Rheology of cohesive granular material with tuneable cohesive strength

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Abstract. We report the findings of an experimental investigation on the flow of cohesive granular materials in a partially filled rotating drum. The inter-particle cohesive force is varied by adding different amounts of glycerol to dry glass beads. In the rotating drum we measure the avalanche angle as a function of liquid content and find a non-monotonic trend. The avalanche angle initially increases with the addition of glycerol, reaches a maximum value and then decreases with further increase in the glycerol content. Another interesting feature observed in our experiments is the formation of agglomerates, which continuously form and break during flow. These agglomerates form if the liquid content exceeds a critical value, and seem to play a key role in the intermittent behavious of the surface dynamics of the avalanches, including the nonmonotonicity in the angle of repose.

1 Introduction

Granular flows are omnipresent in nature and industrial processes. However, their rheological properties are still poorly understood, and they become more complex when there is cohesive force between particles in addition to frictional and elastic forces. Cohesive granular materials have been extensively studied using experiments and computer simulations [1–3]. Both dry cohesion (e.g., Van der Waals interactions and bead surface energy) and wet cohesion (e.g., liquid bridges) have been studied to understand peculiar characteristics of granular material such as the formation of shear bands, clustering, dilatancy, and the variations in the packing densities. Several combinations of granular material and the liquid have been considered in the earlier studies, for example, glass beads coated with liquid solvents (such as epoxy or glycerol) and bead chains with variable lengths[4–8].

In the quasi-static regime, the kinematic behaviour of cohesive granular materials has been predominantly modelled using frameworks developed for non-cohesive systems [9]. Extensions of these models to account for cohesion often involve only a modification of the yield criterion—typically by introducing a threshold stress or changing the onset conditions for flow [10]. However, such treatments largely presume that the post-onset kinematics remain similar to those observed in non-cohesive systems. This assumption has proven insufficient. Empirical observations and discrete simulations suggest that after the onset of flow, cohesive granular materials exhibit qualitatively distinct kinematic behaviour, including persistent agglomerate motion. Simple cohesive extensions of non-cohesive models do not capture these features. Therefore, a critical gap exists in current literature: while the impact of cohesion on flow initiation has been partially addressed, the bulk kinematics during sustained flow in cohesive systems remains poorly understood and insufficiently modelled. Our main aim is to understand the effect of interparticle cohesive force on the kinematics of cohesive granular material and subsequently develop a constitutive model by incorporating the fundamentally different kinematics induced by cohesion during flow. In this study, we investigate delay in flow onset and and post-onset kinematics in the rotary drum geometry.

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2 Experimental setup

Experiments are performed in a rotary drum with a diameter of 100 mm and 20 mm length, filled to 60 percent of its volume with glass beads. The drum is rotated about its axis with angular velocities in the range of 1 and 3 rpm. The front wall of the drum is transparent and a digital camera is used to record the snapshots of the material at several instants for a duration of 10 complete rotations.The mean velocity was obtained using MATLAB-based Particle Image Velocimetry (PIV) analysis of the snapshots. For each frame, we identified the free surface and calculated the average surface velocity. We synthesized cohesive material, by adding glycerol liquid to dry glass beads. The quantity of glycerol added varies to obtain different cohesive strengths. After adding glycerol to the glass beads, the material is thoroughly mixed by rotating it inside the drum for several hours to ensure homogeneity. In the present work, the quantity of glycerol ranges from 0.019 - 0.28 % of the glass beads by volume.

3 Result and discussion

When a cylindrical drum partially filled with the granular material rotates, the material deforms in such a way that the upper layer of grains undergo fluid-like avalanches and the material beneath undergoes solid-like rotation. This is a very generic and broad description, since the actual behaviour depends significantly on the characteristics of the bulk material. For instance, the flow of wet grains can have stark differences from that of dry grains under the same forcing conditions.

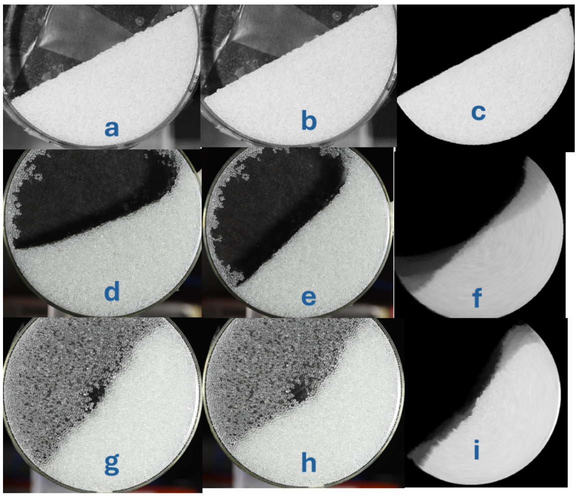

Figure 1. Panel of images (a–i) showing the front view of a rotary drum during the flow of glass beads under different conditions. (a), image at the instant of avalanche trigger and (b) just after the avalanche. (c) mean image, averaged over one avalanche duration for dry glassbeads (d, e, f) Corresponding image sequence for glass beads mixed with 0.038 vol % glycerol. (g, h, i) Similar sequence for glass beads with 0.28 vol % glycerol.

Figure 1 shows images of the flow inside a rotary drum for dry (top panel) and cohesive grains (middle and bottom panels). The first and the second images of each row correspond to the instant just before and after the avalanche, whereas the third image is the mean average of the entire avalanching event. For dry glass beads, it is observed that a thin layer avalanches continuously down the free surface while the grains beneath remain frozen and move like a solid body with the drum walls. Since the flow at the free surface is continuous, no intermittent low behaviour is observed, and the angle of of the free surface remains constant during the flow, which is also evident from Figure 1 (a - b). Thus, the mean image of the flow (Figure 1 (c)) is similar to that of the instantaneous flow field.

When the material is made cohesive with the addition of a small amount of glycerol, the flow becomes intermittent. For instance, for glass beads with (0.038 % glycerol), periodic avalanches are observed near the free surface. During each cycle of the avalanche, the entire material rotates with the drum so the surface reaches a maximum angle (see Figure 1 (d)) that can be sustained by the material, followed by an avalanche leading to a sudden decrease in the surface angle (see Figure 1 (e)). Thus, the material flows for a small duration of the avalanche and behaves like a solid body for the rest of the time. A difference in the free surface profile corresponding to before and post-avalanche states is visible as the grey region in Figure 1 (f). With an increase in the liquid content, grains begin to agglomerate with a corresponding reduction in the avalanching tendency in the flowing layer near the free surface. Since all the grains within an agglomerate are bound together due to cohesive forces, they all move together as long as the agglomerate remains intact. Thus, each agglomerate can be viewed as a particle in itself with size much bigger than the individual grains. As a result, the ratio of interparticle cohesive forces to agglomerate weight, characterized by the Bond number, decreases, shifting the material behavior toward that of a noncohesive granular system. Consequently, the flow becomes less intermittent, as reflected in the pre-, post-, and mean avalanche states shown in Figure 1 (g–i).

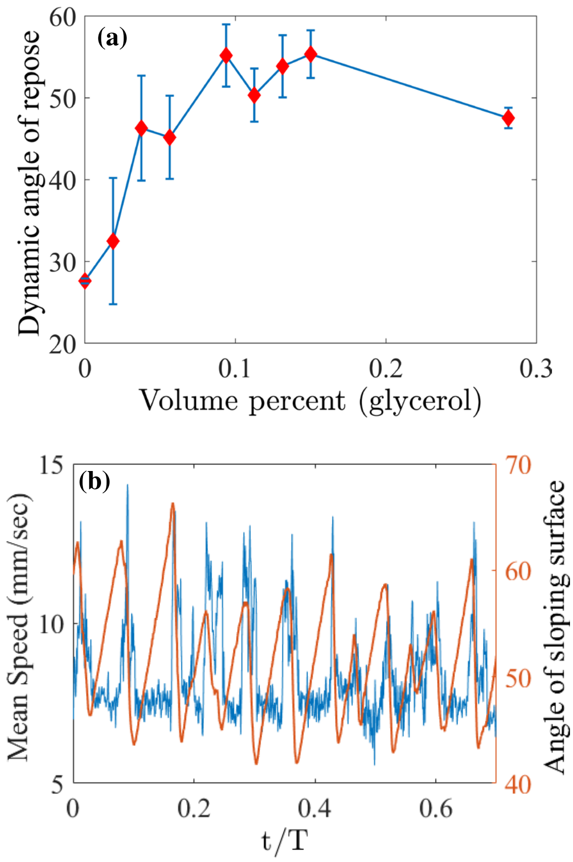

Figure 2. (a) The x-axis represents the volume percentage of glycerol added to the glass beads, while the y-axis shows the dynamic angle of repose. The error bar indicates the difference in angle of the free surface before and after avalanching. (b) The left y-axis indicates the mean speed of the system, and the right y-axis represents the angle of the sloping surface for 0.038% (v/v) glycerol.

To investigate the effect of the liquid content further, we measure the dynamic angle of repose of the free surface and the mean velocity of the bulk material over time, as shown in Figure 2 (b). The observed oscillations in both quantities are attributed to free surface avalanches, as previously discussed. Such variations are not present when grains are dry. Figure 2(a) illustrates the variation in the dynamic angle of repose with glycerol amount. The resulting non-monotonic trend indicates that the yield strength

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initially rises, reaching a maximum at a critical glycerol concentration, beyond which it declines with further addition.

4 Conclusion

This work experimentally explores the dynamics of a cohesive granular material in a rotating drum, varying the cohesion intensity in a systematic manner. The study reveals different kinematic regimes in cohesive granular materials. In the rotating drum, the flow is periodic. Therefore, for further investigation of the kinematics, we are using a cylindrical Couette geometry, where the flow is steady.

Classically, cohesion has been incorporated into constitutive relations by adding an extra contribution to the yield stress. However, our findings show that the kinematics of cohesive granular materials differ significantly from those of dry grains beyond yielding, suggesting that cohesion needs to be incorporated directly into the flow rule.

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