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Effects of container geometry on granular segregation pattern*

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In a set of vibrating quasi-two-dimensional containers with the right-hand sidewall bent inward, three new segregation patterns have been identified experimentally including a Two-Side segregation Pattern, a Left-hand Side segregation Pattern and a pattern where big particles aggregate to the upper left part of the container. In a container with small bending degree, either the two-side segregation pattern or the left-hand side segregation pattern is stable, which is determined by the initial distribution of particles.

Keywords: granular material, segregation, boundary geometry effect
PACC: 4425, 6475, 4720

1. Introduction

Granular materials exhibit many interesting phenomena such as segregation,[1−9] clustering,[10,11] surface waves[12] and convection cells[13−16] under vibration. In a vibrating container with rough vertical walls, particles usually flow upward in a broad region at the centre and downward in a thin stream along the sides.[2] Canting the sidewalls outward from the vertical beyond a transition angle can reverse the flow direction: particles move down at the centre of the container and up along the sides. Experiments[2,3] have also shown that the sidewall canting can also affect the segregation of particles. A segregation scheme for granular binary mixtures[4] was also performed by a vertically shaking asymmetric sawtooth-shaped base in a quasi-two-dimensional box. Hu *et al*[5] found that a bidisperse granular mixture showed size segregation in a slightly tilted compartmentalized chamber. A compartmentalized container[10] and a chamber with N connected compartments[11] were also used to examine the granular gas clustering behaviour. However, despite all of this effort, the effects of the boundary geometry are still not completely understood.

Here, we report the experimental observation of some striking new segregation patterns in a set of containers with the right sidewall bent inward from the vertical to form a narrower centre in the granular bed. In this simple geometry, the behaviour of bidisperse granular mixture shows complicate dynamics. The convection and segregation are considerably affected by the boundary shape and even by the initial distribution of species. And the segregation patterns are different from the "layered cake"[2,7−9] or radially segregated structures[6] published in the literature. Three previously unreported experimental observations are presented in this paper: (i) In an ordinary rectangular chamber, big particles aggregate to both sides of the container and form a Two-side Segregation Pattern; (ii) When the right sidewall is bent slightly inward from the vertical, big particles can segregate to both sides or the left side of the container, depending on the initial distribution of particles; (iii) When the right sidewall is bent inward more, big particles aggregate to the upper-left part of the container.

The paper is organized as follows. In Section 2, the experimental setup and parameters are introduced. In Section 3, the segregation patterns are showed in detail. In Section 4, the connections between heap/slope and segregation are discussed. And

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in Section 5, some points on the initial distribution are shown. The conclusion is given in Section 6.

2. Experimental setup and parameters

Our experimental set-up consists of a set of quasi-two-dimensional perspex containers mounted on a vibrator with adjustable peak acceleration a and frequency f. The containers are 162mm high (H), 100mm wide at the base (W), and the front and rear plates are separated by 20mm. The right sidewall is bent inward at a height of 60mm. The bending degree is characterized by γ with $\gamma = D/W$, where D is the bending inward depth, so that a $\gamma = 0$ container corresponds to an ordinary rectangular chamber. In our experiment, γ changes from 0.0 to 0.8 with a step 0.1.

Several granular mixtures have been used in our experiment. Throughout this paper, we concentrate on a bidisperse granular mixture that consists of these two species unless otherwise stated: soybeans, dry and nearly spherical, with a diameter of approximately 5mm; and glass beads, with a uniformly distributed diameter d=0.45–1.0mm. For all containers, the species volume ratio was determined in this way: we first filled the container with small particles to a height of about 65mm (slightly higher than the bending point), then added big particles to a height of 120mm. The particles were then mixed and the resulting filling height was about 110mm.

In the experiments, we operated the vibrator at a frequency f=25Hz and peak acceleration a=30m/s^2, corresponding to a normalized acceleration $\Gamma \approx 3.0$. Here $\Gamma = a/g$, and g is the gravitational acceleration.

3. Segregation pattern

The segregation was firstly examined in an ordinary chamber ($\gamma = 0$). In this case, two convection cells spontaneously occurred with big and small particles moving upward at the centre of the container. And this led to the formation of a well-defined heap at the centre of the upper surface, with particles surging vertically at the centre of the heap. Once reaching the surface, soybeans rapidly rolled down all the way to the bottom of the heap, always entering the bed near the vertical sidewalls of the container. Glass beads, however, reentered the particle bed at some locations close to the centre without reaching the sidewalls. This process led to the formation of two soybean clusters near both sidewalls. And then a new convection roll occurred within each cluster, in which the soybeans moved up not at the centre, but in two upward paths between the centre and the sidewalls. In this way up, the upgoing soybeans met the down-going glass beads. And a percolation zone was obviously observed here, so that small particles moved down through the small openings of soybeans. The interaction between the convection cells and the percolation zones accelerated the segregation process. In this way, a Two-Side segregation Pattern occurred after about 2 minutes' vibration. And when the segregation pattern formed, the surface heap gradually disappeared. The interfaces between big and small particles were not clear-cut (percolation zones). Sometimes, the resulting distribution might be asymmetric because the particles were not fully mixed initially, as shown in Fig.1(a). The convection cells, soybean clusters and percolation zones are illustrated in Fig.1(b).

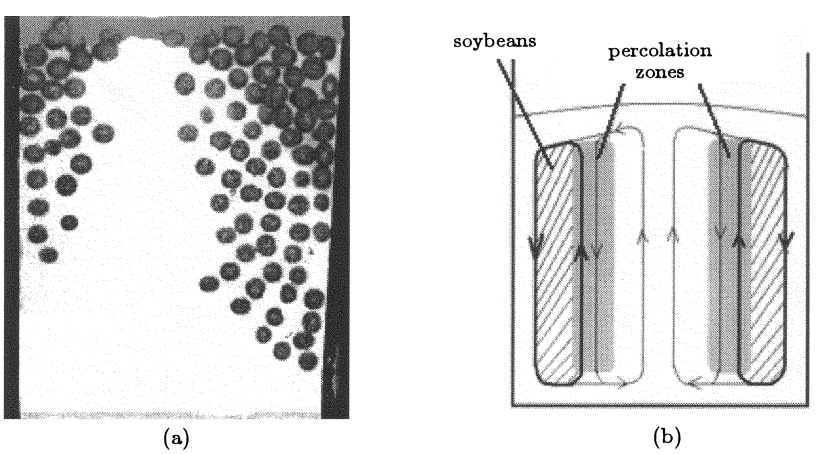


Fig.1. (a) Segregation pattern for an ordinary chamber ($\gamma = 0$). The right-side cluster contained more soybeans because of the asymmetric initial particle distribution. (b) Illustration of convection cells in the granular bed. The thick arrowed lines show the path for soybeans. The thin arrowed lines indicate the path of glass beads. The soybean clusters are shown with line shadows and the percolation zones are shown with dark shadows. The surface heap vanishes after the segregation pattern fully developed.

Different behaviour was observed when the right sidewall was slightly bent inward ($\gamma = 0.1$). In this case, a counter clockwise convection roll appeared at the upper left part of the granular bed and a clockwise convection roll appeared at the lower right part. In the upper-left roll, particles moved upward near the upper part of the right sidewall (above the bending point). And a slope developed at the upper surface soon after the beginning of vibration, which is slightly higher on the right-hand side than that on the left-hand side. The slope angle θ was about 10° relative to the horizontal. When the soybeans reached the surface, they rolled down along the slope to the left sidewall and formed a cluster, leaving glass beads behind. When the soybean cluster grew large enough, a separated convection roll appeared within it, so that upward motion took place near the halfway of the surface slope and downward motion occurred along the vertical left wall. A percolation zone was observed where the upgoing soybeans met the down-going glass beads and accelerated the segregation process. After about 2-min vibration, most soybeans aggregated to the left-hand side of the chamber. When the segregation pattern fully developed, the surface slope disappeared. The photographs of the initial particle distribution, the left-hand side segregation pattern and the illustration of convection cells are shown in Fig.2. The interface between big and small particles was not clear-cut.

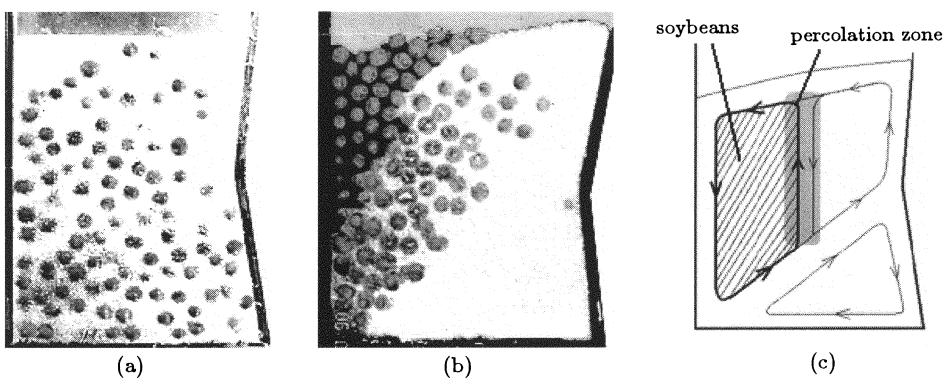


Fig.2. (a) Nearly uniform initial particle distribution led to (b) a left-hand side segregation pattern for a $\gamma = 0.1$ container. (c) Illustration of convection cells and percolation zones in the granular bed.

However, a stable two-side segregation pattern could also appear in this container, but only when the particles were not fully mixed and most of the soybeans were located at the right-hand side of the container initially, as shown in Fig.3(a). In this case, a segregation process similar to that in the $\gamma = 0.0$ container was observed. But the surface heap apex shifted to the right-hand side a little, and the right-hand side cluster contained most of the soybeans, as shown in Fig.3(b) (segregation pattern) and Fig.3(c) (convection rolls). Repeated experiments for a long vibration time (more than 20 minutes) showed that this pattern was not transitional but rather a robust, fully developed state.

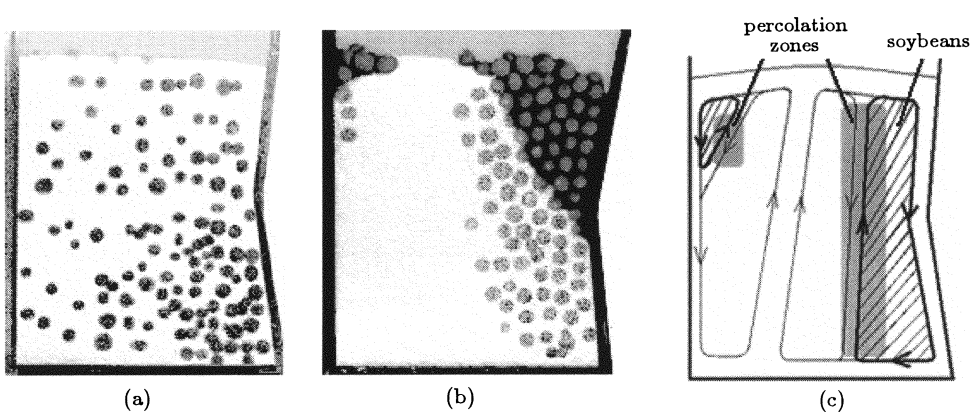


Fig.3. (a) Initially, most soybeans were located at the right side and (b) a two-side segregation pattern appeared in a $\gamma = 0.1$ container. (c) Illustration of convection cells and percolation zones.

Bending the right sidewall inward more ($\gamma = 0.2 - 0.4$), the bistable two-side segregation pattern disappeared and soybeans aggregated only to the left side, no matter what the initial particle distribution was. The difference was that the down-going stream of the left soybean convection roll could not reach the base of the container when $\gamma = 0.2$. The more the right sidewall was bent inward, the bigger the lower-right convection cell grew, and consequently the higher the upper-left soybean cluster was, and thus the more similar the segregation pattern would be to the Brazil Nut Pattern (BNP).

When the right sidewall was bent to $\gamma = 0.5 - 0.8$, the particles below the bottleneck flowed in a single clockwise convection roll, while the convection roll above the bottleneck was counter clockwise. In the upper roll, particles climbed up the right sidewall, rolled down along a surface slope of about 12° towards the left vertical wall. A similar segregation process was observed above the bottleneck, so that soybeans accumulated at the lower side of the slope. Moreover, a percolation effect was also observed at the bottleneck where the down-going stream of the upper roll met the upgoing stream of the lower roll. This also accelerated the segregation process. After about 2-minute vibration, soybeans aggregated to the left part above the bottleneck, as shown in Fig.4. The surface slope vanished after the segregation was completed.

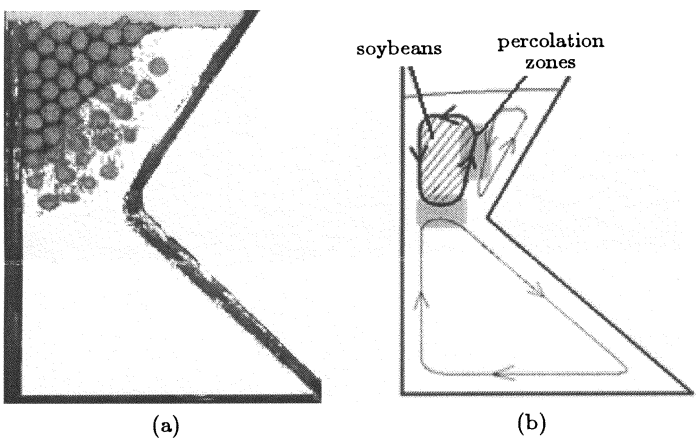


Fig.4. (a) Segregation pattern for a $\gamma = 0.7$ container. (b) Illustration of convection cells and percolation zones.

4. Heap/slope and segregation

In order to understand the underlying mechanism of these segregation patterns, we try to draw the connections among convection, heap/slope, percolation effect and segregation. As shown above, the granular convection led to the formation of a surface heap or slope, and the surface heap or slope was an important factor for the first stage of the segregation process. In the experiment, a surface heap usually occurred before a two-side segregation pattern developed in the granular bed ($\gamma = 0.0, 0.1$), while a slope on the right-hand side being higher than that on the left-hand side would lead to the formation of a left-hand side segregation pattern ($\gamma = 0.1 - 0.4$) or a pattern where big particles aggregated to the upper-left part of the container ($\gamma = 0.5 - 0.8$).

This is quite similar to the experiments of Brone and Muzzio[6] where the surface heap led to a radially segregated pattern in a vibrating cylinder. In their experiment, the formation of surface heap led to a segregated pattern and the destruction of heap corresponded to a homogeneous state. This process was reversible so that they could repeatedly drive the system back and forth between segregated and homogeneous states by increasing and decreasing the frequency of vibration respectively. However, we could not change the segregation pattern simply by changing the vibration frequency or peak acceleration. And the segregation process seemed to be irreversible (even at $\gamma = 0$). An explanation for this difference is that in our experiment the segregation pattern was affected by the spatial distribution of convection cells and percolation zones, and they were affected by the container geometry. Usually, two or more convection cells were presented in the granular bed and the bending of right sidewall led to the competition of these convection cells with percolation zones. For instance, when we bent the right sidewall more inward, the lower-right convection cell grew bigger, and the left-side big particle cluster was lifted more highly, and thus the

segregation changed gradually from a left-hand side segregation pattern to a pattern where big particles segregate to the upper-left part.

We also found that the heap or slope was not essential to maintain the segregation pattern. This behaviour is contrary to that in Brone and Muzzio's experiment. In their experiment, fade-away of the surface heap corresponded to the disappearance of radially segregated pattern. Whereas in our experiment, the surface heap or slope became smooth or gradually vanished when the segregation pattern was fully developed.

5. Segregation affected by initial distribution

The effect of initial particle distribution on segregation pattern was also found in our experiment with glass bead mixtures, such as d=3.2–4.0mm glass beads with d=0.45–1.0mm glass beads, and d=2.5–3.2mm glass beads with d=0.45–1.0mm glass beads. As shown in Fig.5, a stable two-side segregation pattern appeared in a $\gamma = 0.1$ container filled with big and small glass beads. We also operated the vibrator at f=40Hz and $\Gamma = 6$ and the granular bed showed qualitatively similar behaviour. It seemed that $\gamma = 0.1$ was a transition state between the state showing only two-side segregation pattern and the state showing only left-hand side segregation pattern, and we found that the two-side segregation pattern could be stable

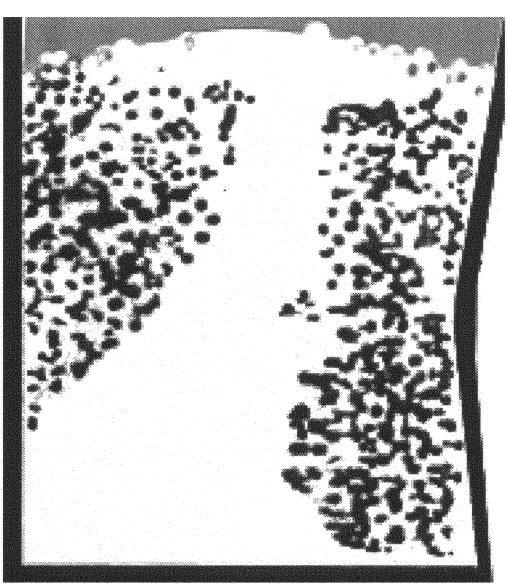


Fig.5. Two side segregation pattern for a $\gamma = 0.1$ container with a mixture of d=3.2–4.0mm and d=0.45–1.0mm glass beads. The surface heap persisted but the glass beads' upflowing path shifted to the right-hand side a little.

even when $\gamma = 0.2$ in the granular bed of $d \approx 5$mm soybeans and d=1.0–1.43mm glass beads. This implies that the transition is gradual.

It is important to note that the flux direction near the upper part of the right sidewall was opposite for these two patterns (compare Fig.2(c) with Fig.3(c)). We suggest that the presence of this phenomenon may be related to the effects of lower-right convection on the motion of particles close to the bending point and thus on the motion of particles above. However, it is unclear why and how the direction changes with initial particle distribution.

Finally, it must be mentioned that recent researches focus on the effect of particle density difference or the effect of interstitial air.[1,7] However, these effects are not so important in our experiment. Similar segregation process was also observed when we used granular mixtures of big and small glass beads, such as d=3.2–4.0mm glass beads with d=0.45–1.0mm glass beads, and d=2.5–3.2mm with d=0.45–1.0mm glass beads. The two-side segregation pattern, left-hand side segregation pattern and the pattern where big particles segregate to the upper-left part of the container were observed with these mixtures. So we are sure that the density difference between big and small particles is not so important to the segregation in this experiment. We also carried out experiments of observing the movement of a large intruder (a glass ball or soybean) in the shaking glass bead bed with different γ. We found that the intruder always moved up and arrived at the surface soon. No interstitial air induced negative buoyancy was observed in our range of vibrating frequency and acceleration.

6. Conclusions

In summary, vibration-driven segregation pattern can be affected by boundary geometry and even by initial particle distribution. In a set of quasi-two-dimensional container, after a leading surface heap or slope induced particle clustering, different segregation patterns appeared with different sidewall bending degree. In some cases, the initial particle distribution may also affect the segregation pattern. We suggest that the resulting segregation pattern comes from the combined effect of the convection cells, the surface heap or slope, and the percolation zones appearing in the granular bed. Though the surface heap or slope is an important factor for the segregation formation, it is not necessary for maintenance of the segregation pattern. The interaction of convection rolls with per-

colation zones accelerates the segregation process and is always present in the granular bed. It is noteworthy that the segregation is irreversible. We think that the experimental observation reported here is of practical significance because the container or channel width in most real engineering devices is not uniform at all.

Admittedly, the results presented here leave many open questions. A more extensive study of boundary effects is needed in order to develop a thorough understanding of the segregation process. While it is clear that the sidewall bending degree γ is an important parameter affecting the transition between segregation states, it would be desirable to know the extent of each segregation pattern as a function of vibration frequency and peak acceleration. Moreover, the effects of initial particle distribution on convection rolls and segregation patterns also need to be examined in more detail.

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