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Influence of geometry on stratification and segregation phenomena in bidimensional piles

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HIGHLIGHTS

- Simulation model considering only steric interactions.
- Systematic study of segregation patterns in piles with two different grain sizes.
- Definition and measurement of two suitable segregation indices.
- Qualitative agreement of the numerical results with experiments.
- Presence of striae although the grains only differ in their sizes.

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ABSTRACT

We present a numerical study of the flow segregation problem in bidimensional piles. To simulate the pile formation, we employ a pseudo-dynamics method. The model allows us to vary the concentration of big and small grains present in the pile and the size ratio between them. The different segregation patterns arising after the pile is finished are studied by analyzing the spatial distribution of the grains. Two different segregation indices are defined and evaluated over the piles. The contact network of the final configuration of grains in the pile is also determined. The conditions under which the different segregation patterns show up are discussed. A comparison with a previous experimental study is performed for all the numerical results obtained in the present paper. The advantages and limitations of the simulation model are also discussed.

1. Introduction

Mixing and segregation processes are still topics of intensive research due to their technological importance and strong industrial applications. Many industries seek to improve the quality of their products through a better use of raw materials and optimizing the processing plants.

The segregation phenomena always occur when a mixture of grains of different sizes is simply poured onto a heap [1–10]. Typical segregation leads to the presence of large grains near the bottom of the pile, whereas small ones near the pouring point at the top of it. In recent works, a spontaneous stratification was observed for grains differing both in size and in shape [11–20]. Granular mixtures of small-rounded grains and large cubic grains stratify in alternating layers parallel to the surface of the pile as they are poured in the cell.

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Makse et al. [12–16] have studied experimentally and analytically stratification and segregation phenomena. In their experiments they built piles inside a quasi bidimensional transparent cell throwing a mixture of two species of grains. They used grains of sand (cubic-shape with angle of repose equal to 35°) and glass beads. In the case that glass spheres have an angle of repose smaller than sand, they observed spontaneous stratification. In addition, when the angle of repose of glass spheres is greater than the sand angle, they found segregation. According to their experiments, the control parameter for stratification seemed to be the difference of the repose angles of the pure species, Θ. For $\Theta > 0$ (small rounded and large cubic grains) stratification was observed. On the other hand, strong segregation, but not stratification, occurred when $\Theta < 0$. They suggested that the resulting stratification derived from the competition between the size segregation and shape segregation. When $\Theta < 0$ and due to the size and shape segregation, the small cubic grains are located on the top of the pile and the spherical large ones are placed at the base of it, thus giving rise to a segregation phenomenon. In contrast, when $\Theta > 0$ large cubic grains segregate by size on the base of the pile and segregate by shape on the top of it. Simultaneously, spherical small grains size-segregate on the top of the pile and shape-segregate on the base of it. As a result of this competition, the resulting pile presents stratification. Additionally, to get stratification, grain flow below a certain limit value is required and the size ratio between large and small grains has to be greater than 1.5.

Grasselli and Herrmann have performed experiments with heaps of binary granular mixtures made of sand (rough) and glass spheres (smooth) that exhibited different internal structures [18]. They studied the pile morphology as a function of the size ratio of rough to smooth particles. For values of size ratio below 0.8, piles present typical segregation. Granular stratification is found to occur only for a size ratio greater than 1.5. They also observed that stratification depends on the separation between the walls of the cell where the pile is built and on the mass flux of the grain mixture.

There are in the literature few simulation models to address the stratification phenomenon. Continuous models [12,14,15] and cellular automata models [19] have been implemented to reproduce the stratification. However, the implementation of models that take into account the dynamic interactions between the grains has been hardly used in the stratification and segregation analysis [20]. Moreover, there are no models that take into account only the geometric aspects of the interaction between particles.

The aim of this work is to study the segregation phenomena using a simple bidimensional model to put into evidence the main aspects involved in the segregation–stratification mechanisms. We will use a pseudo-dynamic model to simulate granular piles of disks. This kind of models allows to show the relevant aspects related to the geometry of the problem. Indeed, our model does not take into account dynamical interactions and the main objective of our study is to pay special attention to the geometrical influence of interacting particles on stratification and segregation mechanisms. This simplification of the problem leads to computational costs being lower compared with other models currently used. Furthermore, these simulations were performed in order to reproduce the main aspects qualitatively obtained in our own earlier experimental results.

2. Experimental background

In a previous work, we have studied the segregation and mixture phenomena during the construction of granular piles [21]. The experimental device allowed us building piles of, at most, two different species of grains inside a quasi bidimensional transparent acrylic plexiglass cell. The piles could be constructed with a controlled vertical and horizontal relative motion between the grain injection point and the top of the pile in formation. It essentially consisted of a fixed grain feeding system and a cell where the pile is constructed. The grains are injected at the central top point of the acrylic cell and this cell can move vertically and horizontally as mentioned above. The feeding system consisted of two vibrating feeders and 3D and 2D static mixers in series to guarantee that the segregation in the piles is due to the build-up process and that the kinetic energy of the grains is the one gained along the vertical path between the injection point and the top of the pile.

We analyzed the influence of the following control parameters: size ratio of grain species, injection flow, height of the injection point (which remained constant during all the construction process), and the magnitude of the longitudinal displacement for the case of experiments with horizontal motion. We worked with three different sizes of glass beads (3, 2 and 1 mm diameter) using two size ratios, 3:1 and 3:2.

Different final structural configurations for the piles were obtained, depending on the parameters used for their construction. For a size ratio 3:1, a small mass of coarse grains and a low injection height, piles presented stratification, as it can be seen in Fig. 1(a). As the injection height or the mass of coarse grains increased, stratification started to disappear.

For a size ratio 3:2, it was not possible to obtain stratified piles. For small mass of coarse grains, piles always showed typical segregation. Fig. 1(b) shows a pile obtained for this case. When the amount of coarse grains or the height of the injection point was increased, piles presented a higher degree of mixing. Finally, in experiments with horizontal motion, the top of the pile became more rounded, the stratification disappeared and the mixture of grains was improved, as shown in Fig. 1(c).

The experimental results were quantified using two segregation indices. These indices were defined in order to distinguish between the two kinds of segregation behaviors obtained in our experiments, i.e., typical segregation and stratification. For a given sample of volume V, one can evaluate the ratio of the volume occupied by the large particles to the total volume V. This is a measure of the local segregation in terms of the larger particles and this ratio will depend on