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EFFECT OF COHESIVE FORCES ON GRANULAR FLOWS IN ROTATING DRUM: LINKING EXPERIMENTS AND SIMULATIONS

N. Preud'homme[1], **E. Opsomer**[1], **F. Francqui**[2], **A. Neveu**[2], **and G. Lumay**[1]

[1] GRASP laboratory, CESAM research center, University of Liège, Belgium

[2] GranuTools, Awans, Belgium

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Abstract. Granular flow is a complex process depending on a large set of parameters such as grain morphology, surface friction, flow geometry, stress field and cohesion (e.g. attractive interaction between grains). The latter arises from the presence of humidity, electrostatic charges and Van der Waals forces within the grains that lead, among other effects, to the appearance of surface flow fluctuations also called avalanches. Those surface fluctuations produce an intermittent granular flow and determine the processability of a powder in many application. In order to link the flow fluctuations and the cohesion between grains, we reproduced numerically with a DEM model the flow of cohesive granular materials in a 2D rotating drum. A simplified cohesive interaction between circular grains has been implemented and the granular flow has been analyzed through the flowing angle and the interface fluctuations. The numerical results are compared with experimental results obtained with GranuDrum instrument and a set of silicon carbide grains with different grain sizes and therefore different cohesiveness. The motivation behind this study is to determine to what extent a simplified model can reproduce a complex flow. The similarities between numerical and experimental results and also the discrepancies are discussed. This comparison gives a fundamental background to the cohesive index parameter measured with GranuDrum instrument from the interface fluctuations. Finally, we show that comparing the flow inside a rotating drum obtained numerically and experimentally is a practical way to calibrate a set of parameters before the simulation of a complex process.

1 Introduction

Over the last decades, granular matter has been the subject of numerous fundamental studies in the physics community [1–3]. In the majority of the experimental, theoretical and numerical studies, the steric repulsion is the only considered interaction. However, cohesive forces between the grains could be induced by the presence of an interstitial liquid, by magnetic or electrostatic interactions, or by Van der Waals forces. It has been shown that the cohesion influences strongly the statics and the dynamics properties of a granular material [4–11].

Experimentally, the most practical geometry to study the flow of a granular material is the rotating drum [12]. At very low angular velocities Ω, the flow is intermittent. The slope of the pile evolves between the angle of repose θ_r and the maximum angle of stability θ_m. At higher velocities, the flow becomes continuous. This transition between the discrete avalanche regime to the continuous flow regime occurs for angular velocities $\Omega \simeq (\theta_m - \theta_r)/\tau$ where τ is the typical avalanche duration [13]. In the continuous regime, the shape of the free surface is essentially flat for low values of the Froude number $F_r = R\Omega^2/g$, R being the drum internal radius and g the acceleration of gravity. When the inertial effects become important, a well known S-shape is observed [14]. Finally, when the Froude number F_r is superior to unity, a centrifugation is observed. With cohesive grains, the behavior of the granular assembly becomes more complex and intermitencies are observed on the entire rotating speed range.

In this paper, we investigate numerically and experimentally the influence of cohesive interactions between the grains on the flowing properties inside a rotating drum. Numerically, a simplified cohesive interaction between circular grains has been implemented in a DEM model and the granular flow has been analyzed through the flowing angle and the interface fluctuations. In parallel, measurements with GranuDrum instrument have been carried out with a set of granular materials with grain of different size leading to different cohesiveness. The similarities and also the discrepancies between numerical and experimental results are discussed. The motivations behind this study are (i) to determine to what extent a simplified model can reproduce a complex flow and (ii) to give a fundamental background to the cohesive index parameter measured with GranuDrum instrument.

2 Powder flow measurement

The GranuDrum instrument is an automated powder flowability measurement technique based on the rotating drum principle [15]. A horizontal cylinder of diameter $D = 84mm$ with vertical glass sidewalls called drum is half filled with the sample of powder. The drum rotates around its axis at an angular speed ranging from 2 RPM to 60 RPM for the present study. A CCD camera takes snapshots (50 images separated by 0.5s) at each angular velocity. The air/powder interface is detected on each snapshot with an edge detection algorithm. Afterward, the average interface position and the fluctuations around this average position are computed (see Figure 1). The flowing angle (also commonly called dynamic angle of repose) is measured at the center of the average interface position for each rotating speed. To obtain the interface fluctuations σ, the standard deviation of the interface position (plotted in green in Figure 1) is integrated along the averaged interface (plotted in red in Figure 1). This dynamic index is close to zero for non-cohesive powders and increases when the cohesive forces intensify. For this reason, this index is called dynamic cohesive index σ in GranuDrum software.

The measurements were carried out with a set of silicon carbide abrasives of different grades. The selected grades cover a range of grain size from $d = 15\mu$m to $d = 100\mu$m.

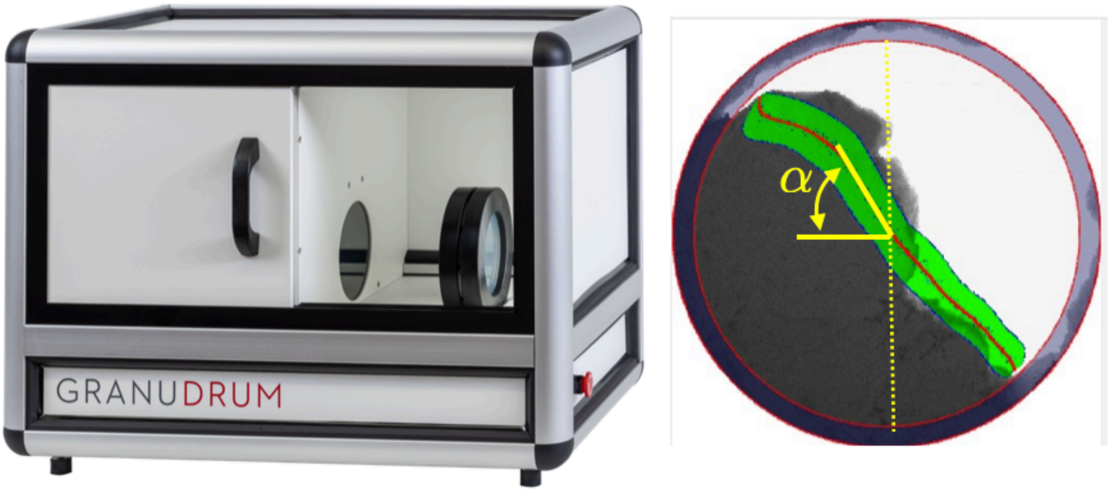

Figure 1: (Left) Picture of the GranuDrum instrument used to perform the flow measurement in the rotating drum. (Right) Snapshoot taken during the image treatment for one rotating speed. In the background, a picture selected in the series of 50 images is showed. The average interface position is plotted in red and the standard deviation is plotted in green. The flowing angle α measurement at the center of the interface is highlighted in yellow.

The grains are angular, hard and roughly monodisperse.

3 DEM simulations

In order to reproduce numerically the granular flow inside the rotating drum, a in-house algorithm based on the soft-particle Discrete Element Method (DEM) has been used [16, 17]. The forces acting on each individual grains are calculated at a chosen frequency and the motion of every single grain is then computed using Newton's second law. Only four different forces determine the motion of the grains: their weight, the normal repulsion force at contact, the tangential friction force at contact and cohesion at moderate distance.

The normal contact forces are modeled using a linear spring dashpot and the tangential forces are computed according to Coulomb's law of friction which is modeled with a linear spring for static friction. Both forces apply between grains and between the grains and the drum. A simple expression for the cohesive force has been voluntarily chosen to mimic a large panel of the different physical cohesive interactions which are encountered. The model considers maximum attraction at contact which decreases quadratically with the grain surface to surface inter-distance δ, with $\delta = 0$ corresponding to grains in contact, $\delta < 0$ corresponding to an interpenetration and $\delta > 0$ corresponding to non-contacting grains. The curvature is chosen so that the attractive force vanishes at a fixed range corresponding to the radius r of a grain *i.e.* $\delta = \pm r$ (see Figure 2). The intensity of this attraction force is expressed with the Bond number Bo. This dimensionless number is defined as the ratio between the attractive force to the weight of the grains:

$$\mathrm{Bo} = \frac{F_c}{mg}. \tag{1}$$

To fulfill these conditions, we defined the attractive force between grains as follows

$$\mathbf{F_c} = mg\mathrm{Bo}\left(\left(\frac{\delta}{r}\right)^2 - 1\right)\hat{\mathbf{n}}, \tag{2}$$

with r the grain radius and $\hat{\mathbf{n}}$ the unitary vector pointing from the center of one grain to the other.

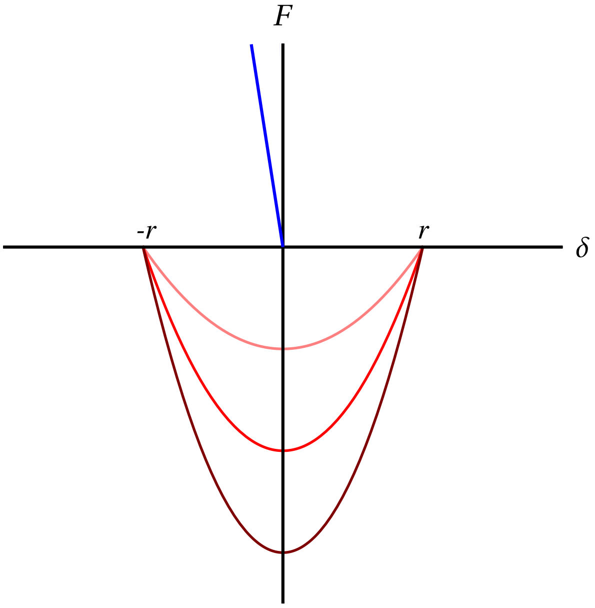

Figure 2: Force-displacement model used for the numerical simulations consisting of an attraction force between the grains in red (shades of red are used to show different intensities of cohesion,i.e. different Bond numbers) and a repulsion force in blue.

Once the dimensions of the system and the parameters of the grains are set, we only have two parameters for the numerical simulations: the intensity of cohesion given by Bo and the rotation speed of the drum ω. To highlight their effect on the flow of granular materials, we selected different values of Bo and ω and performed the numerical simulations several times to avoid statistical fluctuations.

In the framework of the present study dedicated to the effect of cohesiveness on both experimental and numerical results, we focused on 2D simulations for the flow in the rotating drum. The 2D geometry was chosen to avoid the complex effects induced by the side walls of the drum and in particular to avoid an arbitrary choice of the drum thickness. Moreover, in this 2D geometry we neglect the transverse flow and we decrease drastically the computational time.

4 Comparison between experiment and simulation

Figure 3 presents a set of snapshots of the granular flow inside the rotating drum for different rotating speeds and for different cohesiveness. In both numerical and experimental cases, the cohesiveness induces irregularities of the granular-air interface. Experimentally, for larger grains (i.e. without cohesiveness), the typical S-shape is observed when the rotating speed increases. This effect is less pronounced numerically for Bo $= 0$. Numerically, we observe a fluidization at the surface induced by grain bouncing, which is not observed experimentally. The difference between these experimental and numerical observations could be attributed to an over-estimation of the coefficient of restitution and also by the larger size of the grains in the simulations. Moreover, the sidewall friction is not taken into accound in the simulation. Globally, the angular grain shape in the experiment leads to a higher flowing angle.

To compare the results more precisely, we compare the flowing angle α measured at the center of the interface and the interface fluctuations σ. In particular, we do not compare the absolute values of these parameters because the experimental and numerical configurations are not rigorously identical. Therefore, we compare the evolution of these parameters as a function of the rotating speed normalized to obtain a Froude number Fr.

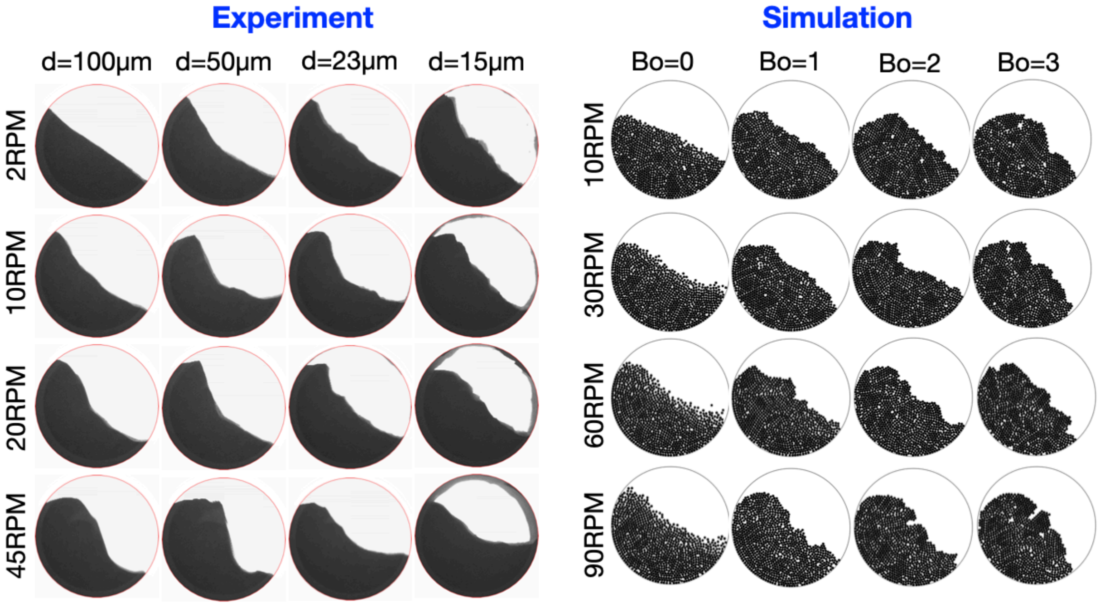

Figure 3: Typical pictures of the flow inside the rotating drum for different rotating speeds and cohesiveness.

Figure 4 (Left) shows the flowing angle α measured in the GranuDrum. When the cohesiveness is low (for larger grains), this angle increases drastically with the Froude number. This increase is a well know phenomenon due to inertia. At the opposite, in the cohesive case (for smaller grains), the flowing angle decreases significantly with the Froude number. This decrease could be explained by a fluidization induced by an aeration of the powder. Indeed, if the powder is aerated due to the flow, the distance between the grains increases slightly and the cohesive forces decrease. All these observations are also valid when considering the interface fluctuations obtained experimentally (see Figure 5 (Left)). An increases of the fluctuations with the rotating speed is observed for non-cohesive granular material, while a decrease is observed for cohesive powders.

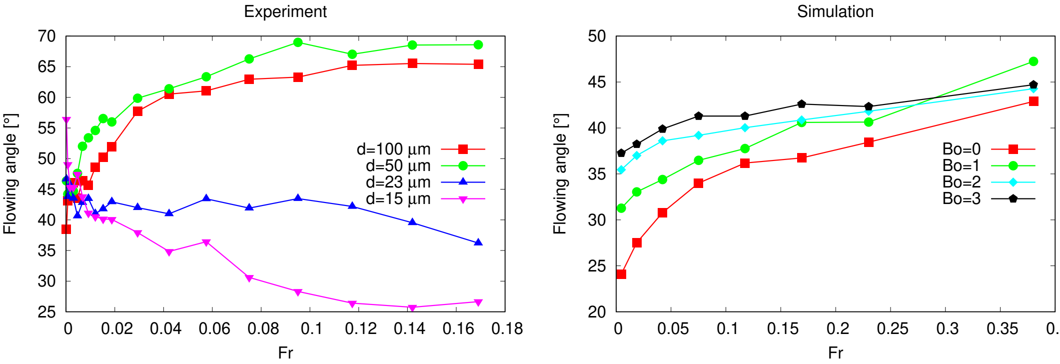

Figure 4: Evolution of the flowing angle α as a function of the Froude number Fr related to the drum rotating speed. (Left) Experimental results obtained with GranuDrum and (Right) numerical results obtained with DEM simulations.

A similar general trend is observed in numerical results however not as pronounced. Concerning the flowing angle (see Figure 4(Right)), the drastic increase with Fr is observed for $\mathrm{Bo} = 0$. For higher Bo the trend is not inverted as in the experimental results. However, the increase is less and less pronounced when Bo increases. Concerning the fluctuations, the increase with Fr for $\mathrm{Bo} = 0$ is also observed and a global decreasing trend is observed for higher Bo. The fact that the fluidization effect is less pronounced in simulations is certainly due to the absence of viscous effect in the numerical model.

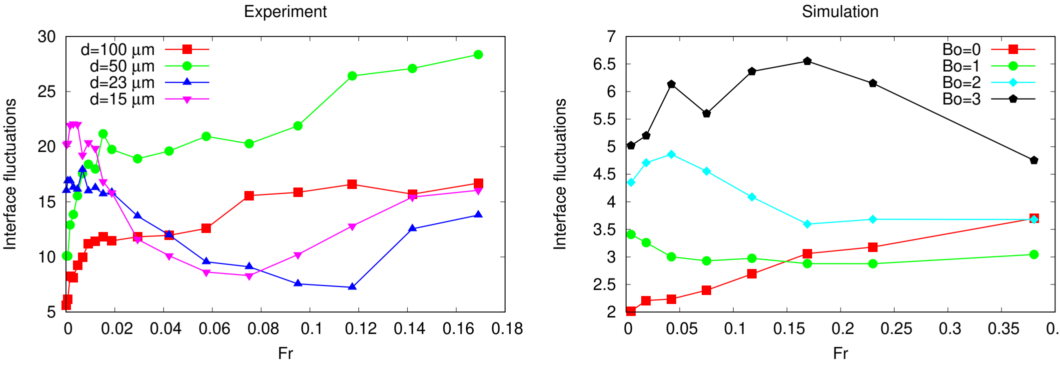

Figure 5: Evolution of the interface fluctuations σ as a function of the Froude number Fr related to the drum rotating speed. (Left) Experimental results obtained with GranuDrum and (Right) numerical results obtained with DEM simulations. In GranuDrum software, these fluctuations are called cohesive index.

If we focus on the interface fluctuations at lower Froude numbers, i.e. lower rotating speeds, it appears clearly from both experimental and numerical results that these fluctuations increases when the cohesiveness increases. Therefore, this parameter is a good candidate to characterise powder cohesiveness and the name "cohesive index" in GranuDrum software is justified. Moreover, the analysis of this parameter evolution according to the flow speed, gives additional information about the rheology of the powder. In addition, the comparison of the flow inside a rotating drum obtained numerically and experimentally is a practical way to calibrate the set of simulation parameters. Afterward, the optimal set of parameters corresponding to a "real" powder could be used to simulate complex processes.

5 Conclusion

The flow inside a rotating drum has been investigated numerically and experimentally. The influence of cohesive interactions between the grains has been analysed qualitatively by comparing flow snapshots and quantitatively through the flowing angle and the interface fluctuation. Moreover, the evolution of these parameters according to the Froude number related to the rotating speed has been explored. The similarities and also the discrepancies between numerical and experimental results has been evidenced.

In both numerical and experimental cases, the cohesiveness induces irregularities of the grain-air interface. At lower Froude numbers, i.e. lower rotating speeds, the fluctuations increases when the cohesiveness increases. Therefore, this parameter is a good candidate to characterise powder cohesiveness.

For granular materials having a low cohesiveness, an increase with the rotating speed of both the flowing angle and the interface fluctuations have been observed experimentally and numerically. At the opposite, with cohesive powders, these parameters have globally the tendency to decrease with the rotating speed. This effect is certainly due to an aeration of the powder at higher speed, decreasing the cohesive forces between the grains. Globally, this effect is less pronounced in simulation because the affect of the air is not taken into account in the DEM model.

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