Shape segregation in granular materials: A game of Go where shape beats size and buoyancy

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The separation of particles of different size in a mixture of granular materials, where the largest particles rise to the top, is ubiquitous as the ”Brazil nut effect”. Based on previous simulations in two dimensions, we investigate the shape segregation in convecting granular material: In a mixture of oblate particles (Go-stones) with round particles, the center of mass of the round particles goes below the center of mass of the oblate particles of the same (or smaller) volume with equal (or even larger) density. It turns out that ”shape segregation” can be stronger than both size-segregation and buoyancy, i.e. oblate particles rise above the round particles even if their volume is smaller and their density larger.

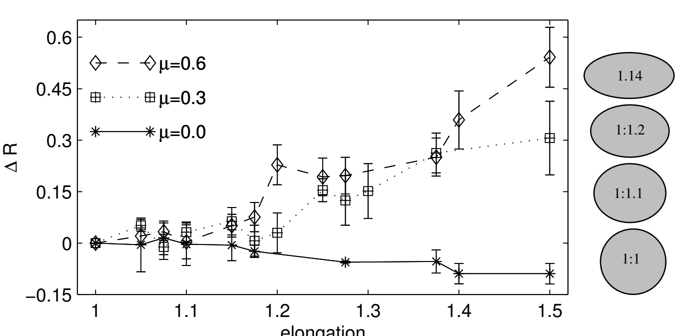


Figure 1: Separation of the center of mass for two-dimensional simulations of shape segregation(left) and particles with diverse elongations (right).

1 Introduction

In a polydisperse mixture of vibrated/ shaken granular materials, size segregation where larger particles move to the top (”Brazil nut effect”) are ubiquitous. In contrast, we found shape segregation in Discrete-Element (DEM) simulations(1) of bi-disperse mixtures of 50 % round discs and 50 % elongated ellipses (Fig. 1, right) of equal size. In this paper, we want to focus on the experimental verification of the two-dimensional simulations by three dimensional experiments. In the simulations, for a given coefficient of friction, the segregation distance (the distance between the average center of mass of the round and the elongated particles, scaled by the system height) increased monotonically with the particle elongation of the non-spherical particles larger than 1.05, see

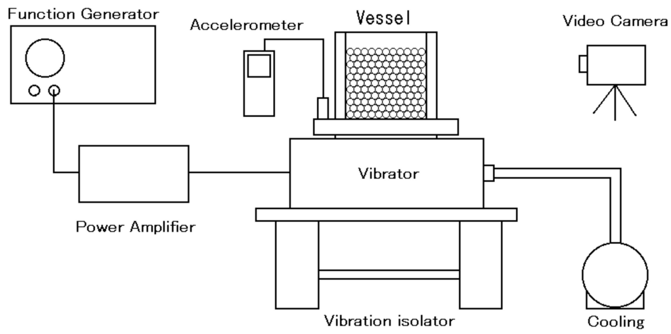


Figure 2: Vibration Test System VS-30-03 by IMV corporation, Power Amplifer VA-ST-03 with Vibrator VE-50; Frequency Generator: NODE corporation Oscillator 6111; Cooling with Ring Blower VFC108P from Fuji Electric CO. LTD; Vibration table: HERZ CORPORATION, Air-suspended Vibration Isolater /HOA-LM series.

Fig. 1 (left). Apart from the elongation, the Coulomb-friction also plays a crucial role: For finite values of the friction, the center of mass of the larger particles rises, whereas for vanishing friction, the center of mass of the round particles rises. In fact, the friction with the wall contributes to the driving force for the convection roll; the segregation is not a thermodynamic effect, but depends effectively on the boundaryies. Deviations from a strictly bi-disperse mixture by e.g. using a distribution around ”average” elongations reduced the segregation distance. In the simulation, no segregation were found when one kind of the particles had straight sides (triangles, squares), so

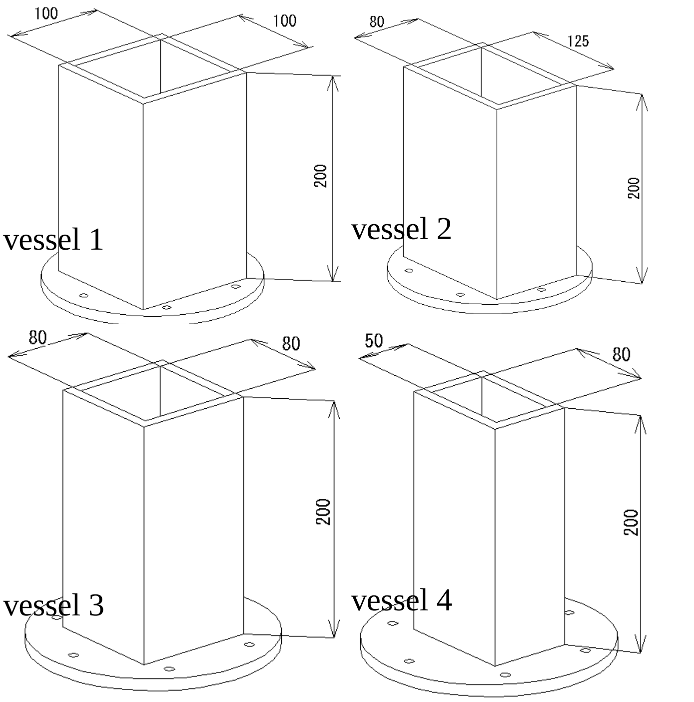


Figure 3: Vessels of different size; dimension in mm.

we limit our investigation in the following to particles with curved surfaces. The recently found ”reverse Brazil nut effect”(3), where the smaller particles of a bi- or polydisperse mixture rise to the top, makes use of a selective distribution of the kinetic energy among the particles. This was not the case in our shape-segregation simulation, where the segregation occurred only after convection had set in, so that the kinetic energy was distributed evenly between the particles irrespective of their shape/elongation.

2 Experiment

The three-dimensional equivalent of the elongated ellipses could be cross sections of ellipsoids either along the longest axis, which would lead to prolate (elongated) ellipsoids, or cross sections along the shortest axis, which would lead to oblate ellipsoids. The simulations(1) had made clear the importance of the alignment of the longest axis of neighboring particles during the convective phase for the segregation process, so we choose to investigate mixtures with oblate ellipsoids, as these can be more likely candidates for stacking/ordering than the prolate ellipsoids. To understand whether our simulation had predictive power also for the three-dimensional case, we started with parameter regimes (Froude number/frequency/amplitude and system size) similar to the ones in the simulation.

	d (mm)	t (mm)	v (cm^3)	m (g)	ρ (g/cm^3)
Go-stone 1	14.75	4.85	0.52	0.80	1.5
Go-stone 2	12.20	4.00	0.30	0.44	1.5
Styrofoam (lacquered)	10.4 $\pm$0.8	–	0.6 $\pm$0.2	0.18	0.3 $\pm$0.2
Soft-Air 1	8.00	–	0.26	0.34	1.3
Soft-Air 2	5.90	–	0.10	0.19	1.8

Table 1: Particle diameter d, thickness t for Go stones, volume v, mass m and density ρ.

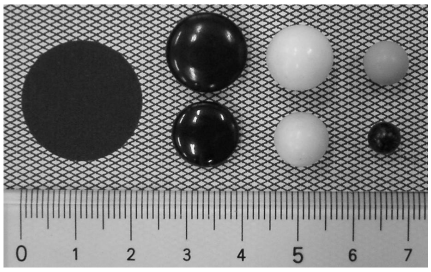


Figure 4: Circle with the diameter (22 mm) of conventional Go-stones made from clam shell, and the particles from Tab. 1 (from left to right) the Go-stones made from plastic, lacquered Styrofoam spheres, and soft Air-gun-beads in two different sizes.

2.1 Setup

On our vibration test system (see Fig. 2) we use vessels of different size (see Fig. 3) made from 1 cm thick acryl, so that the walls are thick enough to eliminate artifacts due to wall vibrations. In our setup, we are able to control both the frequency and the amplitude and so the vibration was chosen similar to the simulation; with 5 mm amplitude and 10 Hz frequency. The error was measured with a laser distance gauge and found to be in the third digit or smaller. The main obstacle for the experiment was to find a suitable materials for the oblate ellipsoids and round particles of the same or slightly larger volume to fulfill the premise assumption of the simulation(1). Finally, we decided to use plastic Go-stones, smaller than the standard Go-stones made of clam shell, and to use soft air-gun beads of two different sizes and lacquered Styrofoam beads as the round particles. In contrast to the simulation result in Fig. 1, for our experiment it was not possible to adjust the friction coefficient continuously, and especially the case with $\mu = 0$ was not accessible. To obtain suitable convection rolls, it is

Figure 5: Snapshot of convection for 50 % black, 50 % white Go-stones. The upright metal cylinder on the right is the accelerometer.

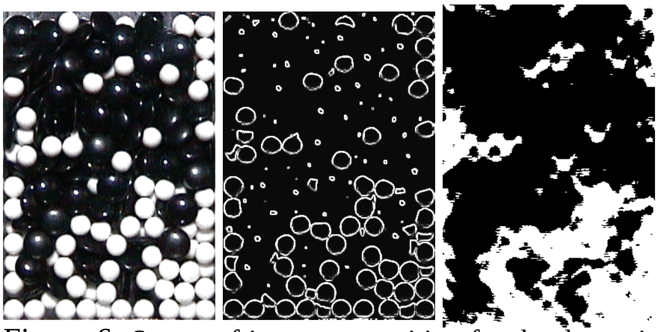


Figure 6: Stages of image recognition for the determination of the center of mass; From left to right: Digital image (jpg-format), binary and frame detection (bmp-Format) and after pattern recognition (pnm-Format).

necessary that the filling height H_l of the vessel in z-direction is at least comparable to the longer of the basis sides in x- and y-direction; we choose constant filling height $H_l = 110$mm for all experiments. Changes of the packing density resulted in changes of the filling height only in the third digit.

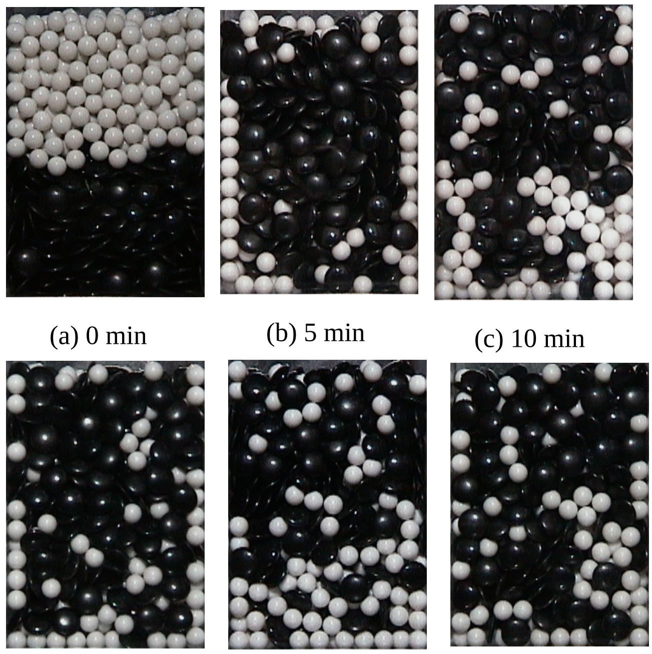
2.2 Measurement and Data processing

As the easiest way to compare the simulations with the experiment, we decided to measure the center of mass of the round particles, which were all white, in the cross section along the middle of the vessel by inserting an acryl shelf into the vessel while removing the front plate. The configuration is then evaluated via image processing techniques, (see Fig. 6), so that the white pixels were used for the computation of the center of mass of the round particles after suitable correction for the . Because the insertion of the acryl plate and partial emptying perturbs the system significantly, we cannot report continuous time series, but each data point was obtained after a new start of the vibration process.

3 Results

Each experiment started with the white spherical particles bedded on top of the black Go-stones (Fig. 7(a)), the formation of convection rolls separated the center of mass of the spherical and oblate particles. If shape and direction of the convection rolls changed too abruptly, segregation was suppressed, as in the case in Fig. 7(f). The pairings for materials and vessels can be seen in Tab. 2. In the following graphics, we plot the dimensionless segregation distance Δr, i.e. the distance of the center of mass of the round particles from the center of mass of all the particles, rescaled by the filling height of the vessel. Because the measurement time is the accumulated time for all timesteps, it took too long to perform a proper configuration sampling with error-bars.

In Fig. 8, we have plotted the segregation distance ΔR for the large Go-stones and the Styrofoam beads. For vessel 3 with a square cross-section of 80mm $\times$



(a) 0 min (b) 5 min (c) 10 min

(d) 20 min (e) 40 min (f) 60 min

Figure 7: Time series of shape segregation; Large Go-Stones are shaken in vessel 4 together with Styrofoam spheres.

80mm, no conclusive result could be obtained. The vessel was so narrow that due to the small size and particle number (846 particles), commensurability effects, as well as the symmetry influenced the convection, so that segregation was inhibited. We obtain shape segregation (rising of the oblate over the round particles) with vessel 1 and vessel 2, i.e. the Go-stones move upward in average though they have higher density and smaller volume than the Styrofoam balls. This shows that the shape segregation can work opposite to buoyancy and opposite to size segregation, and surpass both effects in strength. In Fig. 9, small Go-stones and large soft-air-gun beads again don't show segregation for the vessel 3 with square cross section. The same mixture in vessel 4 with elongated cross section gave segregation, because the direction of the convection-rolls were much more stable. This can be considered as shape segregation as

type	vessel	H_l (mm)	d_s (mm)	d_{go} (mm)	t_{go} (mm)	N
t1	1	110	10.4 $\pm$ 0.8	14.75	4.85	1060
t1	2	110	10.4 $\pm$ 0.8	14.75	4.85	1320
t1	3	110	10.4 $\pm$ 0.8	14.75	4.85	846
t2	3	110	8.00	12.20	4.00	1100
t2	4	110	8.00	12.20	4.00	1100
t3	1	110	5.90	12.20	4.00	1860
t3	2	110	5.90	12.20	4.00	2330
t3	3	110	5.90	12.20	4.00	1490

Table 2: Particle pairings, vessel type, filling height H_l, diameter of the round particles d_s, larger (d_{go}) and smaller (t_{go}) elongation of the go stones and number of particles N computed as $N = WH_l/d_s^2$.

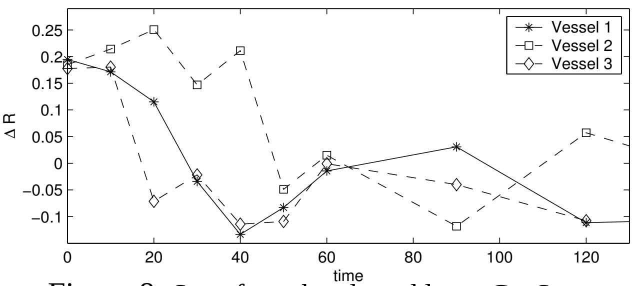


Figure 8: Styrofoam beads and large Go-Stones.

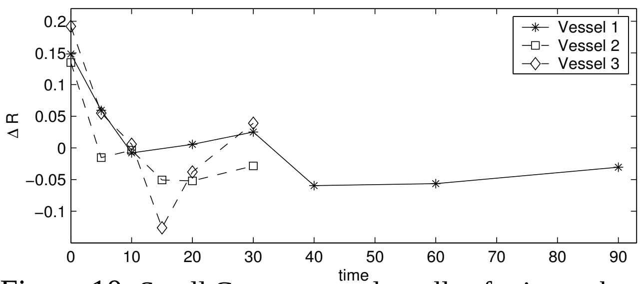


Figure 10: Small Go-stones and small soft-air-gun beads.

the small Go-stones with a volume of 0.3 cm^3 were hardly larger than the large soft-air-gun beads with 0.26 cm^3. Surprisingly, small Go-Stones and small soft air-gun beads don't give conclusive segregation in Fig. 10, though the volume of the spherical beads is smaller than that of the oblate Go-Stones. Our theoretical expectation was that we would find segregation, improved by a slight size-segregation, because the volume of the small-stones is about three times as large as that of the spherical particles. Instead, the round particles with diameter 0.59 cm got trapped between the oblate Go-stones with a comparable thickness of 0.4 cm.

4 Summary and Conclusions

We found shape segregation for various types of mixtures with 50 % round beads and 50 % Go-stones with vibration amplitudes comparable to the particle diameter, similar to our two-dimensional simulations, depending on the shape of the vessel. The center of mass of the Go-stones which were bedded on top of the spherical particles at the start of the experiment, could move below the center of mass of the round particles, irrespective of density and size of the round particles in the mixtures. The segregation was observed on the time scale of hours. For some combinations of vessels and particles, the segregation was suppressed if the convection rolls had no stable direction or size. The experimentally found segregation distance in three dimensions was smaller than that for the simulations in two dimensions.

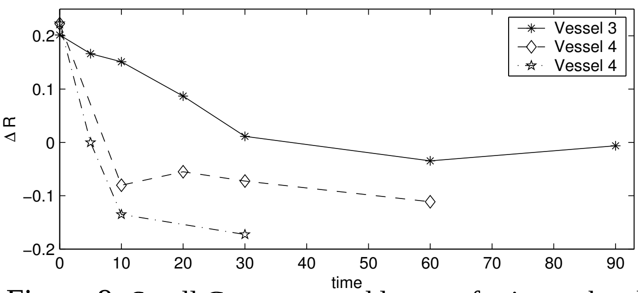


Figure 9: Small Go-stones and large soft-air-gun beads.

Our two-dimensional simulation proved useful in predicting both the effect itself and the appropriate parameter regions for the experiment (trial-and-error experiments in adapting the frequency and amplitude lead either to clogging or to fierce convection). Shape-segregation can dominate both buoyancy and size segregation, as we saw in the case with Go-Stones and Styrofoam-balls or larger volume. If the diameter of the round particles approached the shorter radius of the ellipsoids, (shape- and) segregation was suppressed and perfect mixing occurred.

As we could not investigate the influence of friction on the segregation (an attempt to coat the beads with Teflon-spray did not work out well), no clear picture has yet evolved about the mechanism of the segregation. One conclusion from the two-dimensional simulation is, that the experimental findings in this article can probably not be reproduced in simulations with ellipsoidal potentials(2); these give no unique contact point and therefore are not able to simulate Coulomb friction in a reliable way. In Fig. 1, vanishing Coulomb friction results in a much smaller (and negative) seggregation distance even in strictly bi-disperse mixtures; As the segregation was reduced for polydisperse systems, the variable cross-sections for three dimensions would mimic a polydispersity, so that the segregation would be effectively suppressed.

With regard to the controversy mentioned in Breu et al(3) about the experimental reproducibility, we would like to express the warning that the reproduction of our result will be difficult if e.g. the inner walls of the vessels are not clean enough or the walls are so thin that they vibrate together with the vessel content. Also, if the load is too heavy for the vibrator (the typical weight of 1.8 kg in our experiment is the lower, not the upper limit our apparatus can handle), an asymmetry in the vibration will result in irregular convection patterns and the segregation distance will be reduced.

REFERENCES

[1] Matuttis, H.-G. , Ito N. & Watanabe, H . 2003. Shape segregation for bidisperse mixtures of ellipses in two dimensions, in "Proceedings of Traffic and Granular Flow 2001", ed. M. Fukui, Y. Sugiyama, M. Schreckenberg, D. E. Wolf, p. 455-460, Springer

[2] Perram J.W. , Rassmussen J. , Præstgaard E. & Lebowitz J.L. 1996. Ellipsoid contact potential: Theory and relation to overlap potentials, Phys. Rev. E, 54, p. 565-6572

[3] Breu A. P. J. , Ensner H.-M. , Kruelle C. A. & Rehberg I. 2003. Reversing the Brazil-Nut Effect: Competition between Percolation and Condensation, Phys. Rev. Lett. 90, 014302