Rheological behavior of dense assemblies of granular materials: Experimental Measurements

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Principal Investigator:
• Prof. Sankaran Sundaresan (Princeton University) - Simulation

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Goal for Experimentation: Provide precise and detailed experimental results in simple enough geometries to validate simulations.

Papers
### Table 1.1

1. Fundamental aspects of stress and flow fields in dense particulate systems.

2. Definition of material properties on relevant scales, along with efficient ways to represent properties in models and establish standards for material property measurements.

3. Given the practical need for continuum modeling capability, identify the inherent limitations and how to proceed forward, e.g., hybrid models that connect with finer scale models (DNS, DEM, finite element, stochastic, etc.) for finer resolution.

4. Size-scaling and process control (particle / unit-op / processing system) is critical to industrial applications.
Key questions addressed:

- How to measure stresses and solid fraction in shear?
- How is stress transmitted?
- What parameters control the transitions between granular states?
- Rheological models from quasi-static to intermediate flow regimes?

Action taken in our project:

- Identified and modified instrumentation to measure stresses, fluctuations and porosity.
- Used Jenike cell geometry to demonstrate stress transmission.
- Demonstrated the connection between quasi-static transition to “flow” or Intermediate Regime.
- Developed a constitutive equation for the quasi-static and intermediate regimes directly from experiment.
The Flat Geometry of the Jenike Cell
A Study of Stress Transmission

Principle of Measurement
(schematic representation)

Applied Normal Pressure

Stress Sensor

Tangential Force

Sensor Selected for Measurement

Flexi Sensor by Tekscan, Ma.
Stress Transmission through Granular Layers

0.1 mm glass
L=1.6 cm
Pressure: 1 Psi

2.0 mm glass
L=2.5 cm
Pressure: 1 Psi and 2.0 Psi
Comparison of Experiment and Simulations
The “fast” Jenike cell

- Up to 500 times the Shear Rate in the Jenike cell
- Multiple sensors at different locations
Comparison of Experiment and Simulations

- Glass beads of 5 mm in diameter sheared at a speed of 16 mm/sec with 1 psi applied normal stress.
- Simulation and experiment agree in the mean and fluctuation of the stress.
Normal Stress Measurement in Shearing Zone

Remote normal stress sensors on the rotating Cylinder
Ratio of Shear to Normal Stresses in the Couette for Rough and Smooth PE particles of 4 mm in diameter

\[ \mu = \frac{\tau_{r\theta}}{\sigma_{yy}} = 0.54 + 0.44\gamma \]

\[ \mu = \frac{\tau_{r\theta}}{\sigma_{rr}} = 0.38 + 0.21\gamma \]
Conical, Mass-flow Hopper - Schematic

Normal stress Sensor, $\sigma_{r' r' 2}$

Normal stress Sensor, $\sigma_{r' r' 1}$

Radio transmitter
Stresses in the Mass-flow Hopper.
Porosity Sensor

Porosity Sensor

Radial Normal Stress

Vertical Normal Stresses

Bin

Flat-Bottom

Orifice

σ_{zz1}

σ_{zz2}

σ_{rr2}

Radio Transmitters
Stresses in the Flat-bottom Hopper.

Hydrostatic Pressure, $\rho_B gh$

Height 59 cm

$\sigma$ (KPa)

Time (s)

Filling

Flowing

Detail

Stress Sensors

Bottom Plate: view from above

zz1

zz2

r2
Capacitance Probe for Solid Fraction Measurements
Solid Fraction in the Flat-bottom Hopper.

- No Flow
- Start Flowing
- Material Reaches Probe

Graph showing Solid Fraction and Flow Rate over time.
Conclusions

- Stresses are measured correctly only under shear
- DEM simulation favorably compare to results from “Fast” Jenike cell
- Solid Fraction measurements showed that the bed has to increase its porosity for the transition to the intermediate regime
- Ratio of Shear Stress to Shear rate is constant at low and increases at higher shear rates – experimental correlation can be used as “constitutive equation”.
- Flat bottom (funnel flow) and conical bottom (mass flow) hoppers behave differently and generate different set of Stresses
- Janssen’s yield theory applies more to mass flow hoppers but only at low flow-rates
Future Work Year III

- Couette Experiments – study influence of:
  - Particle size distribution (fines, coarse, mixtures)
  - Interstitial gas
  - Evaluation of DEM and “continuum” models
  - Comparison to MFIIX

- Hopper flow Experiments
  - Conical-bottom (Mass flow)
  - Flat-bottom (Funnel Flow)
  - Evaluation of Hypo-plastic and other models
  - Comparison to MFIIX