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# Simulations on the Flow Segregation Problem in Bidimensional Piles

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**Abstract.** We report a numerical study of the problem of flow segregation in quasi bidimensional piles built up by pouring a mix of grains of two different sizes from a constant height. To simulate the pile formation, we employ a pseudo-dynamics method (PSDM). The concentration of small and big grains is varied. We also try with different size ratios between the beads. The 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 conditions under which the different segregation patterns show up are discussed. A comparison of all the results obtained with our own experimental results, is performed. The patterns and the different conditions for the setting up of segregation are discussed. The advantages and limitations of the simulation model are discussed.

**Keywords:** particulate materials, segregation, heap, simulations.

**PACS:** 45.70.Mg; 45.70.Qj; 45.70.Vn

## INTRODUCTION

Despite the efforts made in recent years, mixing and segregation processes are still topics of intensive research due to their technological importance and strong industrial applications. Many industries seek to improve 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]. 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 [2-4]. 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. Makse et al. [2,3] have studied experimentally and analytically stratification and segregation. According to their experiments, the control parameter for stratification appears to be the difference of the repose angles  $\delta$  of the pure species. For  $\delta > 0$  (small rounded and large cubic grains) stratification was observed. On the other hand, strong segregation, but not stratification occurred when  $\delta < 0$ . The resulting stratification derives from a competition between size segregation and shape segregation: the large-cubic grains tend to size segregate at the bottom of the pile,

while at the same time, they tend to shape segregate at the top of the pile.

In addition, Grasselli and Herrmann have studied, experimentally, heaps of binary granular mixtures made of sand (rough) and glass spheres (smooth) that exhibit different internal structures [4]. They studied the pile morphology as a function of the ratio of the sizes of rough to smooth particles. For values below 0.8, the piles present typical segregation. Granular stratification is found to occur only for a size ratio greater than 1.5. They 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.

In this work we present numerical results obtained for granular piles using a pseudo-dynamic model for disks. The simulations were made in order to qualitatively reproduce, the main aspects already obtained in experimental results of our own. 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.

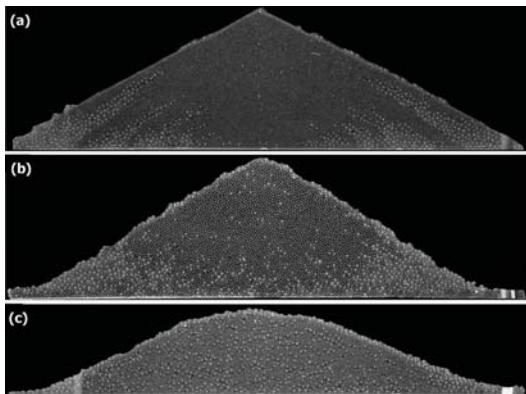
## PREVIOUS EXPERIMENTAL RESULTS

We have studied the phenomenon of segregation and mixture during the construction of granular piles [5-6]. The experimental device allows us building piles of, at most, two different species of grains inside a quasi bi-dimensional transparent acrylic plexiglass cell. The piles can be constructed with a controlled vertical and horizontal relative motion between the grain injection point and the top of the pile in the formation.

We analyzed the influence of the following control parameters: size ratio of grain species, injection flow, height of the injection point (which remains 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 1mm diameter) using two size ratios, 3:1 and 3:2.

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



**FIGURE 1.** Piles obtained with the experimental device for low height of the injection point and small mass of coarse grains. (a) size ratio 3:1; (b) size ratio 3:2; (c) size ratio 3:1 and horizontal motion.

For a size ratio 3:2, it is not possible to obtain stratified piles. For small mass of coarse grains, piles always show typical segregation. Fig. 1(b) shows a pile obtained for this case. When the amount of coarse grain or the height of the injection point is increased, piles present a higher degree of mixing.

Finally, in experiments with horizontal motion, the top of the pile becomes more rounded, the stratification disappears and the mixture of grains is improved, as shown in Fig. 1(c).

## SIMULATION MODEL

The simulations were carried out using a pseudo dynamic method [7,8]. The algorithm allows the construction of bi-dimensional piles using disks of two different sizes. Disks fall or roll a small distance in each iteration step and, after a number of iterations, they find stable positions.

More specifically, a disk performs a free fall of length  $\delta$  if it has no supporting contacts or a roll of arc-length  $\delta$  over its supporting disk if it has only one single supporting contact. Disks with two supporting contacts are considered stable and left in their positions. Particles are moved one at a time, but they perform only small moves that do not perturb to a significant extent the ulterior motion of the other particles in the system. An iteration consists in moving every disk in the system by a distance  $\delta$  or the amount allowed by the constraints imposed by neighbouring disks. Notice that after an iteration many disks may be left in unstable positions. A number of iterations are needed before every disk finds its stable configuration. For very small values of  $\delta$  ( $\sim 7.5 \times 10^{-3}$ ), this method yields a realistic simultaneous deposition of grains with zero restitution coefficient. Given the short extension of the present paper, we encourage the reader to see the details of this method in [6,7].

## RESULTS AND DISCUSSION

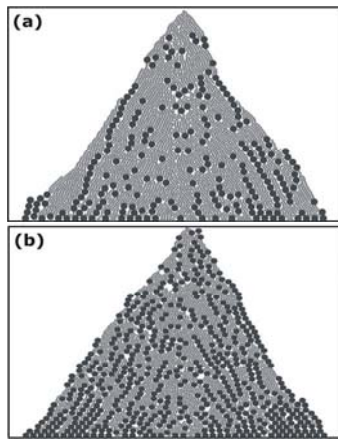
We carried out simulations in order to build piles with two different sizes of disks. As in experiments, we varied the parameters used for their construction. We worked with size ratios 3:1 and 2:1. We employed different flow ratios. We defined RS as the ratio of the surfaces for the two types of disks, i.e.,  $RS = S_1/S_2$ , where  $S_1$  ( $S_2$ ) is the total area of the large (small) disks. The values for RS used in the simulations were 0.5, 1.0 and 1.5.

It is worth noting that the height of the injection point is not relevant in our simulations since this method does not take into account the dynamics of the movement of the disks and any interaction force between grains is calculated. Thereby, the spirit of our simulations is to put into evidence the effect that the geometrical restrictions have on the movement of the particles and the resulting effect on the segregation phenomena.

Finally, we also built piles using a horizontal motion of the injection point with two amplitudes, in

accordance with experiments and in order to show that the segregation phenomena vanished.

Figure 2 shows the resulting piles using size ratio 3:1 and different RS values. When the value of RS is small, piles present striae, i.e., large disks lie parallel to the free surface of the pile forming chains (see Fig. 2(a)). As the value of RS is increased, typical segregation effects become also visible, leading to a greater amount of grains located in the base of the pile, as seen in Fig. 2(b).

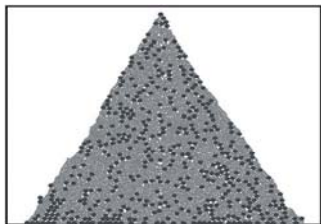


**FIGURE 2.** Piles obtained with simulations, using size relation 3:1 and (a) RS = 0.5; (b) RS = 1.0.

It is important to note from the figures that the slope of the simulated piles is greater than the one corresponding to experiments. This is due to the particular simulation model we used, where any equation is solved to establish the equilibrium state of a particle.

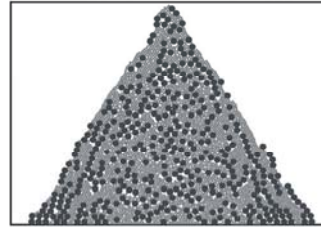
For piles built up with size ratio 2:1, the chains of large grains completely disappear and piles show a tendency to typical segregation. An example of a pile with this size ratio can be seen in Fig. 3.

It is worth to mention that our simulation reproduces qualitatively our experimental state diagram already presented in [6].



**FIGURE 3.** Pile obtained with simulations, using size relation 2:1 and RS = 0.5.

Finally, when the injection point oscillates, the striae almost disappear and the mixture of grains is improved, emulating the experimental results. In Fig. 4 we show a pile corresponding to this case.



**FIGURE 4.** Pile obtained with simulations, using size relation 3:1, RS = 1.0 and horizontal displacement of the injection point with amplitude of 62 times the diameter of smallest disks.

The different final structural configurations of the piles obtained with the simulations were characterized through the definition of two indices of segregation  $I_H$  and  $I_{\perp}$  as in [6].

For a given sample of area  $A$ , one can evaluate the ratio of the area occupied by the large particles to the total area  $A$ . We defined the indices  $I_H$  and  $I_{\perp}$  as:

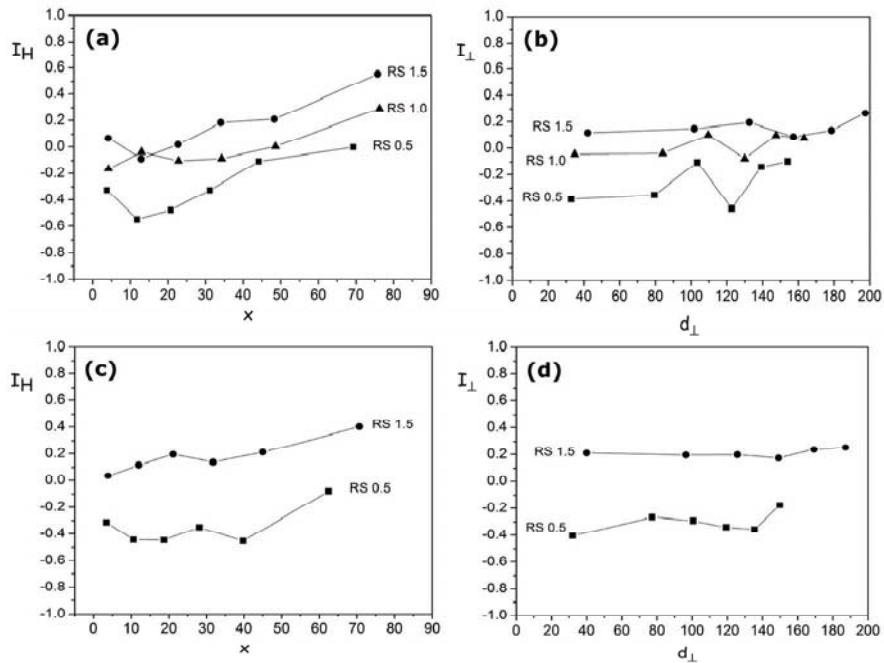
$$I_{H,\perp} = 2 \frac{S_1}{S_1 + S_2} - 1 \quad (1)$$

where  $S_1$  ( $S_2$ ) is the total area of the large (small) disks. In Eq. (1), the samples to calculate  $I_H$  for a given pile are taken over vertical strips all with the same area. On the other hand, the corresponding samples to evaluate  $I_{\perp}$  are taken over strips (all with the same area) parallel to the free surface of the pile.

With this definition, the indices range from  $-1$  ( $S_1=0$ ) to  $1$  ( $S_2=0$ ), i.e.,  $I_{H,\perp}=-1$  ( $I_{H,\perp}=1$ ) means no large (small) particles in the sample surface. A value of zero corresponds to the presence of the same area of large and small disks in the sample.

Figure 5 resumes the results obtained for  $I_H$  and  $I_{\perp}$  for the simulated piles with different size ratio and RS values. As observed, for size ratio 3:1,  $I_H$  shows segregation effects and more presence of large particles when going toward the tail of the piles in all cases (Fig. 5(a)). Besides, an oscillatory behavior of  $I_{\perp}$  (Fig. 5(b)) indicates the presence of striae. This behavior disappears as the value of RS is increased.

For size ratio 2:1,  $I_H$  indicates the presence of segregation, which is moderately reduced as RS is increased (Fig. 5(c)). It is important to note that typical segregation effects obtained in simulations are not as visible as in experiments. This is due to the



**FIGURE 5.** Segregation indices for (a) and (b): size relation 3:1 and three different values of RS; (c) and (d): size relation 2:1 and two different values of RS. Error bars are of the order of symbol sizes.

absence of dynamic effects in our model: here particles find stable positions more easily than in experiments. Consequently, disks would not always roll until the base of the pile and, also, no avalanche processes are to be expected.  $I_{\perp}$  does not oscillate for size ratio 2:1 (Fig. 5(d)), indicating the absence of chains, in agreement with experimental results.

## CONCLUSIONS

We have carried out simulations of bidimensional piles using a simple model. These simulations help us understand the general features of segregation and stratification phenomena that are driven by geometrical constraints. The model implemented has qualitatively reproduced previous experimental results.

We have found the existence of striae for piles formed with disks of size relation 3:1. The visualization of these chains has shown that geometric effects are relevant to the stratification case.

Moreover, it was found that the effect of geometrical restrictions on typical segregation phenomenon is less significant. Numerical results have shown that striae vanish when size relation decreases, in accordance to experiments. Nevertheless, the segregation effect in the simulated piles is less pronounced than in experimental ones. This fact is related to the simulation model implemented, which

does not take into account any dynamical interaction between disks.

## ACKNOWLEDGMENTS

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