SAND2017-10539C

Flow-Arrest Transition and Compaction of Frictional and Cohesive Granular Materials

Ishan Srivastava[1], Dan S. Bolintineanu[1], Leonardo E. Silbert[2], Jeremy B. Lechman[1] and Gary S. Grest[1]
[1]Sandia National Laboratories, Albuquerque, New Mexico [2]Dept. Of Physics, Southern Illinois University, Carbondale, Illinois

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Granular Materials: Definition and Properties

What are granular materials?

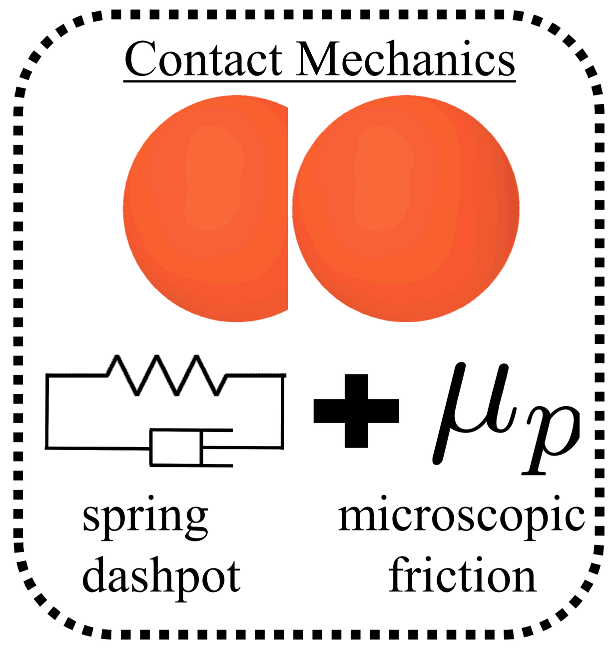
Granular materials are a class of heterogeneous materials that:
- are composed of grains whose interaction energy: $E >> k_B T$
- can co-exist in all three states of matter – solid, fluid and gas, where the transitions between these states are induced by applied stresses, and
- often possess complex inter-granular mechanics, such as hysteretic friction, cohesion, contact plasticity and fluid-induced lubrication, apart from complex shapes of the grains.

Why are they important?

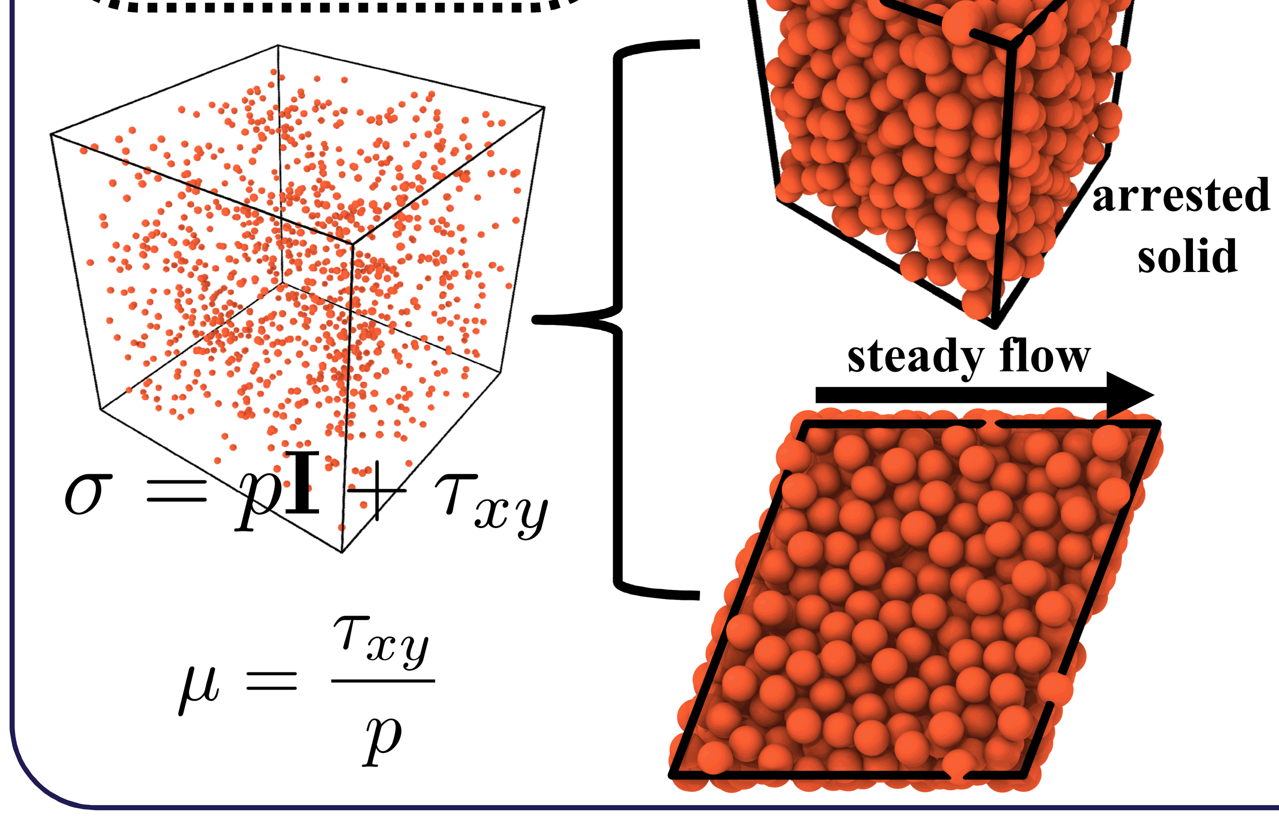
Granular materials are ubiquitous in nature and industry. They are second most used material in the industry after water. Their myriad applications include:
- manufacturing: additive manufacturing, ceramics processing
- energy industry: battery electrodes, energetic materials
- pharmaceutical industry: powder processing for medical tablets
- geotechnical industry: hydraulic fracturing for oil exploration
- natural geophysical phenomena: fault gouge between tectonic plates (earthquakes), snow and land avalanches, river bed flow

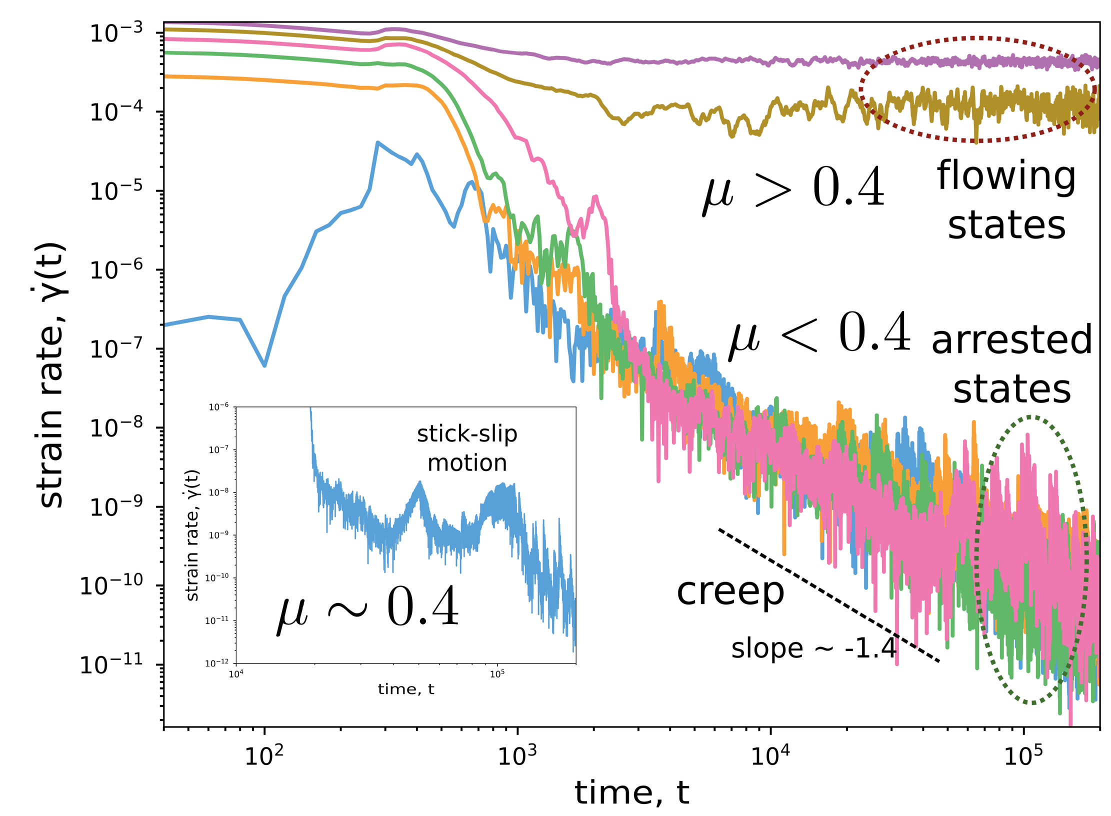
Therefore, their accurate mechanical characterization is crucial

Stress-induced Flow-Arrest Transition in Frictional Granular Materials

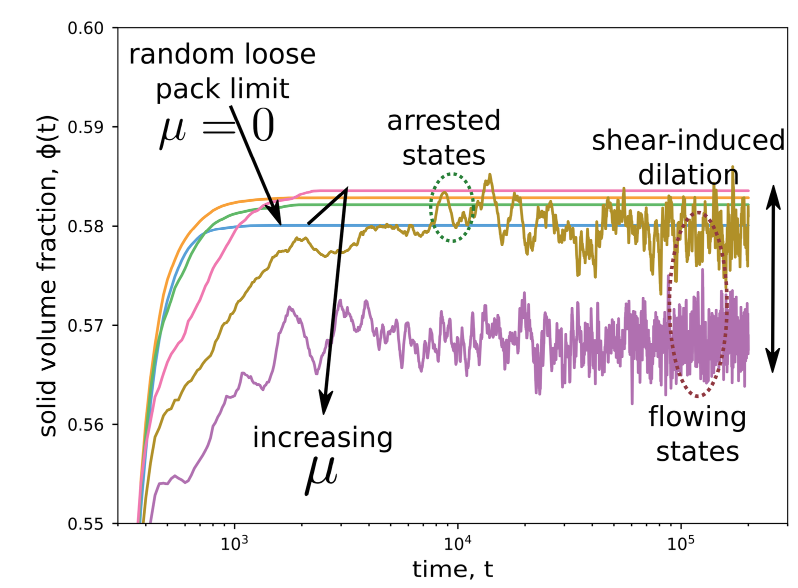


Upon applying shear stress and pressure to a granular gas, it can either arrest into a solid or flow like a fluid, based on the applied stress state.





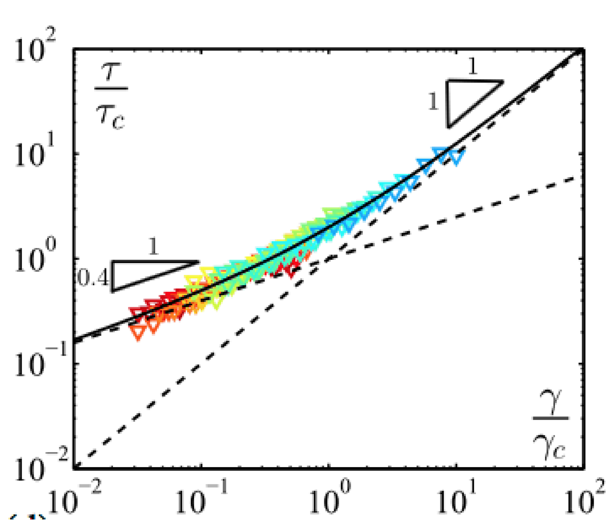
- identify *static* yield stress of frictional granular materials: $\mu_c \sim 0.4$
- significant stick-slip motion in the vicinity of yielding transition indicating rheological instability



- shear-induced flow is accompanied by granular dilation
- however for arrested states (i.e.. below yield stress), shear induces granular compaction

Granular Materials: Complex Mechanics

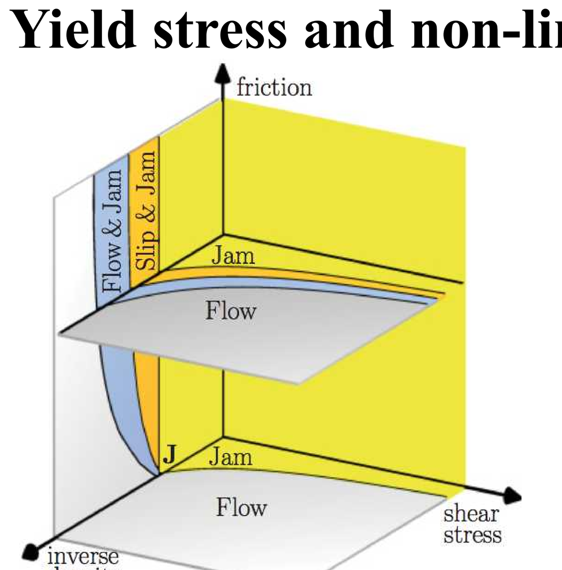
Non-linear mechanics in the solid regime



Granular materials display complex behavior such as fragility and non-affine non-linear mechanical response in the solid state close to a jamming transition. Additionally, mechanical properties vary as a power-law with density near jamming.

non-linear stress-strain curve above jamming
(reproduced from Coulais et. al., Phys. Rev. Lett., 113, 198001, 2014 with permissions from the American Physical Society)

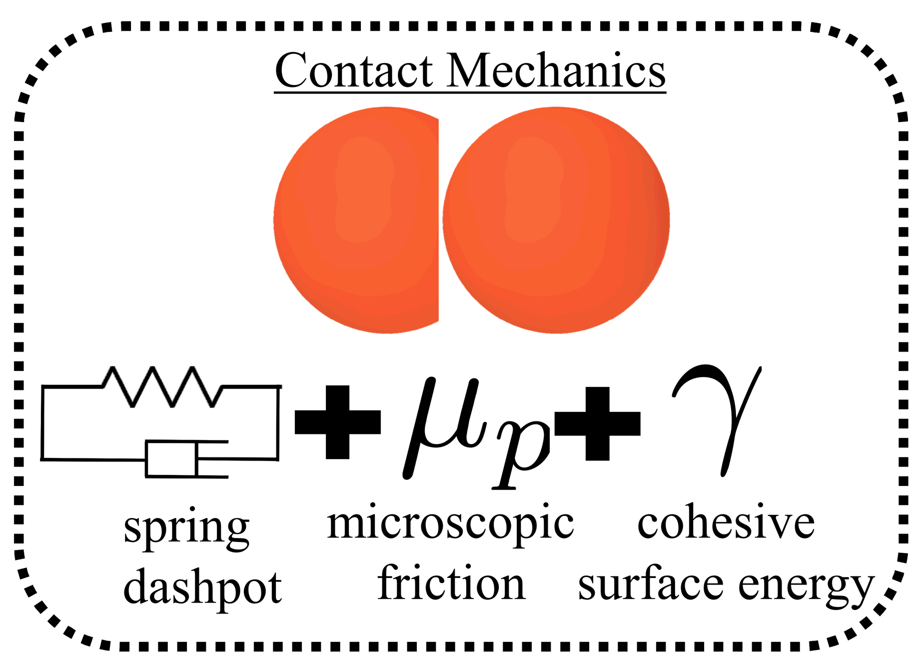
Yield stress and non-linear rheology in the fluid regime

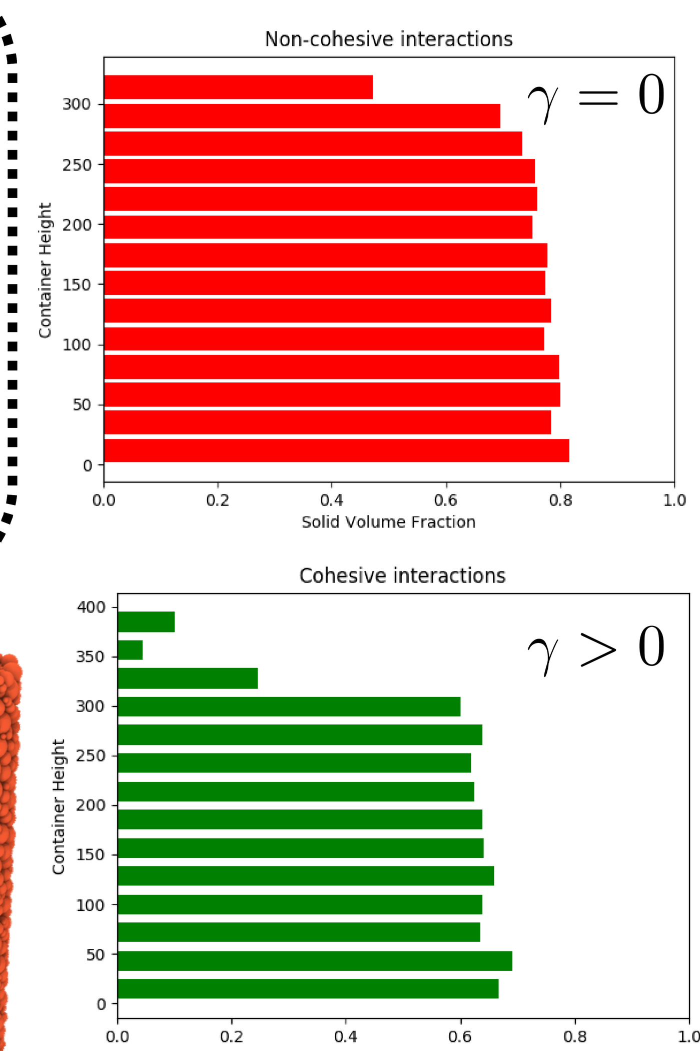


Granular materials exhibit complex rheology near the yielding transition with stick-slip flows and pressure-dependent flow viscosity. Additionally, granular flows are often accompanied by shear banding and shear-induced dilation.

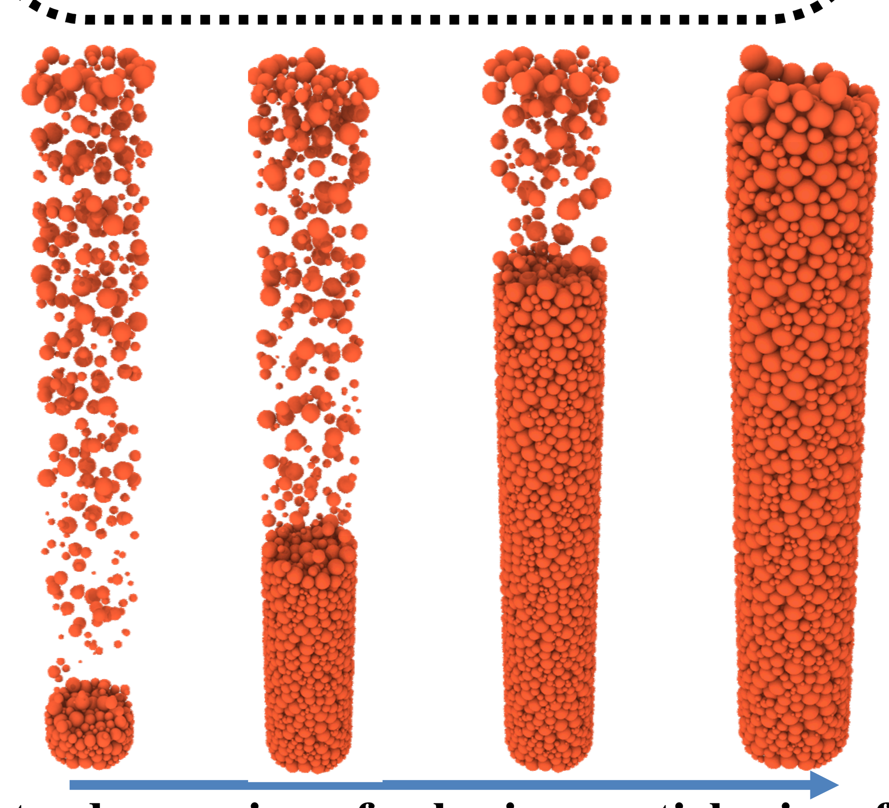
granular phase diagram
(reproduced from Ciamarra et. al., Phys. Rev. E, 84, 041308, 2011 with permissions from the American Physical Society)

Granular Materials with Cohesion





Cohesive particles pack at significantly lower volume fractions than non-cohesive particles.



steady pouring of cohesive particles in a frictional container

Next Steps

Frictional Granular Flows

- identify the phase boundary between flowing and arrested states, and predict the *static yield stress* of a granular material as a function of material properties and microscopic friction
- analyze the difference between arrested and flowing microstructures based on internal fabric analyses
- construct a three-dimensional yield surface based on full tensorial analyses of stress, strain and strain rate
- identify microscopic mechanisms that govern novel phenomena such as stick-slip motion and creep

Cohesive Granular Packings

- analyze internal microstructure, including fabric and inhomogeneous internal pore space as a function of cohesion - critical for applications such as electrodes
- apply uniaxial compression to the poured granular column and extract load-displacement response – critical for understanding the dynamics of pelletization in pharmaceutical tablets and energetic materials
- explore the effect of cohesion and friction of the container walls on packing properties