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The influence of gravity on dynamic properties in sheared granular flows

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A B S T R A C T

The influences of gravity on the granular flow behavior and dynamic properties were experimentally studied in a vertical shear cell device where the shear dilation direction of granular materials was perpendicular to the gravity direction. The particle motions were recorded by a high-speed camera from three different observational views. By using image processing technology and the particle tracking method, the average velocities and granular temperatures in the streamwise and the transverse directions were successfully measured and analyzed. The results show that the anisotropic motions exist in sheared granular flows. The dynamic properties in the streamwise direction are larger than those in the transverse direction. Due to the gravity effect and bulk flow of granular materials, the local packing structure is not homogenous in the vertical shear cell. By comparing the three different observational views in the vertical shear cell, we find that the spatial average velocity and self-diffusion coefficient are the greatest but the shear rate and granular temperature are the smallest when the particles are co-flowing with gravity causing the most dilute packing structure due to the gravity effect. Similar experiments were also performed in a horizontal shear cell where the shear dilation direction of granular materials was against the gravity direction. The dynamic properties are smaller in the horizontal shear cell than those in the vertical shear cell. It is because the horizontal shear cell has the smaller shear rate with the shear dilation direction against the gravity direction.

1. Introduction

Granular solid material may flow like a fluid. Avalanches, hopper flows, and fluidized beds are some examples (Shearer et al., 2008; Datta et al., 2008; Woods et al., 2008). Handling and processing granular materials have economical importance in different industries, such as foodstuffs, pharmaceutical products, detergents, chemicals, and plastics, etc. Shear granular flows are widely found in geologic and in industrial applications, including avalanches, landslides chutes, rotating drums, shear mixers, and silos. However some fundamental mechanisms of granular flow behavior are still poorly understood and the deeper study is necessary.

This study focuses on the granular flow with collections of discrete solid particles dispersed in an interstitial air where the gaseous phase plays a negligible role in the flow mechanics. The dominant mechanism affecting the flow behavior of granular materials is the random motions of particles resulting from the interactive collisions between particles and between particles and wall (Campbell, 1990). Due to the analogy between the random motions of particles in a granular flow and those of molecules in a gas, many researchers tried to revise the dense-gas kinetic theory by assuming the isotropic distributions of fluctuations and granular temperature (Jenkins and Savage, 1983; Lun et al., 1984; Jenkins and Richman, 1985) or to use molecular dynamic simulations (Walton and Braun, 1986; Campbell, 1989; Lan and Rosato, 1995) to analyze and model the shear granular flow behavior. The energy dissipation due to the inelastic collisions and friction effect was also considered in the theory and simulations. However the key assumption of the isotropic distributions of fluctuations and granular temperature in the theory might be failed in most granular material flow systems.

Gravity has a significant influence on granular flows including the avalanches, the sheared flow in shear cell, sandpiles, and landslides. For example, in the sheared flow in the horizontal Couette device, there existed a solid-like region due to the gravity effect mitigating the particles expansion (Hsiau and Shieh, 2000; Hsiau and Yang, 2002). The dynamic repose angle was found to decrease with the increasing gravity-level in a rotating drum (Brucks et al., 2007). Arndt et al. (2006) also found that the flowing layer in a rotating tumbler was independent of the gravity level and that the shear rate in the flowing layer increased with the increase of gravity level from $1g$ to $12g$ where g is the gravitational acceleration. Baran and Kondic (2006) concluded that the presence of gravity had a significant influence on the velocity profiles and stresses in an annular Couette cell by employing three-dimensional discrete element simulations.

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Many researchers in the field of rapid granular flows performed their experimental studies in a Couette shear device because the Couette sheared granular flow is one of the simplest flow models and suitable for fundamental research (Grebenkov et al., 2008; Hsiau and Yang, 2002; Hsiau and Shieh, 2000; Wang and Campbell, 1992; Johnson and Jackson, 1987; Savage and Sayed, 1984). Most studies performed the experimental tests in horizontal Couette devices where the bulk motions of granular flows were perpendicular to the gravity. Wang and Campbell (1992) had a shear cell facility that could be oriented so that the gravity was perpendicular to the velocity gradient, however, they only performed relatively dilute flow experiments with solid fraction less than 0.35.

Dilation may occur when granular materials are under shear force. The dilatancy of granular materials is defined as the need for volume change during the shearing. This phenomenon is the so-called shear dilation. In this study, we used a vertical shear device where the shear dilation direction of granular materials was perpendicular to the gravity. The granular materials may flow with or against the gravity direction in the vertical shear cell therefore we could study the gravity effect on the dynamic properties in sheared granular materials using the simple vertical shear device compared to the complicated and expensive experimental facility using to investigate the gravity effect on granular flow in past studies (Brucks et al., 2007; Arndt et al., 2006). The velocities, granular temperatures, and self-diffusion coefficients will be investigated. The similar experiments were also performed in a horizontal shear cell where the shear dilation direction of granular materials was against the gravity direction in comparison with the vertical shear cell.

2. Experimental procedure

A vertical rotating shear cell was constructed to generate the shear granular flow, as shown in Fig. 1. This facility is very similar to our earlier experimental device (Hsiau and Shieh, 1999; Hsiau and Yang, 2002) but was orientated by 90° so that the gravity direction is perpendicular to the rotation axis of shear cell and to the velocity gradient of the granular flow. The shear device consists of a rotatable right disk and a stationary left disk. The right disk, with outside diameter of 450.0 mm, is driven by a 3 hp AC motor and the rotation speed is controlled by a variable speed inverter and can be measured by a tachometer. The right disk is made of plexiglass for observation purpose. An annular trough (inside diameter: 316.7 mm; outside diameter: 420.2 mm; depth: 45.0 mm) was cut in the right disk. The stationary left disk could be inserted into the trough where the granular materials were put in the test section. The test section width could be adjusted and measured by a dial indicator. However, the channel width (w) was fixed at 20.0 mm in this study.

The glass beads (colors of black and white) with an average diameter d_p of 2.0 mm (standard deviation of 0.04 mm and particle density of 2.508 g/cm^3) were used as granular materials in the experiments. The narrow size distribution was used to avoid size segregation in this study. The total mass of glass beads was 2090.0 g with 3% white particles and 97% black particles. The white particles were served as tracer particles in the experiments and were mixed uniformly with background particles before each experiment. The average solid fraction was calculated from the total particle mass (2090.0 g) in the test section divided by the particle density and the test section volume. In this study, we expected both walls (left and right walls) had highly frequently interactive collisions with granular materials, and the granular could occupy most space in the test section, therefore a relatively high solid fraction was chose. However the solid fraction could

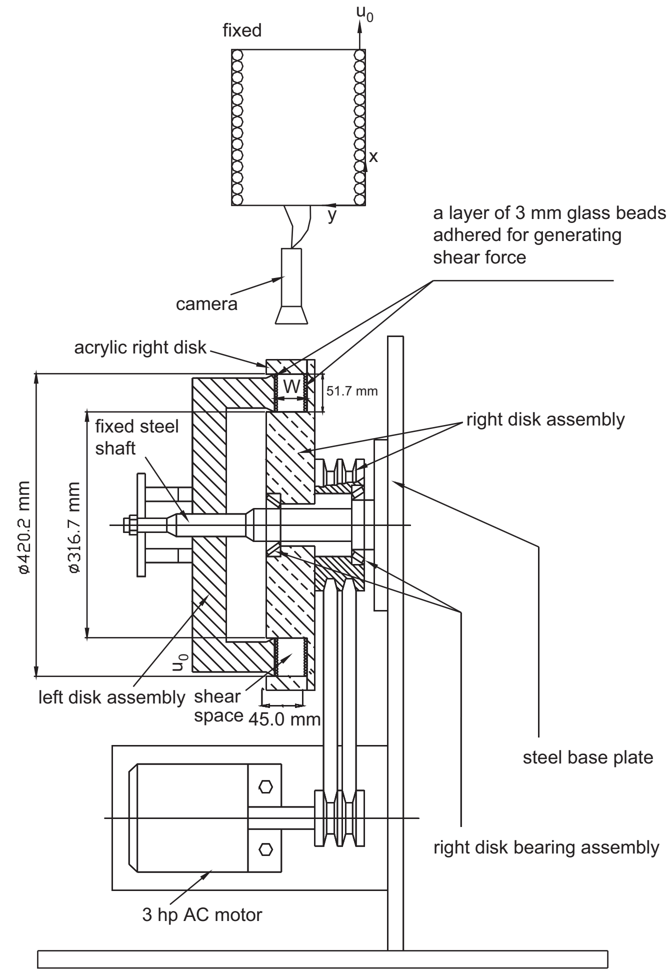

Fig. 1. The schematic drawing of the experimental apparatus.

not be too high causing jamming of granular materials. So, in this study, the average solid fraction was fixed as 0.6112. A layer of 3.0 mm glass beads was adhered to both the left and the right wall surfaces, in a random packing organization, to generate enough shear force in the flow and to avoid the forming crystallization configuration. The friction coefficient of the 2.0 mm glass beads and the wall (adhered by 3.0 mm glass beads) was 0.52 from the measurement using the commercial Jenike shearing Tester. The granular flow in the test section is assumed to be two-dimensional with streamwise direction (u direction) as x-axis and transverse direction (v direction) as y-axis (y=0 at the moving boundary wall), as shown in the upper small insert plot in Fig. 1. Because of the limitations of observation, only the flows adjacent to the outer surface of the annular trough in the right disk could be recorded and analyzed. Before each experiment, the inner surface was cleaned and polished by wax to reduce the wall friction effect. The velocity of the right wall u_0 was calculated from the product of the rotational speed of the right disk and the outside radius of the trough. Four different u_0 of 0.22, 0.44, 0.66, and 0.88 m/s were used in this study.

A high-speed camera was used to record the motions of granular materials. The images were grabbed at a speed of 500 frames per second. The average and fluctuation velocities in the streamwise and transverse directions were measured by employing particle tracking method and image processing technology. The cross-correlation technique was used to process the stored images and to decide the shift of each tracer particle in every two consecutive images. The details of the