SAND2019-7151D

Flow-Arrest Transition and Viscometric Rheology of Granular Materials

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U.S. DEPARTMENT OF ENERGY Office of Science

Background

Flowing granular materials can often arrest or jam during processing and handling. To engineer solutions for such undesired events, the following questions must be addressed with reasonable precision and accuracy:

1. Will a flowing granular material arrest at a specific stress?
2. If yes, when will a flowing granular material arrest?
3. What is the rheology near the flow-arrest transition?

In practice, these questions are concerned with the ***flowability*** of a granular material (powders), which is often characterized using a rheometer. However, the stress and velocity fields within a rheometer are complex, and the extraction of bulk rheology from experimental data is significantly challenging.

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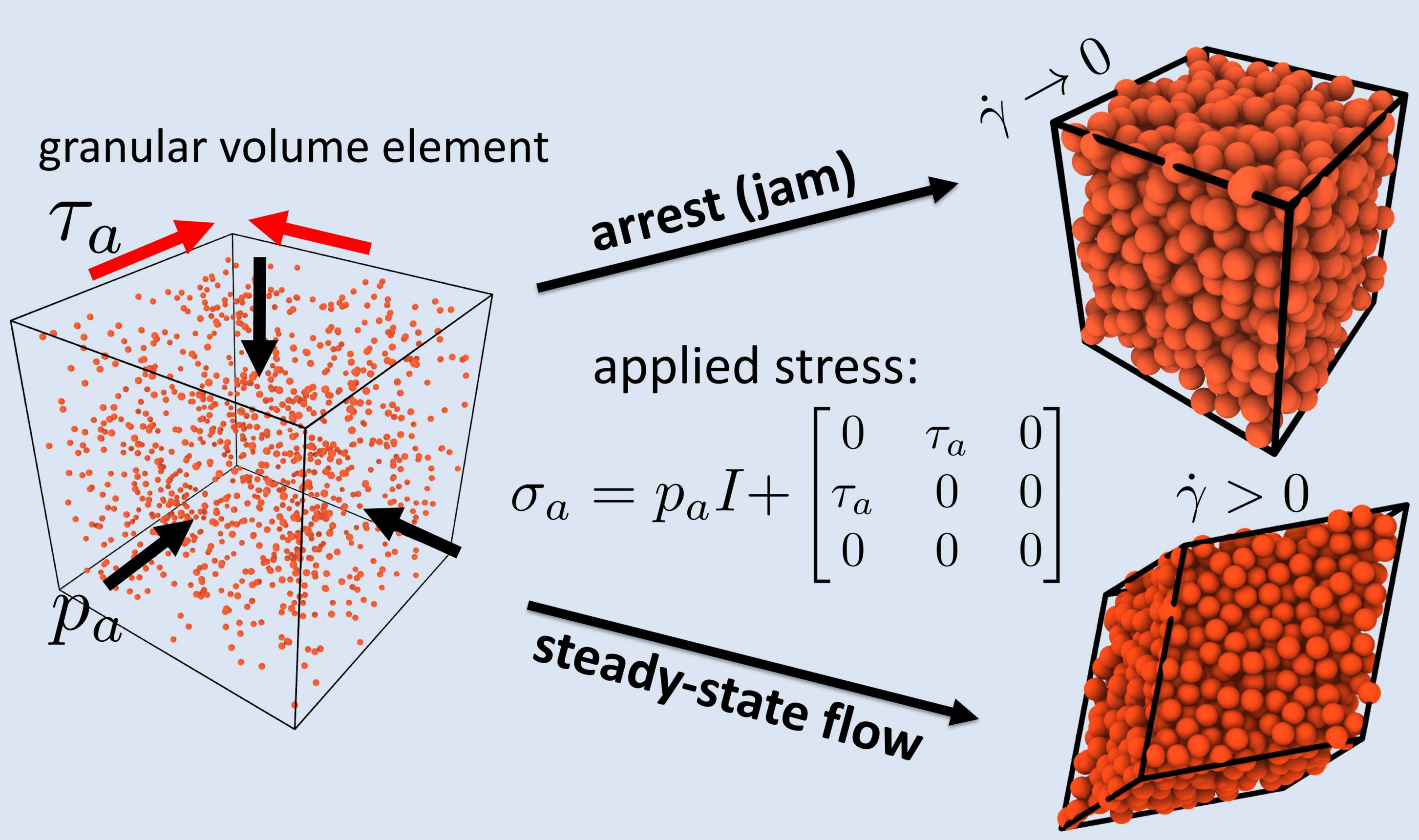
Aim: Use discrete element simulations to:

1. Map a flow-arrest state diagram for granular matter
2. Characterize the statistics of time for flow to arrest
3. Describe rheology near flow-arrest transition

Constant Stress DEM Simulations



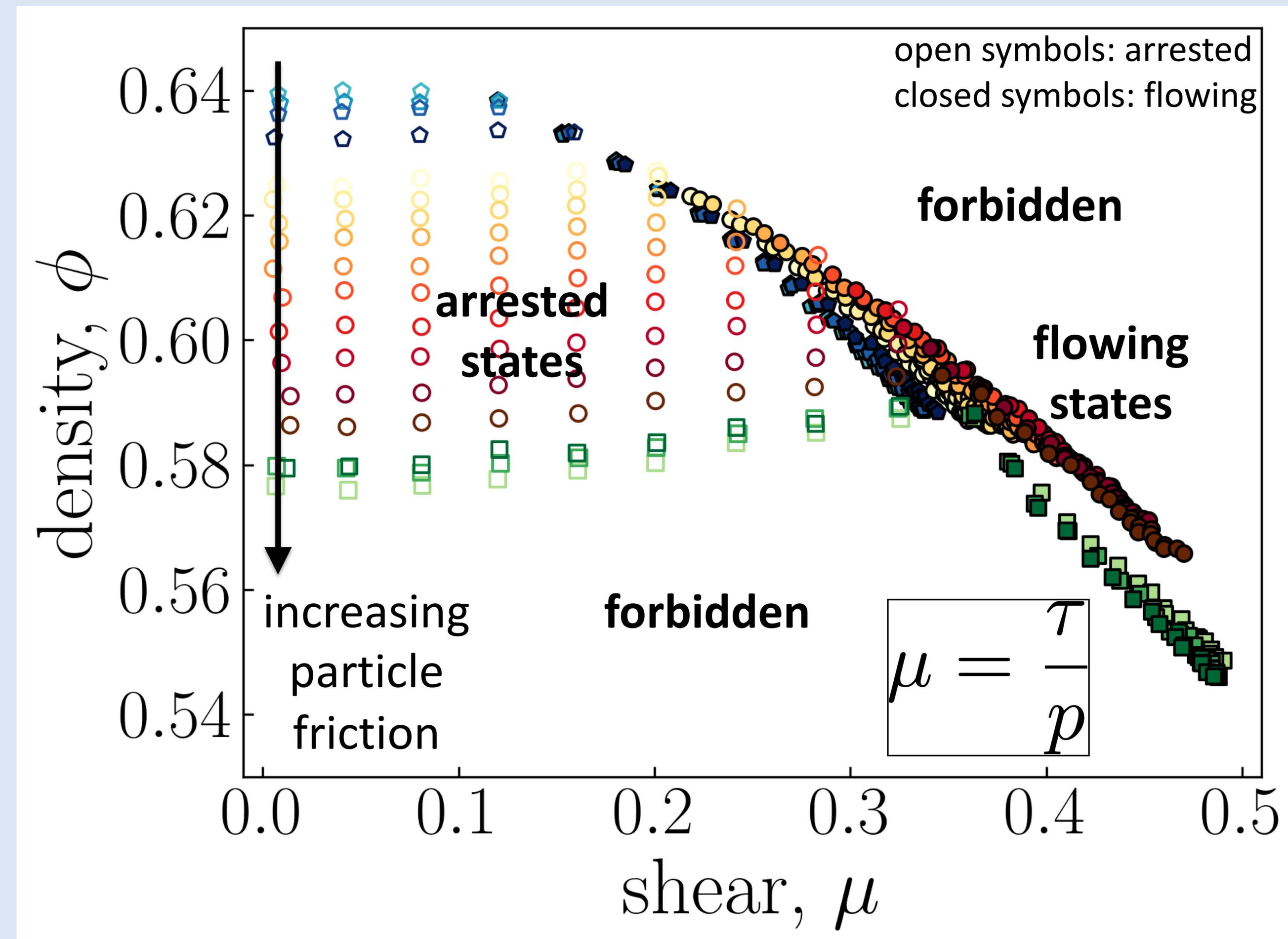
Method: Apply constant pressure and shear stress at the periodic boundaries of a dilute collection of frictional grains. Monitor the evolution of density, stress and strain with time.

Analysis:

1. Cauchy stress and pressure at which flow arrests
2. Time taken for the flow to arrest
3. Bulk rheology of the flow near flow-arrest transition

Flow-Arrest State Diagram

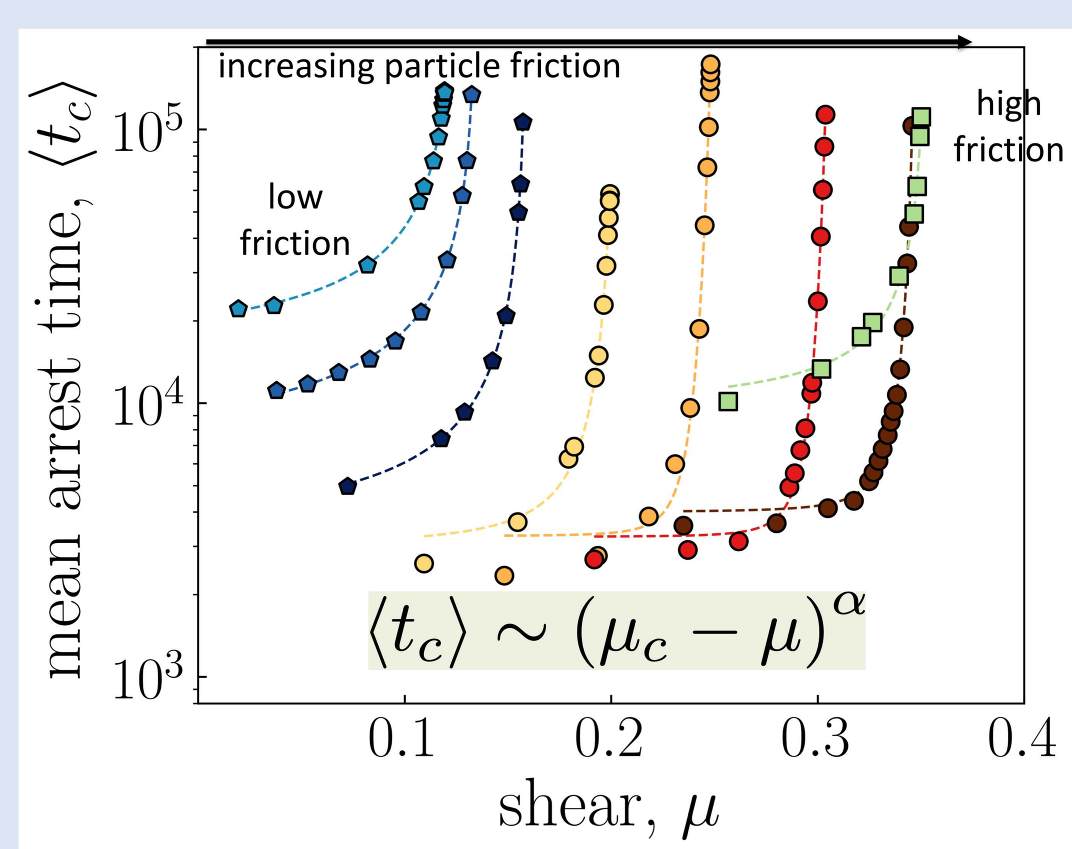
The long-time state of a granular material with internal shear stress τ, pressure p, and density ϕ, is either: steady shear flow or shear arrest



given density and internal stress → long-time flow or arrest

Time to Arrest: Statistics

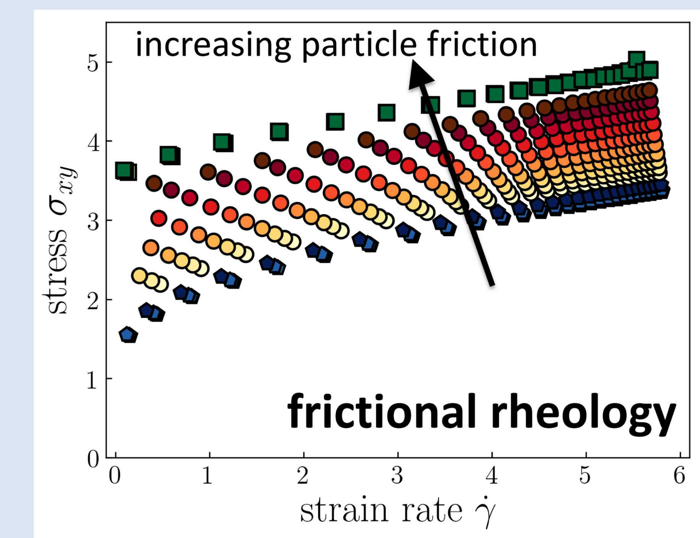
Below a critical shear stress ratio μ_c, flowing granular material is guaranteed to arrest. But the time to arrest t_c is highly stochastic (log-normal distribution) with long tails. Furthermore, the mean time to arrest $\langle t_c \rangle$, (calculated from 10^5 simulations) diverges as a power law near critical shear μ_c.

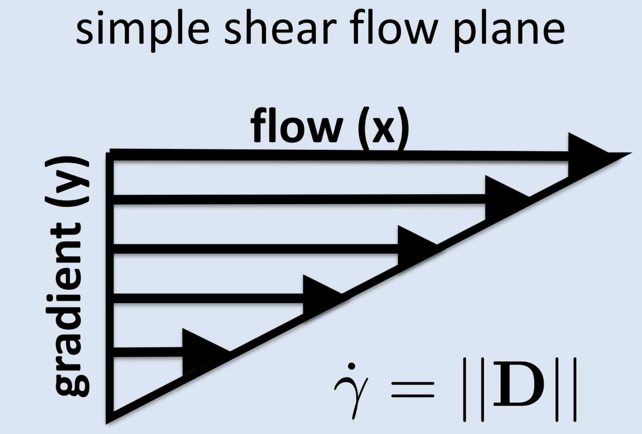


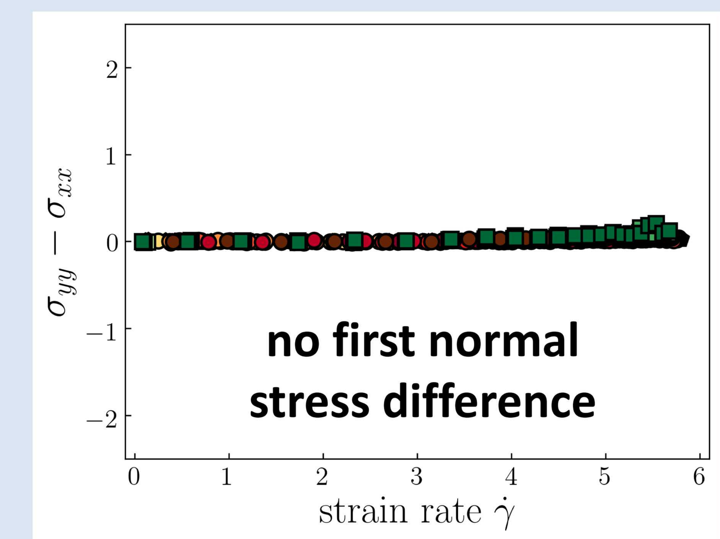
mean time for flow to arrest → diverges at a critical stress

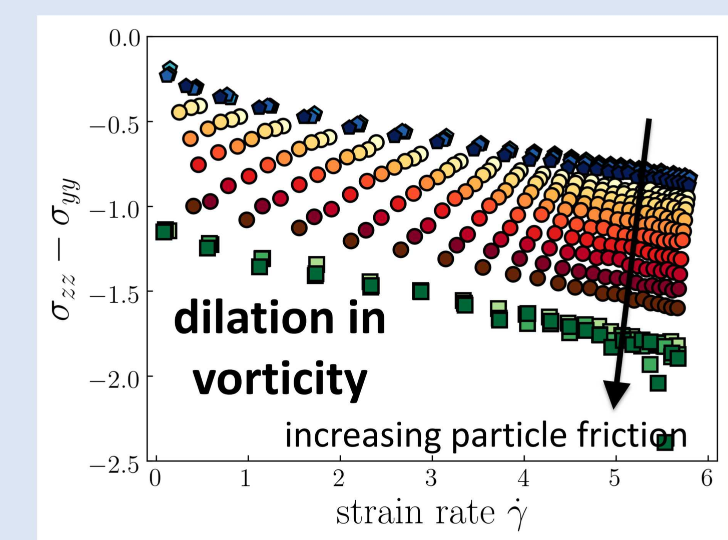
Viscometric Rheology

Project the internal Cauchy stress tensor σ on to the flow plane, defined by a strain rate tensor $\mathbf{D}$ to extract rheology:









- **lesser normal stress in the vorticity direction → linked to granular dilatancy**
- **rheology is second-order viscometric (Reiner-Rivlin):**

$$\boldsymbol{\sigma} = -P\boldsymbol{I} + \eta(\dot{\gamma})\boldsymbol{D} + \alpha(\dot{\gamma})\boldsymbol{D}^2$$

hydrostatic viscosity normal stress

Future Work and References

Future Work:

1. Extend the analysis to non-viscometric flow scenarios: extensional and triaxial shear flows
2. Predict velocity flow fields in realistic geometries (such as a rheometer) using the extracted rheology
3. Examine the influence of particle shape, interparticle cohesion on rheology and flow-arrest transitions

References:

1. Srivastava et al., Phys. Rev. Lett., 122 (2019)
2. Srivastava et al., Gran. Matt., *in review*

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

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