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Original Research Paper

Density-driven sinking dynamics of a granular ring in sheared granular flows

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ABSTRACT

This study reports experimental findings on the sinking dynamics of a heavy granular ring caused by the density-driven segregation effect in sheared granular flows. Specifically, this study systematically investigates the influences of the density ratio, shear rate, and solid fraction of the granular material on the sinking behavior of a heavy granular ring. The parameters of the dimensionless sinking depth and sinking rate, respectively, describe the change in the granular ring position and quantify the particle sinking speed. Experimental results show that both the dimensionless sinking depth and the sinking rate increase as the bottom wall velocity (shear rate) and solid fraction increase. The dimensionless sinking depth and the sinking rate also exhibit a linear relation. The dimensionless sinking depth does not increase monotonically as the density ratio increases. The sinking rate increases linearly with the final steady-state sinking depth for the same heavy granular ring structure, regardless of the wall velocity (shear rate), solid fraction, and density ratio.

1. Introduction

Granular materials are ubiquitous in our daily life, and are widely applied in many industries. The handling and processing of granular materials have economic importance in numerous industries, including foodstuffs, pharmaceutical products, detergents, chemicals, mineral processing, paint, mineral, and plastics. Depending on the driving conditions, granular matter can behave like a solid, liquid, or gas. In addition, a solid-like region and a liquid-like region (i.e., a shear band region) may coexist in the same flow system [1–4]. Shear cells have been extensively used to investigate the fundamental mechanism of granular materials because the sheared granular flow is one of the simplest flow models and is suitable for fundamental research [5–14].

Granular segregation has become an important issue in many industrial processes (e.g., pharmaceutical products, foodstuffs, detergents, chemicals, and plastics) and in natural sciences (e.g., avalanches, landslides, and debris flows) in the past decades [15–28], but remains complex and poorly understood processes. Therefore, numerous researchers have studied the segregation mechanism of granular materials over the past few decades. The segregation phenomenon occurring in granular materials can be influenced by external driving conditions, interstitial fluid, container geometry, and particle properties such as size, density, restitution coefficient, shape, and friction coefficient. Golick and Daniels [16] investigated the mixing and subsequent re-segregation of different-sized particles in an annular shear cell. They found that the mixing rate behaved as expected at low confining pressure. Segregation also occurs in a binary-mixture system with various densities because of the buoyancy effect of denser particles sinking to lower levels in the flowing layer while lighter particles rise [17].

In the past, some theoretical models were developed to investigate the density-induced granular segregation [22–28]. Tripathi and Khakhar [22] studied the sedimentation of a heavier particle in a steady, gravity-driven granular flow of otherwise identical spheres, on a rough inclined plane by taking a hydrodynamic approach. They indicated that the drag force is given by a modified Stokes drag law and the buoyancy force by Archimedes' principle. Khakhar and his colleagues also reported the form of the inverse drag function by considering movement of particles differing in density through an effective medium and showed that the drag increased with an effective temperature in his recently reported studies [23,26]. Fan and Hill [27] employed the kinetic theory and mixture theory to study the density-induced granular segregation in a vertical chute. They showed that in sparse flows,

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the heavier particles segregate to the lower shear rates. There is no segregation reversal at high solid fraction in density-induced segregation systems. They also showed that the kinetic theory predicted well the segregation at low solid fraction but breaks down at the higher solid fractions.

The size-induced segregation of granular materials has received considerable attention in the past few decades. However, relatively few studies have focused on density-driven segregation, particularly in sheared granular materials. Although the density-driven segregation of granular materials is an important process in many industrial processes and natural geophysics, the mechanism of density-driven segregation remains unclear. Therefore, this study presents a series of experiments to investigate the sinking dynamics of a heavy granular ring caused by the buoyancy effect in a binary mixture with identical particle sizes and various particle densities in a shear cell device. The analysis in this study also considers the effects of the density ratio, shear rate, and solid fraction on the sinking dynamics of a heavy granular ring in sheared granular flows.

2. Experimental procedure

Fig. 1(a) shows a schematic representation of the shear cell apparatus. The shear device consisted of a rotating bottom disk and a stationary upper disk. The rotating bottom disk had an outside diameter of 0.45 m, and was driven by a 3 hp AC motor. The rotation speed was controlled by a variable-speed inverter, and measured by a tachometer. The bottom disk was made of transparent plexiglass to facilitate observing and recording the particle motion. An annular trough (inside diameter: 0.32 m; outside diameter: 0.42 m; depth: 0.045 m) was cut into the bottom disk. The stationary upper disk could be inserted into the trough where the granular materials were placed in the test section. The height H of the test section could be adjusted by moving the upper disk and measured by a dial indicator (Mitutoyo Jeweled Dial Indicator, range: 0–50 mm, accuracy of 0.01 mm).

Four types of beads with the same particle size (3 mm with the standard deviation of 0.05 mm) but different densities (stainless steel = 7.93 g/cm^3, glass bead = 2.48 g/cm^3, polyformaldehyde (POM) = 1.41 g/cm^3, and polypropylene (PP) = 0.90 g/cm^3) were used as the granular materials. Five density ratios were used to investigate the sinking dynamics of the heavy granular ring in this study. The density ratios were ρ_t/ρ_b = 8.81, 5.62, 3.20, 2.76, and 1.76, where ρ_t is the density of the heavy particles (granular ring) and ρ_b is the density of the light particles (background particles) in the binary mixture. To study the sinking dynamics of the granular ring, we carefully poured a flat layer of lighter particles (84% of total test particle volume) in random packings on the bottom of the annular channel, followed by a flat layer of heavier particles (16% of total test particle volume). These heavier particles formed a granular ring and served as tracer particles in each experiment (Fig. 1(b)). The average solid fraction (ν) was calculated from the total particle mass in the test section divided by the particle density and the test section volume:

$$\nu = \frac{m_t/\rho_t + m_b/\rho_b}{H\pi(r_0^2 - r_i^2)} \tag{1}$$

where m_t and m_b represent the mass of the whole granular ring (heavy particles) and the mass of background (light) particles, respectively, r_i is the inside radius, and r_0 is the outside radius of the annular trough. In this study, we chose a relatively high solid fraction and both walls (bottom and upper walls) had frequent contacts with granular materials, thus the granular material occupied most of the space in the test section. However, the solid fraction we could perform has a limitation because a too high solid fraction flow is easier to get the jamming of the granular materials. In this study, we changed the mass of the background (lighter) particles to obtain the different solid fractions. An electronic balance (Precisa XS12200D, range: 0–12.2kg, accuracy of 0.1g) was used to measure the weight of granular materials. The channel height H was fixed at 33.35 mm. Thus, five amounts of granular materials were poured into the annular channel to generate different solid fractions in this study (ν = 0.5852, 0.5903, 0.5953, 0.5981, and 0.6003). A 3.0 mm layer of glass beads was adhered to both the bottom and the upper wall surfaces in a random packing organization to generate enough shear force in the flow to avoid crystallization. The small insert plot in Fig. 1(a) shows a 2D granular flow in the test section with a streamwise direction (u direction) as the x-axis and transverse direction (v direction) as the y-axis (y = 0 at the moving boundary wall). Because of the limitations of observations, only the flows adjacent to the outer surface of the annular trough in the bottom disk were recorded and analyzed. Before each experimental run, the inner surface was cleaned and polished by wax to reduce the effect of wall friction. The velocity of the bottom wall u_0 was calculated from the product of the rotational speed of the bottom disk and the outside radius of the trough. This study considers six wall velocities u_0 of 0.31 m/s, 0.38 m/s, 0.46 m/s, 0.54 m/s, 0.61 m/s, and 0.69 m/s corresponding to the shear rates $\gamma = \mathrm{d}\langle u\rangle/\mathrm{d}y$ of 9.293 1/s, 11.394 1/s, 13.793 1/s, 16.192 1/s, 18.291 1/s, 20.690 1/s, respectively. Table 1 shows the experimental parameters used in this study.

To investigate the sinking dynamics of a granular ring, flow motion was recorded using a high-speed camera at a resolution of 628 × 540 pixels (IDT MotionPro X3 PLUS; highest speed of 2000 FPS and a resolution of 1280 × 1024 pixels). Fig. 1(c) shows a schematic drawing of the experimental setup. Images were captured at a speed of 30 FPS. Image-processing technology and a particle-tracking method were used to digitize each frame with gray levels ranging from 0 to 255 to show the colors of the tracer particles and background particles. This approach revealed the positions of the heavy particles and the average height of the heavy granular ring in every frame. Thus, the sinking process of the heavy granular ring can also be determined. To quantify the sinking strength of the heavy granular ring, we defined the dimensionless sinking depth, S_d, as follows:

$$S_d = \frac{h_0 - h(t)}{H} \tag{2}$$

where h_0 is the initial average height of the heavy granular ring that is determined by averaging the heavy particles positions, and $h(t)$ is the average sinking depth of the heavy granular ring that is determined by averaging the heavy particles positions in each frame. The channel height H was fixed at 33.35 mm, as Fig. 2 shows. The experiments were performed at least three times for each case to calculate the average value in this study.

3. Results and discussion

Fig. 3 shows snapshot images of the heavy particle ring position varying with time from the initial state (Fig. 3(a)) to the steady state (Fig. 3(b)) with the solid fraction ν = 0.5953, u_0 = 0.54 m/s, and density ratio of 1.76. The white particles are glass beads (heavier particles), and the POM beads are black. The heavy particle ring sinks gradually and reaches a steady-state sinking depth because of the buoyancy effect when a shear force is applied. To quantify the sinking dynamics of the heavy granular ring, the dimensionless sinking depth, S_d was plotted as a function of time with 6 wall velocities (shear rates), and the solid fraction and the density ratio are 0.5953 and 8.81, respectively (Fig. 4). In each case, the dimensionless sinking depth gradually increases until reaching the