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Effect of Wall Protrusions on Granular Segregation in a Vertically-Shaken Vessel

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Abstract

Here we study segregation in a vertically-shaken vessel, in which short protrusions are introduced normal to the wall with the intent of interrupting the circulatory flow. Simple visual analysis tools are used to study the segregation of a binary-sized mixture, specifically the speed and extent of segregation in both vertical and horizontal directions.We find that, as the length of the protrusion increases, the extent of vertical segregation increases. However horizontal segregation varies non-monotonously with protrusion length; there is an 'optimum' protrusion length for which horizontal segregation is both hastened and maximised.

Introduction

Granular materials are made up of discrete solid particles, and typically in large quantities. These discrete particles may vary according to their physical properties including, but not limited to, particle size, density, surface, and geometrical characteristics. Due to these differences, a granular mixture has the capability to exhibit a phenomenon known as segregation — spatial de-homogenisation. This occurs when different transportation behaviours emerge based on differences in the physical properties of these discrete solids [7]. The 'Brazil nut effect' is a simplified example of segregation, where an originally homogeneous mixture of nuts separates according to size upon shaking, with the larger nuts on top [2].

Depending on the application, granular segregation is either beneficial or detrimental. In material separation facilities, this naturally occurring phenomenon is useful. However, when uniform material compositions are required, reducing and even removing segregation is necessary. Many studies have focused on the underlying mechanics of segregation [1, 2, 3, 4, 7]; however oftentimes the mixture composition cannot be changed and therefore investigation needs to turn to parameters outside of the mixture. While there have been several experimental studies to this end [2, 5, 6], there is no wholly conclusive determination on how different parameters affect segregation. Nonetheless, granular convection is an acknowledged major player in segregation [4, 8, 9], and thus in order to affect segregation, the convective flows in the system must also be affected. For our investigation, we focused on segregation in a vertically-shaken container.

Granular segregation in a vertically-shaken vessel is interesting in that there are actually two phenomena taking place. The first is the formation of a circulatory flow when the container is shaken vertically at a consistent frequency and amplitude. The simplest manifestation is when particles sink downwards along the outside edges of the container, travel along the base to the centre of the container, rise vertically back up to the top and finally spread out towards the sides again. The second phenomena is segregation - the separation of granular particles by physical characteristics such as relative size, density or shape - which is triggered when a non-homogeneous granular mixture is excited. The presence of the circulatory flow can thus encourage segregation due to the formation of the flow patterns, while also hindering segregation by breaking up any segregation clusters. Here, we used physical protrusions (applied to the container walls) to disrupt the convective flow in a vertically-shaken container, and studied the ensuing segregation of the binary mixture within. We present a portion of our results in this paper.

Segregation in a Vertically-Shaken Container

For a vertically-shaken system, the main causes of granular segregation are percolation and granular convection. Percolation is the process whereby smaller particles move downwards through the spaces between larger particles, as studied in [1]. Granular convection, on the other hand, occurs when a collection of granular material form convection rolls which are attached to the vessel wall [9]. Typically the particles sink downwards along the outsides of the container, travel inwards to the centre along the base, and then use rise vertically again in the centre. This behaviour is caused by a combination of interstitial air and particle-vessel wall friction [8]. We see that segregation caused by granular convection involves two competing mechanisms: larger particles are encouraged to re-enter the bulk motion, enhancing mixing; on the other hand granular convection encourages larger particles to remain on the top of the heap [9], due to their dimensions being larger than the width of the narrow convection streams which exist on the sides of the container [4]. It is reasonable to believe that either mechanism can be enhanced or reduced by varying external factors, such as the vessel wall design.

Experimental Setup

The experimental setup consists of 4 components: a vertical electric shaker with parts from Oriental Motors, an open-top acrylic box, sets of protrusions (acrylic slides) and a binary mixture of spherical beads. Figure 1 shows a schematic of the acrylic container with a pair of protrusions of length L (varying from 0.5 to 4cm) fixed 4cm above the base.

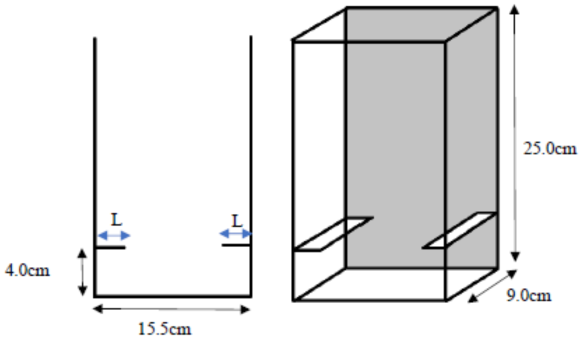

Figure 1: Schematic of vertically-shaken container and attached protrusions.

The setup was filled with spherical beads (see Table 1 for mixture properties) to a height of 5.5 cm, a short distance above the protrusions. This was to ensure that when the initially flat top surface becomes heaped during the vertical shaking, the protrusions will be at an appropriate height to target the top of the downward convection stream. The larger white beads were placed at the bottom and the smaller red beads layered on top, which is the opposite segregation pattern expected from this system — due to the larger size and lower density of the white beads, full segregation should be as in the classic Brazil Nut pattern with the white beads on top.

	small beads	large beads
Colour	red	white
Material	glass	coated plastic
Diameter (mm)	3	6
Density (kgm^{-3})	318	137
Unit Mass (g)	0.036	0.124
Total mass (g)	1200	36.75

Table 1: Properties of binary mixture. Quantity of large (white) beads was chosen so as to form a single layer on container base.

The vertical shaking was conducted at a frequency of 160 Hz and amplitude of 4.25 cm, resulting in a peak vertical acceleration of 11.93 ms^{-2}, and maintained for 10 minutes for each run. The runs were repeated between 3–5 times, depending on observed variance among repetitions. For all runs, video recordings (1080p resolution and 30 fps) were taken of the top and front views, and images later extracted for analysis.

Image Processing and Analysis

Image analysis began only when at least 5 white beads reach the top, indicating that the mixture has gone through half of a convection cycle. ImageJ, an opensource image processing software developed by the National Institute of Health (US), was used to determine the area fraction occupied by white beads in the extracted images.

Top views were split into 3 equal regions as shown in Figure 2.

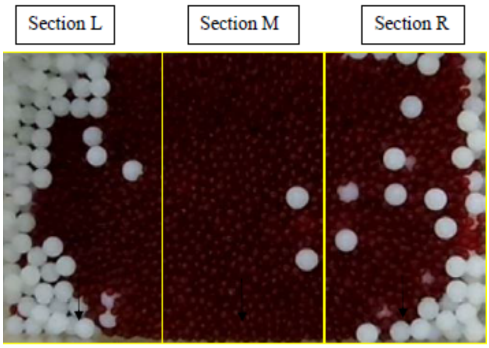

Figure 2: Top view image for analysis, showing the left (L), middle (M) and right (R) sections.

We use a ratio x_{wall}, which compares the area covered by white beads near the walls, to that over the entire top surface. We can express x_{wall} in terms of the area fractions ϕ (occupied by white beads) of the sections L, M and R:

$$
\begin{aligned}
x_{\text{wall}} &= \frac{\text{average `white' area in sections L and R}}{\text{`white' area in sections L, M and R}} \\
&= \frac{\phi_L + \phi_R}{6\,(\phi_{L+M+R})}\,. \qquad (1)
\end{aligned}
$$

The values of x_{wall} range from 0 (no white beads near walls), to $\frac{1}{3}$ (uniformly mixed) to $\frac{1}{2}$ (all white beads near walls). We then scale this such that a value of 0 corresponds to a uniform mixture and 1 corresponds to all white beads segregating to the walls:

$$
S_{\text{wall}} = 6x_{\text{wall}} - 2 = \frac{\phi_L + \phi_R}{\phi_{L+M+R}} - 2\,. \qquad (2)
$$

In this form, the sign of S_{wall} would immediately indicate whether the white beads are moving towards (positive) or away (negative) from the walls.

As seen in Figure 3, side views were also split into three regions — the top (A) from the apex to the affixed protusions, and the middle (B) and bottom (C) sections.

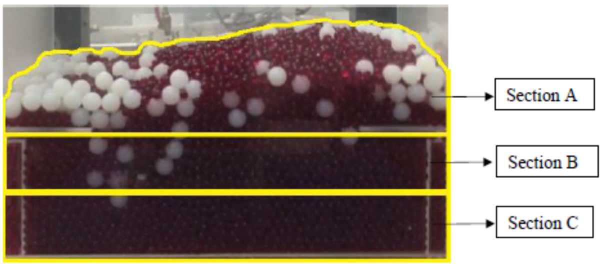

Figure 3: Side view for analysis, showing the top (A), middle (B) and bottom (C) sections.

Similarly to the top view, we define a ratio which compares the area covered by white beads near the top to that over the entire side surface, in terms of the area fractions of the sections A, B and C, and scale it in the same manner:

$$
S_{\text{top}} = \frac{3}{2}\,\frac{\phi_A}{\phi_A + \phi_B + \phi_C} - \frac{1}{2}\,. \qquad (3)
$$

In this form, a positive S_{top} indicates that the white beads are moving upwards.

Results and Discussion

General Evolution

Figures 4 and 5 show a series of photos (in 32-bit grayscale format) taken from both the top and the side, for one of the experiments using the 2cm protrusion. The behaviour observed here was generally the same for all the experiments — the white beads took a few minutes to travel from the bottom of the container to the top, appearing in random locations. They then rolled down the peak towards the two sides. Some of the white beads were reabsorbed into the convection flow and sunk down through the mixture again; others remained at the top of the mixture. As a whole, the system appeared to remain largely unchanged after about 6min of shaking.

Vertical Segregation — Side View

The evolution of vertical segregation (as observed from the side view), when different protrusion lengths were inserted, is plotted in Figures 6–8. The data is split across three graphs for clarity, and also because the behaviour observed was slightly different.

In Figure 6, the protrusion lengths inserted were small (0–1cm, ≈1.7 white bead diameters). The initial S_{top} is high — due to the initial appearance of white beads at the top — before gradually decreasing to a generally low steady-state (compared to the larger lengths shown as grey lines). This implies that the width of the granular convection stream is greater than the protrusions, and the majority of the white beads are able to move past them

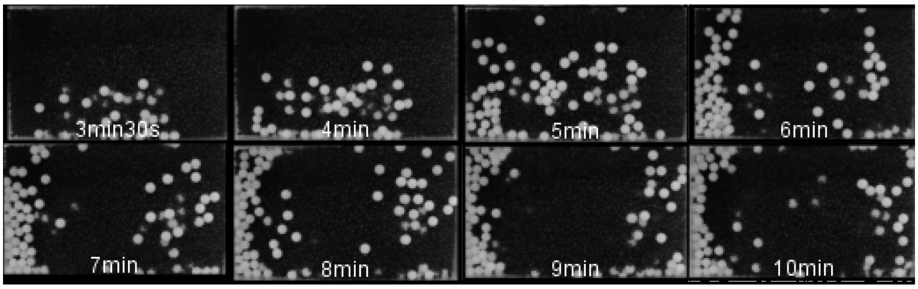

Figure 4: Snapshots of top view during experiment with 2cm protrusion inserted. Time progresses from left to right, then from 1st row to 2nd row.

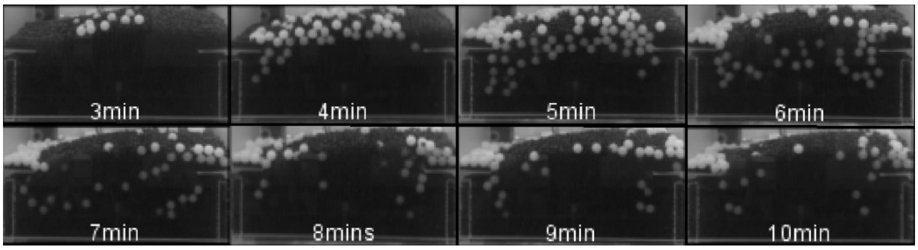

Figure 5: Snapshots of side view during experiment with 2cm protrusion inserted. Time progresses from left to right, then from 1st row to 2nd row.

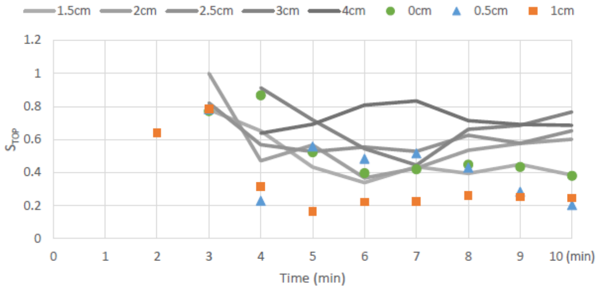

Figure 6: Evolution of S_{top} with time, for small protrusion lengths (0–1cm). The data for longer protrusion lengths are also included (grey lines) for comparison.

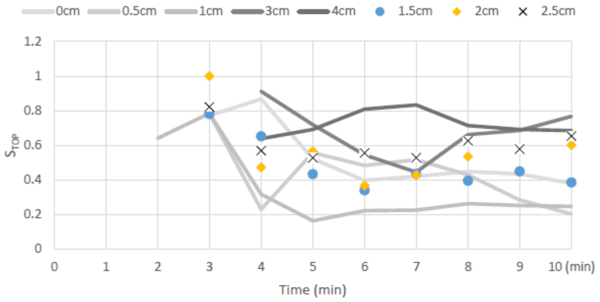

Figure 7: Evolution of S_{top} with time, for the middling protrusion lengths (1.5–2.5cm). The data for shorter and longer protrusion lengths are also included (grey lines) for comparison.

back into the convective flow. Thus we may conclude that the small protrusions do not have significant effect on segregation.

For slightly longer protrusions (see Figure 7) up to 2.5cm ($\approx$4 white bead diameters), S_{top} also exhibits an initial decrease, but reaches a higher steady-state value than for the shorter protrustion lengths. This indicates that the protrusions are now longer than the width of the granular convection stream, and the convective flow is being disrupted. Additionally, S_{top} increased over time after approximately 7min for all three protrusion lengths. This is due to the formation of a 'dead zone' above the protrusions, in which the white beads that have entered are cut off from the convective flow. Intuitively we would then expect that the longer the protrusion length, the larger this 'dead zone', and therefore the greater the steady-state value of S_{top} — which is indeed observed here.

Figure 8 shows the S_{top} evolution for the longest protrusions tested (3–4cm, $\approx$5–6.7 white bead diameters). Here, the S_{top} values are consistently higher than for all the shorter protrusions. This implies that the convective flow was able to transport white beads to the top, but they generally remained trapped there. In other words, larger protrusions are better for disrupting convective flow and therefore encouraging segregation.

Horizontal Segregation — Top View

The evolution of horizontal segregation (as observed from the top), when different protrusion lengths were inserted, is plotted in Figures 9–11. As with the previous graphs, the data is split across three graphs for clarity.

For the shortest protrusions (see Figure 9), S_{wall} steadily increases and then plateaus around 0.5. We observe that S_{wall} is generally higher when there are protrusions than without, and the increase happens fairly quickly. This indicates that not only does having protrusions encourage the accumulation of white beads near the wall, it also speeds up the segregation.

In Figure 10, for the middle range of protrusions, S_{wall} increases with time and then plateaus at a value higher than that for shorter and longer protrusions. This implies that there may be an optimal protrusion length in this range, for which horizontal segregation is minimised. Looking closely, we note that the rate of increase is slower than for shorter protrusions — this is because the protrusions are now long enough to affect the granular heap's height. Specifically, the heaps decrease with protrusion length; white beads thus require more energy to roll down the

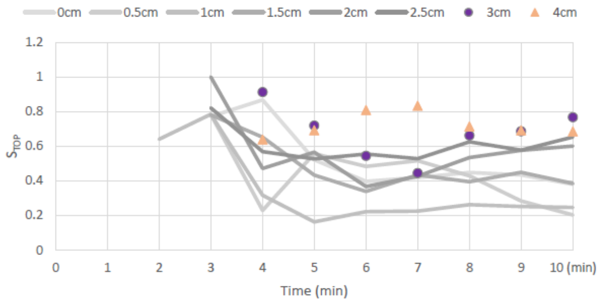

Figure 8: Evolution of S_{top} with time, for long protrusion lengths(3–4cm). The data for shorter protrusion lengths are also included (grey lines) for comparison.

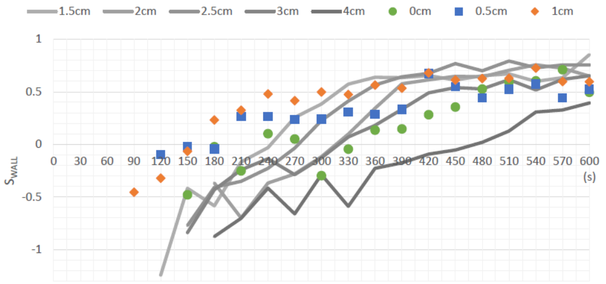

Figure 9: Evolution of S_{wall} with time, for small protrusion lengths (0–1cm). The data for longer protrusion lengths are also included (grey lines) for comparison.

gentler slopes. Considering both this slower rate as well as the increasing steady-state S_{wall}, the optimal protrusion length may be around 2.5cm (4 white bead diameters).

For the largest protrusions lengths (see Figure 11), the granular heap is nearly flat. This means that the white beads have very little tendency to roll to the sides, resulting in the relatively slower rate of increase in S_{wall}. Additionally, the convective flow is effectively disrupted as the white beads are only able to rise to the top in a much narrower stream.

Conclusions

In a vertically-shaken container, both vertical and horizontal segregation occurs simultaneously. Vertical segregation increases with protrusion length. However, the rate and extent of horizontal segregation appears to have a maximum when the protrusion is ≈4 large particle diameters. Thus, the choice of 'optimal conditions' depends on the desired outcome – if extraction of a specific component is done via vertical separation, then long protrusions would be useful. However if extraction is from the sides, then the protrusions' length should be limited.

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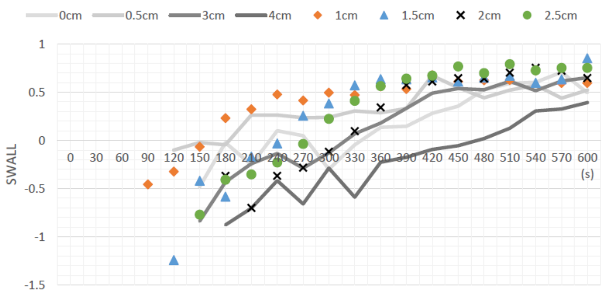

Figure 10: Evolution of S_{wall} with time, for the middling protrusion lengths (1–2.5cm). The data for shorter and longer protrusion lengths are also included (grey lines) for comparison.

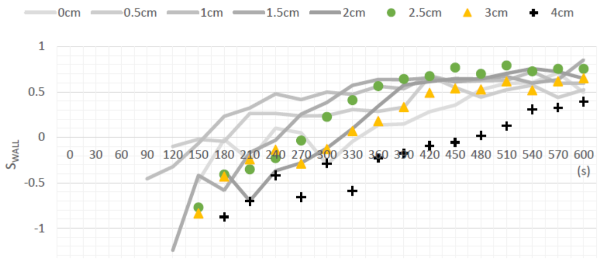

Figure 11: Evolution of S_{wall} with time, for long protrusion lengths(3–4cm). The data for shorter protrusion lengths are also included (grey lines) for comparison.

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