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Velocity profiles of avalanches during hopper discharge

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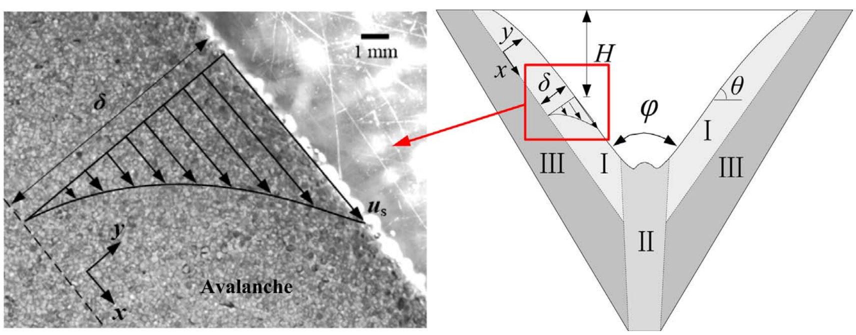
GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we investigate avalanches during the fully developed stage of the discharge in a quasi-two-dimensional wedge-shaped hopper. The velocity profiles of the avalanches are measured by employing a high-speed camera. The velocity profiles vary along the flow, but remain invariant in shape and follow a pure parabolic decrease from the surface. The velocity profiles can be expressed by two parameters of surface velocity and flowing layer thickness. These two parameters increase along the flow, and are both functions of the descending height. Therefore, the velocity profile can be predicted with the descending height. Moreover, a shear-thinning viscosity model is deduced to account for the granular flow behaviour.

1. Introduction

The granular matter is a complicated and unpredictable disordered system. It can not be simply explained by the mechanics of standard solid or liquid. The granular system yields and transforms from a solid state to a liquid state only when the stress exceeds a critical value [1–5]. The study of granular flows has attracted great interest from physicists and engineers due to their ubiquitous applications in numerous natural and industrial situations, such as dunes migration, snow avalanches, and powder handling.

One of the oldest and most important cases of granular flow is the discharge of particles through an orifice. Continuous efforts have been dedicated to understand different features presented by this type of flow, such as free-fall arch [6,7], clogging [7–15], density fluctuations [16,17], segregation [18] and collapse of silos [19] during discharge. Effects of the particle properties [20], gas drag [17,21–25], geometry [10,26–30], and inserts (obstacles) [9,31,32] on the flow behaviour in the silo have also been extensively studied to optimize the design and operation of the hopper.

The velocity field in a hopper is a fundamental indicator of

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discharge dynamics. Therefore, many experiments [7,29,33–38] and numerical simulations [16,39–41] have been carried out to obtain the whole velocity field. The digital particle image velocimetry methodology is usually used to obtain the flow field in the discharge experiments [29,33–37,42]. The flow in the hopper is usually distinguished into two types: mass flow, where all the particles are in motion, and funnel flow, where flow takes place only in a central region surrounded by stagnant particles. In funnel flow, a "V" shape crater usually forms at the surface of granular bed, and avalanches occur at the surface of the crater. Albaraki and Antony [29] studied the effect of the internal angle of the hopper on the flow pattern, and presented the mean velocity vector of grains inside the hoppers for both mass flow and funnel flow, but no expression of the velocity field is obtained. Avalanches, which are also called the surface flows and are usually studied on a heap [4,43–47] or in the rotating drum [2,48–52], can also be observed in the late period of the funnel flow for large internal angle. Maiti et al. [33] investigated the granular discharge in eccentric silos and mainly focused on the velocity profiles in the flow region above the orifice. Ferrari and Poletto [42] measured the particle velocity field near the outlet in an aerated hopper, and found that when the aeration rate increases to a certain extent, the initial static particles begin to flow. In the study of dynamical arching with photoelastic particles, the average velocity field is described using a combination of harmonic angular functions and a power law of radial position [7]. In a recent simulation of the mass flow in a conical hopper, the velocity profile is also a power law function of the distance from the orifice but with a different exponent and expression [39].

So far, a number of studies have been performed to investigate the hopper discharge, and studies of the velocity field in the hopper mainly focus on the mass flow and the central region above the orifice in a funnel flow. Detailed expressions for predicting the velocity field in the hopper especially in the avalanches of a funnel flow are still lacking. Here in this paper, we conduct a funnel flow in a quasi-two-dimensional wedge-shaped hopper, and investigate avalanches during the discharge. Moreover, velocity profile for predicting the surface flow are obtained, and a viscosity model is also deduced.

2. Experimental

The experimental setup is simple in its principle, as sketched in Fig. 1, consisting of a high-speed digital camera (Fastcam SA2 by Photron Limited), a digital scale and a quasi-two-dimensional wedge-shaped hopper with an open angle of 60°. We use glass beads of density ρ_p = 2490 kg/m^3 and of particle size d_p = 131 μm and 237 μm. The cumulative particle size distributions of the glass beads are shown in Fig. 2. Both particle sizes ensure a good flowability of the material. The vertical sidewalls of the hopper are made of two transparent glass plates to allow visualization. The gap between the two sidewalls is w = 4.5 mm making the front and rear boundaries close enough to achieve a quasi-two-dimensional condition. The flow rates calculated from the measured particle velocities at the outlet match well with the measured flow rates with discrepancies within 8.3%. Therefore, the wall friction in the following is neglect [53,54]. The vertical height of the hopper is 275.0 mm and the width of the outlet is 30.0 mm. The hopper is initially fulfilled with glass beads, and a slide lock is employed at the outlet to control the onset of the discharge.

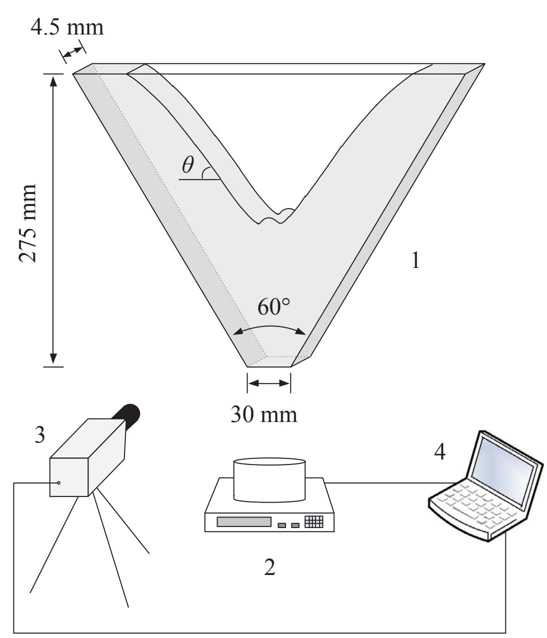

Fig. 1. Sketch of the experimental setup. 1-two dimensional wedge-shaped hopper, 2-digital scale, 3-high-speed digital camera, 4-computer.

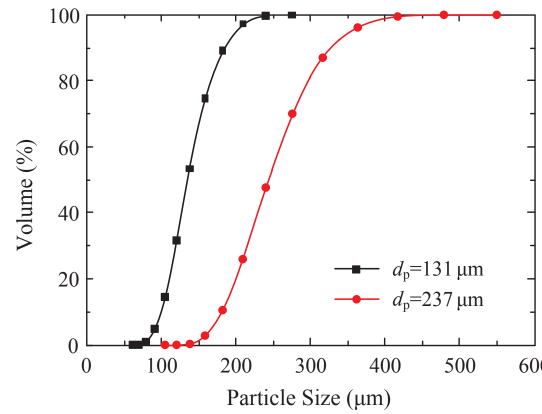

Fig. 2. The cumulative particle size distributions of the glass beads.

The mass flow rates of the glass beads recorded by the digital scale are constant during the discharge, and are highly reproducible from run to run. The mass flow rates are 95.5 g/s and 107.4 g/s for particle size d_p = 131 and 237 μm, respectively. A funnel flow is observed during the discharge, and the granular bed is distinguished into three flow regions (see Fig. 3): downslope flowing layer I, central flow II, and stagnant zone III. The discharge begins with a rapid upward propagation of the central flow region, and once the central flow region reaches the upper surface, the initially horizontal surface becomes concave, and a "V" shape crater is therefore developed at the surface. The evolution of the crater angle φ (defined as the angle between the steepest tangents to the flow surfaces) is shown in Fig. 4. The crater angle φ decreases dramatically in the first second, and then attains a plateau. This can be explained as follow: During the emptying period, the discharge rate is constant, which indicates a constant area variation rate of the crater. Therefore, in the early stage when the crater is small, the combination of increases in both the crater size and the avalanche angle θ (the angle

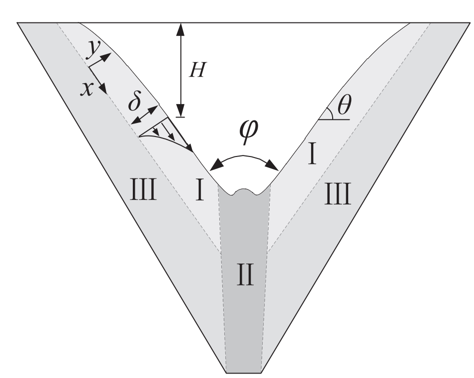

Fig. 3. Schematic of the granular flow in the hopper.