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Combined effects of internal friction and bed height on the Brazil-nut problem in a shaker

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ABSTRACT

We experimentally studied the influence of an intruder's friction coefficient and bed-filling height on the Brazil-nut effect in a quasi-2D vertical vibration granular bed. The motion of intruder was successfully measured using a high-speed camera and the rising time of intruder was determined by using a particle tracking method with the help of image processing technology. The results show that an intruder's friction coefficient and filling bed height play significant roles in the rise dynamics. The results also show that the rise time increases when the intruder's friction coefficient increases, which is reduced when the filling bed height decreases. Penetration length and friction drag force were also determined in this study. The penetration length was reduced and the friction drag force was enhanced with the increase of an intruder's friction coefficient and bed height. Additionally, the variation between the rise times of the smooth and rough intruders was not significant with the lower bed-filling heights.

1. Introduction

Granular materials may flow like a liquid or a gas, or behave like a solid. These three motion states may occur simultaneously or exist individually in granular systems [1]. Granular materials are ubiquitous in nature and exhibit a wide range of nontrivial rheological behavior. The rheological behavior of granular materials is complex, but an understanding of granular materials is imperative in many industries, such as the pharmaceutical industry, food storage and transportation, polymer manufacturing, cement manufacturing, and metallurgy. Furthermore, an understanding of granular materials can also be applied to environmental problems such as debris flows and landslides. The segregation phenomenon of granular materials is a critical issue in industrial processes, and this fascinating phenomenon also occurs in vibrated granular beds. The so-called "Brazil-nut problem," which involves an exceptionally large particle immersed with smaller granular materials in a container that vibrated using a shaker, has been widely studied in recent decades [2–16]. It is well-known that segregation can occur in binary mixtures that have components of different sizes, densities, surface roughnesses, and restitution coefficients. Understanding the segregation mechanisms of granular material is a key scientific and technological challenge to both engineers and scientists.

Granular segregation induced by internal friction is a central issue in many industries. Srebro and Levine [14] observed segregation at compactivities in binary mixtures of grains exhibiting differing frictional properties. Plantard et al. [13] observed the occurrence of friction-induced segregation in a granular slurry shear system, finding that rough circular particles behave similarly to smooth but larger circular particles. Ulrich et al. [16] experimentally demonstrated the transition from the reverse Brazil-nut effect to the Brazil-nut effect when the particle coefficient of friction increased after a long shaking time. Kondic et al. [17] demonstrated the occurrence of segregation by friction in a container with a small "hill" in the middle under horizontal shaking. However, Pohlman et al. [18] demonstrated that, although the repose angles of the rough and smooth particles may be different, radial segregation is still not found in the rotating drum. Zamankhan [19] indicated that friction coefficient of granular materials has significance on the formation of bubble in a vertical vibration bed. In addition, the filling bed height is also an essential parameter for investigating the dynamics of granular material in a vertical shaker. Hsiau et al. [20] indicated that the convection strength, convection size, and overall average granular temperature lead to a two-peak phenomenon with an increase of bed height. They also demonstrated that this two-peak phenomenon is because of the formation of a solid-like region in the granular bed. Bose and Rhodes [21] studied a regime in which the intruder was less dense than the bed-immersed granular materials, determining that bed height plays a significant role in the rise dynamics of the intruder.

The vertical shaker is widely used in industries for drying, mixing, and segregating granular materials. Previous studies have shown that internal friction and bed height have a significant influence on dynamic properties and the Brazil-nut mechanism. However, the combined effects of internal friction and bed height on the Brazil-nut problem have not been examined simultaneously. In this study, we experimentally studied the combined effects of internal friction and filling bed height on the Brazil-nut problem in a quasi-2D vertical shaker. Imaging technology and a particle tracking method were employed to measure

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the rise dynamics of intruders in a vertical vibrating granular bed. The penetration length and friction drag force were also determined and are discussed in this paper.

2. Experimental setup

Fig. 1 shows a schematic drawing of the experimental apparatus. An electromagnetic vibration system (Techron VTS-100) was employed as the vertical shaker driven using sinusoidal signals produced by a function generator (Meter Inc. DDS FG-503) through a power amplifier (Techron Mode 5530). The vibration frequency f and vibration acceleration a were measured using an accelerometer (Dytran 3136A) fixed to the shaker and connected to an oscilloscope (Tektronix TDS 210). The radian frequency ω and the amplitude A of the vibration could be calculated by $\omega = 2\pi f$ and $A = a / \omega^2$, respectively. The dimensionless vibration acceleration Γ is defined as $\Gamma = a / g$, where g is the gravitational acceleration.

The bed container was equipped with glass plates at the front and back walls and plexiglass at the side and the bottom wall. The height, width, and depth of the inside of the container were 150.0 mm, 60.0 mm, and 4.0 mm, respectively. To record the intruder dynamic motion, the quasi 2D vibration granular bed was used to study the brazil-nut problem in this study. For the immersed granular material, we used smooth mono-sized glass beads. Each bead had a diameter d of 2 mm and a density ρ_p of 2.476 g/cm^3. Three surface roughness cylindrical intruders with a diameter of 6.0 mm and a height of 3.0 mm were used in this study. The intruders were composed of stainless steel with the same density of 7.5 g/cm^3. The curved surfaces of two intruders were coated with glue and covered with silica sand. Silica sand with size ranges of 425–500 μm and 212–250 μm (Fig. 2) was used to produce two grades of surface roughness. The flat surfaces of the intruders that face the front and back walls of the container did not have silica sand glued onto them; therefore, only the curved surfaces of the intruders interacted with the immersed glass beads. A commercial Jenike shearing tester was used to measure the friction of the intruders to quantify the surface roughness of the intruders. Because we could not use the prepared intruders to obtain friction coefficients and three stainless steel plates were used to replicate the surface roughness of the intruders. One was left smooth, whereas the other two had silica sand with sizes ranging from 425 to 500 μm and 212 to 250 μm glued onto them. These plates were then used with the commercial Jenike shearing tester to measure the friction coefficient between the plates and the 2.0 mm glass beads. The friction coefficient for bead–wall interaction can be determined likewise. Using this method, we determined that the friction coefficients between the 2.0 mm glass beads and the walls were 0.143 (smooth), 0.405 (glued with 212–250 μm silica sand), and 0.523 (glued with 425–500 μm silica sand). Each case was repeated at least three times to calculate the average friction coefficient values. The value for the bead-wall friction coefficient can also be regarded as the same as that for the intruder-bead coefficient in the bed container. However, this value does not describe the true physical interaction between intruders and beads in the experiments.

In 2D granular beds, rougher side-walls induce stronger convection cells [19, 21]. Emery paper (KA961 P60) was glued to the sidewalls to generate sufficient shear in the flow field. The intruders were placed at the center line 9 mm from the bottom of the container in all experimental runs (see Fig. 1). A high-speed charge-coupled device (CCD) camera (IDT X-3 Plus with a grabbing speed of 100 FPS) was employed to record the front view of the intruder motion. The CCD camera was set up in front of the vibration container, and the relative position of the camera and the vibration container is shown in Fig. 1. Using a particle tracking method accompanied by an image processing system, the positions and velocities of the intruder at different times could be measured [20, 22, 23–26]. The path of the intruder to the bed surface is shown in Fig. 3. A series of experiments was conducted with a vertical shaker using different friction coefficients of intruders and filling bed heights to investigate the Brazil-nut problem. The vibration was controlled at $\Gamma = 3$ and $f = 35$ Hz. The detailed experimental parameters are listed in Table 1. Each case was repeated at least three times to calculate the average rise-time values.

3. Result and discussions

Fig. 4 shows the position of the intruder plotted as a function of time with different bed height h_f and intruder-friction coefficient μ_p. In all cases, it shows that the intruder rises upward from the bottom to the free surface of the bed because of the Brazil-nut effect. The rise time was less with each reduction of the intruder's friction coefficient at each bed height. The motion of the rougher intruder was mitigated because of the larger drag force existing between the intruder and the

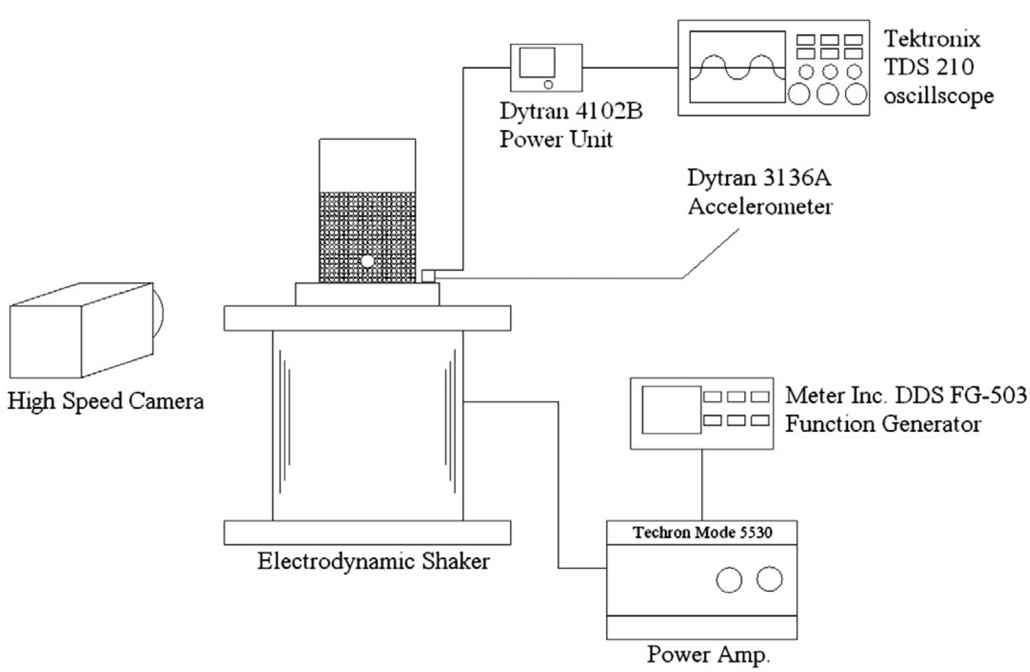

Fig. 1. The schematic drawing of the experimental apparatus.