315a Plane Shear Flow of Cohesive Granular Materials

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Assemblies of granular materials behave differently when they are flowing rapidly from when they are slowly deforming. The behavior of rapidly flowing granular materials is commonly related to the properties of the constituent particles through the kinetic theory of granular materials [e.g., see 1,2]. The same cannot be said for slowly moving or static granular materials. For instance, a continuum description of the yield characteristics of dense assemblies of particles in the quasistatic flow regime cannot be written explicitly on the basis of particle properties even for cohesionless particles. The description of the continuum rheology in the intermediate regime is even less understood [e.g., see 3,4,5].

A qualitative understanding of the different regimes of flows for uniformly sized, cohesionless, frictional particles has emerged from the DEM (discrete element method [6]) simulations performed by Campbell [3]. Campbell categorized assemblies by how the stress scaled with the shear rate. In the inertial (i.e. rapid flow) regime – typically obtained at high shear rate – the normal and shear stresses were proportional to the square of the shear rate; in this regime, the particles flowed freely and the contact interactions were dominated by binary collisions. In the elastic-quasistatic regime - typically observed at very low shear rates and high volume fractions - the shear and normal stresses did not vary appreciably with shear rate; in this regime, the particles were confined to force chains that continually rotated, broke, and reformed. At intermediate conditions, labeled by Campbell as the elastic-inertial regime, the normal and shear stress scaled linearly with the shear rate.

The primary purpose of the present study is to examine the effect of interparticle attractive forces on the regimes of rheology manifested by dense assemblies. As a model problem, we consider cohesion resulting from van der Waals force acting between uniformly sized, spherical particles. Specifically, we consider plane shear flow of particle assemblies in periodic domains, employing Lees – Edwards boundary conditions [7] across the faces. Simulations were performed for different strengths of cohesion, shear rates and particle volume fractions and coefficient of friction. From each simulation, we have extracted the average normal and shear stresses and the average coordination number, as was done by Campbell for the cohesionless case. We have also extracted results on the fabric tensor, the distribution of coordination numbers and the statistics of the temporal fluctuations in the stresses.

Not surprisingly, the three regimes of flow reported by Campbell [3] for the case of cohesionless particles – namely, inertial, elastic-inertial and elastic-quasistatic regimes – persist when cohesion is included. A striking result observed in our simulations is that the influence of cohesion on stress becomes more pronounced with decreasing particle volume fraction. When an assembly is composed of cohesionless particles, the elastic-quasistatic regime can only be obtained at the highest volume fractions (at least 0.62 for the particle properties used in our simulations) and small shear rates; when cohesion is added to such an assembly, very little change in stresses results.

At somewhat lower volume fractions (e.g., 0.57), an assembly of non-cohesive particles only exists in the elastic-inertial or inertial regime, and the elastic-quasistatic regime is not realized even at very low shear rates. However, when the particles are allowed to interact cohesively, the elastic-quasistatic regime reappears at low shear rates, and the difference between the stresses obtained with cohesionless and cohesive particles becomes appreciable. This difference increases with increasing strength of cohesive interaction and with decreasing volume fraction. If the shear rate is increased so that the cohesive assembly enters the intermediate elastic-inertial regime, the stresses quickly approach those for the cohesionless assembly.

The macroscopic stress tensor is the volume-average of the stresses acting on individual particles, which in turn were calculated from inter-particle forces (used to calculate the contact and tensile stresses) and velocities (used to calculate the momentum flux). In the range of conditions where we have performed our simulations, the contribution of the momentum flux to the stresses is negligible. For cohesionless particles, one then simply has the contact stress contribution, while in the case of cohesive assemblies the total stress tensor is the sum of the positive (i.e. compressive) contact stress and negative (i.e. tensile) cohesive stress.

The cohesive (tensile) stress for an assembly of cohesive particles is an increasing function of volume fraction but depends only weakly on shear rate. As the particle volume fraction is decreased, the dependence of the tensile stress on shear rate grows, but for all volume fractions, this dependence is much weaker than that of the total stress. The cohesive, tensile stress is in good agreement with that given by the Rumpf [8] model.

The apparent internal angle of friction, which is the ratio of the shear stress to normal stress, depends on volume fraction, shear rate, and cohesion. It grows with decreasing volume fraction and increasing cohesion. As both the normal and shear stresses decrease with decreasing volume fraction, this behavior indicates a stronger dependence of the normal stress (than the shear stress) on volume fraction. Similarly, as cohesion leads to more contacts, the behavior of the apparent internal angle of friction implies a greater dependence of the shear stress on cohesion.

Our simulations revealed a systematic dependence of the average coordination number on shear rate in the different regimes, irrespective of whether the assembly is cohesive or cohesionless. In the elastic-quasistatic regime, the coordination number decreases with increasing shear rate, while in the other two regimes, it increases with increasing shear rate.

In summary, our simulations of dense cohesive assemblies have not revealed any new regimes of flow (over those already known for cohesionless systems). The window in the shear rate - particle volume fraction space over which the elastic quasistatic regime is obtained expands as the strength of cohesion is increased.

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