PARTIALLY-COHESIVE GRANULAR FLOWS: RHEOLOGY AND SEGREGATION

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Summary Heterogeneous and cohesive granular flows are investigated by contact dynamic simulations. A given fraction of the spherical grains is cohesive. We study first the rheology of such mixture in a shear plane geometry: we show that a simple law accounts for the influence of the cohesive fraction on the effective friction coefficient. Then we study the flow of the mixture on an inclined plane. A segregation of cohesive grains occurs whose speed depends on the cohesion intensity.

INTRODUCTION

Industrial processes of handling granular materials often require mixing steps between grains and liquids like for building materials, pharmaceutic or food industry. Although the mixing of fluids or grains only are studied for a long time, such heterogeneous granular systems are less understood. For low liquid fraction, the liquid is known to induce attractive forces between grains through liquid bridges: How does the rheology evolve when the liquid spreads inside the media? What is its structure? On the other hand, the rheology of homogeneous granular matter is better understood since the past decade [2, 3]. Can the same approach be successful if we focus on heterogeneous cohesive granular systems? In this paper, we simulate a tridimensional mixture of non-cohesive and cohesive grains, first to measure and to model the influence of the fraction of cohesive grains on the rheological law, second to study the segregation occurring in heterogeneous free-surface flows.

HETEROGENEOUS GRANULAR SYSTEMS

We use tridimensional contact dynamic simulations [1]. The grains are frictional hard spheres of density ρ and of mean diameter d with a weak polydispersity of 9%. The cohesive and non-cohesive grains (W and D) are randomly chosen in the sample up to a given fraction X_c. The grains will keep their properties all along the simulations. The nature of grains at contact defines three different contacts: DD, DW and WW. First, all grains interact through frictional force with a friction coefficient $\mu = 0.3$. Second, we decide of the intensity of the cohesion force for the DW and WW contacts independently. These attractive forces f_c are constant, aligned with the centers and disappear as soon as the contact breaks.
We simulate two geometries. The first one is a simple shear system, which is periodic in the three directions to avoid wall effects and allows to obtain the rheological law with only 2000 grains in a box of lateral size $12d \times 12d$. The two control parameters are the vertical confining pressure P and the strain rate γ. Once the steady regime is achieved, we measure the stress tensor and the properties of the flow. We use a 3D version of a code developed during C. Voivret's Ph-D. The second system is a flow on an inclined plane made of the same grains. The system is biperiodic and a dense flow develops due to the gravity. We measure the evolution of flow properties, specially the velocity profile and the spatial distribution of the particles. For this part, we use the code LMGC90 [5] with 5000 grains and a larger polydispersity ($d_{max}/d_{min} = 1.5$).

SHEAR-PLANE RHEOLOGY

Results

We focus on steady state for large Inertial number $I = \gamma d/\sqrt{P/\rho}$ [2] ($I > 0.1$) and moderate Bond numbers, Bo= f_c/Pd^2 lies between 1 and 30. We thus avoid localized shear bands in the systems, so the velocity profile is well defined and linear. Figure 1-*left* shows the evolution effective friction coefficient (equal here to the ratio q/p averaged in time in the steady state where q and p are the deviatoric and the isotropic part of the stress tensor) with respect to the cohesive fraction X_c for different Bo and I, when the contacts DW and WW behave with the same laws. First, no segregation occurs when shearing, the systems are still uniform. The second result is that, for a given I and X_c, the friction coefficient q/p increases with the Bond number, in agreement with the results on fully cohesive simulations done by Rognon *et. al* [3]. Moreover for given I and B_o, we observe an increase of the friction coefficient with X_c which is faster at the beginning and then saturates around $X_c = 70\%$. This behavior seems to be independent of the couple (I, Bo). We plotted (not shown) that the friction coefficient is a function of the solid fraction. The two sets of data collapse on a same trend for all cohesive fraction. This result provides clues that the rheological law of the mixture may be described in simple terms from the properties of both the fully non-cohesive system and the fully cohesive system.

Model

Based on the homogeneity of the system and on the scaling friction coefficient as function of the solid fraction, the simplest assumption we can make is that the resistance against the shear is linked to the relative proportion of the cohesive

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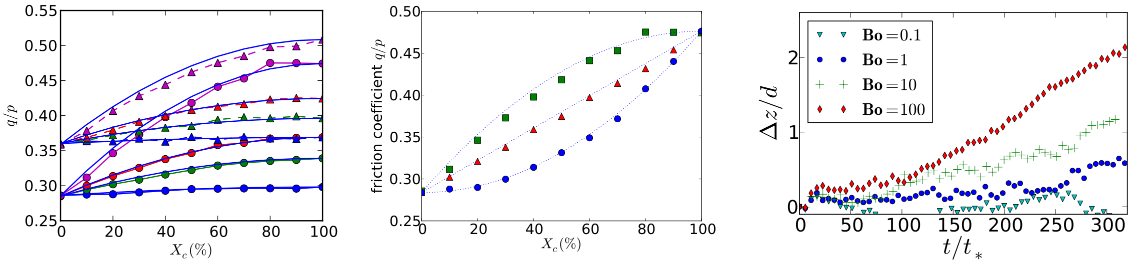

Figure 1. (left-middle) Effective friction coefficient q/p as a function of the fraction of cohesive spheres in the system. **left**) Simulations for $I = 0.1$ (○) and 0.3 (△) and for increasing Bo: 1, 5, 10, 30 (from blue to purple). The predictions of the model are the blue lines. **middle**) Same parameters as purple circles in (left), but the force at contact DW, from bottom to top : $Bo_{DW} = 0, 11.6, 30$. **right**) Mean increase of the altitude of the cohesive grains in inclined plane flow, $t^* = \sqrt{d/g}$ for increasing Bo. The plane is inclined at 28^o.

and non-cohesive contacts inside the system. Given X_c and assuming the particles are still randomly distributed as well as the contacts nature, one can compute the theoretical proportion of the three different contacts: $P_{WW} = X_c^2$, $P_{DD} = (1 - X_c)^2$ and $P_{DW} = X_c(1 - X_c)$. For a genuine test, we assume q/p to be the weighted average of the friction coefficients that a system with a single type of grain (cohesive or not) would produce for the same value of I: $q/p = \mu_{DD}P_{DD} + \mu_{DW}P_{DW} + \mu_{WW}P_{WW}$. These predictions are plotted in figure 1-*left*. The good agreement is very surprising since such theoretical proportions do not match the measured distribution which would produce large errors. Indeed, in the present case, we observe a lack of DD contacts with respect to the random distribution, to increase DW contacts. A clue may be that when looking only at the strong-forces network, then the distributions become more random. We test this heuristic law against two other set of parameters: for the first one, the cohesion force is set to zero for DW contacts, and for the second one, we try to obtain a linear curve for the friction coefficient as function of X_c. We have to guess the value of the control parameter f_c for those DW contacts. Using the former law, we know that μ_{DW} has to be the average of the others. So we fit a curve $q/p(X_c = 1)$ as function of Bo to guess the intensity of the force for the heterogeneous contact. The results of the simulations are shown in figure 1-*middle*, again a good agreement is observed and a linear dependence is indeed obtained.

SEGREGATION ON INCLINED PLANE

We carried out simulations with a dilute concentration of cohesive grains ($X_c = 2\%$) and we choose an identical cohesive force for DW and WW contacts. To follow the evolution of the structure inside the material, we plot the average position of the cohesive particles in figure 1-*right* as a function of time. The first offset is due to dilatancy, then we observe a migration of cohesive particles toward the free surface at a velocity depending on Bo= f_c/mg: the more cohesive the faster. This results is interpreted using the well known size segregation [6]: for large Bo, a cohesive cluster behaves like a large particle. However for low cohesion, the cohesive particles change their neighbors at high rate forming only transient clusters: in other words, the characteristic time for a cluster to diffuse toward the surface is much longer than its life time. The average coordination number of the cohesive grains supports this idea: it increases with the Bond number, up to 10. One main difference with the usual segregation of large spheres is that, for high Bo, we can create a more cohesive layer inside the flow when the density of cohesive grains increase. This changes the velocity profile and modifies the segregation speed.

CONCLUSIONS

We have shown that a mixture of cohesive grains does not segregate when intensity of joint contacts is equal to the cohesive-cohesive contacts. In the inertial regime and for moderate cohesion, the rheological law is described by a friction coefficient like in homogeneous systems and can be modeled by a very simple law which must now be linked to the microscopic structure. We also show that partial cohesion induces vertical segregation in free-surface flows due to the effective size of transient clusters. This work is a first step before study the issue of mixing of liquids and grains when the liquid distribution is highly heterogeneous.

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