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Shape segregation for bidisperse mixtures of ellipses in two dimensions

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Abstract. Whereas size segregation is a fairly common phenomenon in granular material research, up to now shape segregation was has not been observed. We present simulations of bidisperse shaped (elliptic and round) granular particle systems which exhibit a demixing of round and elongated particles. The effect is not only controlled by the particle elongation, but also by the Coulomb friction coefficient in the system.

1 Introduction

Spherical particle simulations are very common in granular materials research. Nevertheless, there are phenomena which seem not to be accessible by round particles. Our aim in studying systems of elliptic particles[1] was, that this shape seems to be the next simplest shape after spherical particles, allowing a continuous transition from round to elliptic shapes. Size segregation has been a common phenomenon in granular materials[2], sometimes under names like "Brazilnut-effect" or "physics of muesli"[3]. Our research interest was to investigate, whether segregation could not only be caused by different size particles, but also by particles with different shape.

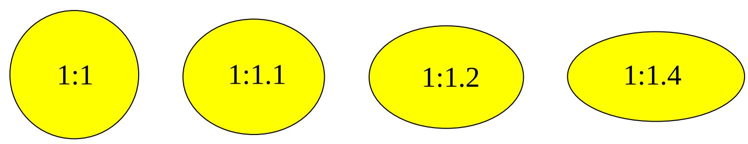

Fig. 1. Example of ellipses with the same area but different elongation.

2 Setup and simulation parameters

We simulated a vibrated box of bidisperse particles (round and elliptic) with **identical** volume/ area in two dimensions. The mixture consists of 50 % round, 50 % elongated particles. The box was driven with a frequency of 90 Hz and an amplitude of 25 mm. The particle diameter was about 8 mm. In the simulation, we monitored the center of mass of the spherical particles and the elongated particles. We investigated the dependence of the shape segregation from different elongations (see Fig. 1) and from the Coulomb friction coefficient.

The interaction law has a "hardcore repulsion" (Youngs modulus= 10^6N/m), the normal damping/dissipation (coefficient of restitution) is so large that particle particle collisions are practically inelastic (we varied the numerical value, but the effect was negligible), tangential Coulomb friction after Cundall and Strack[4] have been implemented using Coulomb coefficients between $\mu = 0.0$ and $\mu = 0.6$. The force law was derived for polygons[5] but could be adapted for ellipses without modifications[1].

3 Time evolution

The system was chosen so that the volume occupied by the particles was of approximately square shape. If the system is too shallow, the segregation is suppressed. An example of the quantitative time evolution, i.e. the motion of the center of mass of the elongated and round particles, is shown in Fig. 2. In Fig. 3, some snapshots from during the simulation are shown.

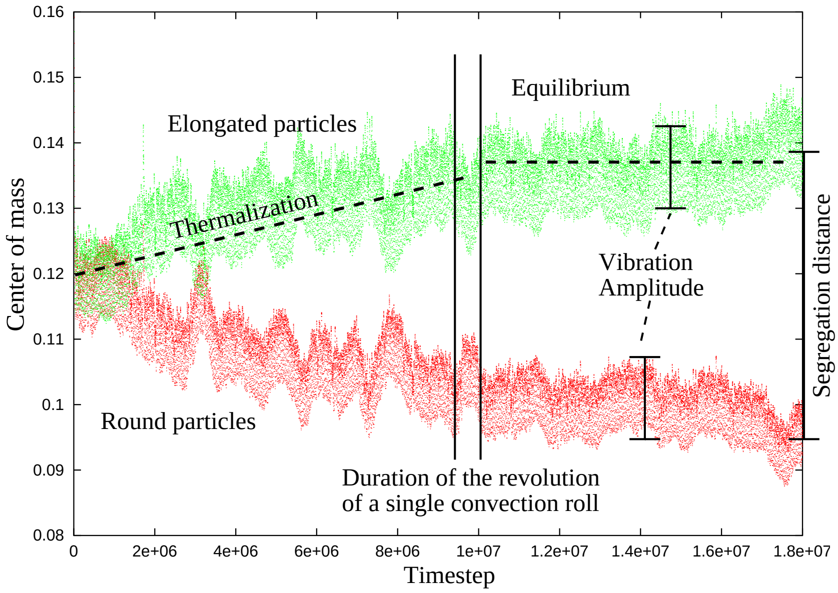

Fig. 2. Typical time evolution of the center of mass of the spherical particles and of the elongated particles.

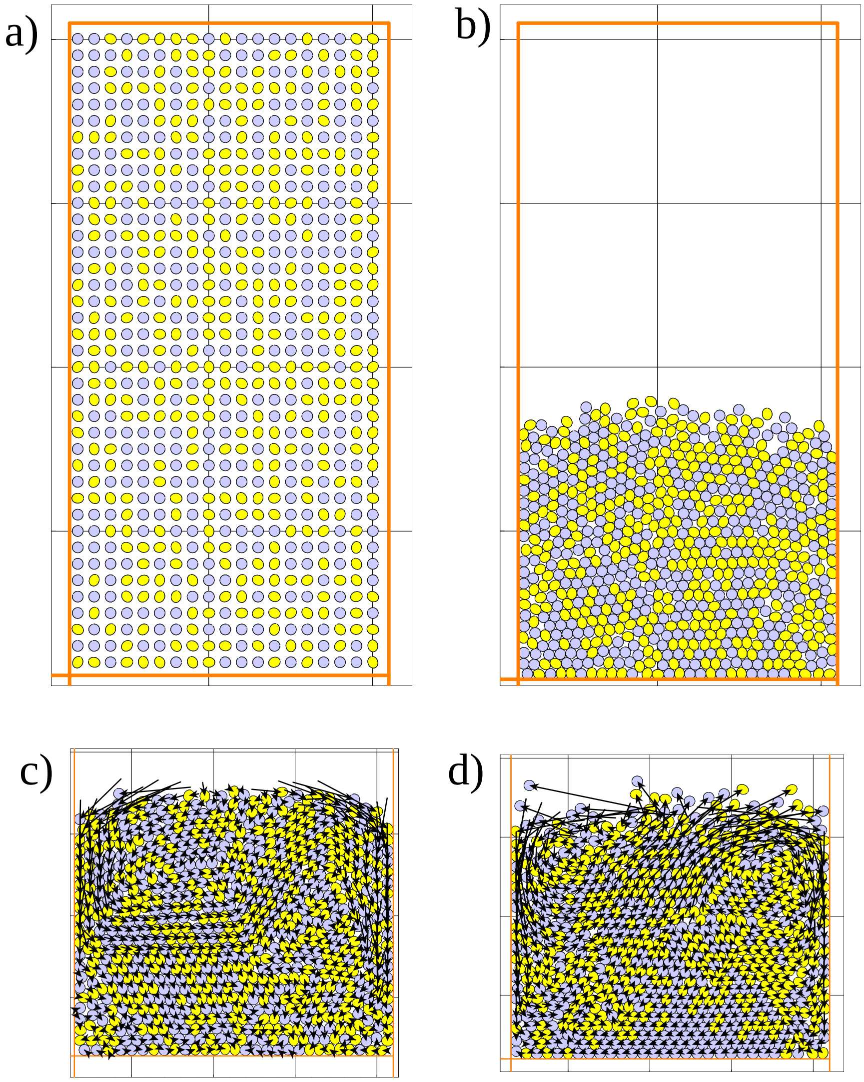

Fig. 3. Time evolution of the shape segregation in elliptic particles: a) Setting up the system with a random distribution of round (blue) and elongated (yellow) particles. b) Initial relaxation leads to a random packing. c) Onset of the convection after the particles are sufficiently compacted. d) Segregation result: Elongated particles (yellow) rise to the top. Black arrows show the velocities in arbitrary units.

4 Influence of the friction coefficient

It turned out that the determinating parameter of the segregation was not the elongation of the particles alone, but the Coulomb friction coefficient (we use the same friction coefficient for static and dynamic friction) was also crucially influencing the outcome.
The direction of the convection rolls is the same for all friction coefficients $\mu = 0.0 - 0.6$. Nevertheless, for friction coefficients $\mu = 0.3 - 0.6$, the elongated particles rise to the top, whereas for friction coefficient $\mu = 0.0$, the spherical particles rise to the top, see Fig. 4. The error bars indicated in Fig. 4 and Fig. 5 are the fluctuations around the equilibrium position as indicated in Fig. 2.

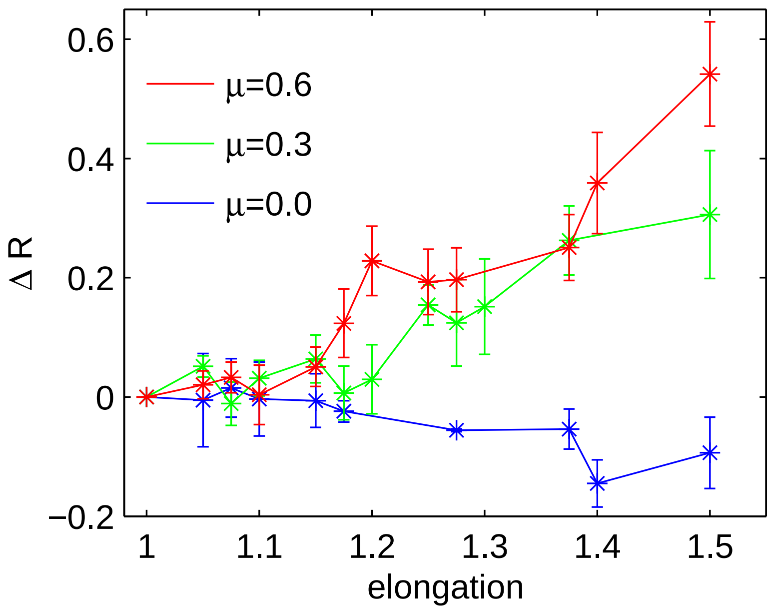

Fig. 4. Coulomb friction dependence of the shape segregation effect for friction coefficients $\mu = 0.0, 0.3, 0.6$. The ΔR for the y–Axis is the hight of the distance between the center of mass of the elliptic and the round particles, rescaled by the center of mass.

It turns out that both friction and elongation can be used to control the transition from a non-segregating system to a segregating system. For systems with 350 and 700 particles, the transition occurred at practically the same elongation of about 1.175. Bidisperse systems for a given elongation l of the longer particles show clearer segregation than polydisperse mixtures with an average elongation of $\langle l \rangle = l$.
No shape segregation could be found for bidisperse mixtures of spherical particles and triangles and for spherical particles and square particles. The simulation

using elliptic particles was about five times Shape turns out to be stronger than size: As long as the longer axis of the elongated particles is longer than about 1.15 of the diameter of the round particles, the elongated particles (at least for our test at $\mu \geq 0.3$) will rise to the top, even if the area of the round particles is larger than the area of the elliptic particles.

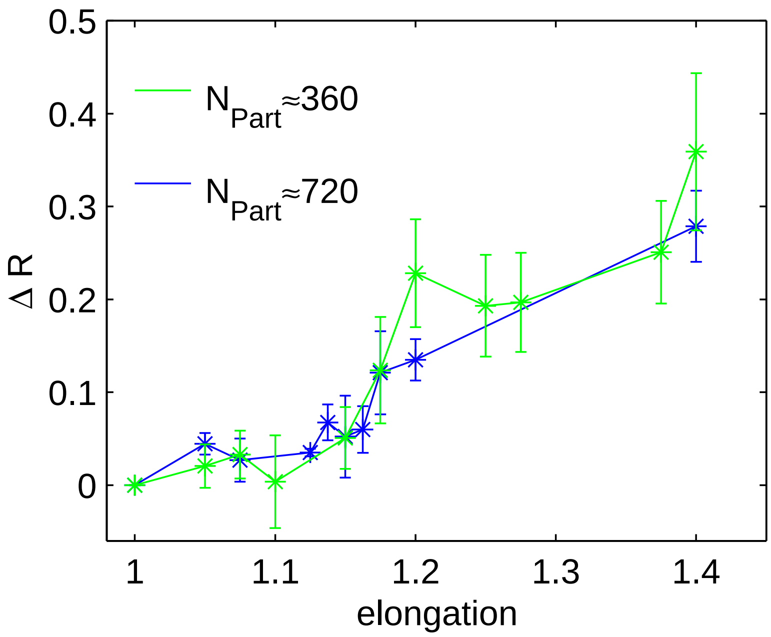

Fig. 5. Size effect of the shape segregation for a friction coefficient of $\mu = 0.6$. The $\varDelta R$ for the y–Axis is the hight of the distance between the center of mass of the elliptic and the round particles, rescaled by the center of mass.

5 Summary

We have found that a shape segregation effect in granular materials in two dimension exists. It is not only dependent on the shape alone, but depends also on the friction in the system. Fig. 6 shows a tentative explanation on geometrical grounds (wedging effect) why elongated particles can rise over round particles. This explanation should work independent of the friction coefficient, and is therefore insufficient.

We have up to now also not been able to derive a microscopical explanation, neither interface energy(between clusters of spherical and elongated particles) nor entropical arguments are tractable to include the effects of friction.

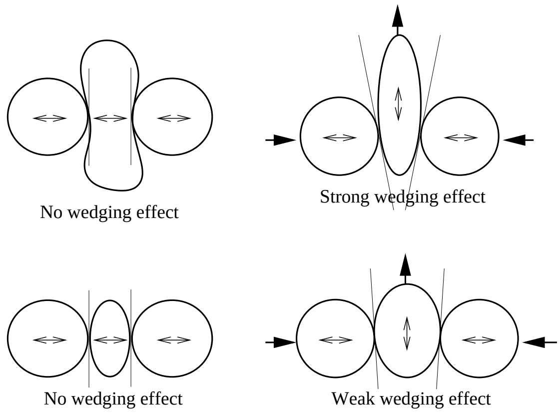

Fig. 6. Possible geometry-dependent segregation mechanism for the shape segregation: The elongated particles are wedged upwards by the round particles. If the long axis of the elongated particles is too short, no wedging can take place. If the particle is of convex shape or has parallel sides, also no wedging can take place.

Friction has been found to be able to reverse the dynamic behavior of the frictionless system, i.e. the round particles are rising to the top for sufficiently large systems. This poses the interesting question, up to which point the investigation of a statistical system (with normal dissipation, but without tangential friction) is really relevant for the investigation of a granular system (with tangential friction).

A macroscopic explanation of the shape segregation may give insights into the existence of a "configurational entropy". We further have to narrow down the regime for numerical value of the elongation for which the onset of the segregation can be observed. Currently, we find this "critical elongation" to be of $\approx 1.175 \pm 0.025$. We further will try to find out whether there is a "critical friction coefficient" for which no segregation occurs, and whether it is universal for all elongations. We are also looking for suitable materials which will allow an experimental realization for 3 dimensions.

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