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Wet granular materials in sheared flows

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Abstract

The transport properties of wet granular materials in a shear cell apparatus have been studied. If the particles are wet, the flow becomes more viscous forming liquid bridges between particles. The dynamic liquid bridge forces are considered as the cohesive forces between particles to restrict their movements. The cohesive forces make the particles stick tighter with each other and hamper the movement of particles. The mixing and transport properties are influenced seriously by the amount of moisture added in the flow. This paper discusses a series of experiments performed in a shear cell device with five different moisture contents using 3-mm glass spheres as the granular materials. The motion of granular materials was recorded by a high-speed camera. Using the image processing technology and particle tracking method, the average and fluctuation velocities in the streamwise and transverse directions could be measured. The self-diffusion coefficient could be found from the history of the particle displacements. The self-diffusion coefficients and fluctuations in the streamwise direction were much larger than those in the transverse direction. Three bi-directional stress gages were installed to the upper wall to measure the normal and shear stresses of the granular materials along the upper wall. For wetter granular material flows, the fluctuation velocities and the self-diffusion coefficients were smaller.

Keywords: Moisture content; Cohesive; Granular flows; Shear cell; Self-diffusion coefficient; Stress gage

1. Introduction

Granular materials are collections of discrete solid particles dispersed in vacuum or in an interstitial fluid. The voids between particles are filled with a fluid-like air or water. Therefore, the flow behavior of granular material can be treated as a multiphase flow. Granular flows are widely found in nature, such as avalanche, soil liquefaction, landslides and river sedimentation. In industries, granular flows include mixing and transport processes of foodstuffs, coal, pellets, and metal mine. In chemical industry, more than 30% of the products are formed as particles (Shamlou, 1988). All granular flows are highly dissipative. The energy supplied to a granular flow, through vibration, gravity, or shearing is rapidly dissipated into heat. Thus, energy must be constantly supplied to the system to maintain a granular flow.

The dominant mechanism effecting the flow behavior is the random motion of particles resulted from the interactive collision between particles (Campbell, 1990). Since the random motion of particles in a granular flow is analogous to the motion of molecules in a gas, the dense-gas kinetic theory (Savage and Jeffrey, 1981; Jenkins and Savage, 1983; Lun et al., 1984; Jenkins and Richman, 1985) and molecular dynamic simulations (Campbell, 1989; Lan and Rosato, 1995) are utilized to analyze and model the granular flow behavior. However, the granular flow is not completely analogous to molecular dynamic theory. In this study, we use the dense-gas kinetic theory to analyze the granular flow.

The presence of a small amount of interstitial fluid in the system introduces another degree of complexity due to the cohesive forces between particles in addition to the core repulsive force and the force of friction in a dry granular matter. An increase in repose angle is the most well known effect of the presence of interstitial fluid in a granular system and has become a topic of current interest (Tegzes et al., 1999; Halsey and Levine, 1998). The interstitial fluid also

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alters the percolation of particles, and the particles tend to behave as clumps rather than individual grains. The research about wet particles is more important at present. When the particles contain slight amount of water, they would gather together and hinder the movements by themselves. Ambient humidity, for instance, causes serious disruptions by creating clumps of particles that are more or less mobile. We know from common experience that wet sands could be fairly cohesive, whereas dry sands crumble apart readily. Due to the appearance of the liquid bridge between particles, the capillary force should be considered as an important force affecting the motion behaviors of the granular system. Calculating the capillary force that keeps two wet spheres in contact is far from trivial. Several methods have been proposed to avoid the difficulties associated with solving the Laplace–Young equation (Erle et al., 1971; Lian et al., 1993).

The Couette granular flow is the simplest and suitable for fundamental research. Some examples of the related experimental studies include the investigations by Savage and Mckeown (1983); Savage and Sayed (1984); Hanes and Inman (1985); Johnson and Jackson (1987); Wang and Campbell (1992) and Hsiau and Shieh (1999). Most earlier experiments measured only the average stresses from the transducers and assumed that the flow in the cell was a simple sheared flow. However, the assumption should not be true in a shear cell because of the gravitational force as demonstrated in the study of Hsiau and Shieh (1999). In our earlier research (Hsiau and Yang, 2002, 2005), we started using the bi-directional stress gages to measure the normal and shear stresses of granular materials along the upper wall. The granular flows with different wall friction coefficients and solid fractions have been discussed in the earlier works. The self-diffusion coefficients of granular flows increase with the increase in wall friction coefficients. However, they decrease with the increase in solid fractions. This paper focuses on the effect of the presence of moisture. We performed experiments in a shear cell device supplied by a constant external energy using granular materials with five different moisture contents. The present paper employed the imaging technology and particle tracking method to investigate the granular flow transport properties in the shear cell. Three bi-directional stress gages were buried in the upper wall to measure the normal and shear stresses of granular materials along the surface. The dependence of the measurements on the moisture content will be discussed.

2. Experimental setup

Soda lime beads with an average diameter, d_p, of 3 mm (standard deviation of 0.04 mm and particle density of 2490 kg/m^3) have been used as the experimental material. There are 5% identical red soda lime beads serving as tracer particles. The average solid fraction v of the test is calculated from the particle mass (1.5 kg in this paper) divided by the particle density and the test section volume. In this study, we control the average solid fraction v as 0.6285. A certain amount of water and test particles were weighed by an electronic scale with an accuracy of 0.001 g. The water and the particles were put into a sealed jar. The sealed jar was shaken to mix the water and particles. The wet particles were then put into the test section of the shear cell apparatus. We also measured the weight of the sealed jar and the residual water, which coherences the sealed jar. The accurate values of the masses of water and particles, which were put in the shear cell, and the dimensionless liquid volume V^* could be calculated. The dimensionless liquid volume, $V^* = V_l/(V_l + V_p)$, was used as a control parameter in this study, where V_l and V_p were the volumes of water and the particles, respectively.

The annular shear cell apparatus is schematically shown in Fig. 1. The experimental setup has a rotating bottom disk (outside diameter: 45.00 cm; thickness of 4.50 cm), which is driven by a 3 hp AC-Motor. A tachometer was used to measure the rotation speed of the bottom disk. In this study, the AC-Motor supplies a constant energy into the shear cell. The bottom disk is made of plexiglass for visualization purposes. An annular trough (inner diameter: 31.67 cm; outer diameter: 42.02 cm) was cut in the bottom disk. The stationary upper disk was inserted into the trough after the wet granular materials were put in the test section. A dial indicator is installed in the apparatus to measure the adjustable height h of the test section.

Three bi-directional stress gages were installed along the upper wall to measure the normal and shear stresses, as shown in Fig. 1. The detecting surfaces of the stress gages are in the same plane with the upper wall surface. The stress gage is based on a simple ring dynamometric element, which is provided with semiconductor strain gages (Smid, 1980). The normal and shear stresses are realized by two different wiring systems of the strain gages, and the normal and shear stresses can be measured simultaneously.

The stress gage utilizes two different full bridge semiconductor strain circuits to measure both stress components simultaneously and independently. The diameter of the measuring surface of the gage is 2.0 cm. The measuring surface can be replaced with the same wall material as the upper surface of the test section. A stable voltage of 10 V is supplied to each stress gage by a DC power supply. When the stress gages sense the normal and shear forces from the granular materials, the voltage signals are translated from the gages to a personal computer through a data acquisition card (Advantech PCL-818HG). A series of calibration tests were carefully done along two directions. The accuracy of the pressure gages is over 99%. The normal and shear stresses are determined from the average signals obtained from the three stress gages.

In this study, the influence of the moisture conditions on the flow behavior is investigated. The friction coefficients between particles and walls, and among particles were measured by a commercial Jenike shear tester. The detail method of operation is in the handbook of Jenike (1964). The Jenike