Vibration induced segregation of single large particles

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Abstract. The vibration-induced segregation (e.g., rising of one large intruder - so called Brazil Nut Effect (BNE)) is studied by discrete element method. Vibration frequency and amplitude are two dominating factors in the occurrence of BNE and a phase diagram is constructed. For fixed vibration amplitude, segregation only occurs when vibration frequency is within a certain range. Larger vibration amplitude can expand the range of vibration frequency for BNE. Size ratio and the intruder shape are studied under certain vibration conditions. Larger size ratio can enlarge the segregation intensity. The shape of the intruder influences the segregation process by the intruder′s orientation. Standing-like initial orientation can increase the time required for the intruder to reach the top while lying-like initial orientation cannot significantly affect the vertical segregation.

1 Introduction

Segregation occurs due to the difference in particle properties and has been widely studied in scientific research. Segregation is mostly observed in free surface flows and vibrated containers. The vibration-induced segregation demonstrates that vibrations drive large particles to move upward within bulk solid of small particles, which is so called "Brazil-nut Effect (BNE)". Ahmad and Smalley [1] conducted physical experiments to study this phenomenon, and the importance of vibration acceleration and density was addressed through their findings. Cooke et al. [2] did further experiment with the advanced high-speed camera, through which they found the motion of the large intruder is largely affected by the size ratio. Many other mechanisms for BNZ have been proposed, for example [3-6]. Researchers also applied different numerical techniques to study this phenomenon, for example, Monte Carlo models to investigate the effects of shaking conditions and particle properties [7]. Poschel and Herrmann [8] used Molecular Dynamics to study the convection patterns in vibrated granular bed. In particular, discrete element method (DEM) has been widely used due to its advantages in generating detailed parameters such as velocity, force and positions [9]. Many researchers have used this method to conduct parametric studies including the effects of particle size ratio, vibration acceleration, initial depth of the large intruders, and particle density ratio [10, 11]. However, the influence of particle shape and vibration conditions have not been fully understood, especially when the vibration amplitude is large. A comprehensive study of the effect of vibration conditions and particle properties were conducted in this work based on a DEM model for ellipsoids. The single large intruder was put at the

bottom of the granular bed, and one-dimensional vertical vibrations were introduced for the base of the cylindrical container. Several interesting features were observed including a come-back pattern of the large intruder and disappeared BNE at high vibration frequency.

2 Simulation method and conditions

2.1 Discrete element method

In DEM, two types of motions are considered: translational and rotational. Such motions obey Newton's second law of motion. DEM for ellipsoids has been developed in our previous studies [12]. Comparing with spheres, the key features for ellipsoids include: (i) the normal force can generate a toque to make the particle rotate when the normal force does not pass through the particle centre; (ii) calculation of radius $R*$ to determine the contact forces where $R*$ is closely related to radii of the curvature at a contact point; (iii) geometric potential algorithm used to detect the contacts between ellipsoids; and (iv) particle orientation is described by three Euler angles on the basis of the so-called quaternion method.

2.2 Simulation conditions

In the simulation, the dimension of the cylindrical container is 240 mm in diameter and unlimited in the vertical direction. The granular beds are pre-packed at the base before vibration starts, and the single large intruder is put at the bottom in the centre of the bed. The vibration imported on the container base follows the pattern of simple one-dimensional vertical vibrations

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with amplitude A and frequency f. The granular materials used in the simulations contain small spherical particles and large intruders (the intruder′s shape is spherical or ellipsoidal). The exact physical properties of the particles were set to those of glass beads. Wall have the same properties as particles. Details of the physical properties and other input variables are shown in Table 1.

Table 1. Parameters used in the simulation

Input variables	Value
Size of small particles (d_p)	10 mm
Size of large particle (D_p)	15, 20, 25, 30 mm
Number of particles	1 for large, 2000 for small
Aspect ratio of intruder (ellipsoid)	0.5, 0.7, 0.9, 1, 1.2, 1.5, 1.8, 2, 2.5
Young's modulus	1×10^8 N/m^2
Poisson's ratio	0.3
Sliding coefficient	0.4
Particle density	2.7×10^3 kg/m^3
Vibration frequency, f	5 Hz to 80 Hz
Vibration amplitude, A	1 mm to 15 mm

3. Results and discussion

3.1 A phase diagram

The importance of vibration conditions to segregation has been highlighted by many researchers (for example, [3-5, 7-9]). However, they mainly focused on the parameter of vibration acceleration, and the effects of vibration frequency and amplitude still need further studies. In order to investigate the effects of vibration parameters, a phase diagram was constructed first considering the appearance of BNE (shown in Fig. 1). Several findings can be observed from the diagram: (i) for fixed vibration amplitude, BNE only occurs within a range of vibration frequencies; (ii) Increasing vibration amplitude can enlarge the range of frequency for BNE; (iii) With the amplitude increasing, the critical maximum frequency increases and the critical minimum frequency decreases. Moreover, the fact that high frequency stops the segregation are against the common sense that higher frequency can induce stronger BNE. Also note that for the conditions considered (Table 1), when the amplitude is low (for example, less than $0.4d_p$), BNE occurrence cannot be observed.

In order to further understand this phenomenon, the time evolution of the intruder′s position and local averaged coordination number (LACN) is recorded and the results are shown in Fig. 2. It can be observed that the relative height of the large intruder increases first and keeps a relatively constant value (Fig. 1(a)). However, at the time of 800k to 1100k timesteps, its height is low which indicates that the large intruder falls down again (so called come-back pattern in this paper). With time, the height increases again (shown in Fig. 2(b)). Note that the LACN describes the time-averaged number of contacts with the large intruder, which can show the information about the local voidage of the

intruder. Low LACN corresponds to large voidage. The figure demonstrates the relation between the LACN and intruder's vertical motion, showing that when LACN is large (low local voidage), the large intruder will start getting back to the particle bed from the surface, which explains the appearance of the come-back behaviour.
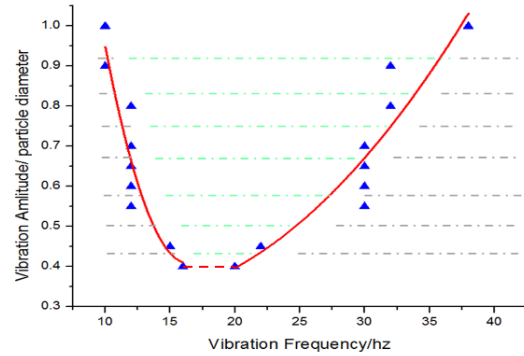

Fig. 1. Phase diagram of BNE versus vibration parameters. The grey dash-dot area represents the conditions where BNE cannot occur while the green dash-dot area represents the conditions where BNE can be observed. The particles used: 20 mm for large spheres and 10 mm for small spheres.
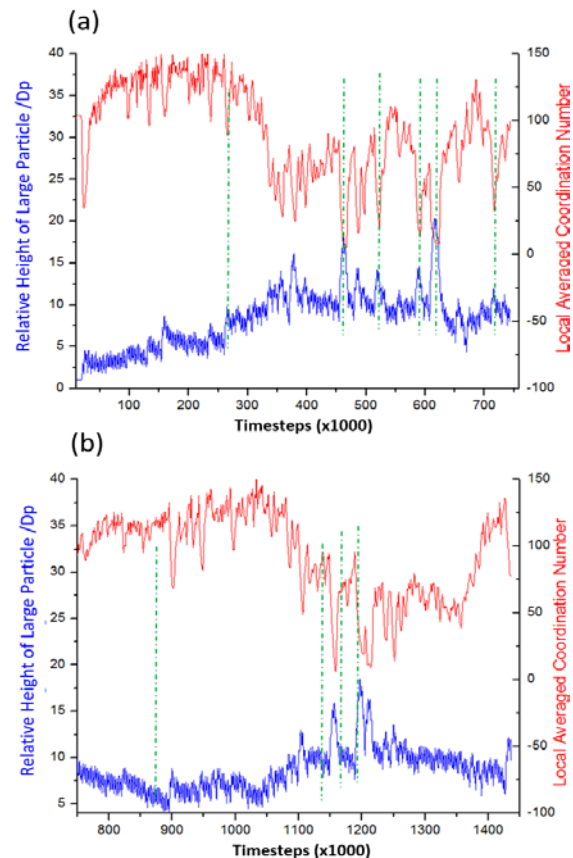

Fig. 2. Time evolution of the relative height of large particles and the local averaged coordination number (LACN). Vibration frequency: 20 Hz; vibration amplitude: 10 mm. Two figures are shown: (a) from 0 to 570k timesteps; and (b) from 750k to 1450k timesteps.

Another finding is the disappearing of BNE under high vibration frequencies. As shown in Fig. 3, when the vibration frequency is increased to 50 Hz, the motion of the large intruder shows more frequent oscillations. However, as there is no sudden decrease in LACN, the

uprising motion of the large particle cannot be triggered, which demonstrates the disappearing of BNE in a microscopic view. This finding also shows that a stronger vibration may not result in stronger oscillations in LACN, and is not able to induce greater segregation.
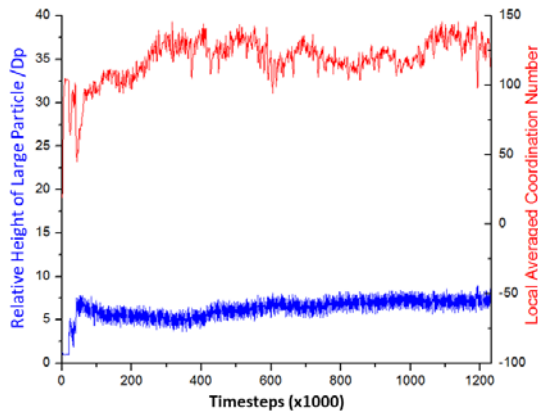

Fig. 3. Time evolution of the relative height of large particle associated with its LACN. Vibration frequency: 50 Hz; Vibration amplitude: 10 mm.

Previous researches have studied effects of vibration amplitude on the vertical segregation, finding that larger amplitude can directly result in stronger segregation. The simulations conducted in this work also confirm this conclusion. To demonstrate the effects of amplitude on the intruder′s motion, the time evolution of the intruder′s vertical position was constructed and shown in Fig. 4. It can be found that the segregation becomes stronger with increasing vibration amplitude. Moreover, when the vibration amplitude is large enough, the come-back behaviour of large intruder is also observed. As mentioned in the previous section, the come-back behaviour is largely decided by the large intruder's LACN (e.g., the local porosity). While larger amplitude can induce stronger jumping effects of the large intruder, it will indeed extend the upper and lower limitations of the LACN, which will consequently result in the come-back behaviour.

The effects of vibration amplitude are also studied in terms of the averaged bed coordination number. As shown in Fig. 5, the vibration pattern of CN cannot be affected by changing vibration amplitude. However, the vibration of CN can be simply enlarged with increasing vibration amplitude. The relation of CN distribution with vibration frequency needs further investigation to explain BNE occurrence.

3.2 Effects of particle properties

With fixed size (10 mm) of small particles, the size of large intruder was changed from 12 mm 30 mm to investigate the effects of particle size ratio. The motion of the large intruder was recorded in Fig. 6. Several conclusions can be made based on the simulations. Firstly, the rising behaviour of the large intruder is still triggered by vibration conditions which means BNE can still occur with rather low size ratio under proper vibration conditions. Moreover, as shown in Fig. 7, the come-back pattern of large intruder exists in all size

ratios which also demonstrate the dominating effects of vibration conditions. But through comparisons among different size ratio, it can be found that under same vibration conditions, larger size ratio can enlarge the segregation intensity by accelerating the motion of the large intruder.
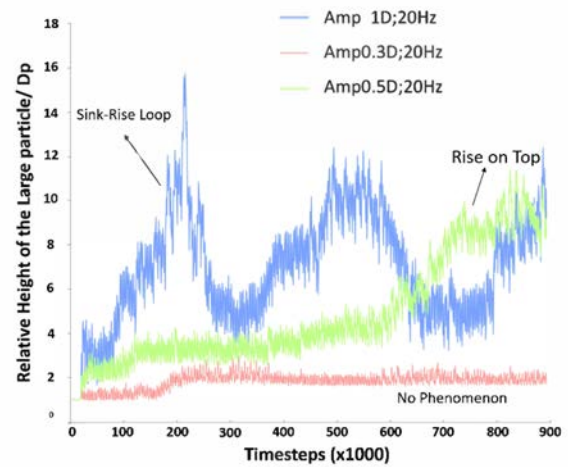

Fig. 4. Time evolution of the large intruder′s vertical position relative to the vibrated base.
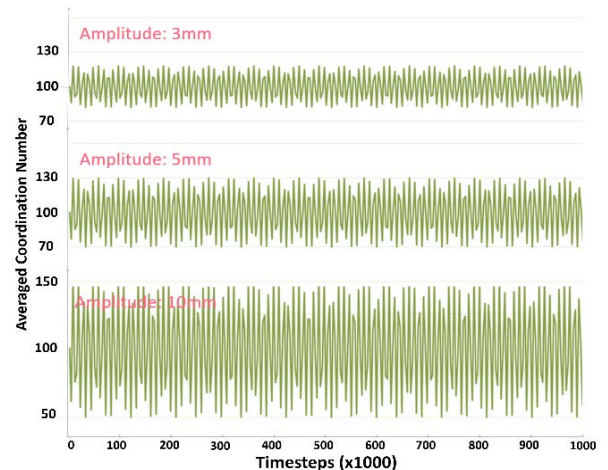

Fig. 5. Time evolution of ACN with different vibration amplitude. Note that the recorded ACN is quite similar for the three cases. The BNE only occurs in the case with the amplitude at 10 mm. Vibration frequency: 20 Hz.
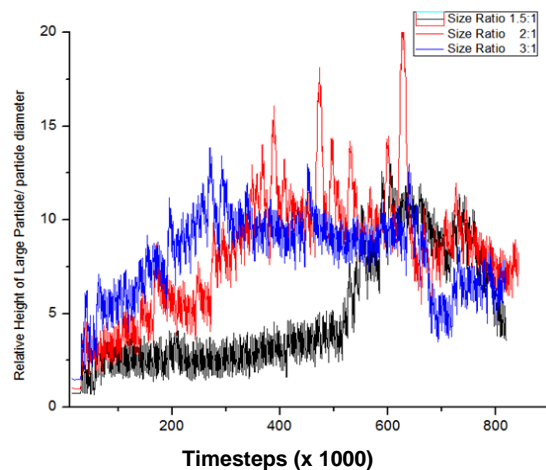

Fig. 6. Time evolution of the large intruder′s vertical position relative to the vibrated base. Vibration frequency: 20 Hz; vibration amplitude: 10 mm.

To clearly identify the effects of intruder shape, simulations based on the DEM ellipsoidal model were conducted, and by changing the shape of the large intruder from prolate to oblate, it was found that effect of intruder shape is largely related to its initial orientation. For ellipsoidal particles, the two extreme particle orientations are shown in Fig. 8, showing the natural lying pattern and unstable standing pattern. From the simulations, the intruder with standing initial orientation was first motivated to a lying-like pattern and then rises through the bed, while the lying-patterned can be directly driven to rise like the motion of spherical intruder.
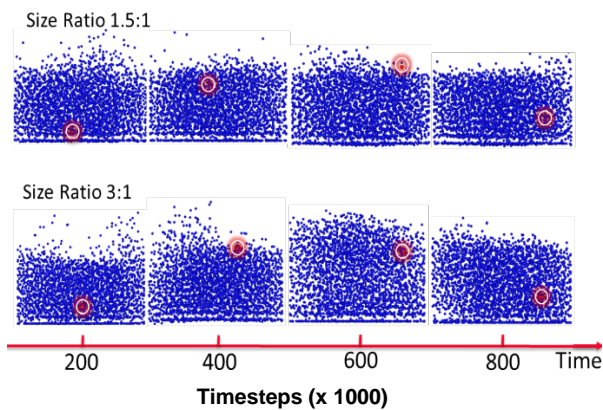

Fig. 7. Time evolution of the flow patterns under same vibration conditions but different size ratios. Vibration frequency: 20 Hz; vibration amplitude: 10 mm.

Based on the difference of motion patterns between different initial orientations, it is found that for fixed aspect ratio, when the intruder's orientation changes from the lying pattern to the standing pattern, the time required to reach the particle surface gets longer. More importantly, if the initial intruder orientation stays as the lying pattern, the shape effects are very weak that there is showing little difference from the BNE obtained with spherical intruder.
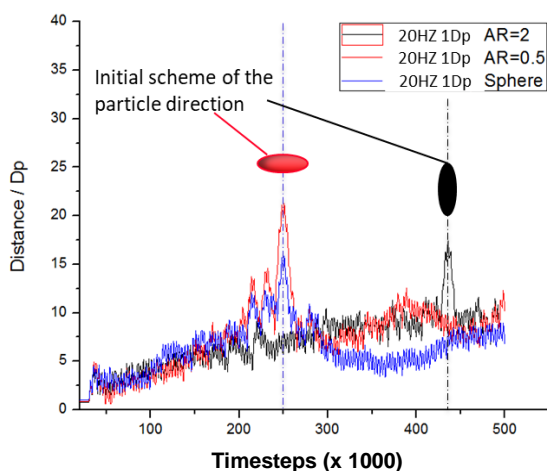

Fig. 8. Time evolution of the vertical position of the large intruder. Vibration frequency: 20 Hz; Vibration amplitude: 10 mm. The equivalent size of the large intruder: 20 mm.

4 Conclusions

In this work, the vibration-induced segregation with one large intruder is studied under different conditions. Vibration parameters such as vibration frequency and vibration amplitude are two dominating factors for the occurrence of BNE. A phase diagram was constructed. For fixed vibration amplitude, segregation only occurs when vibration frequency is within a certain range, and the critical points of the range is related to vibration amplitude while larger vibration amplitude can expand the range of vibration frequency. On the other hand, there is no upper limit for vibration amplitude as larger amplitude can directly induce stronger and faster BNE.

The effect of particle properties such as the size ratio and the intruder's shape are studied under certain vibration conditions. For the size of the single large intruder, it is found that larger size ratio can enlarge the segregation intensity during the vibration process, but it cannot significantly affect the occurrence of BNE. For the intruder's shape, the conclusion varies for the shape of the large intruder and the shape of small particles. The shape of large intruder influences the segregation process by the intruder's orientation. More specifically, standing-like orientation can increase the time required for the intruder to reach to the top while lying-like orientation cannot affect the vertical segregation much.

Acknowledgements

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