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Original Research Paper

Testing steady and transient velocity scalings in a silo

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ABSTRACT

Gravity-driven discharge experiments were performed in a perspex 3D flat bottomed silo which was filled with a granular material, and had a variable discharge orifice size. The granular material used was amaranth seed with an average diameter of 1 mm. Particle Image Velocimetry (PIV) analysis was performed on a high-speed video recording of the discharge, and used to quantify the velocity field within the silo both at steady state and during the development of flow. We verified not only that the steady-state velocity of the granules in the silo scales with the flow rate, but, additionally, the transition to a steady-state regime is also rate-controlled by the volumetric discharge. We present evidence that, away from the discharge orifice, the flow behaves identically, regardless of the orifice diameter, in a scaled time. We discuss these results with reference to the physics and mathematical modelling of granular flows.

1. Introduction

Flowing granular media behave in very complex ways, even in simple geometries. For this reason, despite intense study, descriptions of their motion are lagging behind those of flowing liquids. At different shear-rates the grains can act as a solid, flow like a fluid, or, at high shear, even behave like a gas [1]. The friction which develops between grains has been shown to be shear-rate dependent [2], and the medium is somewhat compressible and amenable to developing dilation and shock waves [3,4]. Granular materials have been stored in silo-like constructions for thousands of years [5,1], and the most common way of emptying such vessels is by gravity discharge through an orifice. The flow rate is controlled by the orifice diameter and obeys the so-called Beverloo scaling [6,7]. In industrial granular flows the design of silos has implications for product quality and control. Since it is of obvious industrial importance, the silo has formed the basis of many studies of dense granular flow in recent years including experimental investigations [8–11], discrete mathematical models [12–15], and continuum models [16–22]. It has been suggested [16,11] that the mean steady-state velocity profile for granular flow from a silo is flow-rate dependent, rather than time dependent. The effect of changing the flow rate (by changing the orifice size) is to simply speed up or slow down the same process. Kamrin [16] describes this as "*watching the same movie at a different speed*". Experiments to test velocity scaling in silos have previously been performed using numerical modelling [23], in silos of small depth (where the depth of the silo is slightly larger than the particle size) [24,25], very close to the orifice [26,27], over short time-scales [25], and for single orifice size (single flow rate) [25]; few studies have rigorously tested the transient scaling. However, experimental verification of flow-rate dependent scaling in large-scale systems is still necessary, particularly in the transient regime. Motivated by the need for a deeper understanding of the dense flow behaviour of granular materials in large scale silo systems, and the necessity of data to improve and test mathematical models, the objective of the current work is to measure the velocity of a draining granular material from a 3D flat bottomed silo in the transient and steady regime in a large scale silo, over the whole silo area (i.e. close to and far from the orifice), for various orifice sizes, from flow initiation to steady flow. The silo system described herein has depth 15× larger than the particle diameter, significantly wider than previous experiments where this ratio was slightly greater than one [27]. We endeavour to test if flow-rate dependent scaling holds in both the transient and steady regime in the silo.

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2. Experimental method

A diagram of the experimental apparatus is displayed in Fig. 1. The 3D silo was built of perspex which allowed clear view of the flowing particles. The silo has dimensions 200 mm width, W, 350 mm height, H, and 15 mm depth, D. When the experiments are performed the apparatus is connected above to a feed hopper to ensure a constant volume of material in the silo, and below to a collector section, both of which are at atmospheric pressure. At the bottom of the silo are two sliders, one of which acts as an initiation mechanism, while the other has a centrally located slot orifice of width D_0 which the particles flow through. Amaranth seeds were selected for this study since they have a moderate particle size (1 mm diameter), was very compatible with the Particle Image Velocimetry method to be discussed below, and were found to be free flowing. The particle density was measured as 1310 ± 10 kg/m^3, and, once loaded, the bulk density was measured as 870 ± 10 kg/m^3. The internal angle of friction and wall friction against perspex have previously been measured as 28° and 25° respectively [10]. Since the wall friction is close to the internal angle of friction we expected the wall motion measured by PIV to be representative of the velocity in the bulk. Particle tracking tests indicate that the velocity at the walls was between 2 and 5% lower than in the bulk. For each experiment the silo is loaded from above with the initiation slider closed, then, once ready, the slider is remotely opened to allow flow to initiate. The development of the flow is recorded using a high-definition, high-speed, black and white camera (Basler acA2000-340 km) at 500 frames per second (FPS), and then downsampled to 62.5 FPS. The camera recorded images on one face of the silo only, hence our analysis herein is considered to be quasi-2D. It was found that approximately 40 *s* of footage was required for the flow to reach steady state at the slowest flow rate. The flow rate was controlled by changing the width, D_0 of the slot orifice. In this study we used $D_0 = 8, 10, 12, 14,$ and 16 mm respectively. Once the recordings were made, each frame was processed using the software PIVlab [28,29] to obtain the velocity field at each time-step.

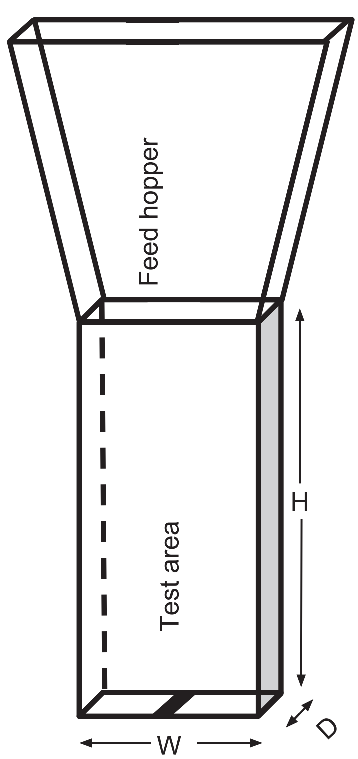

Fig. 1. A diagram of the experimental apparatus used for this study. The silo was constructed from perspex.

3. Results

To measure the volumetric flow rate (per unit silo depth) at steady state we used the velocity components measured using PIV. We firstly averaged the last 5 s of the flow in the steady regime, then, at various heights above the orifice, numerically integrated the vertical velocity component, v, using the trapezoidal numerical integration;

$$Q = \int_{-w/2}^{w/2} v dx,$$

where w is the width of the silo, and x the horizontal coordinate and Q is the volumetric flow rate per unit silo depth. At the various heights the flow rate was seen to be effectively constant, so a simple average of the measurements was taken.

3.1. Results and scaling at steady state

We here test the hypothesis that the velocity at steady state scales with the volumetric flow rate in the large ($D = 15\times$ particle diameter) system. To reduce the error due to noise (in the PIV analysis), 5 s of images at steady state were analysed using the PIV method, then the resulting velocity components averaged to achieve a smooth velocity field. Fig. 2 displays contour plots of the velocity magnitude for the five different slot diameter experiments at steady state, where the colours represent the magnitude of flow velocity. Each plot is given at the same contour levels. Although (as expected) the larger slot orifices produce larger velocity magnitudes, the same basic structure is present in each image.

We now introduce the well-known velocity scaling, or normalisation, to attempt to confirm the flow-rate dependence at steady state. If we define our length scale to be d = 1 mm, the diameter of the amaranth grains, then the natural velocity scale is given by Q/d, where Q is the volumetric flow rate per unit depth of the silo. Therefore, we rescale our velocities such that

$$v_N = vd/Q, \quad (1)$$

$$u_N = ud/Q, \quad (2)$$

where u, v are the (unscaled) horizontal and vertical velocity components, and those with the subscript N are the normalised (scaled) components. Fig. 3 displays contour plots of the normalised velocity magnitude for the five different slot diameter experiments at steady state using the velocity scalings given by Eqs. (1) and (2). As before, each plot is given at the same contour levels. Visually, the results are consistent with the hypothesis that the system is indeed flow rate controlled, since the five velocity field diagrams look very similar. To quantify this visual observation we plot the original, v, and normalised, v_N, vertical velocity components at three heights above the orifice, 0.05 m (50 particle diameters), 0.1 m (100 particle diameters), and 0.15 m (150 particle diameters). Fig. 4 displays the results of this scaling at the three heights for the scaled and unscaled velocity. The normalised velocity profiles all collapse onto a single curve, consistent with flow rate system control. Such a scaling has been shown to hold at steady state in previous investigations ([11,27], for example). Close to the orifice, at height 0.05 m, the vertical velocity component has a Gaussian-like shape, as is commonly encountered in granular silo flows. However, further from the orifice, such as in the 0.1 m and 0.15 m plots, the Gaussian-like curve is flattened somewhat near the peak. In these regions, far from the orifice, the stresses are lower than near the orifice. However, shearing still occurs, but at a lower rate.

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