Powder Technology 247 (2013) 14–18

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

An investigation of forces on intruder in a granular material under vertical vibration

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ARTICLE INFO

Article history:
Received 17 November 2012
Received in revised form 10 May 2013
Accepted 14 May 2013
Available online 20 May 2013

Keywords:
Granular separation
Vibrated bed
Buoyancy force

ABSTRACT

By vertically placing a rod in a granular bed consisting of small glass beads under a vertical sinusoidal vibration, the vertical force on the rod is equal to its weight when the rod stays at the equilibrium height. By changing the rod's weight, the relationship between the force and the equilibrium height ($F_{rod} \sim h$) is measured, which shows an inflection point. The inflection point divides the bed into two zones — zone (I) where F_{rod} increases along the bed depth and zone (II) where F_{rod} decreases along the bed depth. The force on a completely immersed sphere, which is calculated based on the force on the rod, is not monotonic along the bed height and has the greatest value (F_{max}) at the inflection point. When the sphere's weight is smaller than F_{max}, the vertical force on the sphere is equal to its weight at two positions along the bed height. The rising/sinking of the sphere is affected by its initial position and density, and the vibration strength.

1. Introduction

When an object (referred to as “intruder” hereafter) is placed in a liquid, the buoyancy force on the intruder is equal to the weight of the liquid displaced by the intruder, as stated by the famous Archimedes' law. The buoyancy force on the intruder is expressed as $F_{b,A} = \rho_{liquid} g V_{intruder}$, where ρ_{liquid} is the density of the liquid, $V_{intruder}$ is the immersed volume, and g is the gravity acceleration. When the Archimedes buoyancy force ($F_{b,A}$) is larger than the intruder's weight, the intruder rises; otherwise, it sinks.

Granular materials consist of a system of macroscopic particles whose diameter is larger than 1 μm. Examples of natural granular systems include ores, sand, grains, and tablets. A granular material behaves like a liquid when agitated [1,2]. The intruder rises or sinks in the liquid-like granular material based on the “Brazil Nut” effect and “Reverse Brazil Nut” effect [3,4]. However, granular materials differ from liquids as heavy intruders can float to the surface [5,6] and light ones can sink to the bed bottom [7–9].

Nichol et al. [10] placed a rod in a granular bed of glass beads and stirred the granular bed via a rotating bottom. The results showed that material far from the main stirring behaves like a liquid, and that the force on the rod is proportional to its immersed volume. Tripathi et al. [11] simulated the sedimentation of a sphere in a steady, gravity-driven granular flow. Their study indicated that the force on the sphere is proportional to its volume. Huerta et al. [12] placed spheres of different sizes in a granular bed consisting of glass beads and agitated the granular bed via horizontal vibration. Their conclusion is similar to Tripathi's. When a granular material is stirred, sheared and horizontally vibrated, the force on the intruder in the granular material is equal to Archimedes buoyancy force on the intruder. The result has been proved by both simulations [11,13,14] and experiments [10,12].

Granular material also can show a case of liquid-like buoyancy force under vertical vibration at high frequencies [15]. Alam et al. [16] showed that there are three other forces (thermal buoyancy force $F_{b,T}$, static compressive force $F_{ge,st}$, and dynamic tensile force $F_{ge,dyn}$) on the intruder in a vertically vibrated bed aside from the Archimedes buoyancy force. The total force of the granular bed on the intruder can be expressed as: $F_{intureder} = F_{b,A} + F_{b,T} + F_{ge,st} + F_{ge,dyn}$. The total force is nearly the same as $F_{b,A}$ (i.e., $F_{intruder} = F_{b,A}$) only when the diameter of the intruder is considerably bigger than that of the small particles ($d_l >> d_s$), and the dissipation energy is significantly less than the kinetic energy of the particles. The Archimedes' law is applicable only under certain conditions. When an intruder is placed in a vertically vibrated bed, generally, it rises or sinks in a non-uniformly accelerated manner [17–20]. The position of the intruder is affected by vibration parameters, and the size, mass, shape and initial position of the intruder.

This paper aims to clarify the force on intruder in a vertically vibrated bed. A rod is vertically placed in a granular bed consisting of small glass beads under a vertical sinusoidal vibration. When the rod is at an equilibrium position, the vertical force on the rod is equal to its weight. By changing the rod's mass, the variations of the force on rod along the bed depth are calculated. Based on the force

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http://dx.doi.org/10.1016/j.powtec.2013.05.025

Table 1
Physical properties of the particles.

Particle	Mean diameter d (mm)	Diameter distribution (mm)	Material Density ρ (kg/m^3)	Static packing density ρ_{bed} (kg/m^3)
Glass bead (Silicate)	0.6	0.54–0.66	2556	1508

on the rod, the force on a completely immersed sphere is evaluated to explain its separation.

2. Experimental setup

A cylindrical bed (made of smooth plexiglass with an inner size of Φ100 mm × 150 mm) is fixed on a vibrator (LDS V555) with adjustable amplitude and frequency. The granular material is glass beads and its physical properties are listed in Table 1. The rod (intruder) has a hollow rigid shell with 10-mm outside diameter (D_{rod}) and a closed bottom. The mass of the rod can be changed by packing steel balls into its shell, and the steel balls are agglutinated with the rod as one body. The horizontal movement of the rod is restricted by a pair of locating rings, thus it can only move vertically with freedom (as shown in Fig. 1).

The rod is vertically placed on the bed surface or bed bottom. When the bed is vibrating, the rising/sinking of the rod is captured by a video camera at 60fps. The diameter of the bed (100 mm) is much larger than that of the rod (10 mm); thus, changes of the granular layer's height can be neglected even if the rod sinks. When the rod is stable, its height is recorded as h_s. The relationship between the mass and the equilibrium height ($m_{rod} \sim h_s$) is obtained by changing the rod's mass. Experiments are performed in triplicate, and the average of the three measurements is calculated and presented.

3. Experimental results

The bed is filled to 80 mm height (H_{bed}) with glass beads, and the vibration parameters are set to $\Gamma = 2.7$ and $f = 60$ Hz, where Γ is defined as $\Gamma = A(2\pi f)^2/g$, and A and f the vibration amplitude and frequency, respectively. Regardless of the rod's initial placed location, it always stays eventually at a relatively fixed position, with its bottom tip at height h_s.

The rising and sinking of the rod of 10.0 mm diameter (D_{rod}) is shown in Fig. 2. When the rod is light ($m_{rod} = 5$ or 11 g), it gradually rises or sinks from its initial height to the equilibrium height h_s no matter if it is initially placed on the bed surface or at the bed bottom [Fig. 2(a)]. When the rod is heavy ($m_{rod} = 35$ g), it sinks and remains at the bed bottom [Fig. 2(c)]. When the rod's mass is between 15 and 29 g ($m_{rod} = 19$ or 25 g), the rod initially placed on the bed surface

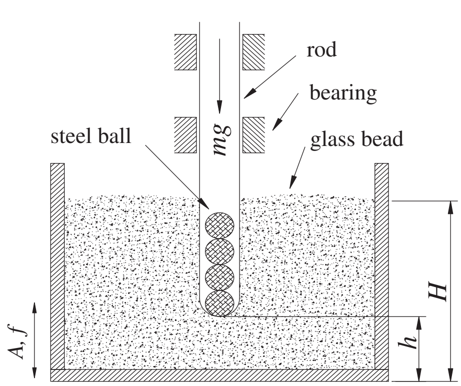

Fig. 1. Diagram of the experimental setup.

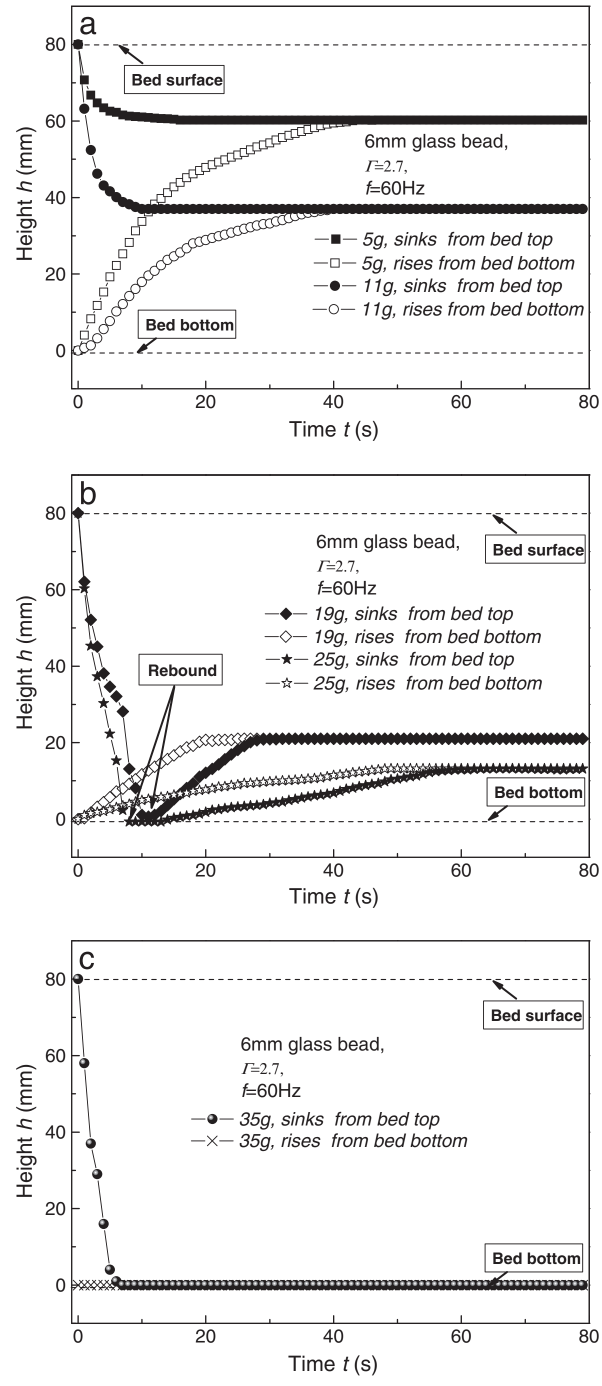

Fig. 2. Rising and sinking of rods with different weight.

first sinks rapidly until it reaches the bed bottom, and then rises to the equilibrium height h_s [Fig. 2(b)].

At the starting that the rod is on the bed surface, its weight is much larger than the force from the bed ($m_{rod}g >> F_{rod}$). Therefore, it sinks quickly. The force on rod (F_{rod}) increases gradually during the rod's sinking, and $m_{rod}g = F_{rod}$ when it sinks to the equilibrium position. At this time its kinetic energy can be expressed as the following equation by considering the granular bed as a fluid: $E = (m_{rod}g - F_{av\_up\_s}) \times (H_{bed} - h_s)$,where $F_{av\_up\_s}$ is the average resistance force on the rod before it sinks to the equilibrium position (h_s), and H_{bed} is the height of the granular bed. The rod continues to sink because of its inertia, and then returns to the equilibrium position.

The bed wall is smooth and the bed is placed horizontally. Locating the vertical rod in different places (not only in the center), the