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# PARTICLE PERCOLATION THROUGH A POROUS MEDIUM

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In this paper we study transport of particles due to gravity in a porous medium simulated by a packing of large beads. We determine the dependency of the mean transit time for different percolating particle batches and for different packing heights. We compare our results with numerical simulations based on the Discrete Element Method to extend experimental studies and to analyze the part play by the coefficient of restitution and the aspect ratio between the two size of beads.

## 1 INTRODUCTION

Transport of granular materials are important in many fields and are often cause of problems. One of them is size segregation, which is a non random spatial distribution of the different grains species. A classical example is the “Brazil Nuts segregation” (Rosato et al. 1987). In this article, we focus on the spontaneous interparticle percolation in a granular medium. The spontaneous interparticle percolation phenomenon is defined as the motion of fine particles through an arrangement of larger spheres simply due to gravity. When two grains species are very different in size (with a ratio  $D_{small}/D_{large} < 0.1547...$ ), it is possible for the smaller to drain totally through the porous medium. During the percolation process, energy is dissipated at the time of frictional and inelastic collisions which ones induce lateral and longitudinal dispersions. This kind of segregation was previously studied by Bridgwater (Bridgwater et al. 1969) and more recently by Samson (Samson 1997).

Unlike these previous studies, we are interested here by the transport of a large number of particles into a porous medium, where collective behavior plays an important role. Preliminary studies were investigated by Oger (Oger et al. 2002). It is evident that the presence of many particles falling together induces many additional collisions and collective effects.

## 2 EXPERIMENTAL SET-UP

Our experimental set-up, shown in Fig. 1, is made of mono disperse beads packed inside a parallelepiped tank of  $26\text{ cm} \times 26\text{ cm} \times 51\text{ cm}$ . The packing, constructed under gravity, can be made of spheres of different sizes  $D$  and it plays the role of a porous medium with a reproducible porosity of 0.4. Another

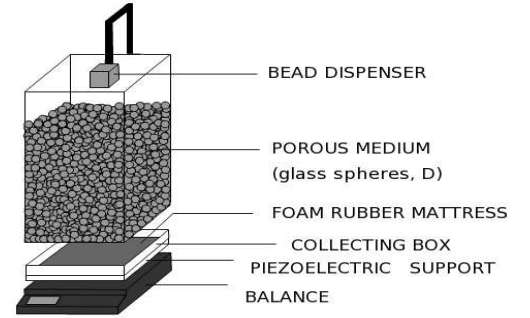


Figure 1: *Schematic drawing of the experimental set up.*

packing made by small iron beads of diameter  $d$  is put in a box placed on a handle. These percolating beads are quasi-instantaneously launched in the porous structure by using a vertical opening hatch. The detection system consists of an electronic balance topped by a piezo-electrical material with an amplifier. In order to have reproducible results, the humidity rate is kept constant to a value of 60%. We use also concentric cubes that we can insert in the bead dispenser to maintain the launched packing as punctual as possible.

We work far from the percolation threshold with a ratio  $\frac{d}{D} = 0.0625$  in order to free ourselves from trapping events. The mean transit time is deduced from the signal gathered at the output.

## 3 EXPERIMENTAL ANALYSIS

The main phenomenon, which occurs inside the porous space, is lateral and transverse dispersion which is classically described as a Gaussian law for a fluid passing through a porous structure. So the concentration of beads at the output will follow an *erf* function which is solution of the convection-diffusion

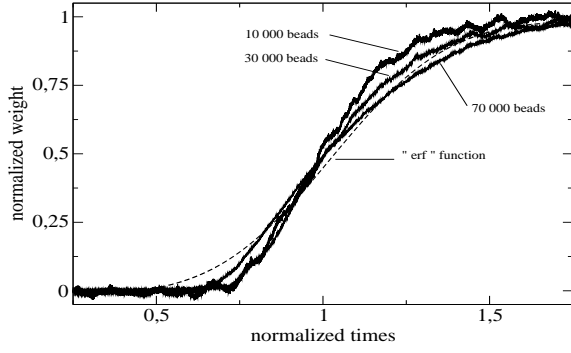


Figure 2: Evolution of the mass of beads gathered at the output. An adjustment with an *erf* function is also represented.

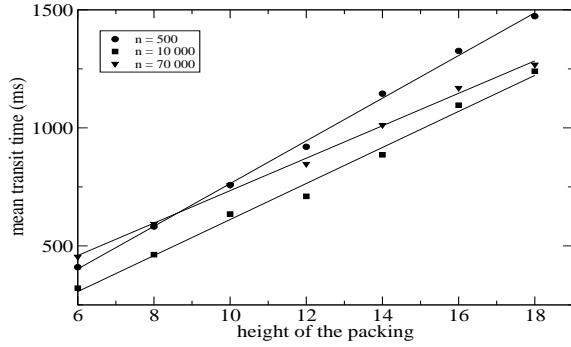


Figure 3: Dependency of the mean transit time with the height  $H$  of the packing, for a launched of 500, 10000, 70000 particles of 1 mm.

equation:

$$\frac{\partial c(r,t)}{\partial t} + V \nabla c(r,t) = D_{//} \frac{\partial^2 c(r,t)}{\partial x_{//}^2} + D_{\perp} \frac{\partial^2 c(r,t)}{\partial x_{\perp}^2}$$

where  $V$  is the interstitial velocity of the flow and  $D_{//}$  and  $D_{\perp}$  are respectively the longitudinal and transversal diffusion coefficients (Charlaix 1987). As our weight scale will see the cumulative weight of falling beads as shown in Fig. 2; we can already notice the difference with the best *erf* function fit drawn in the same figure. In others words, the transit time distribution is not exactly a Gaussian law. Some lateness appear due to trapping of beads during the percolation process. Nevertheless, as, in a first order analysis, we are interested by the mean transit time determination, Fig. 2 shows that this Gaussian adjustment can be used.

By this way, we have determined the mean transit time for different packing heights and for variable batches of small iron spheres (between 1 to 100 000). As we can see in Fig. 3 the residence time is proportional to the packing height even for different batch sizes. It has been showed by Samson (Samson 1997) that, for the case of a single particle falling down in a porous medium, the percolation velocity is also constant.

In other words, a steady state is reached with a constant percolation velocity if the size of the pack-

ing is large enough to avoid or minimize the influence of some transition regime in the beginning of the process. Indeed, this stationary state appears for height higher than a threshold value, of the order of few grain sizes, below which no granular temperature equilibrium can occur. We have not report measurements of mean transit times for  $H$  smaller than 5 cm, i.e. approximatively 3-4 large bead's layers, mainly for the reason described previously and for strong differences on the transit time due to some time fluctuations of the beads during the entering of the porous structure. This implies that the mean transit time could not be measured accurately. In the Fig. 3, we can also mention that three curves are not parallel which suggests that the percolating velocity depends of the number of percolating particles.

#### 4 COOPERATIVE FLOW REGIME

If only one particle falls down through a porous structure, it can explore the complete free space without any perturbation, but it's no longer true if several particles fall at the same time. In this case, all these moving particles can interact all together and also with the fixed ones. In complementary analysis we can mention that the number of particles which can pass through the same pore at the same time depends of the volume occupied by the batch so by consequence to their number and their size ratio. If we are near the critical value, which was defined previously, only one or two particles can pass together through the same pore. If several particles transit in the porous medium, they have to pass one after the others. On the other side if we work far from the percolation threshold, a large number of them can pass through the same pore like a fluid. However the Fig. 2 let us bow to the fact that an analogy with a fluid is not fully applicable.

Another set of experiments was done to study the impact of the number of percolating spheres to the mean transit time. We have plotted in Fig. 4 the mean time evolution with the batch bead numbers for a height of  $H = 16$  cm. Following our previous observation, it won't be foolish to think that the percolation velocity will decrease with the particle number due to the pores jamming. In other words, the mean transit time would increase with the number of percolating particles due to their difficulty to find accessible pores. Nevertheless the Fig. 4 shows that the phenomenon is more complex as we can observe the existence of three domains of flow.

In the first, from 1 to approximatively 10000 particles, the mean transit time decreases when the number of falling particles grows. In all this study, we have two main effects of the spontaneous gravitational percolation: an important rebound of a falling bead on fixed spheres (due to a large restitution coefficient) and also a large decrease of moving bead

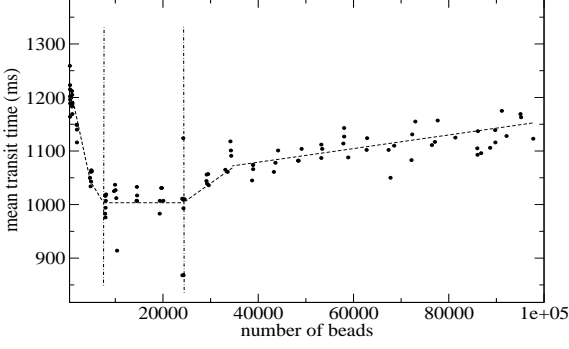


Figure 4: Dependency of the mean transit time with the number of particles (1 mm) for  $D = 16$  mm and  $H = 16$  cm.

velocities due to the fact that the falling particles collide themselves and with the fixed ones. In the first regime, due to the small numbers of neighbors and the relative large volume ratio between the pore and the bead batch they gain few energy during the falling process and they loose more and more energy by collisions with their neighbors which implies that they are mainly falling down directly in the lower pore structure without bouncing around. As the number of the small beads increases, an equilibrium between the direct falling process and the interparticle collision events is obtained and can be observed in a second domain from  $\approx 10000$  to  $\approx 25000$  small beads. In this regime, the mean percolation velocity is quite independent of the number of particles.

If we continue to increase the number of falling beads higher than  $\approx 40000$  beads, we can see the third regime. The particle velocities slow down due to the crossing of many particles simultaneously through the same pore. This jamming effect grows slowly with the number of particles. This effect is the consequence of accumulation of a lot of particles in pores connections what make more difficult the crossing of each one.

The Fig. 5 represents the same evolution of the mean transit time for three packing heights. For  $H = 8$  cm, the three regimes of flow are also visible. The second domain seems to appear for smaller number of particles than for  $H = 16$  cm. For  $H = 23$  cm, the height of the packing is so important that we can not observe the previous increase of the transit time for a number of beads lower than 100000. Indeed, as the flow goes down in the packing, the dispersion occurs and decreases the influence of bead accumulation which controls the jamming phenomenon. Complementary studies with larger number of small beads are under progress in order to observe the evolution of the transit time for very large amount of falling beads.

## 5 NUMERICAL SIMULATION

In order to analyze the influences of different geometrical and mechanical parameters, we couple experi-

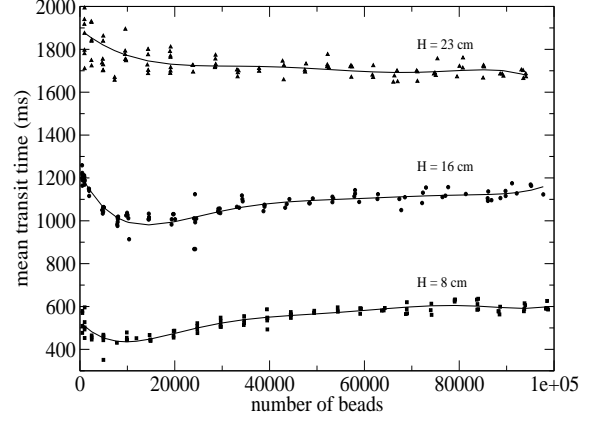


Figure 5: Dependency of the mean transit time with the number of particles of diameter  $d$  (1 mm) for different packing heights ( $H = 8$  cm, 16 cm, 23 cm) made with particles of diameter  $D$  (16 mm).

mental results with numerical simulations. We have chosen to make a model as close as possible as real process which occurs when we launch a packing of small particles through packings made with larger spheres.

A lot of algorithms exist to build a random 3D packing of mono-size spheres (Oger et al. 1999). We have chosen to use the Powell's algorithm as that constructed packings are built like "under gravity". Our porous structure is made by 56000 spheres of radius  $D = 1$  inside a box of  $40 \times 40 \times 200$ . We have introduced a small size distribution of spheres radii (5%) in order to avoid local ordered zones and also to reproduce the natural dispersion size of a bead set. We build an upper box containing another packing of spheres of diameter  $d$ .

This box is horizontally centered on top of the previous one and are almost cubic. To simulate the motion of large numbers of small spheres through a static packing of large ones, we use the Event-Driven method for the dynamic part of the simulation. In this approach, the collisions are considered as instantaneous and binary what implies that only one collision can occurs at a given time. At the beginning of the simulation, the program calculates for each small spheres, the shortest time when occurs its collision with one of its neighbors. Then, all the collision event times are sorted out and the program goes to the shortest collision time. Only the positions of the two concerned spheres are evaluated, the event collision is computed and the program calculates the new velocities of the two spheres involved in this collision. After that, all the possible new collision event which can occur for these two spheres are computed and integrated in the sorting event tree. Then the newly next event is treated and so on.... The percolation process ends when all the small spheres have reached a height equal to their radii (i.e. when they touch the bottom of the packing). We have simulated experiments for dif-

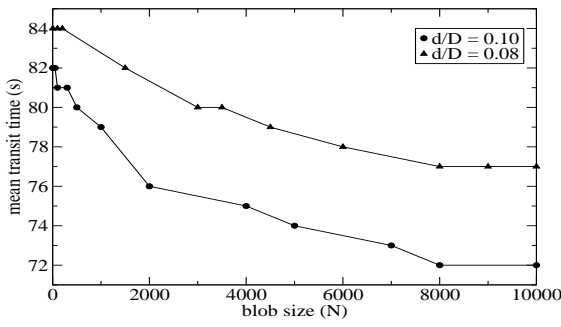


Figure 6: Evolution of the mean transit time with the blob size ( $N$ ) for two size ratios  $d/D$ .

ferent particle batch sizes  $N$ . As we can see in Fig. 6, the mean transit time decreases with  $N$  and reaches a constant value for  $N = 10000$ . This behavior is in full agreement with experimental results presented previously.

In order to analyze the effect of the size ratio we have performed various simulation dealing with  $d/D$  and also the restitution coefficient  $e$  (Fig. 7).

This figure shows that the mean transit time increase with  $e$  and confirms our assumption: For higher coefficients of restitution  $e$ , bounces of falling particles are more important and exploration of the pore structure is made easier. The probability that a particle can almost go back to its previous path, is not negligible.

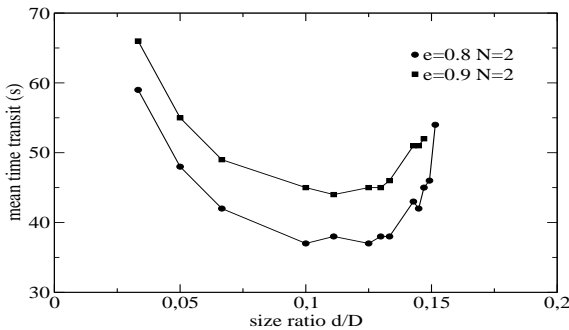


Figure 7: Mean transit time evolution versus the size ratio for two coefficients of restitution.

Contrary to the experimental case, our simulations let us to have access to the internal porous structure and more precisely to the displacement of the particles. As it is showed in Fig. 8, we can follow inner path of each moving bead from the entry to the output of the structure.

## 6 CONCLUSIONS

An experimental study of numerous particles flow in a porous structure has been realized. The steady state which is reached during the percolation process shows us that vertical percolation velocity is constant. This behavior is comparable to the case of a monoparticle flow previously studied. Collectives effects due

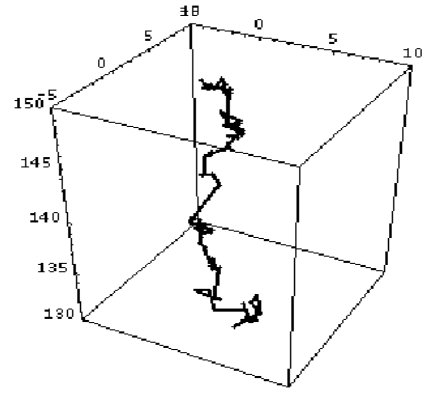


Figure 8: Example of particle trajectory.

to the transit of many particles in the structure induce acceleration of the transit process and also jamming effects with particular consequences on the flow velocity. Despite of these considerations, the separation between individual effects and collective ones is not trivial. Our numerical model lets us to examine influence of some physical parameters on the transit process and can be helpful to understand the experimental problems.

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