

Granular heaps

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Abstract. A granular heap is formed when grains are continuously poured on a surface. The characteristics of such a heap can vary significantly depending on the pouring protocol. In the present work, we show that the velocity at the base of a granular heap, during a steady flowing state, varies significantly when the pouring protocols differ. We performed discrete element simulations of a granular heap formed on a thin rectangular base for two pouring protocols – i) grains poured through a narrow stream and ii) grains poured through a wide stream spanning the entire base. The kinematic properties of grains at the heap base highlighted some interesting characteristics, notably the transition from slow flow to rapid flow and the absence of a static region in the centre of the heap. These results are significant from the viewpoint of stress distribution in bulk granular systems since the orientation of granular contacts and the distribution of forces within the bulk are influenced by the velocity field during flow.

1 Introduction

Granular materials are found everywhere in nature and play a key role in many industrial processes, which has led to a lot of interest in understanding their behaviour under different conditions, both when they are flowing and when they are at rest (Khakhar et al. 2001). Granular materials can transit between static and flowing states. In stationary conditions—such as in heaps or storage containers—granular material exhibits complex stress distributions, including the well-known stress dip observed at the base of a granular pile (Molenda et al. 1996; Vanel et al. 1999).

Earlier experimental studies demonstrated that when a granular heap is formed by pouring grains from a narrow orifice, there is stress dip at the centre of the heap, whereas no such dip is observed when grains are rained uniformly over an area (Vanel et al. 1999; Geng et al. 2001b). Many of the subsequent studies were focused on explaining the fundamental mechanism for the presence of the stress dip in granular heaps. Some of the most notable explanations include the formation of arches by the idea of Edwards & Mounfield (1996) and the ‘fixed principal axis’ model (FPA) by Wittmer et al. (1996). Recently, Krishnaraj and Nott (2004) exploited the fact that the fabric of the grain assembly in a heap is anisotropic and spatially inhomogeneous. They demonstrated that the anisotropy is dependent on the pouring protocol and thus the velocity in the bulk.

Although such behaviours have been studied for decades, the underlying mechanism at the particle scale remains unclear. One of the main challenges is understanding how particles move within a granular heap during its formation. It is commonly believed that

only the surface layer of the heap is active during flow, while the deeper regions remain static. However, recent studies suggest that particle movement in the bulk could play an important role in determining the overall behaviour of the heap (Krishnaraj and Nott, 2004). Investigating the internal dynamics of grains beneath the surface is therefore crucial for gaining deeper insight into granular flow and for addressing long-standing questions, such as how the method of pouring influences the stress distribution at the base.

2 Simulation Setup

To study the behavior of granular heaps, we carried out discrete element method (DEM) simulations using the open-source solver LIGGGHTS (Kloss et al., 2012). The simulation domain consisted of a rectangular base with dimensions $200 d_p$ in length and $5 d_p$ in width, where d_p denotes the particle diameter, taken as 2 mm. Periodic boundary conditions were applied along the width of the domain. The base surface was flat and rough, with a particle–wall friction coefficient of 0.4. Particles were modeled as soft spheres, and inter-particle contact forces were calculated using Hertzian contact theory for both normal and tangential directions, consistent with the approach used in Mathews et al. (2022). Sliding friction was applied at all contact points. Two different pouring protocols were employed: in the first, grains were introduced as a narrow stream of width $20 d_p$, and in the second, grains were poured uniformly across the full width of the base (henceforth referred to as raining).

The following section presents the results for steady flowing heaps, where grains poured from the top fall off from the edges of the rectangular base. During the

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steady state, the heaps maintain a constant shape and a constant angle of repose under both pouring protocols.

3 Results

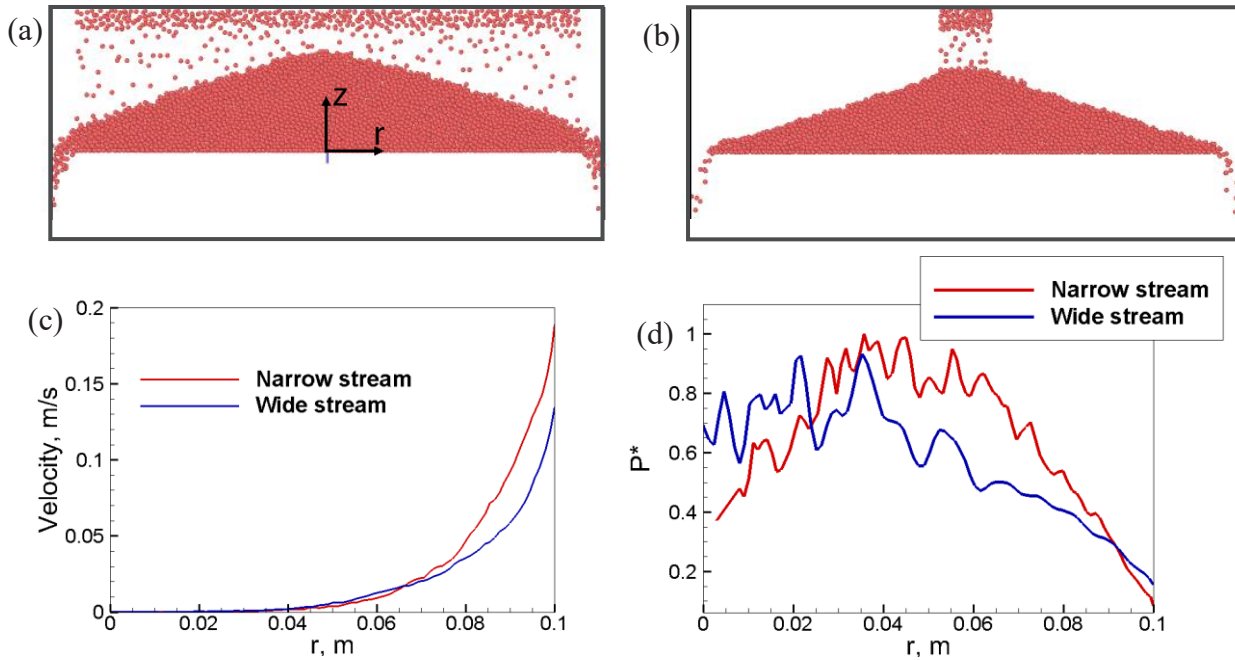


Figure 1: (a) Granular heap formed by pouring grains through a wide stream, (b) through a narrow stream, (c) time-averaged velocity, and (d) pressure (normalized by the maximum pressure at the heap base) distribution at the base of the steady flowing heaps.

Figure 1(a) and 1(b) shows snapshots of a steady-flowing granular heap formed by pouring grains in a narrow stream and raining, respectively. These snapshots are taken from the discrete element simulations performed using the open-source solver LIGGGHTS. To ensure a controlled comparison, all other parameters—including the dimensions of the base, particle diameter, and pouring velocity—are kept identical across both cases. By varying only the width of the incoming grain stream, we aim to understand how the mode of pouring influences the internal structure and the kinematics within the granular heap.

The first qualitative observation from Figure 1(a) and 1 (b) is the noticeable difference in heap shape during the flowing state, depending on the pouring protocol. When grains are rained, the surface of the resulting heap exhibits a slightly curved profile. In contrast, pouring grains through a narrow stream leads to the formation of a sharply defined, triangular-shaped heap with a well-established angle with the base. Additionally, the overall size of the heap is significantly larger in the wide stream case compared to the narrow stream, highlighting the strong influence of the pouring method on the geometry and extent of the granular pile.

To investigate this difference further, we analyzed the flow velocities and pressure distribution at the base of the heaps. These quantities are computed by spatially binning the simulation domain in all three directions and averaging over an extended period during the steady state. The resulting time-averaged velocity is presented in Figure 1(c). In both pouring protocols, the base velocity exhibits an exponential increase from the center of the heap toward the outer edges. In the narrow stream case, grains are primarily deposited near the apex of the heap, from where they freely slide down the slope under the influence of gravity. As these grains descend, they accelerate and reach relatively high velocities near the edges of the heap before eventually falling off the base. In contrast, when grains are rained, the deposition is more distributed, and not all particles experience the same downhill travel or acceleration before leaving the heap. As a result, the grains in the wide stream configuration generally exhibit lower velocities near the outer regions. This difference in particle deposition and transport dynamics explains the higher base velocities observed near the edge of the heap in the narrow stream case, as shown in Figure 1 (c). The time-averaged pressure distribution at the base is shown in Figure 1(d). The pressure is normalized by the peak pressure value observed at the base for both protocols. This is done because the objective here is to compare the qualitative trend and not the magnitude of the pressure. Since the velocity of grains in the central region of the heap is very small, a very long duration of the simulation time is

needed to get a smooth time-averaged flowfield. In the present case, the pressure data appears to be noisy, and more so near the central region, because the simulations were done for small durations after the steady state is achieved. Nevertheless, the difference in the pressure at the base due to the two protocols is clearly visible. We see that the pressure in the narrow stream case increases as we move radially into the heap, reaches a maximum value, and then decreases again, leading to a stress dip at the centre. No such local minimum is observed in the case of a wide stream deposition protocol.

The difference in velocity at the base is an important observation, as the two cases (pouring protocols) result in very different stress distributions at the base. Several experimental and numerical studies have established that when heaps are formed using different pouring protocols, they may look similar macroscopically during the static state but exhibit very different stress distributions at the base (Molenda et al. 1996; Vanel et al. 1999). The difference in the stress distribution is due to the arrangement of grains and the force chains through which stress is transmitted in the bulk. The orientation of the contact forces and the force chains relies on the velocity field, as is also demonstrated by Krishnaraj and Nott (2024).

The present results indicate that the velocity fields differ significantly between the two pouring protocols, and importantly, that flow occurs throughout the entire bulk of the heap. In the central region of the heap, the flow is relatively slow but transitions into an inertial regime near the free surface, where grains move more rapidly. This implies that as long as grains continue to be deposited from above, there is continuous rearrangement of particle contacts within the heap. These internal rearrangements lead to differences in the granular fabric, which influence the stress distribution at the base. Therefore, the pouring protocol plays a crucial role in shaping the internal structure and stress response of the granular heap. A thorough understanding of the flow behavior during the steady state can thus offer valuable insights into many of the long-standing and puzzling features observed in static granular systems.

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