# "Rheological Behavior of Dense Assemblies of Granular Materials"

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## OBJECTIVE(s)

The overall objective of this project is to construct: (i) validated continuum models for frictional flow of granular materials in the quasi-static and intermediate regimes, including transitions from stagnant-to-shearing, quasistatic-to-intermediate and intermediate-to-inertial regimes; and (ii) closures for the parameters appearing in the models in terms of particle scale properties. Towards this end, we will first seek a better physical understanding of the mean stress levels and fluctuations accompanying particle flows in the presence of enduring contact between particles, and then develop and validate constitutive models for (a) frictional, quasi-static flow that capture the essential features of the elastic and plastic regimes and the transition between them and (b) the intermediate regime that smoothly bridge the quasi-static and inertial flow regimes.

## ACCOMPLISHMENTS TO DATE

We have studied steady and unsteady simple shear flow of nearly homogeneous assemblies of uniformly sized, spherical particles in periodic domains under constant volume and constant normal stress conditions using the discrete element method. Simulations were performed for different strengths of cohesion, shear rates, particle stiffness, particle volume fractions and coefficients of friction. We find a new scaling which permits collapse of all steady shear data at various strengths of cohesion and shear rates into a single master curve for each particle volume fraction and coefficient of friction. Although the dynamic stress response in the quasi-static regime is rate-independent as shown by the collapsed stress-strain curves at different shear rates, strong history dependence of the stress response is found. The normal and shear stresses undergo a transition after shear reversal that requires a shear strain of order unity to evolve; in contrast, they reach the previous steady state stress level rapidly when shear is resumed in the same direction. The development of shear-induced anisotropy and the correlation of the stress transition after shear reversal with the microstructure rearrangement (as characterized by the fabric tensor) are observed.

DEM simulations of simple shear flows with wall boundary conditions have also been performed. Velocity, volume fraction and stress distributions are found to be inhomogeneous in space. The flow regimes and stress scaling with local shear rates are observed to be the same as those under periodic boundary condition.

The main achievement of the experimental program was the development of three, very specialized pieces of instrumentation and the methodology to collect in-situ data from stress sensors on a shearing surface inside the bulk material. First, an axial-flow Couette device was developed in which the solid fraction of the bulk could be adjusted by regulating a slow axial flow superimposed on the radial shearing of the material. Second, a Jenike-type shear cell was developed to accommodate larger particles and faster shear rates required for testing of the simulation code without requiring excessive computation times. Finally, a normal stress measuring device was modified and equipped with radio-transmitters to enable stress measurements inside a flowing stream of powder.

**FUTURE WORK**

In the coming year, we intend to refine the hypoplastic model by incorporating the fabric evolution. We plan to complete assessment of order parameter based continuum rheological model using data from DEM simulations of uniaxial and triaxial tests, plane shear computational data on stress evolution and experimental data. Couette flow experiments at low overburden levels for large, millimeter sized glass chips and sand particles will be performed. Simulation of Couette flow experiments is also in preparation and detailed analysis of the stress inhomogeneity and microstructure will follow.

**Published Articles and US Patents:** L. Aarons and S. Sundaresan. Shear flow of assemblies of cohesive granular materials under constant applied normal stress. Powder Technology, 183(3):340–355, 2008.

**Completed/Future Presentations:**

a) M. K. Langroud, J. N. Michaels and G. I. Tardos, Stress measurements in dry, dense powder flows using a Couette device, Paper accepted to the Gordon conference on Granular & Granular-fluid Flow, ME, June, (2008).
b) J. Sun, L. A. Aarons & S. Sundaresan, Memory and microstructure of quasi-static granular flows under unsteady simple shear, Paper accepted to the Gordon conference on Granular & Granular-fluid Flow, ME, June, (2008)
c) L. A. Aarons & S. Sundaresan, Shear flow of assemblies of cohesive materials, Paper presented at the AICHE Annual Meeting, November 4-9, 2007, Salt Lake City, UT.
d) L. A. Aarons & S. Sundaresan, Unsteady shear flow of assemblies of cohesive materials, Paper presented at the AICHE Annual Meeting, November 4-9, 2007, Salt Lake City, UT.

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