Pushing through the sand: local jamming, penetration, and drag in granular media

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Collaborators

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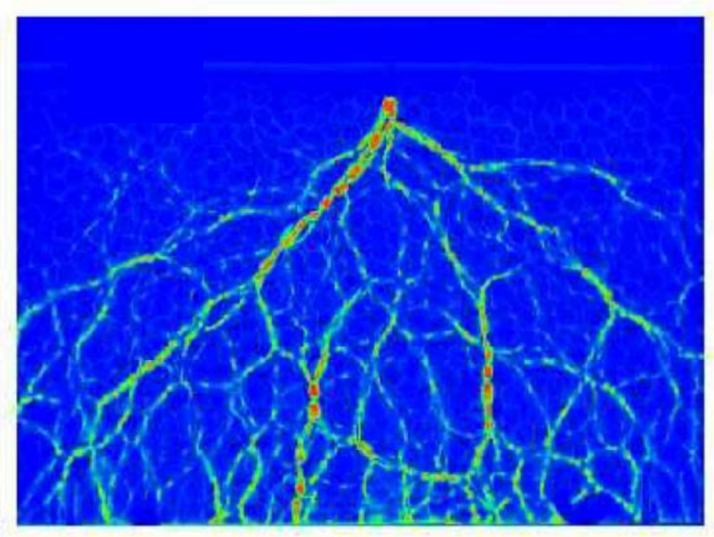
Funding: NASA and NSF REU program

Part 1: Pushing an object through grains

When a stress is applied to a dense collection of grains, the grains form a rigid "jammed" structure to resist the stress

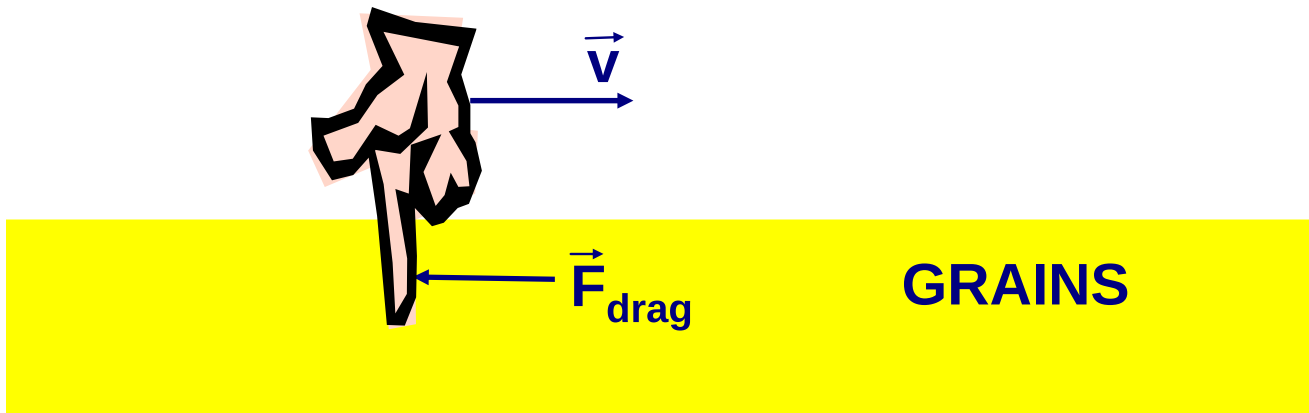
What is the nature of the jammed state resulting from a locally applied stress?

How strong are jammed states? How do they fail?

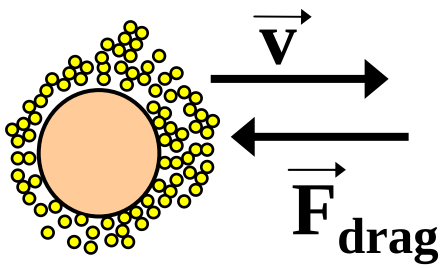


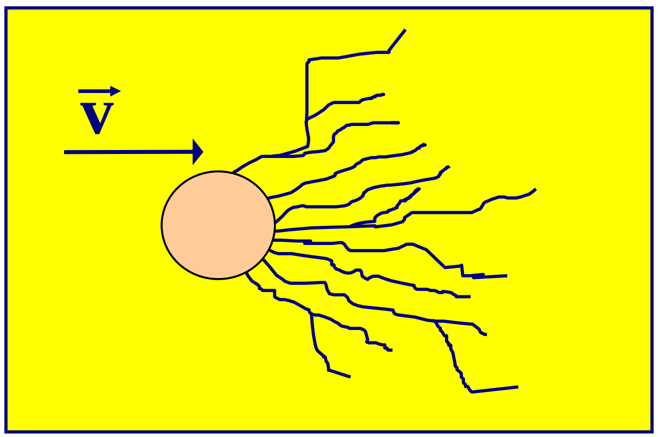
Behringer group

Study the granular drag force



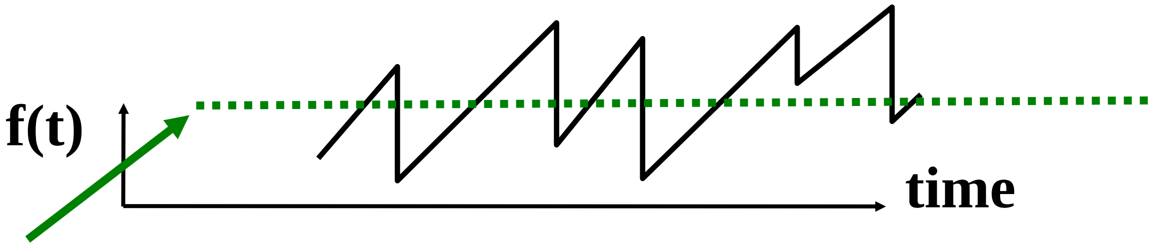
Drag is force required to reorganize grains to allow motion





Principles of granular drag at low velocities

Grains jam, and then jammed state breaks



F_{drag} ≡ avg. force to reorganize static grains

F_{drag} should be velocity independent -- akin to friction

Simple mean-field or detailed calculation suggests:

$F_{drag} = \eta g \rho d_c H^2$ for vertical cylinder

η = dimensionless constant (grain surface/morphology/packing)

ρ = density of grain material

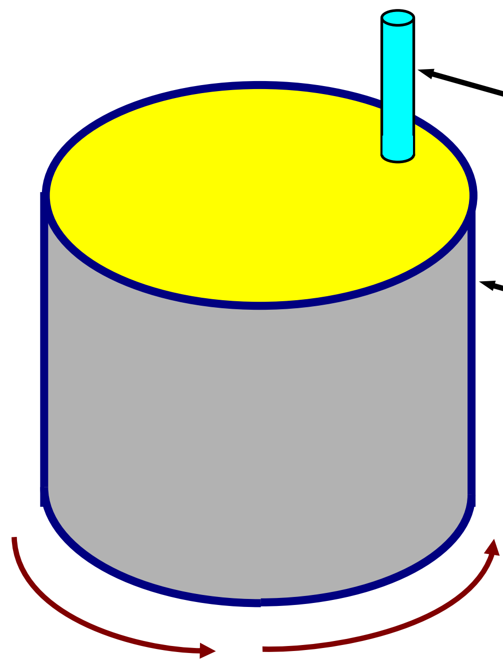
d_c = cylinder diameter

H = depth of insertion

Measure Drag Force at Low Velocities

Rotating Bucket of Glass Spheres, Cylinder Dipped In

Measure Force to <u>Keep Cylinder Fixed</u>



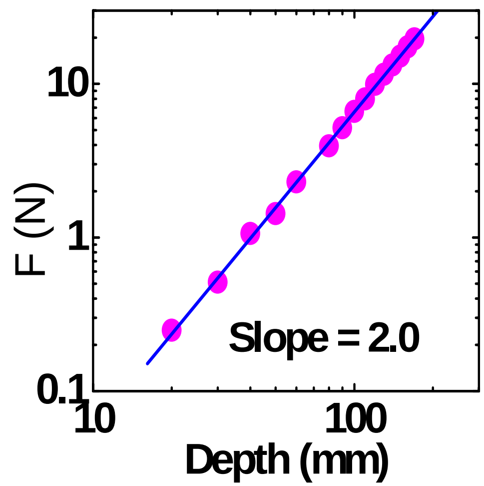
Vary grain size, velocity, depth, cylinder diameter

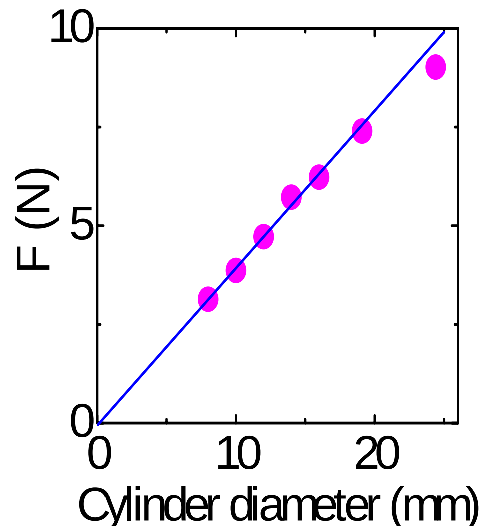
Drag Force: Vertical cylinder moving horizontally

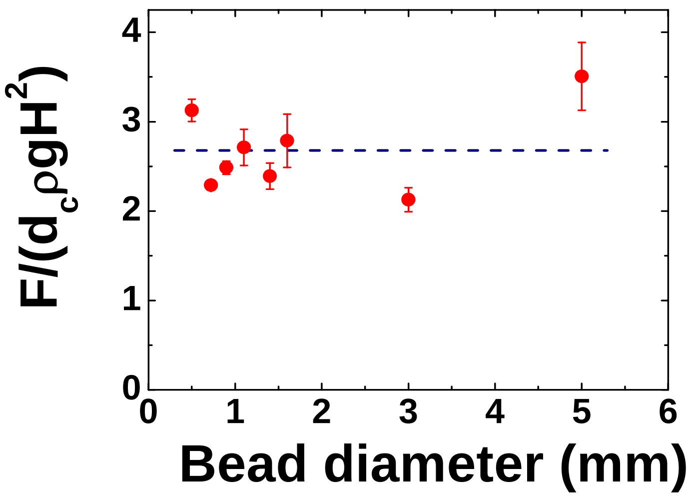
<u>Phys. Rev. Lett.</u> **82,** 205 (1999) and **84** 5122 (2000)

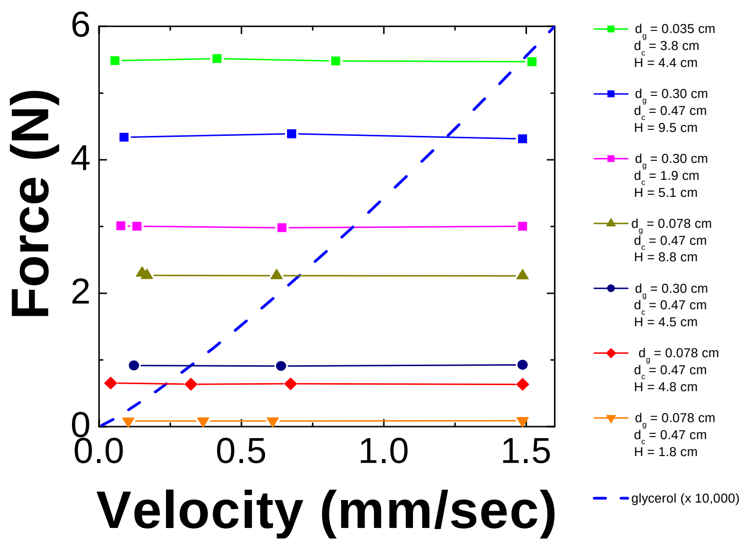
$F_{drag} = \eta g \rho d_c H^2$ in agreement with theoretical expectations

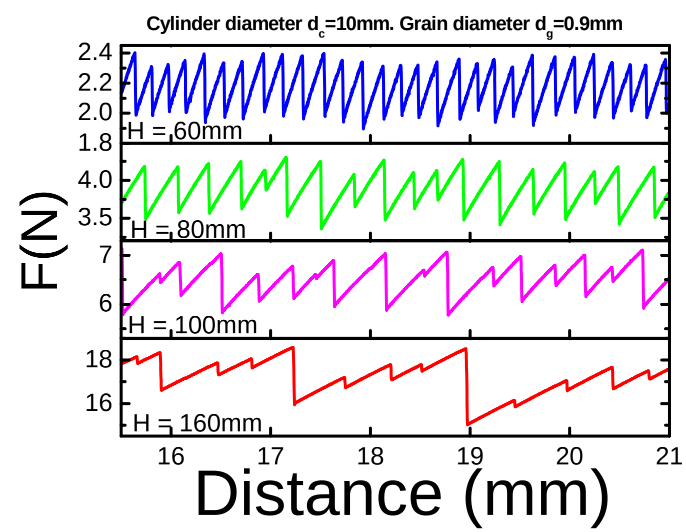
independent of velocity and grain size





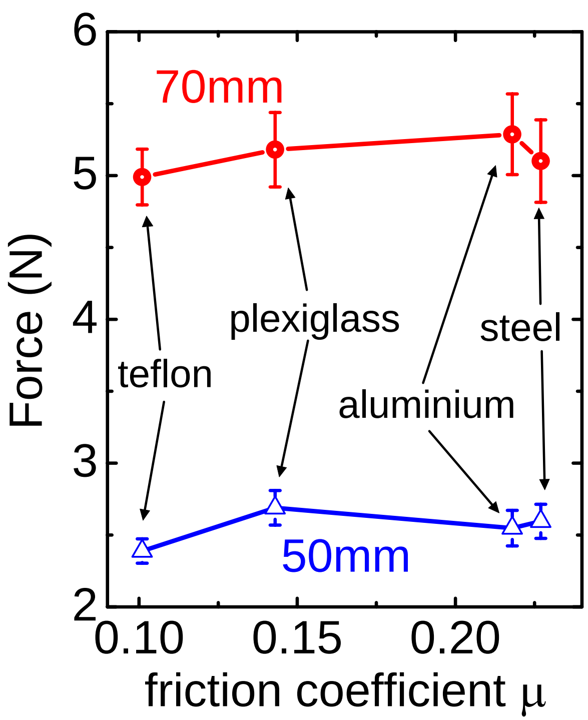


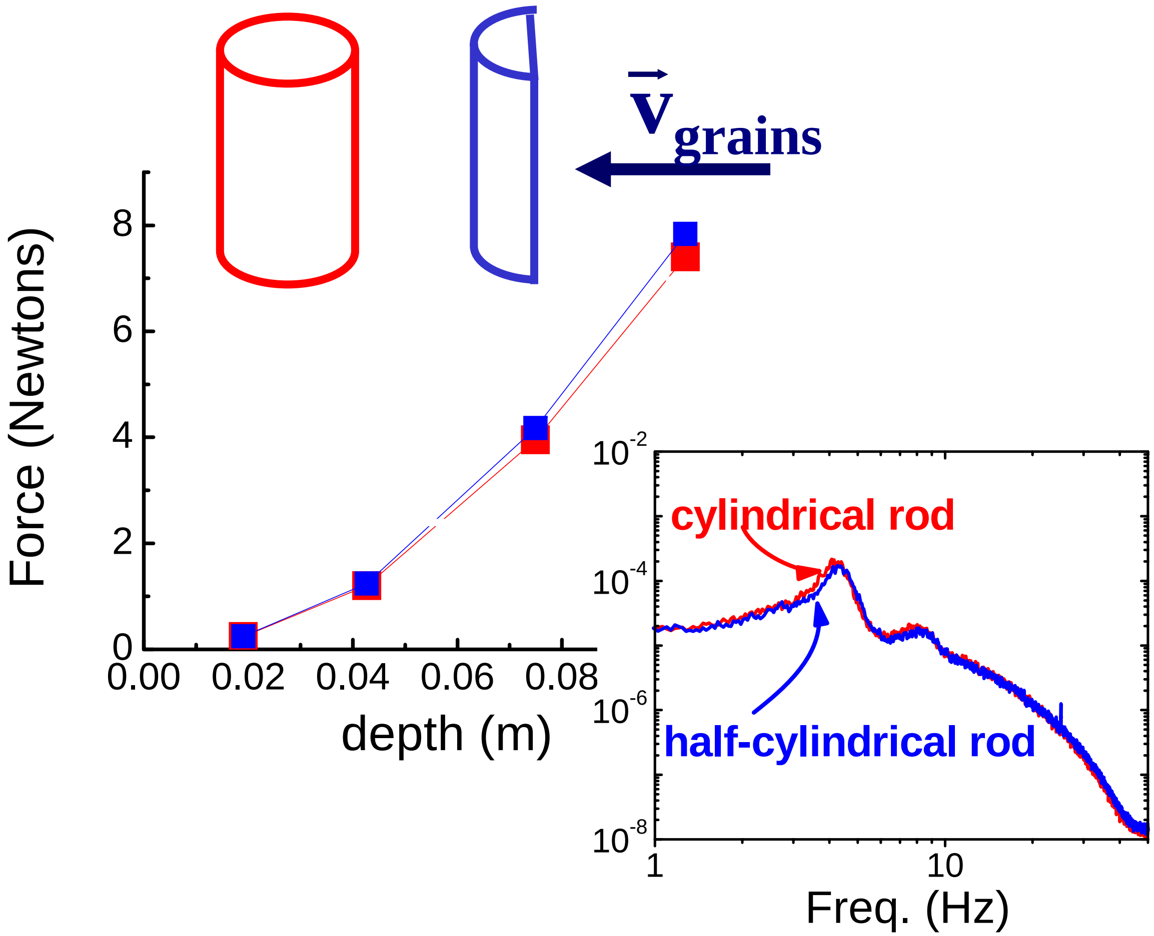




Drag does not depend on cylinder surface

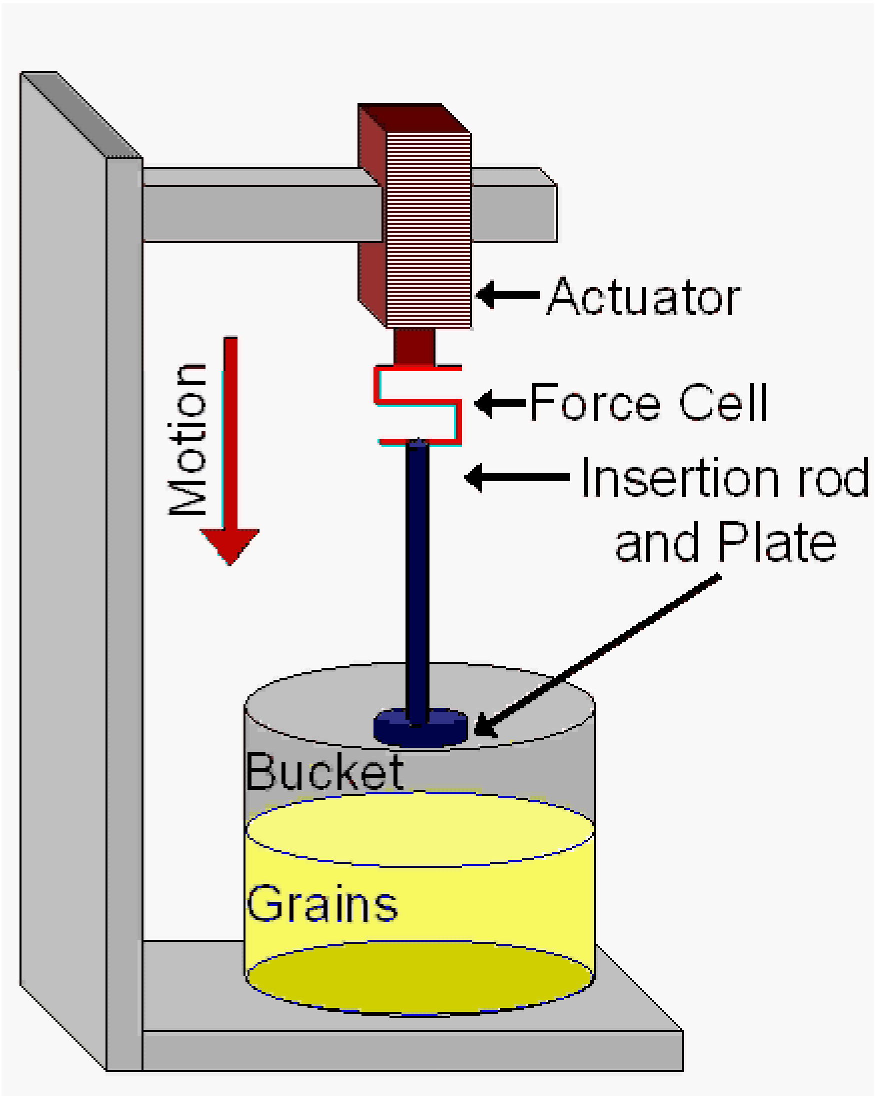
Phys. Rev. E 64, 031307 (2001) and **64**, 061303 (2001)





Drag determined by the force needed to collapse the bulk jammed state

Look at finite size effect with penetrometer



Nature **427**, 503 (2004)

Phys. Rev. E **70**, 041301 (2004)

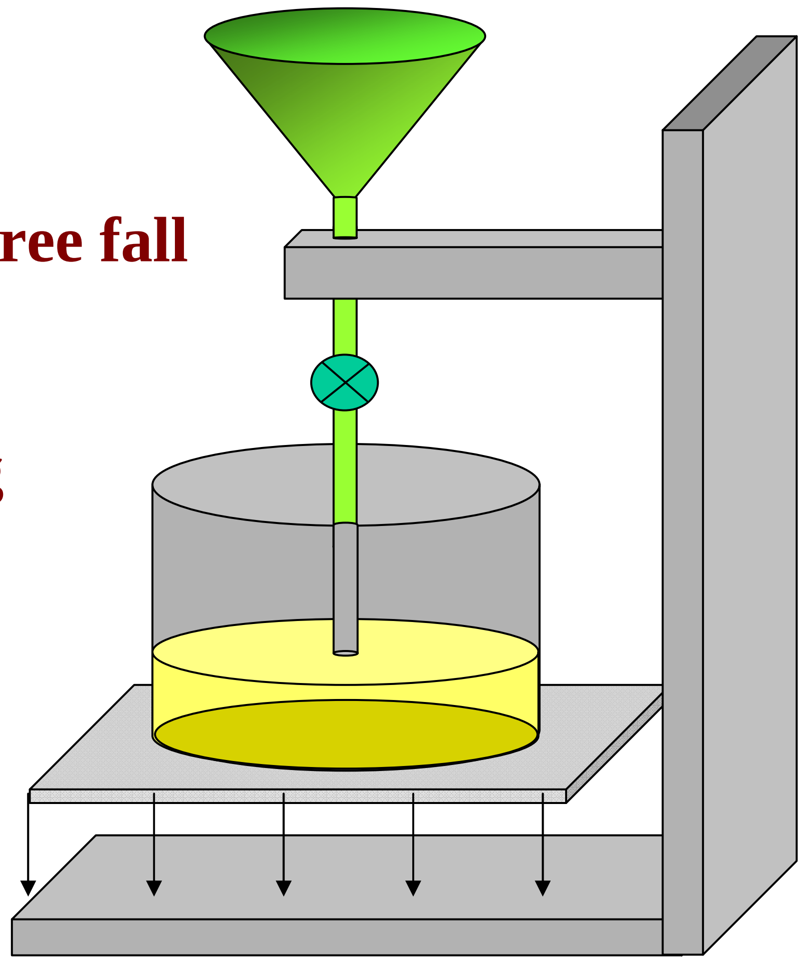
- **Probe effects of boundaries on strength of jammed state by measuring resistance to penetration**

- **Vary:**
  bead diameter
  bucket size
  diameter of plate
  velocity,
  texture of bottom surface

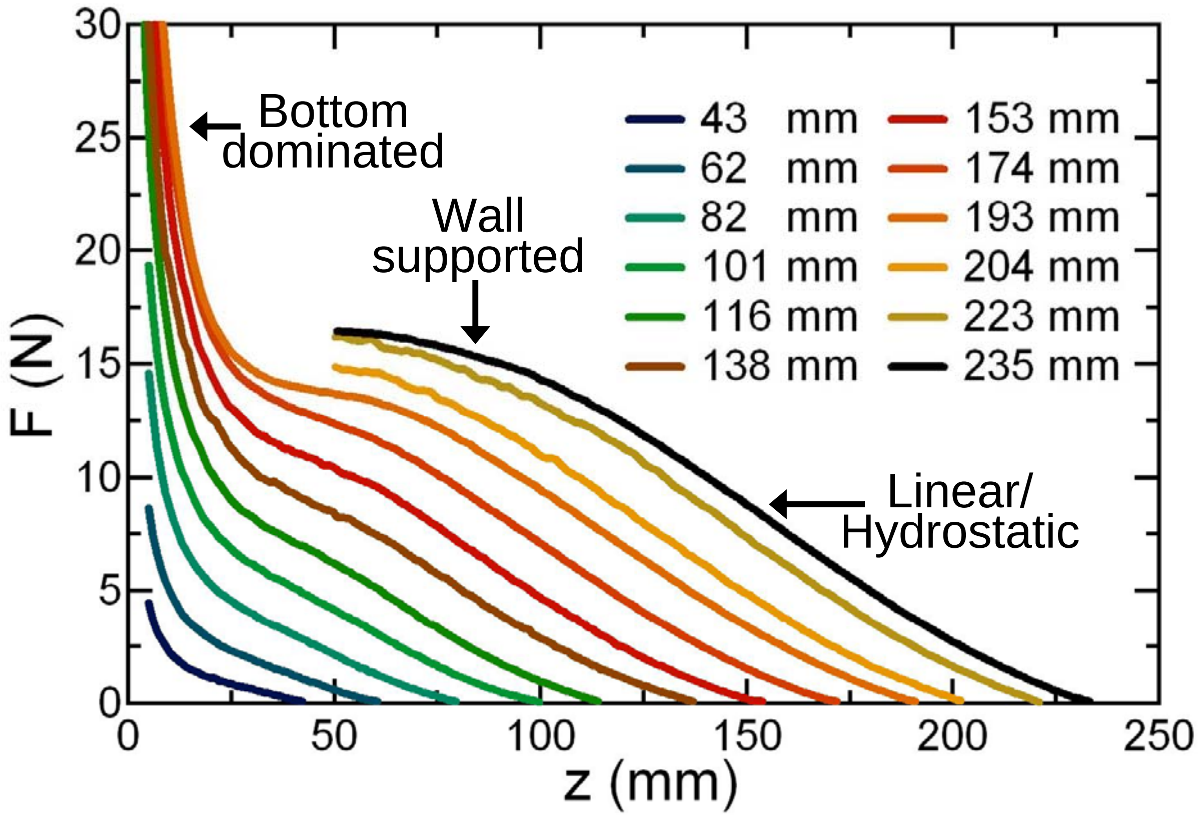
Careful filling procedure required

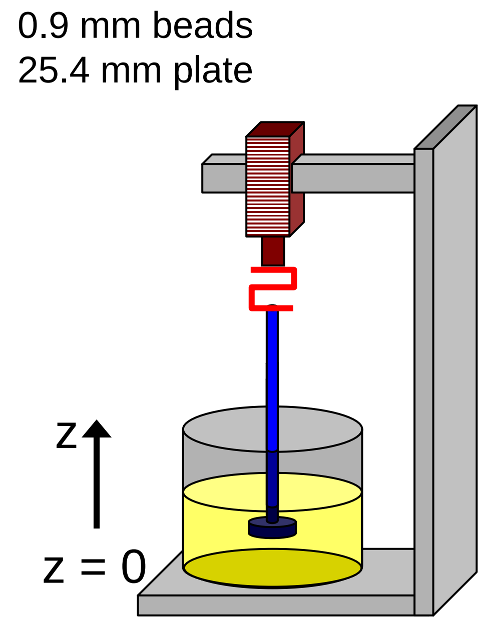
Slowly lower bucket
so grains fill without free fall

Get reproducible and
homogeneous packing
fraction ~ 59%



Height dependence of penetration force

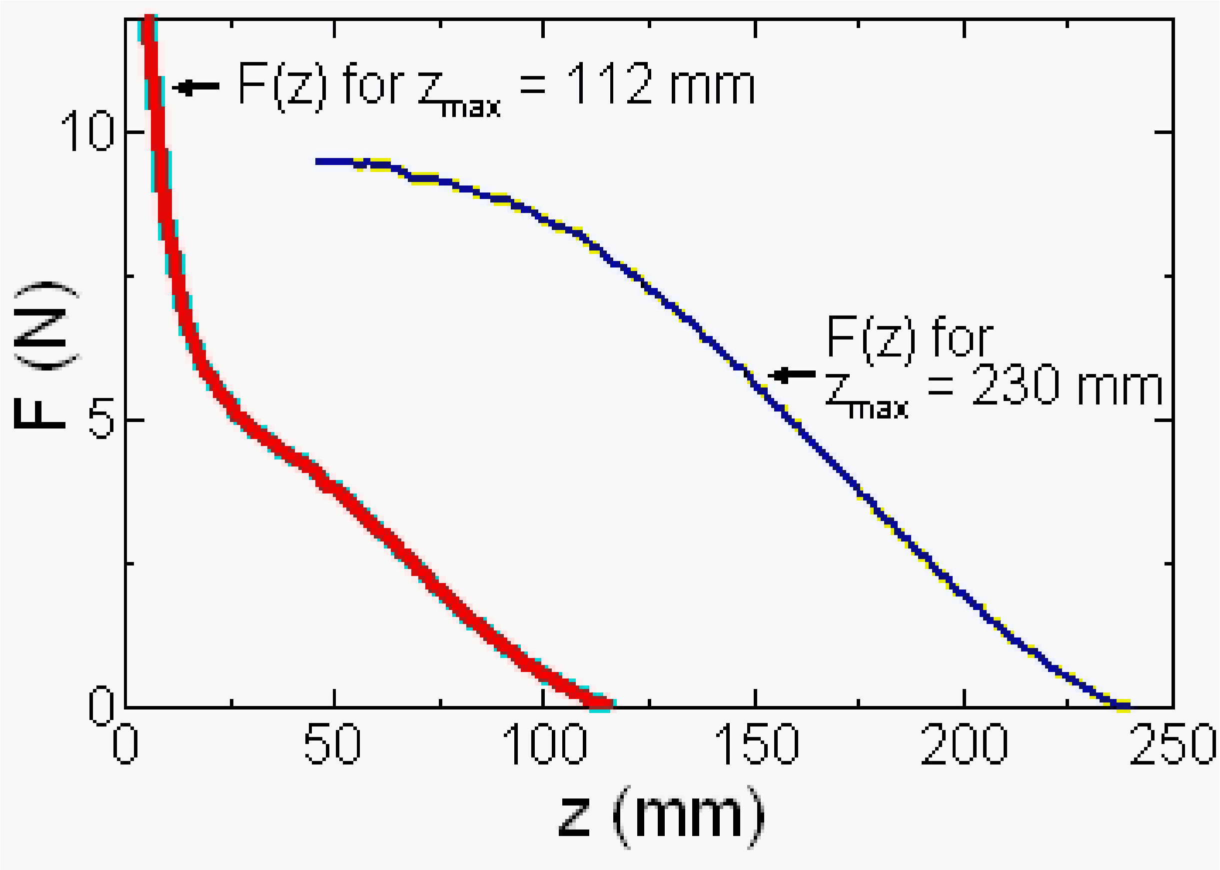




- **Initial linear force distribution with subsequent rollover**

  Vanel and Clément Eur. Phys. J. B (1999)
- **Rapid increase as penetrometer approaches bottom**
- **Work in a regime of no bucket size or velocity dependence**

Obtain the effect of the bottom by subtracting off data taken with deeply filled bucket



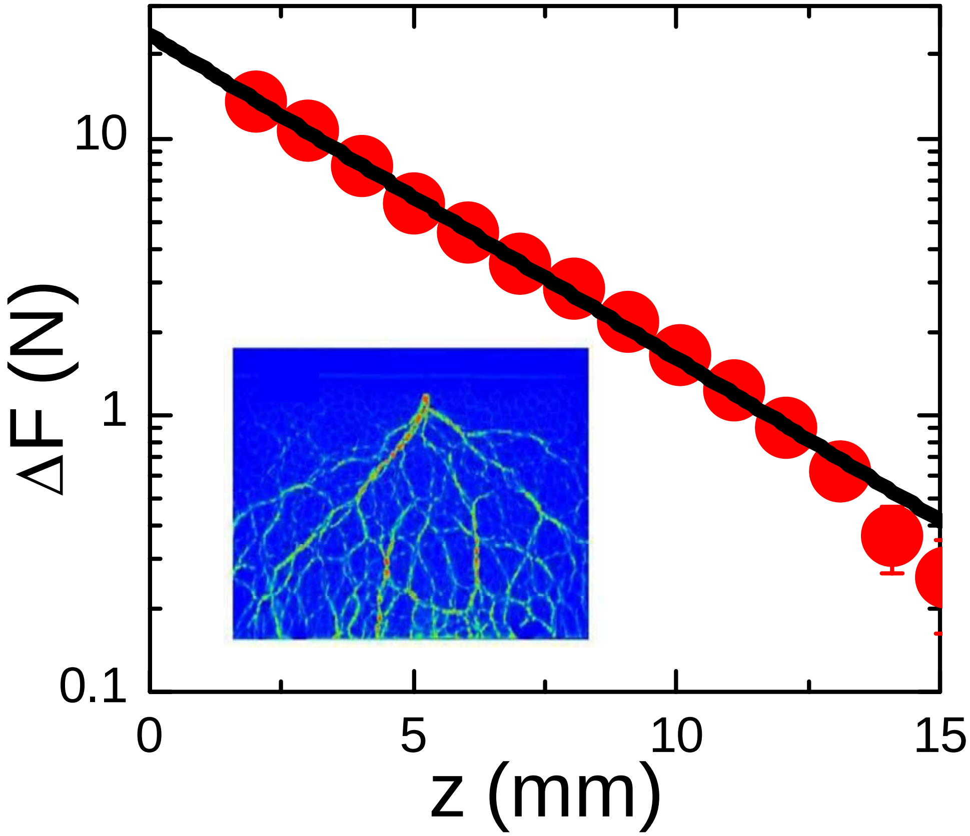
Obtain:

"Bulk" force as a function of depth, F_{bulk}

Measure of stress at bucket bottom, F_0

0.9 mm beads
25.4 mm plate

How close to the bottom boundary does the penetration force reflect that a bottom exists?



$\Delta F \propto e^{-z/\lambda}$

For all grain sizes and real sand

Implies the existence of an intrinsic length scale

Length scale determined by….

Pressure? Plate Diameter? Grain Diameter? Something else?

Grain diameter appears not to affect length scale

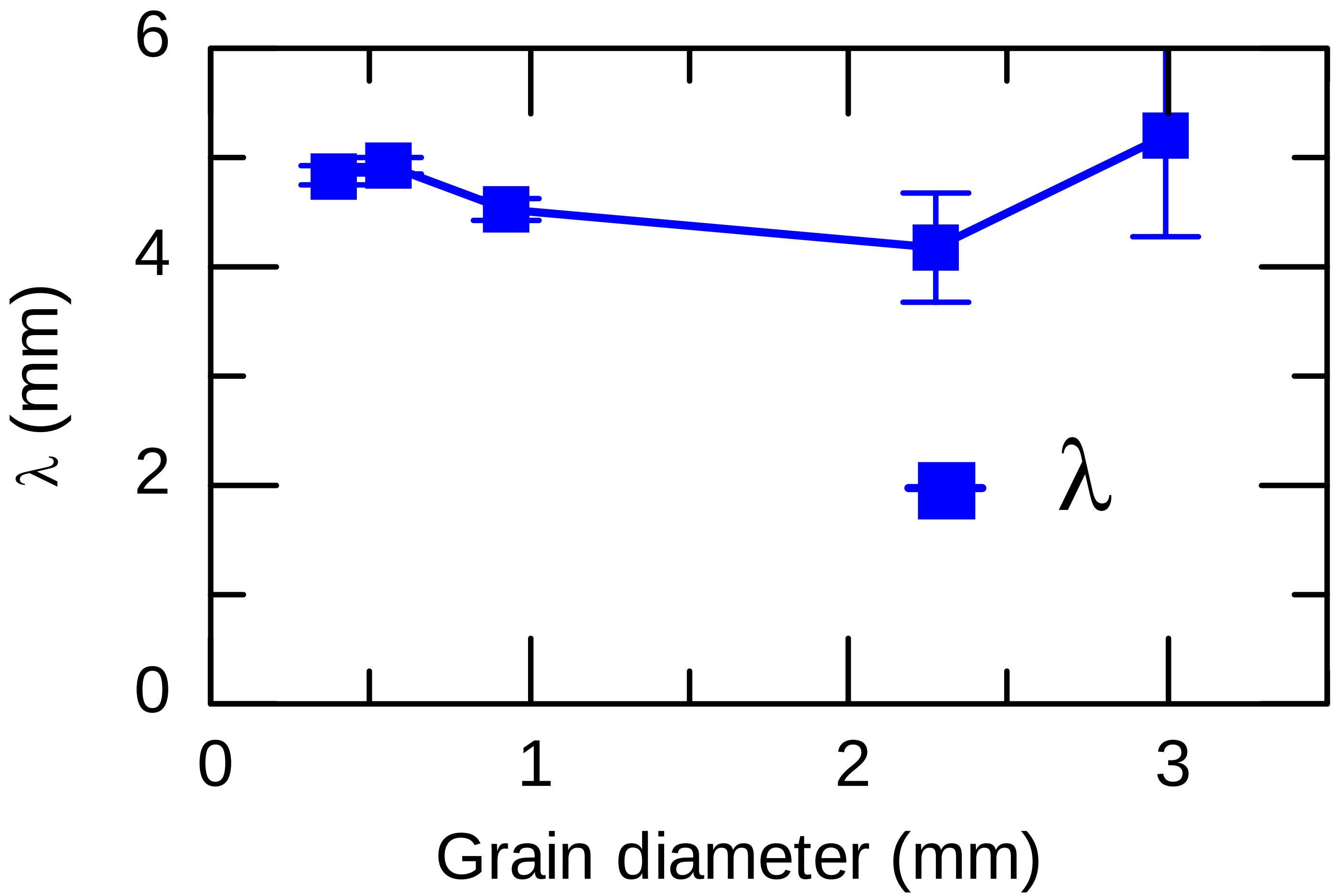
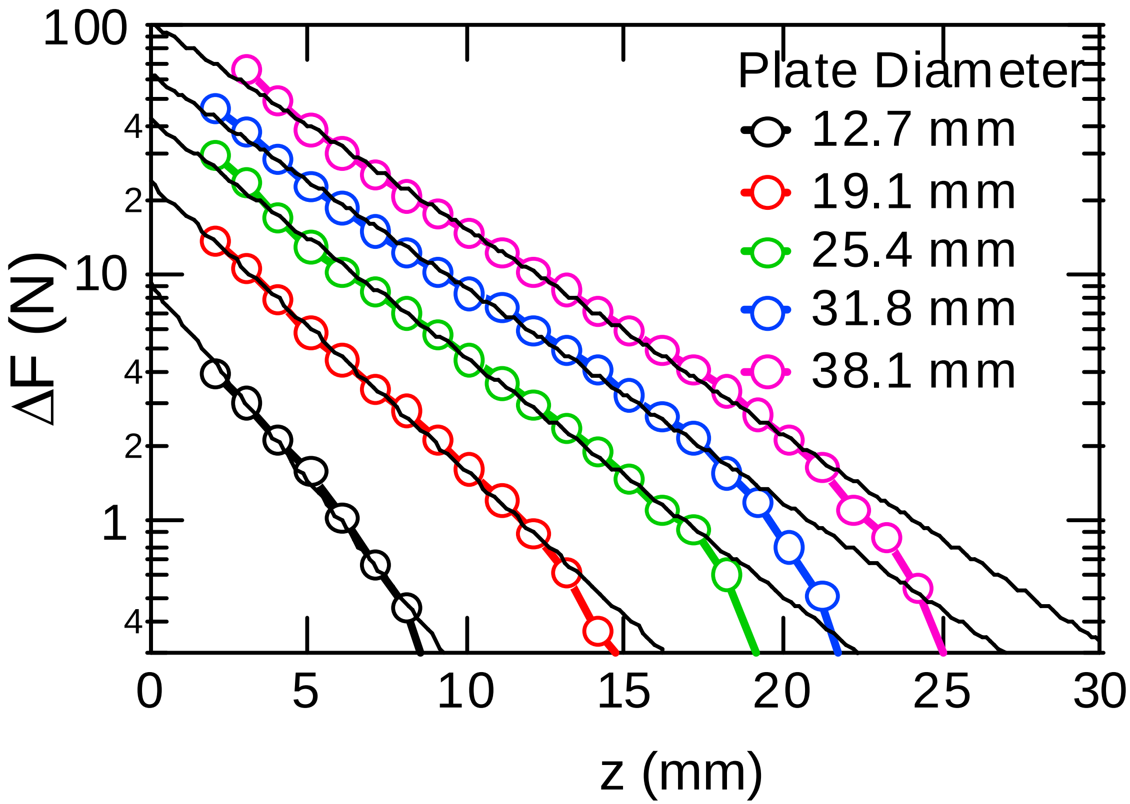


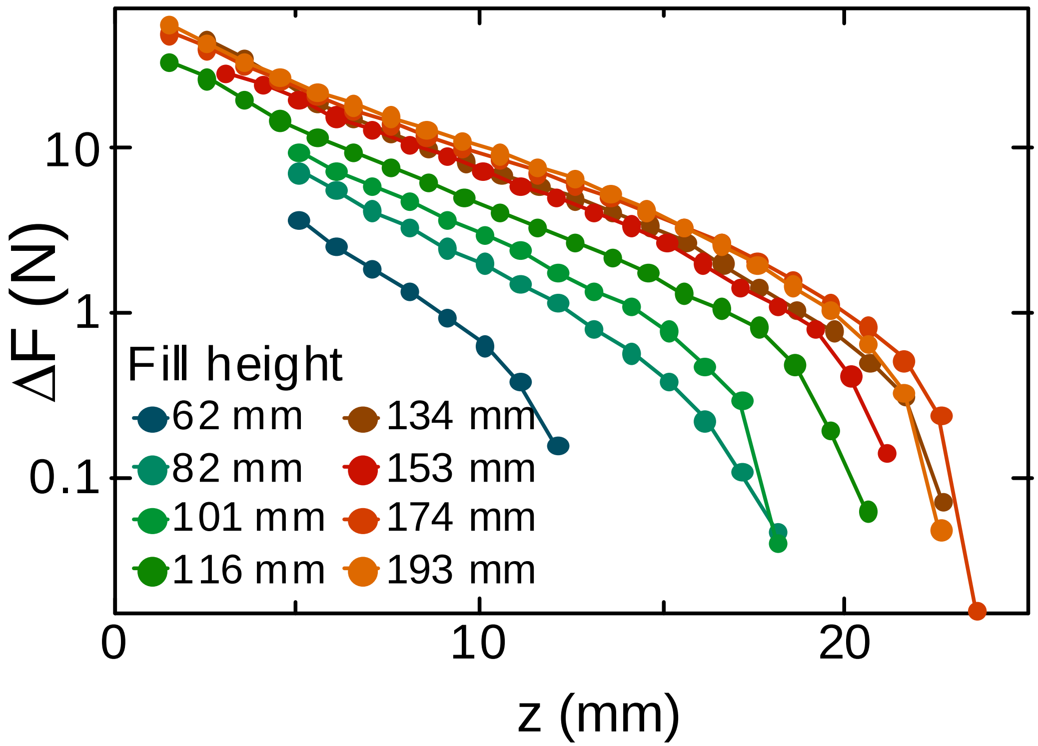
Plate diameter dependence of length scale



$\Delta F \propto e^{-z/\lambda}$

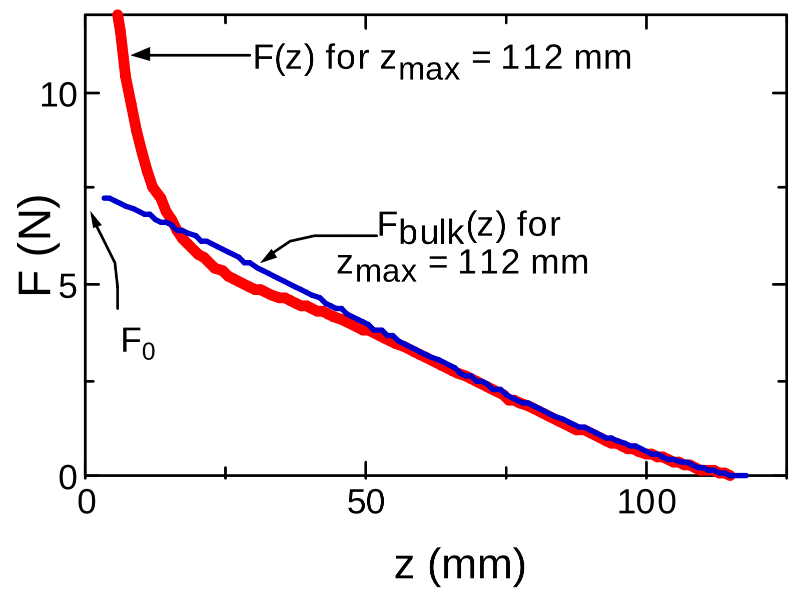
- **λ increases with penetrating plate size**
- **Larger penetrating object detects bottom earlier**

Fill height dependence of length scale



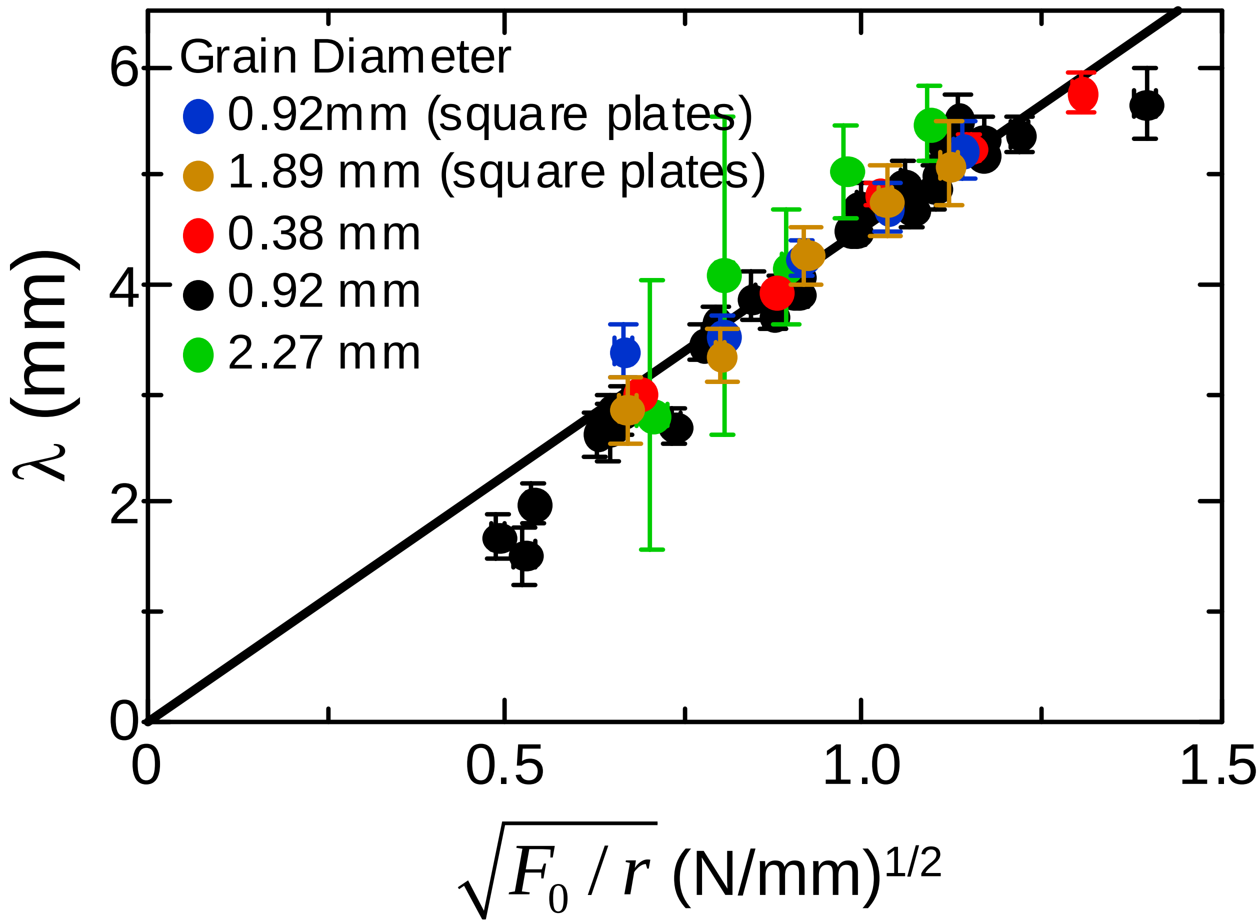
Fill height affects λ through ambient stress

Get measure of stress through $F_0 = F_{bulk}(z = 0)$



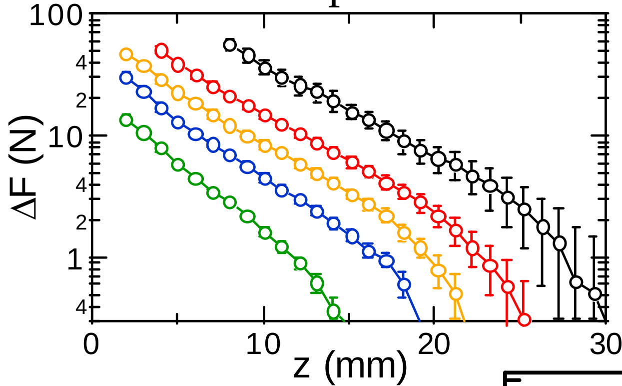
Dependence of length scale on system parameters

$$\lambda \propto \sqrt{F_0 / r}$$



Scaling of length scale

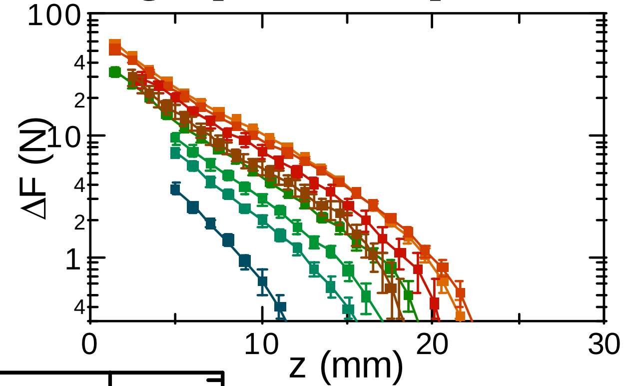
Plate size dependence

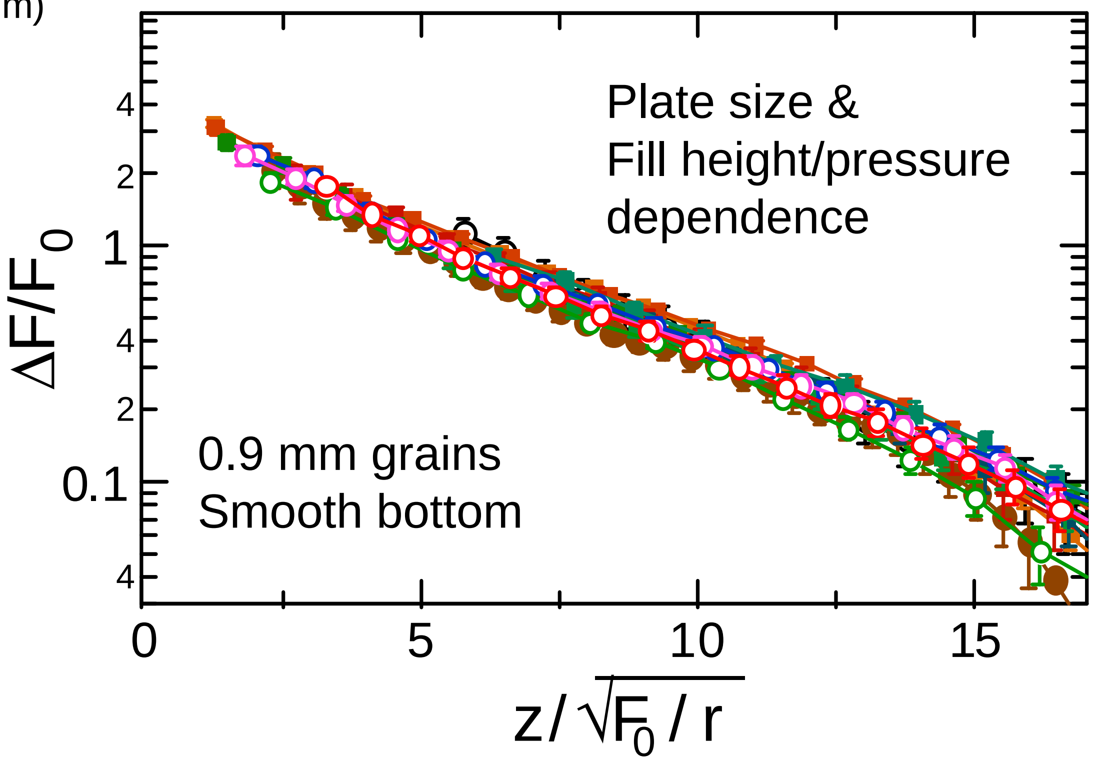


$$\Delta F \Rightarrow \Delta F / F_0$$

$$z \Rightarrow z / \sqrt{F_0 / r}$$

Fill height/pressure dependence





Where does dependence of length scale come from?

$$\lambda \propto \sqrt{F_0 / r} \ ???$$

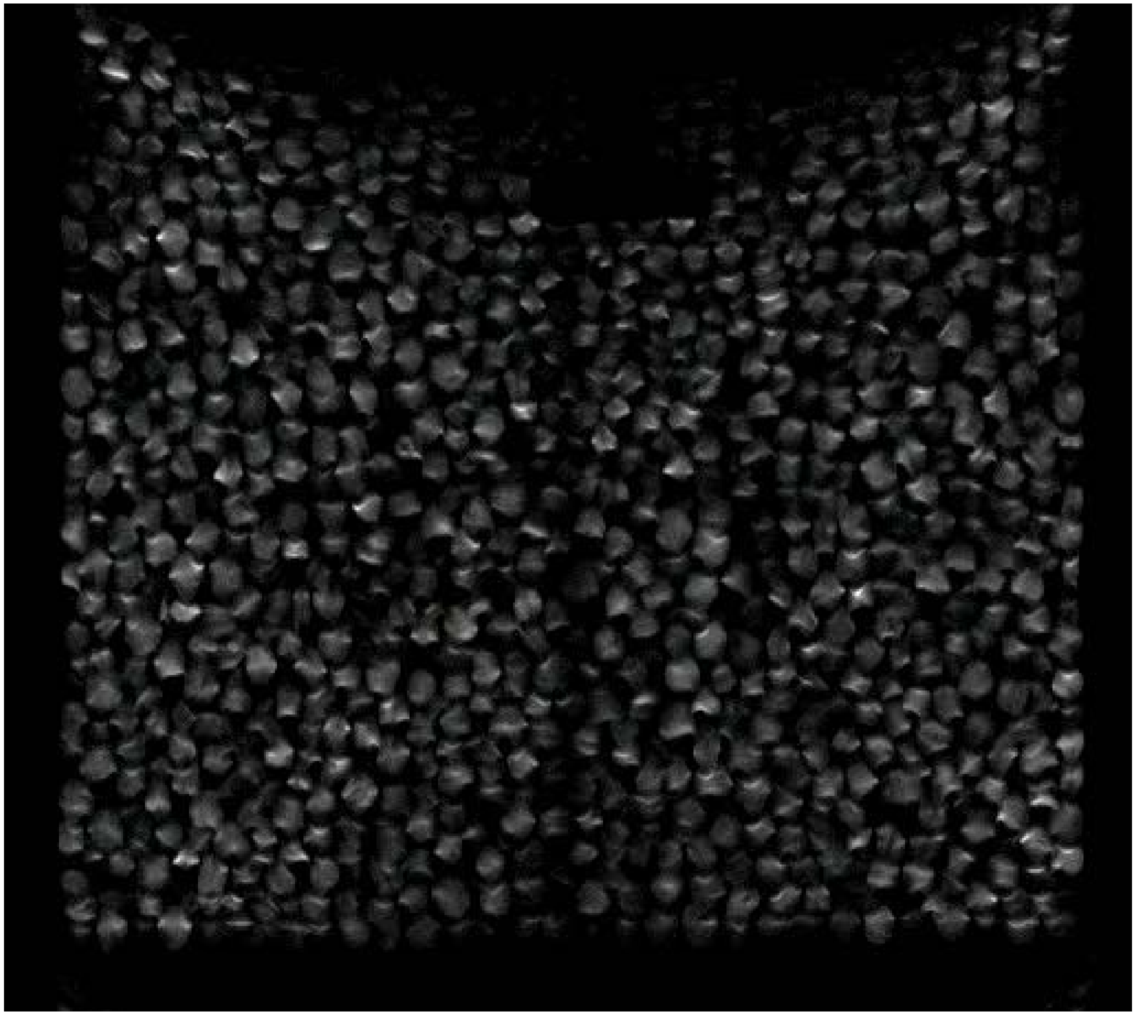
If we take $F_0 = P_{eff}(\pi r^2)$ where P_{eff} is an effective granular pressure we get:

$$\lambda \propto \sqrt{P_{eff}\, r} \ ???$$

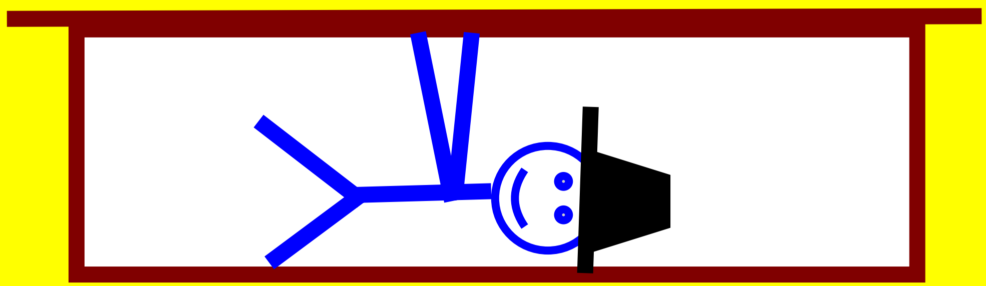
Since λ is the effective size of the jammed state caused by penetration, it would be interesting to understand its origins…theory needed!!!

What does length scale mean?

Image inside 3 dimensional bead pack: MRI on mustard seeds: <u>preliminary data only</u> (Igor Veretennikov, Notre Dame)



What's next: the effect of a free boundary



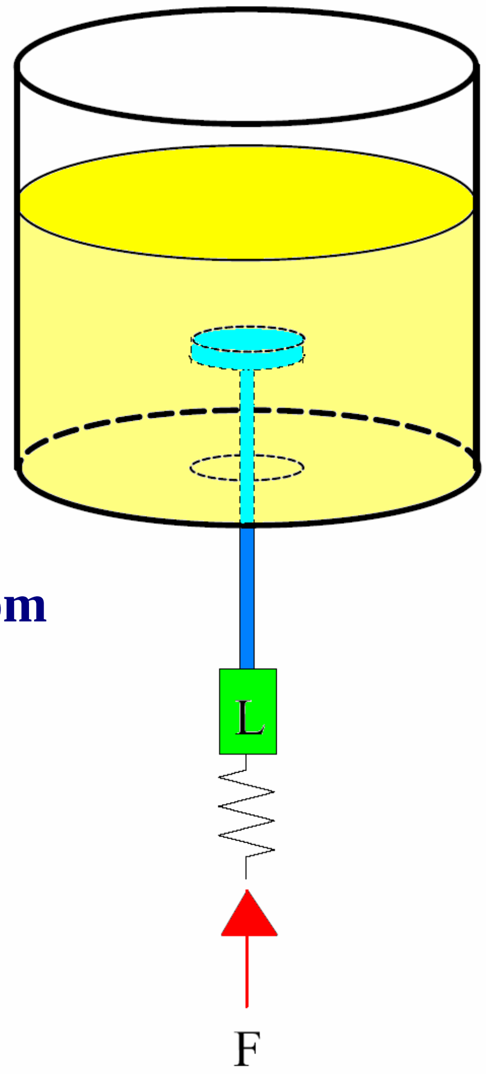
How much force is needed to lift the coffin lid?

Of great interest to "taphephobics"!

New apparatus (preliminary data): <u>penetration from below</u>

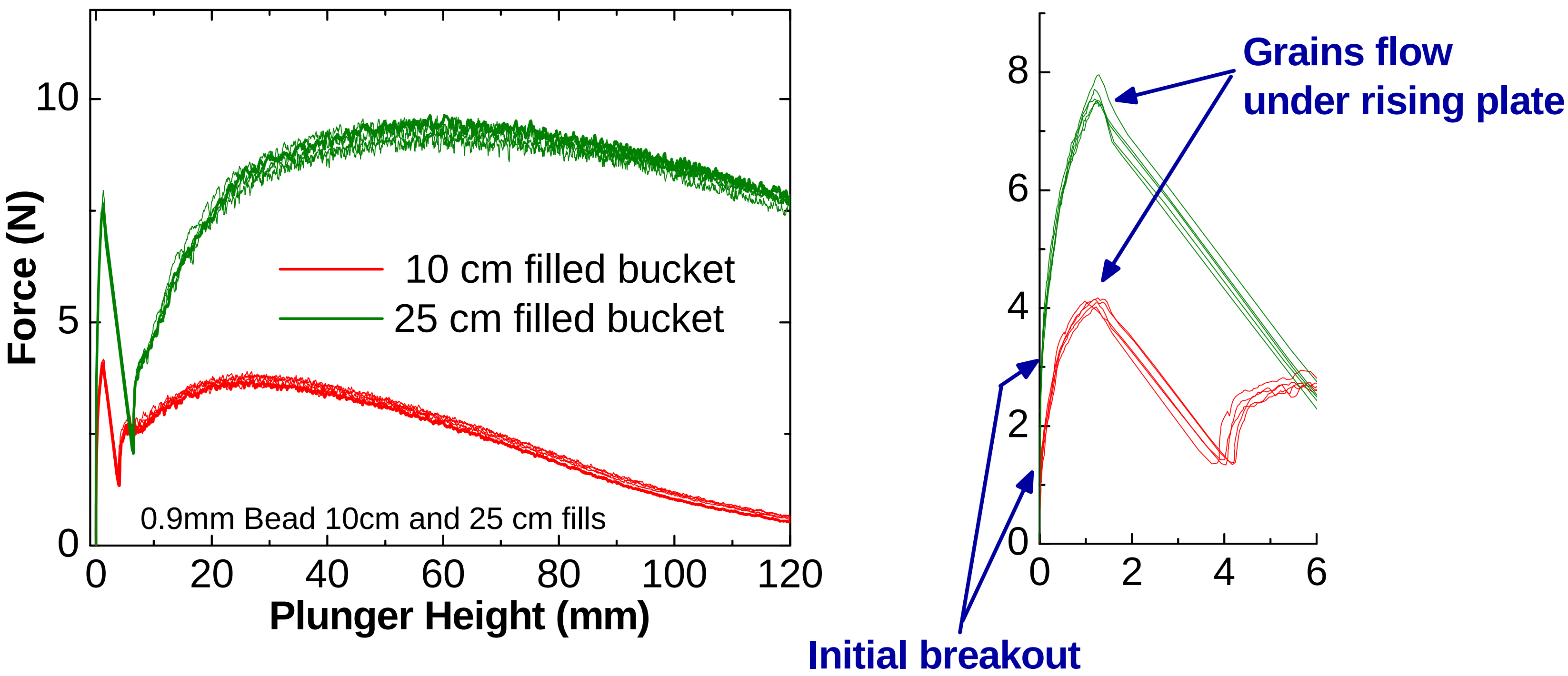
What is initial force needed to start motion?

How does free boundary affect resistance?



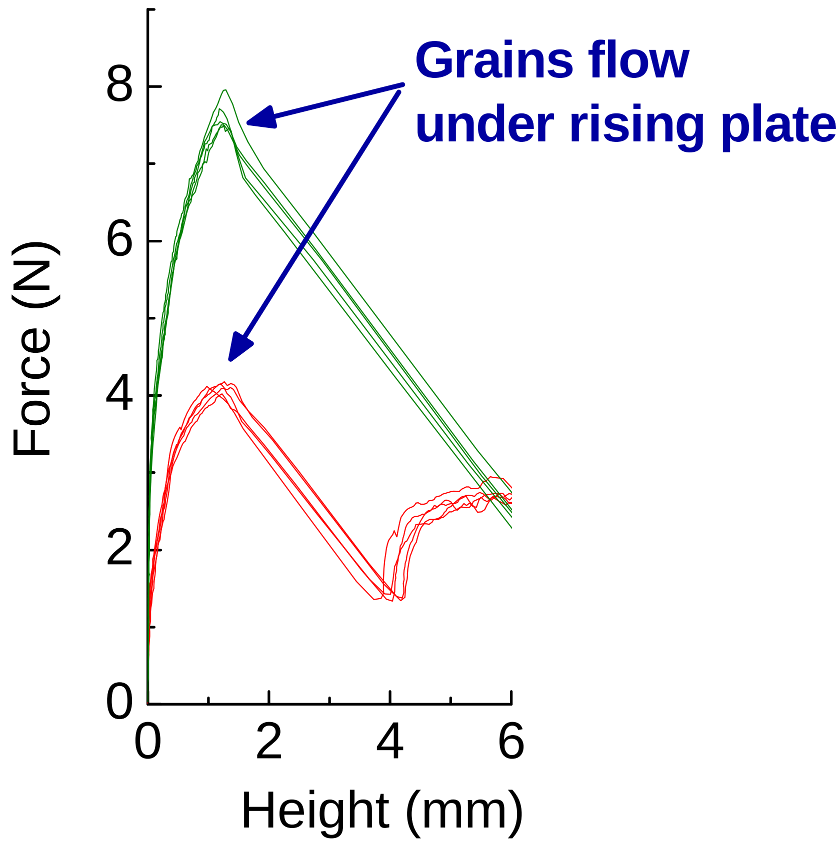
- **Minimal friction through bearing**
- **Careful and reproducible filling**
- **Plate (d_{plate}>> d_{grain}) which starts flush with the bottom**
- **Controlled elasticity through spring**

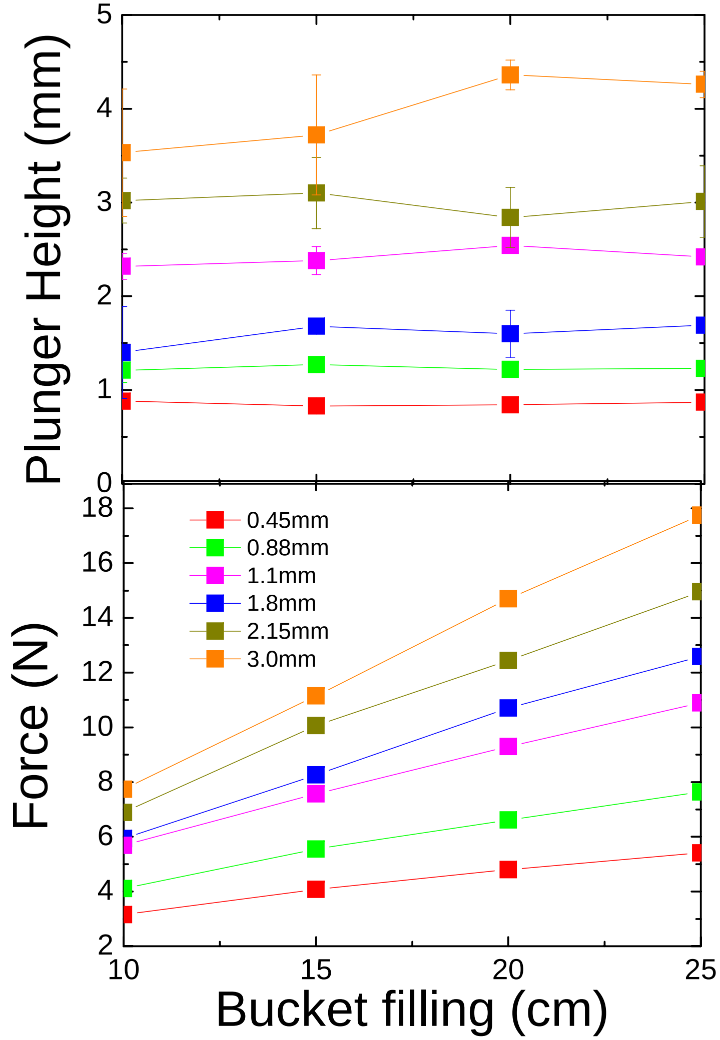
Raw Data: Force vs. Height



Rich set of phenomena to investigate….

Point where grains flow under the plate depends on grains size





Makes sense, since need a crack at least one diameter wide!

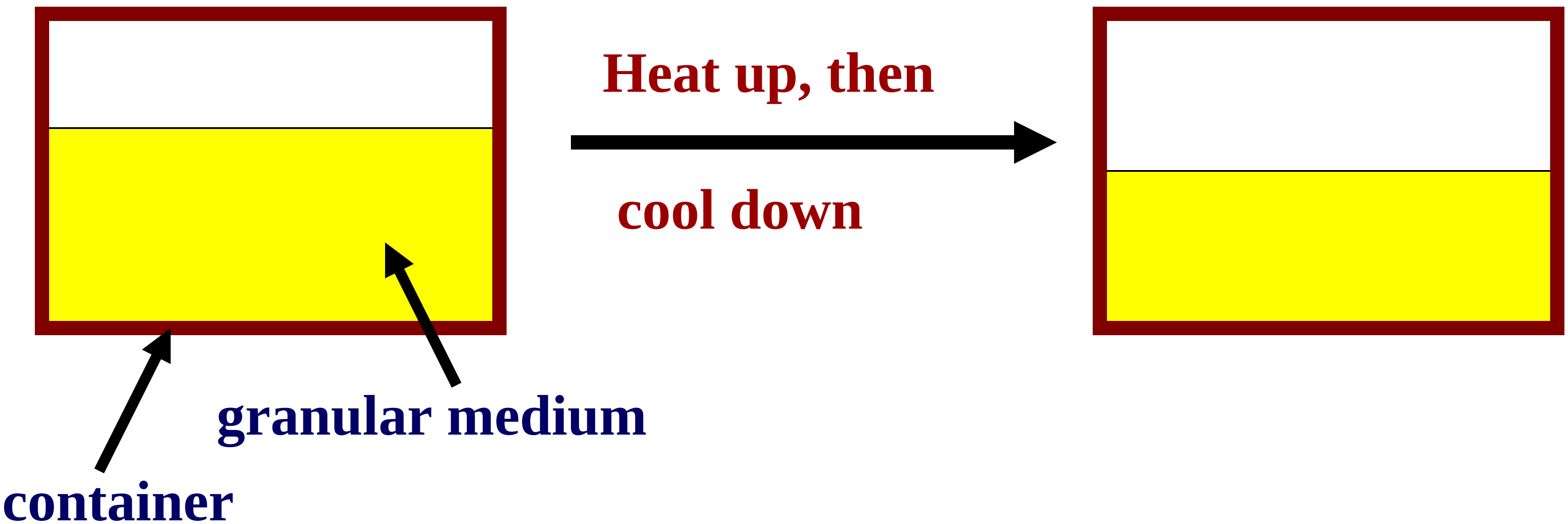
Part 2: Temperature effects on granular materials

In studies of granular media, we usually only consider temperature as a statistical measure of grain kinetic energy

But grains are made of materials which change with changing temperature….

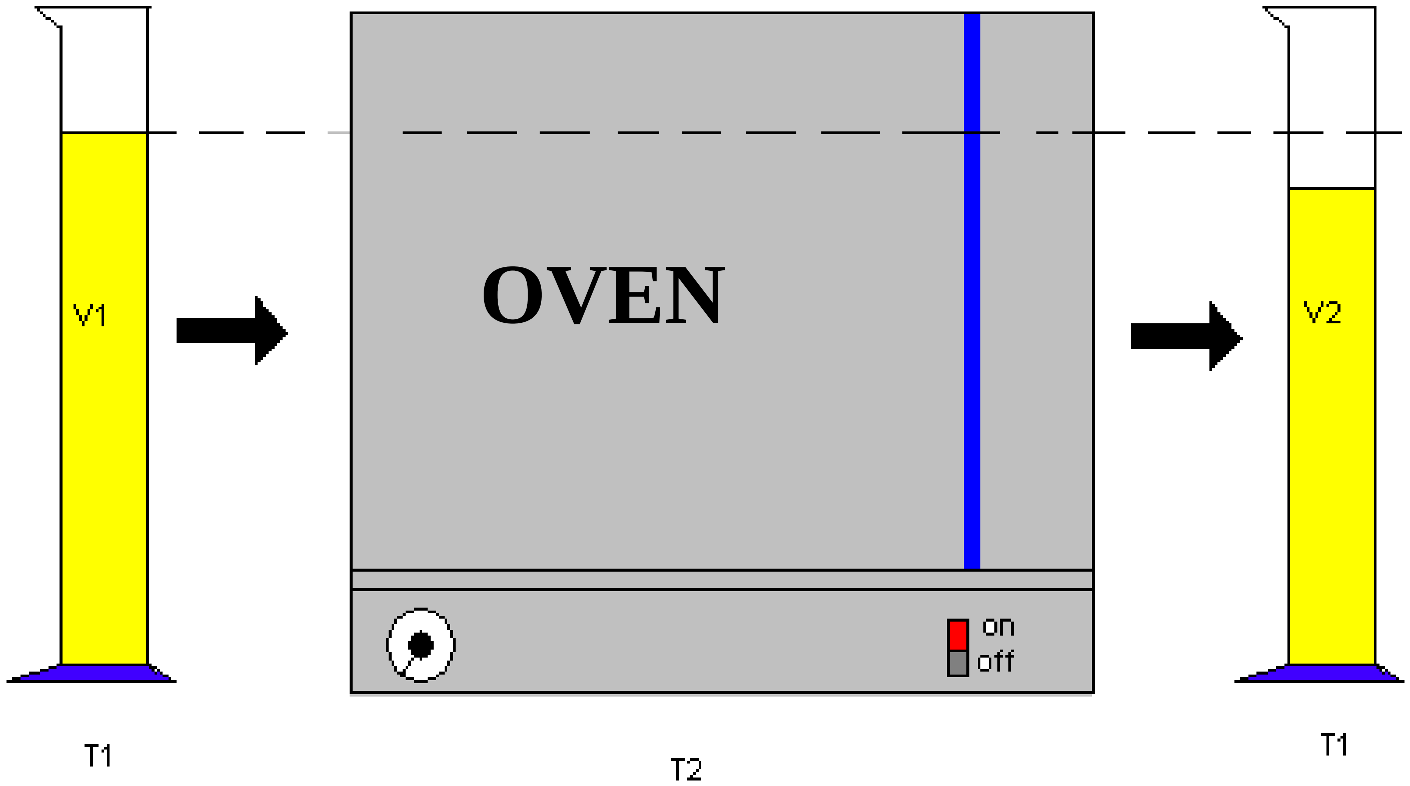
Thermal cycling can effect granular samples….

Difference in thermal contraction between container and medium will cause the grains to settle each time there is a thermal cycle



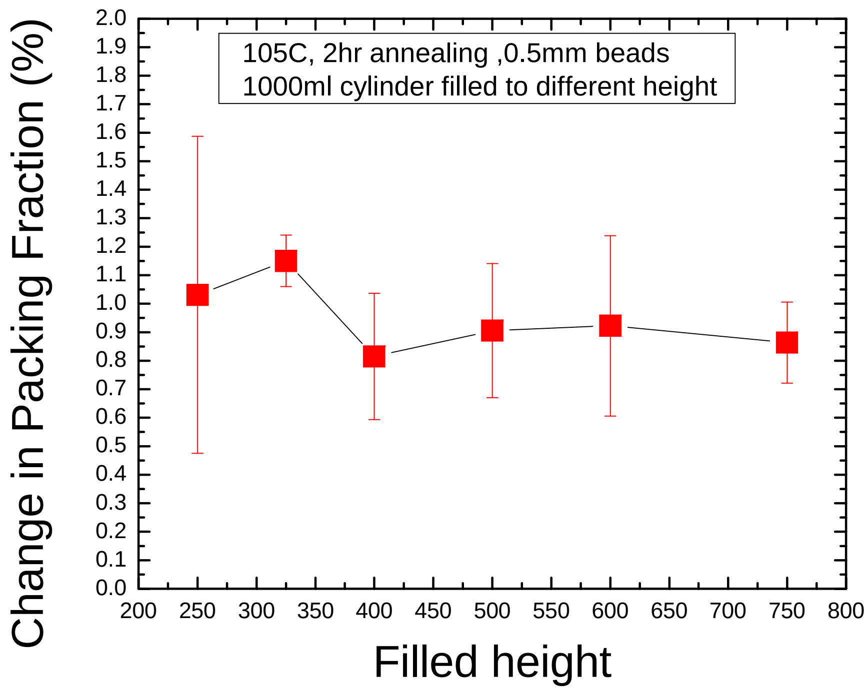
Change in packing changes granular properties, can have more drastic effects…

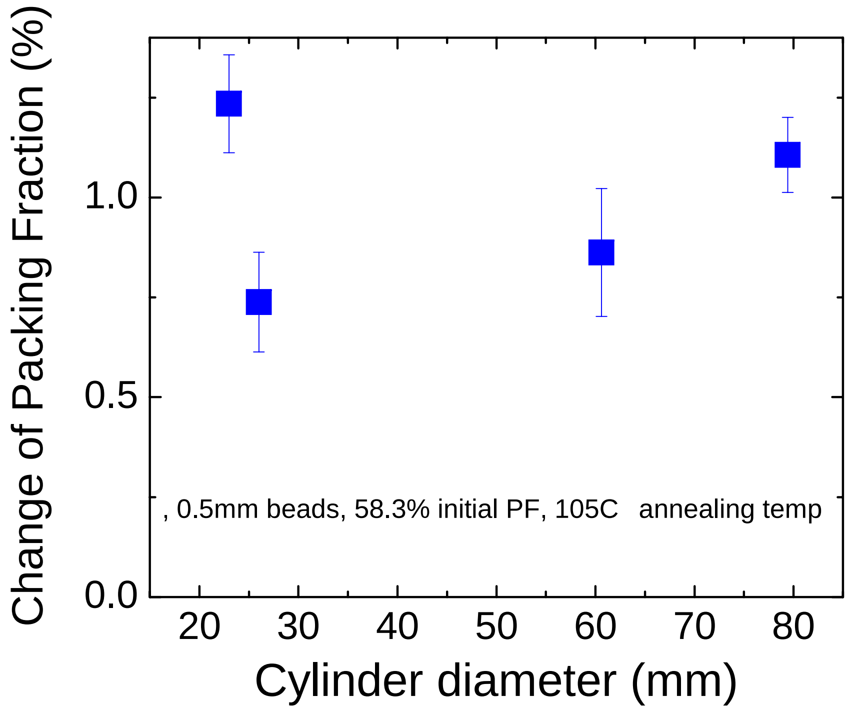
Simple thermal cycling experiment



Glass beads and plastic container

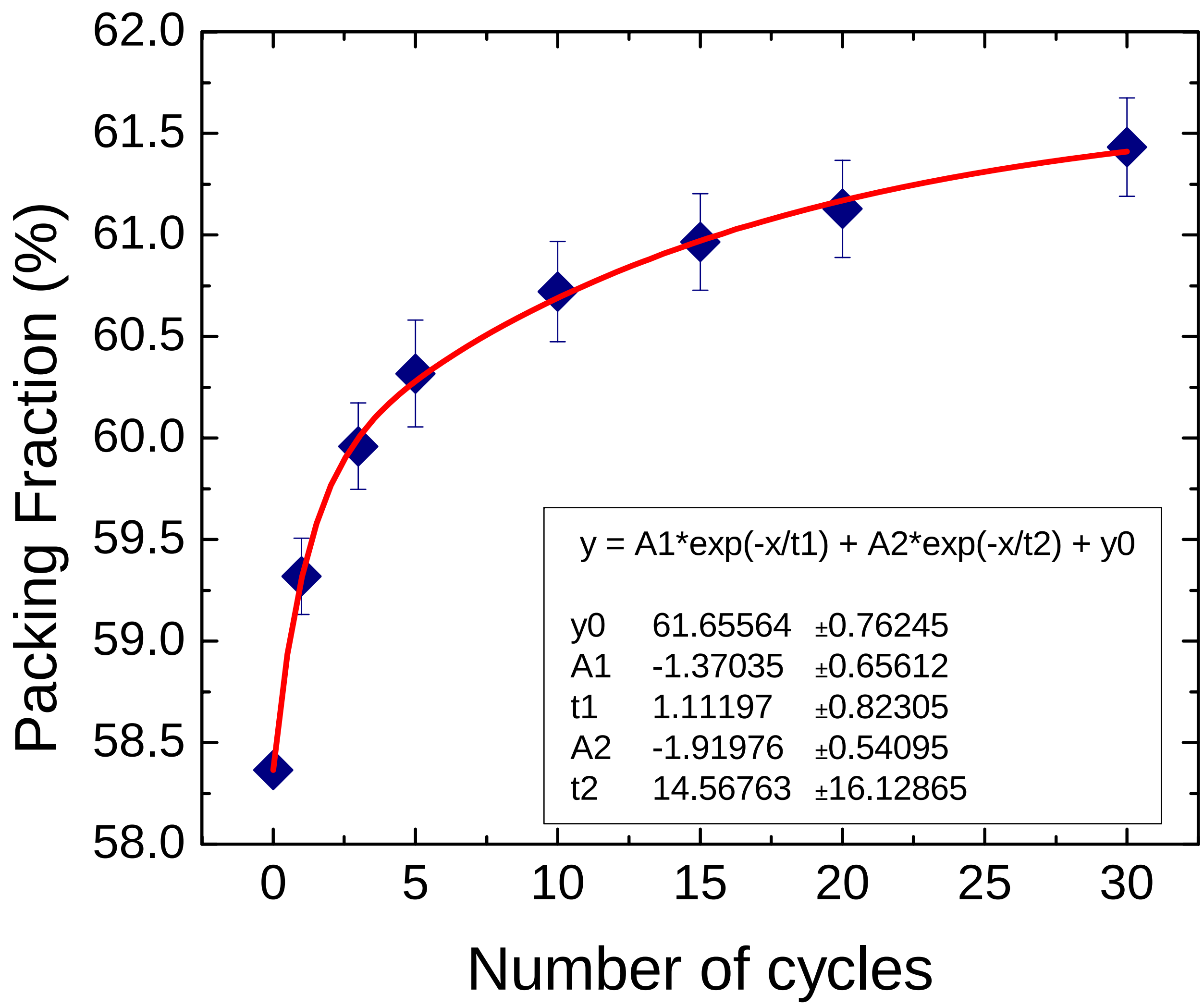
Thermal cycling results do not depend strongly on filling or cylinder diameter (preliminary data)





Multiple cycles result in increased packing

Can be fit well by double exponential



Conclusions/Questions

Interesting physics in local perturbations

- **What defines the length scale for the jammed state?**
- **What are the microscopic dynamics of the collapse process?**

Temperature can be an important parameter in granular media

- **New way to study packing**
- **What will happen as we change thermal expansion coefficients/initial packing/etc.?**