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Effects of convection and segregation generated by granular materials in a pseudo-2D rectangular container under vertical vibration

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ABSTRACT: This research examined the effect of convection and segregation generated by granular materials in a pseudo-2D rectangular container under vertical vibration. This experiment used different wall angles with vibration frequencies to affect the convection speed of granular materials. The angles of the container wall were 90, 85, 80, and 75 degrees, while the frequencies of the vibrator were 28, 29, and 30 Hz. The convection of the bed materials and the intruder materials resulted in a flow cycle along the left side of the container wall and surrounded the bed materials. In continuous vibrating experiments, the top surface of the bed materials was tilted. Afterward, the intruder material moved along the top surface of the granular material. Subsequently, the invasive granular materials traveled up along the right wall of the container and descended to the bottom along the left wall, completing an entire cycle to the starting point. When the angle of the container wall and the frequencies were increased, the intruder materials convected cells significantly faster, forming a smaller, asymmetrical loop. In contrast, the intruder material would slowly develop a more extensive, asymmetrical loop when the angle and frequency of the container wall decreased. The segregation effect was generated by the container wall with the vertical vibration of granular materials.

KEYWORDS: convection, segregation, granular materials, vertical vibration

INTRODUCTION

Granular materials have numerous applications in various fields, including industry, geology, and materials science. One application is in the design of industrial processes involving granular materials such as fluidized beds, mixing, and separation systems. Understanding the convection and segregation behavior of granular materials can help optimize the performance and efficiency of these processes. For example, the control of convection and segregation in fluidized beds affects heat transfer and mixing efficiency, leading to improvements in the overall process [1]. In geology, the study of granular materials is important for understanding natural processes such as sedimentation and soil formation. Convection and segregation effects play a significant role in the formation of geological structures such as sand, dunes, river channels, and rock formations. Research on the behavior of granular materials has helped to better understand these natural processes and predict their effects on the environment [2, 3]. In materials science, research on granular materials can lead to the development of new materials with improved properties. By studying the behavior of granular materials under different conditions, researchers can gain insights into the relationships between the microstructure of materials and their mechanical and physical properties. This understanding has led to the creation of materials with superior attributes like greater strength, longevity, and resistance to heat. In essence, researching the convection and separation of granular substances benefits numerous sectors, refining industrial methods, deepening our grasp of natural phenomena, and fostering the innovation of materials with improved features [4].

When granular materials are subjected to vertical vibration in a pseudo-2D rectangular container, convection and segregation effects can be observed. Convection pertains to the movement of particles as a result of energy or heat exchange within the system. For granular materials experiencing vertical vibrations, the kinetic energy from the vibrating foundation transfers to the particles, prompting them to engage and shift. This can result in the emergence of convective patterns, wherein particles circulate in defined loops inside the container [5]. On the other hand, segregation refers to the separation of particles based on their size or other properties. In a granular system under vertical vibration, segregation occurs due to differences in the responses of particles to vibration. Larger particles may be more resistant to movement and remain at the bottom of the container, while smaller particles may be more easily lifted and moved toward the top. This can lead to the formation of distinct layers of particles within the container [6]. When granular materials undergo vertical vibrations, convection and segregation play crucial roles in determining their behavior. Convection results in particle intermingling and the emergence of intricate patterns. On the other hand, segregation influences the packing compactness and the mechanical attributes of the material. Recognizing these impacts is vital for several industrial and scientific uses, including designing granular filters and fluidized beds and understanding geological phenomena. However, convection specifically relates to circular or recurrent movement patterns of the granular material. This makes it possible for particles denser than the foundational material to serve as the subject of study [7]. Bed particles are bulk materials of the same size in a container to carry the intrusion material, which must be less dense than the bed particles. Frequency denotes the number of waves passing through a point in one second. It is measured in hertz (Hz) or cycles per second (1/s). On the other hand, amplitude represents the degree of change due to vibration and is quantified in millimeters (mm). Convection patterns under vertical oscillation have been studied using frequencies of 15–150 Hz [5].

The granular materials exhibit various convection patterns such as symmetric, asymmetric, one, two, and multiple convection roll rings. The frequency of vibration is significant for the number of convection rings and the direction of flow or convection [8]. When using frequencies in the range of 28–32 Hz, the convection of the granular materials is only one band, and the surface of the granular material will be tilted. The granular materials move up on the left container from the wall of the bottle to the highest point. They then move down from the surface of inclined materials to the right container wall. Finally, they move down against the right wall to the bottom of the container and generate circles to the left in a horizontal plane. A cycle of circular motion is formed until the end of the cycle back to the original point. At an oscillating frequency of 28 Hz, the slope of the granular surface has the greatest amplitude [5]. In addition, the study of the behavior of spherical particles flowing down a 3D inclined trough at a fixed angle has generally modeled the way that the Digital Elevation Model (DEM) is currently the standard tool for numerical studies such as fluidization, gas, and solid. The DEM is modified to simulate the rotation of the pellet stream. Given the aim of future extensions such as the study of splitting (rotating) granular streams and polydispersion or mixing of two kinds of granular particles with different densities, multiple inspection procedures are required. In the first step of this study, the DEM simulation was compared with the test of monodispersed glass spherical particles.

In a semi-cylindrical displacement setup inclined at a steady angle, the flow was consistent. Average particle surface speed and the height of granular materials in the chute were measured using methods like Particle Image and Trace Particles. The pattern of flow exchange was notably influenced by the rotation speed of the chute. With higher rotation rates, centrifugal and Coriolis forces impacted particle velocities, causing more lateral movement. The specific shape of the given particle proved to be equally significant. However, factors such as mass rate, inclined angle, and rotation speed determine the particle flow near the chute entrance after only a short distance. The DEM prediction model aligns well with experiments that gauge the height and speed of surface grain materials [2]. Segregation refers to the movement of granular materials separated by a segregation mechanism, including material type, material size, and time. Time refers to the duration taken to move granular materials with a unit in seconds (s). The angle of the wall means the angle between the side wall of the container at an angle and the floor of the x-axis container in degrees. According to a study on the convection and separation of granular materials under a vertical vibrating system in rectangular containers, it was found that the convection of materials in the container was symmetrical. The direction of movement for the materials moved from the center of the bottom of the container to the top and then circled down by the side of the container and finally circled up to the top again, which was considered normal when increasing the corner of the container wall.

When the angle of the container wall surpasses the transition angle, typical convulsions decrease even further, leading to reverse convection. This creates a looped movement, starting from the top center, moving to the bottom, and then circling sideways from the bottom to the top along the side walls of the container. The wall texture and the vibration amplitude were observed to influence the convection. In typical convection, the segregation of larger granular materials was driven by the material convection. Conversely, reverse convection originated from granular materials migrating to the container base. Notably, the rate of separation was in direct relation to the average convection speed [6]. Based on the aforementioned statement, this study aimed to examine the effects of convection and segregation generated by granular materials in a pseudo-2D rectangular container under vertical vibration. We determined the angles of the vessel wall to the convection of the granular material at 90, 85, 80, and 75 degrees and vibration frequencies of 28, 29, and 30 Hz to affect the convection speed. The analysis of video recording and material tracking was performed using Tracker version 4.9 as a guideline for the further development of knowledge concerning granular materials and the agricultural and industrial applications related to granular materials.

MATERIALS AND METHODS

The following experiments were performed in a narrow rectangle sand bed with dimensions of 6.00 cm (length), 1.00 cm (width), 8.00 cm (height) at the wall angles ($\theta_w = 90°$). The height of the granular material decreases as the angle wall decreases (θ_w). As shown in Fig. 1, the angle of the left and right container walls can be adjusted to 90, 85, 80, and 75 degrees.

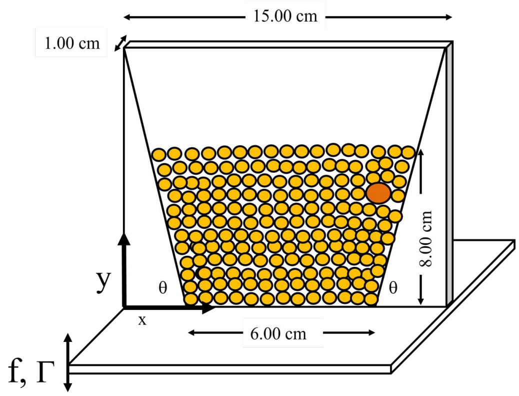

Fig. 1 A diagram of the vertical vibrating experiment.

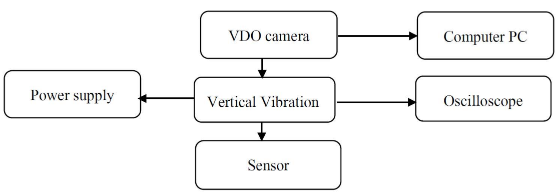

Fig. 2 A diagram of the vertical vibrating experiment.

The device was installed to test the vertical vibration system and the system balance as shown in Fig. 2. An experiment was carried out to bring bed particles such as sand-sized 0.10 ± 0.05 cm into a rectangular container at 15.00 cm (length), 1.00 cm (width), and 15.00 cm (height) in size. The intruder plastic granules of 0.8 ± 0.01 cm were placed on the top surface of the sand, 1.00 cm from the left edge of the container wall, as noted in Table 1. After that, the sand was put over it until it reached a total height of 8.00 cm at the wall angles ($\theta_w = 90°$); when increasing the wall angles (θ_w), the height granular bed decreased (h). The vertical vibrating system was turned on using vibrating frequencies equal to 28, 29, and 30 Hz with an amplitude of 1.30 ± 0.15 mm. A video of the experiment was recorded. The size of the wall angles was changed with different containers. The experimental results were analyzed using Tracker version 4.9, which can generate sinusoidal vibration in the form of $y(t) = A(x)\sin(2\pi f t)$, where $A(x)$ and f are the vibration amplitude and frequency, respectively. In addition to this, the dimensionless vibration acceleration (Γ) is from 4.102, 4.400, and 4.708, where $\Gamma = A^2(2\pi f)/g$ and g is the gravitational acceleration.

Table 1 Physical properties of the two kinds of particles selected in this experiment.

Material	Diameter d (cm)	Material density (g/cm^3)
Sand	0.10±0.05	1.52±0.15
Plastic	0.80±0.01	1.37±0.05

RESULTS

The study of convection patterns for granular materials in a 2D virtual rectangular container under a vertical vibration system utilized an experiment to determine the convection patterns of sand granules as ground materials and plastic pellets as invasive materials. There were four corners of the wall angles at (θ_w) 90, 85, 80, and 75 degrees, while the frequency was 28, 29, and 30 Hz at an amplitude of 1.30 mm, i.e. the experiment has dimensionless vibrations Γ at 4.102, 4.400, and 4.708. Through this study, we observed distinct behaviors in the convection of granular materials within containers, specifically when varying the angles of the two side walls. When subjected to these conditions, the base material (sand) was encircled by the intruding material (plastic) in a circular pattern along the left side of the container. Continuous vibration over a period led to a noticeable tilt in the top surface of the base material. The intruding particles exhibited a circular trajectory over this tilted surface, subsequently progressing along the container right wall. These particles then descended along the left container wall, completing their loop and returning to their initial position. This patterned motion emphasizes the intricate interplay between the container geometry, material properties, and external stimuli like vibration. Subsequently, when increasing the frequency or dimensionless acceleration of the system, the granular material moved in a circular motion that narrowed as the frequency increased as shown in Fig. 3. When experimenting with containers comprising both side wall angles of θ_w = 90, 85, 80, and 75 subjected to vertical oscillations of frequencies 28, 29, and 30 Hz at an amplitude of 1.30 mm, it was found that the convection of materials, ground materials and intrusion materials, had a circular convection along the left side of the container wall surrounding the ground materials as shown in Fig. 4. Thus, it was discovered that the top surface of the ground materials was tilted upon vibration of the system for a period of time. The intrusion materials then moved in a circular motion along the top surface of the ground materials. Subsequently, the ground materials moved along the right wall of the container and then descended to the bottom of the container wall to the left until they reached the starting point. It was a loop along the next container wall, and when increasing the frequency to the system, the granular materials would move in a loop that became less narrow as the frequency increased as shown in Fig. 3. When the particles collide with the same wall, the force acts as if it has encountered another diameter particle d at the point of collision, meaning two forces act against the system: On the one hand, gravity $g =$

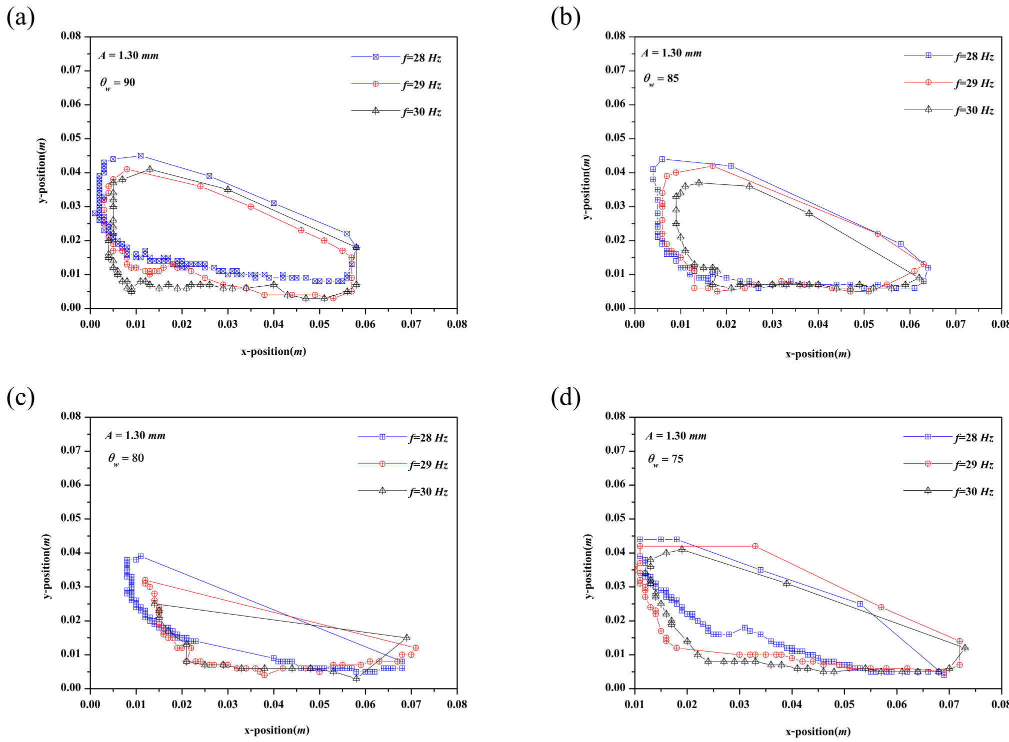

Fig. 3 Motion of intruder granular materials in containers under vibration with side wall angles of (a) $\theta_w = 90$, (b) $\theta_w = 85$, (c) $\theta_w = 80$, and (d) $\theta_w = 75$ (at $A = 1.30$ mm and $f = 28$, 29, and 30 Hz).

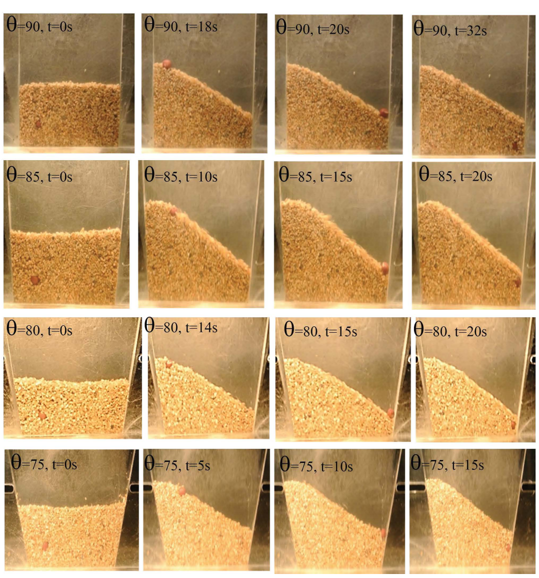

Fig. 4 Convection forming and segregation generated by container wall angles of $\theta_w = 90$, 85, 80, and 75 degrees (at $A = 1.30$ mm, $f = 28$ Hz, and $\Gamma = 4.102$).

9.8 m/s^2 pulls each particle down. On the other hand, the bottom of the container is subjected to the oscillating motion described by:

$$y(t) = A(x)\sin(2\pi f t) \qquad (1)$$

where f is the frequency and amplitude A can have clear spatial formatting

$$A(x) = A_0[1 - B\cos(2\pi x/L))]. \qquad (2)$$

Two initial positions were taken into account: either uniformly situated at the base of the container as described in [9] or positioned arbitrarily within an area ten times the height. Particles were either densely packed with an initial velocity of zero or placed in a randomly determined manner. Subsequently, these particles were permitted to descend freely due to gravitational forces and were given adequate time to settle, spanning between ten to twenty cycles of vibrational displacement.

The study of convection velocity in a 2D quasi-square vessel under a vertical oscillation system examined the influence of the vessel wall angle and the vibration frequency on the convection velocity in the 2D quasi-square-shaped vessel under the vertical vibrating system of granular materials with the container wall

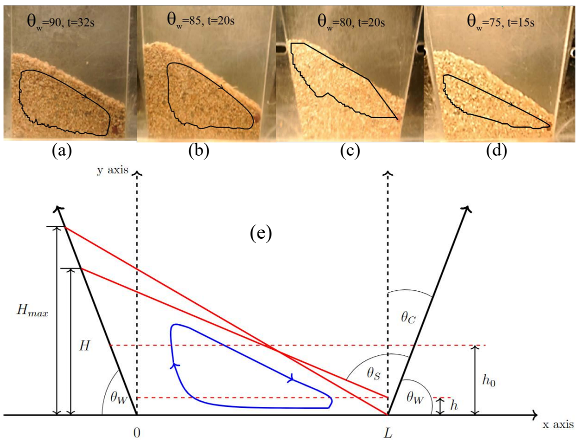

Fig. 5 Different types of granular convection rolls at (f = 28 Hz). (a) $\theta_w = 90$, (b) $\theta_w = 85$, (c) θ_w =80, (d) $\theta_w = 75$, and (e) a schematic of convection.

angles at 90, 85, 80, and 75 degrees on both sides. The ground material was determined as grains of sand with plastic pellets used as the invading material. It was found that the angle of the container wall and vibration frequency affected the convection velocity of granular material in a 2D virtual rectangular container under a vertical vibrating system. Analysis was carried out from video recording and material tracking using Tracker version 4.9 as shown in Fig. 5a–5d. Furthermore, it was observed that the convection in each position would not be equal if the ground material and the intrusion material moved in a circular motion with a lateral wall angle of 75 under vertical vibration of 1.30 mm amplitude and frequencies of 28, 29, and 30 Hz; when the frequency showed less dimensionless acceleration, the intrusion granular material moved in a slow circular motion. It was observed that the angle of the container wall and the frequency affected the velocity and convection of the granular material because the granular material would move slowly and take a lot of time to move when the vibration frequency and the dimensionless acceleration of the system were negligible as shown in Fig. 6.

On the other hand, it was found that the granular materials moved faster and took less time to move when increasing the vibration frequency and the dimensionless acceleration of the system. In addition, the convection speed of the ground material to the top surface was faster than that at the bottom of the container. Moreover, when the granular materials were exposed to vibrations, the question of whether convection was an essential ingredient for size segregation was addressed by distinguishing between situations where vibrations were not sufficiently energetic to promote a mean flow of the bulk solid and those cases where convective flow did occur [7]. Fig. 5e presents a diagram illustrating the convection on an inclined surface, coupled with internal convective transportation within the vibrated container bed. The granular system employed sand as its primary mass [10].

$$WLH_{\max}\frac{\rho_1}{2} = WLh_0\rho_2 = m \qquad (3)$$

where ρ_1 is the bulk density with slope at rest and ρ_2 is the bulk density with a flat surface. When the vibration parameters remain constant, the structure of steady tilt is reached after vibration for a sufficient amount of time. The height to the granular layer h and the dynamic slope θ_s become independent of the time t, i.e. $h(x,t) = h(x)$, after reaching the final steady state, $\mathrm{d}h/\mathrm{d}t = 0$. According to the volume conservation of the granular system,

$$\int_0^L h(x)\,\mathrm{d}x = \frac{m}{\rho} + \Delta h W L \qquad (4)$$

where ρ is the density of sand, m is the mass of sand, L is the length of send, W is the width of sand, and h_0 is the height of the granular layer at position $x = W$. The effect of variation in height is due to the expansion or compression of the granular layer under sustained vibration, which is regarded as a function of the average height of the layer, which can be written as:

$$\Delta h = \varphi\frac{H+h}{2}. \qquad (5)$$

According to the layer shape and geometrical features, the dynamic slope after reaching the steady state will satisfy the following relationship $\tan\theta = \frac{H+h}{w}$; h is the dynamic height of the granular layer at position; the average incoming vibration energy can be expressed as

$$\phi = \frac{1}{T}\int_0^T m(-A\omega\sin(\omega t))\,\mathrm{d}t = \frac{mA^2\omega^2}{2} = \frac{mg^2\Gamma^2}{8\pi^2 f^2}. \qquad (6)$$

We can obtain the dynamic slope of the granular layer as

$$\theta_s = \arctan\left(\frac{\frac{2m}{WL} + (\varphi-2)h(\phi)}{W(1-\varphi)}\right) - \theta_c. \qquad (7)$$

We can obtain $\theta_c + \theta_w = 90$. Consistent with the experimental observations, Eq. (7) implies that, at a given frequency f, the angle slope θ_s decreases with the increase of vibration acceleration Γ. The result can be understood as follows: the vibration energy pumped into the granular layer is increased with the increasing of Γ. Thus, the fluidization of grains becomes stronger. The granular system behaves more like a liquid, leading to a decrease in slope θ_s [10].

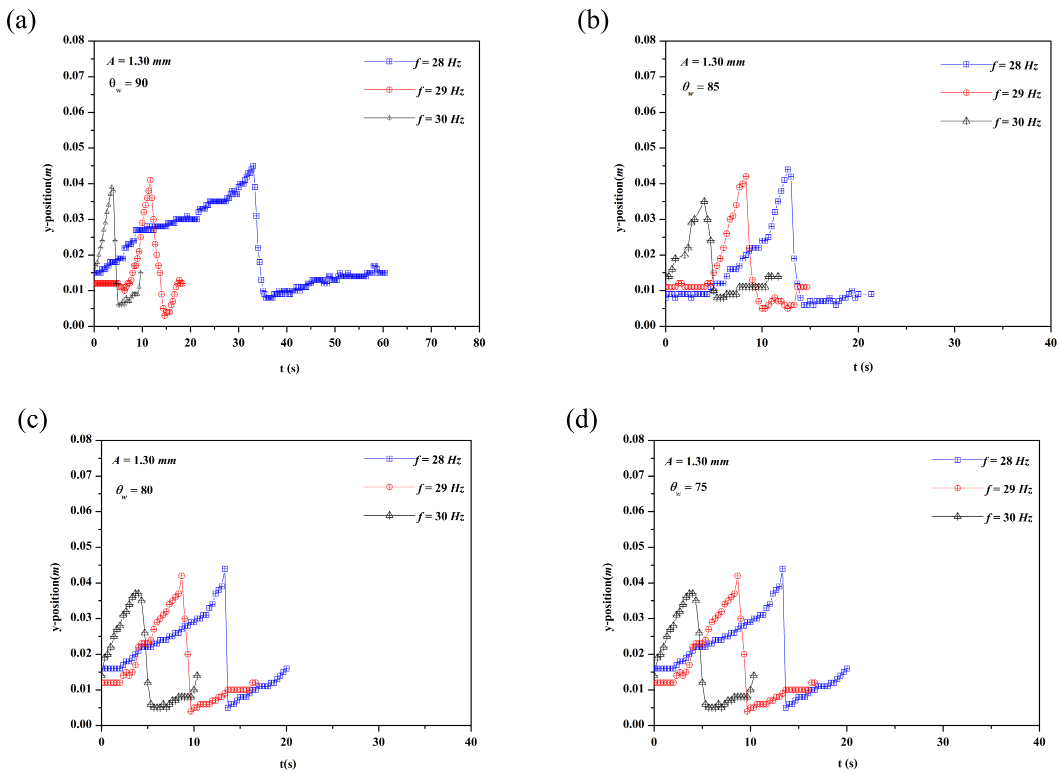

Fig. 6 The y-axis position (m) and t-axis time (s) by side wall angles at $f = 28$, 29, and 30 Hz and $A = 1.30$ mm. (a) $\theta_w = 90$, (b) $\theta_w = 85$, (c) $\theta_w = 80$, and (d) $\theta_w = 75$.

DISCUSSION

Derived from this extensive research on the impacts of convection and segregation induced by granular materials within a pseudo-2D rectangular container under vertical vibration, it is a well-established fact that agitating a granular bed can initiate circulating convection as highlighted in reference [5]. Specifically, this phenomenon becomes apparent when the container wall angles are precisely set at 90, 85, 80, and 75 degrees. Furthermore, when delving into the oscillation dynamics, frequencies of 28, 29, and 30 Hz were identified, combined with an amplitude of 1.30 mm and dimensionless accelerations of 4.102, 4.400, and 4.708, respectively. For clarity and comprehensive understanding, the outcomes of this research are bifurcated into two distinct sections as outlined below.

According to the study of convection patterns for granular materials in a 2D virtual rectangular container under a vertical vibration system, the results showed that the convection patterns of different granular materials, when using different angles and frequencies of dimensionless acceleration in vibrating, affected the convection pattern of granular materials in a 2D quasi-square container using a container with a small wall angle and frequency. The granular materials moved in a large and asymmetrical loop. The greater the dimensionless acceleration, the more granular material moved in small and asymmetrical loops. This is consistent with research on convection patterns under vertical oscillations, in which the convection patterns depend on the angle of the magnitude of the convection container wall. Thus, when submitted to vertical vibrations for frequencies from 15 to 150 Hz, granular materials show several convective patterns such as symmetric, asymmetric, one single, one pair, and multi-pairs of convection rolls [5] and then the convection behavior of ellipsoidal particles in a 2D bed under vertical vibration. Several patterns were observed at the dimensionless vibration acceleration (Γ) values of 1–6 within a frequency (f) range of 12–70 Hz. The displacement vectors are a single roll.

According to the study of convection velocity in a 2D virtual rectangular container under a vertical vibration system, the results showed that angles of 90, 85, 80, and 75 degrees and vibrating frequencies of 28, 29, and 30 Hz influenced the convection pattern of the granular materials in the 2D quasi-square container under vertical vibration. This is because the granular materials exhibit slow convection when the angles and frequencies are small, while the granular materials will have faster convection when the angles and frequencies increase. This can be demonstrated by vertically vibrating single light particles in a narrow bed. The bed shows five different patterns of granular motion, including global convection, symmetrical heap, unsymmetrical heap, local convection, and pseudo-solid state, by increasing the vibration frequencies from 15 Hz to 70 Hz with dimensionless vibration acceleration greater than 3.0 ($\Gamma > 3.0$). The alteration between these patterns is mainly influenced by vibration frequencies, and acceleration is a minor factor. However, the heavy particles (steel beads) cannot be fluidized at these vibrating conditions.

The bed only shows a pseudo-solid state [7]. In addition to this, a study concerning the details of the particle feeding pattern is important only for the flow of particles near the entrance of the chute. After a relatively short distance, however, the particle flow depends only on other factors such as the mass ratio, inclination angle, and rotating rate. The DEM model predictions in this study agree well with the experimental measurements for bed height and surface velocity [2]. The wall was tilted, and the outward angles were changed to observe the direction of the convection roll [6, 11]. When using a high vibration frequency and a small vibration amplitude in the studied process at low cohesion, the segregation of both spherical and cubic particles is only slightly influenced by cohesion. However, the spheres segregate and move slightly faster than the cubic particles at the early stages [10, 12]. Furthermore, the study examined the Discrete Element Method (DEM), which was employed to simulate the process of the intruder rising through small background particles from the bottom to the top in a cylindrical container. The experimental results were consistent [3].

CONCLUSION

When using the wall angles of 2D quasi-square containers, i.e., 90, 85, 80, and 75 degrees, and vibration frequencies of 28, 29, and 30 Hz, the convection of the ground materials and the intrusion materials were convective, looping along the left side of the container wall that surrounded the ground materials. When vertically vibrating to the system for some time, it was found that the top surface of the ground materials was tilted. The invasive granular materials then moved along the top of the slope surface of the ground granule materials. After that, the invasive granular materials moved along the right wall of the container and then descended to the bottom of the container wall to the left until positioned at the initial starting point. As the angle and frequency increased, the intrusion materials formed a smaller, asymmetric convection pattern. When the angle and frequency decreased, however, the intrusion material formed a larger, asymmetric convection pattern. Furthermore, the granular material moved fast when the angle and frequency increased (with increasing Γ), but the granular material moved slowly when the frequency decreased. Thus, the fluidization of grains becomes stronger. The granular system behaves more like a liquid, leading to a decrease in slope θ_s.

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