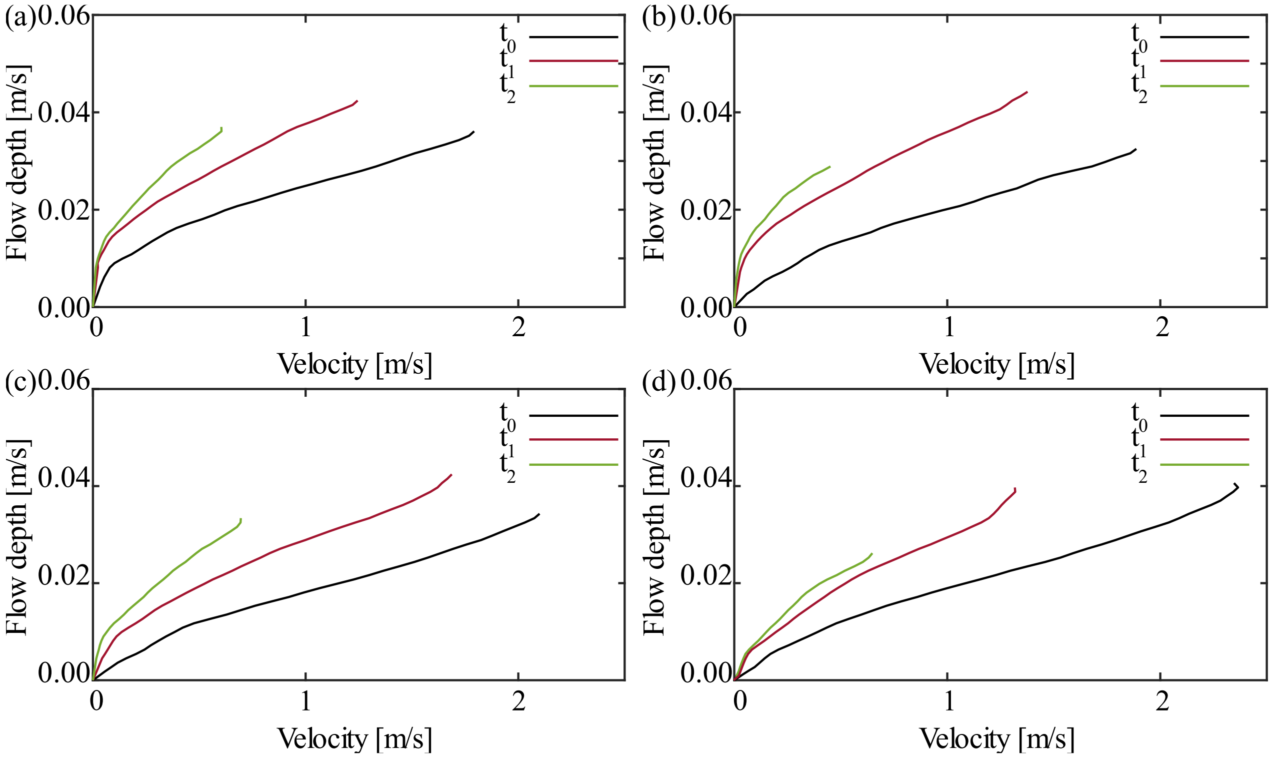

Figure 4. Velocity profiles corresponding to different H/d ratios and dam break scenarios: (a) H/d=17, (b) H/d=20, (c) H/d=25, and (d) dam break, for the selected time frames. The labels t_0, t_1, and t_2 refers to the same instants reported in Figure 3.

flow depth is explained by the complete exit of mass through the gate, resulting in the inability to sustain the flow due to the absence of material.

Regarding the flow velocity, a comparable pattern is evident. However, in accordance with Equation 1, an increase in flow depth is expected to result in a reduction in velocity. In the final moments of the test, the continuity condition is not met, indicating insufficient mass to sustain the flow. Consequently, the continuum hypothesis is no longer valid during these instants leading to a non-continuum regime.

The flow depth and velocity display similar behaviour for $H/d = 20$ and $H/d = 25$ (panel *b* and *c*). Nevertheless, the period during which the flow may be considered steady-state or presumably steady-state is shorter. This reduction in time can be attributed to the higher H/d ratio, leading to an increased flow discharge, and consequently a shorter duration of the steady-state condition

The dam break case (Figure 4, panel *d*), none of the phases can be seen. The flow velocity decreases exponentially. The flow depth increases up to a peak and decreases once the peak is reached. This behaviour may correspond to the absence of a steady-state condition for the tested conditions, specifically regarding the release mechanism.

It is important to emphasise the significant impact of the release mechanism on the experiment duration. Specifically, in the case of $H\ /\ d = 17$, the experiment lasts approximately 5.0 s. In contrast, the duration is reduced by approximately 30% in the case of a dam break. This observation is significant as shorter emptying times may lead to higher flow depth and velocity, influencing the interaction with any structures placed in the flume. In the literature, little attention has been given to the influence of release mechanisms, although they could play a crucial role in flow studies. Specifically, forces acting on structures are often computed using either the hydrodynamic or hydrostatic approach (Equations 2 and 3, respectively):

$$P = k\rho\boldsymbol{u}^{\mathbf{2}} \tag{2}$$

$$P = \alpha\rho g h \tag{3}$$

Where P represents the pressure acting on a structure, α, and k are empirical parameters that consider the non-Newtonian behaviour of the flow and other dynamic aspects. ρ, g, and h represent the flow density, gravitational acceleration, and flow depth, respectively. Changes in release mechanisms can impact both h and u, subsequently influencing the resulting pressure. Therefore, it is crucial to consider the influence of release mechanisms at the laboratory scale.

The findings suggest that the choice of release mechanisms may influence flow characteristics. Quantifying this influence is crucial, especially considering the observed phases of the flows undergo - an initial rise in flow height, followed by a phase of constant flow height, and finally a decrease in flow height. Each of these phases occurs at specific times denoted as t_0, t_1, and t_2, respectively. Figure 4 presents the velocity profiles corresponding to these three instants. Notably, the choice of release mechanism significantly influences the velocity profile. This observation holds particular importance in flow studies, where the interaction between flows and structures often overlooks the release mechanism as a critical element in analysis. Furthermore, the consideration of velocity profiles becomes crucial when employing numerical models. Specifically, in the case of using numerical models with open boundary conditions (like Zou & He, 1997), it is customary to impose analytical velocity profiles under steady-state conditions (Hecht & Harting, 2010; Pasqua et al., 2022, 2023). This study suggests that the velocity profiles may also be influenced by the release mechanism, resulting in deviations from the expected analytical profiles.

4 CONCLUSIONS

The primary objective of this study was to explore the impact of diverse release mechanisms on flow characteristics within a controlled setting. The investigation encompassed the analysis of various release mechanisms, evaluating their effects on flow depth, flow velocity, and velocity profiles at specific time frames. The findings reveal a discernible influence of the release mechanisms on both flow velocity and height. Notably, the double gate system, with an $H\ /\ d$ ratio close to 17, exhibited the potential to achieve a presumed steady-state flow. Conversely, as the $H\ /\ d$ ratio increased or in a dam break case, the steady-state condition was either not met or sustained for brief durations. Furthermore, a notable observation was the reduction in the time required to empty the tank with higher $H\ /\ d$ ratios and in the case of a dam break. This suggests that the discharge is indeed influenced by the chosen release mechanism, potentially leading to different interactions with mitigation structures.

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