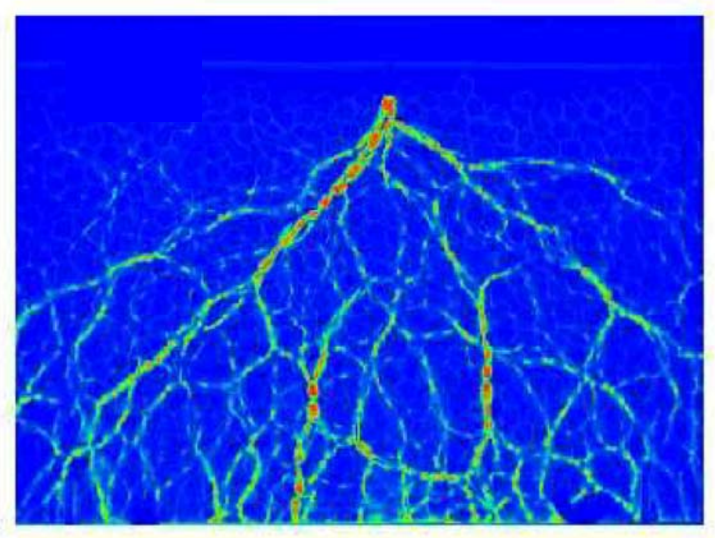
Drag and Local Jamming

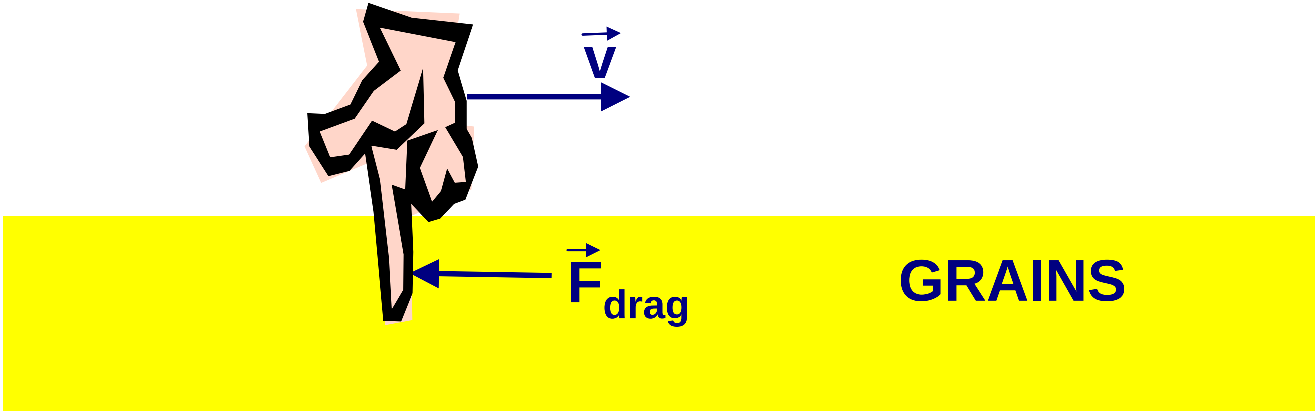
When a stress is applied to a dense collection of grains, the grains form a rigid "jammed" structure to resist the stress

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

How strong are jammed states? How do they fail?

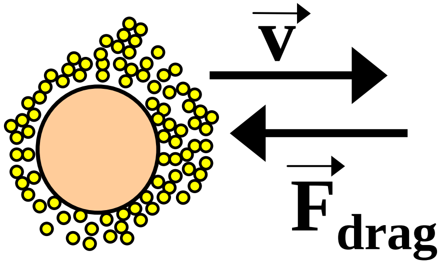


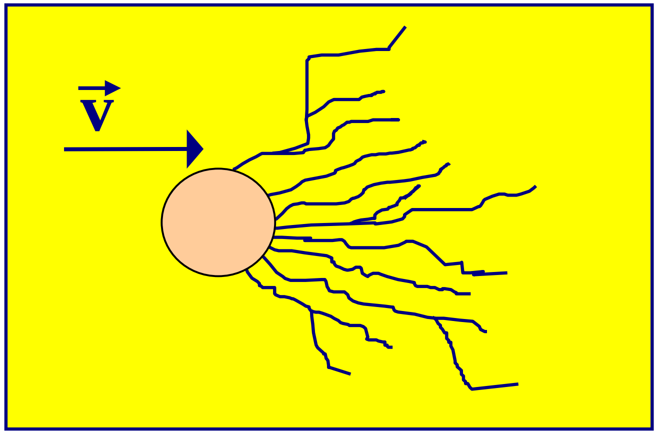
Local Jamming is Manifested in Drag Force



Drag is force required to reorganize grains to allow motion

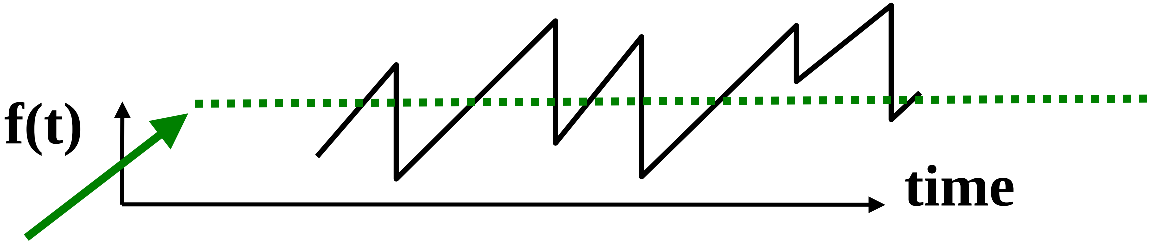
Force is transmitted through inhomogeneous force chains of jammed grains





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:

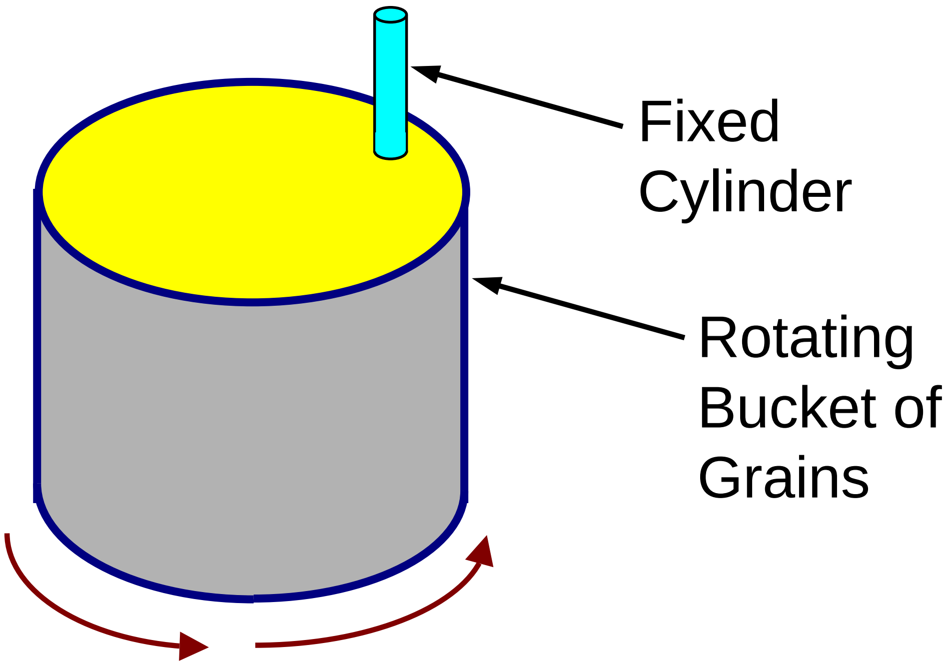
$F_{drag} = \eta g \rho d_c H^2$ **for vertical cylinder**

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

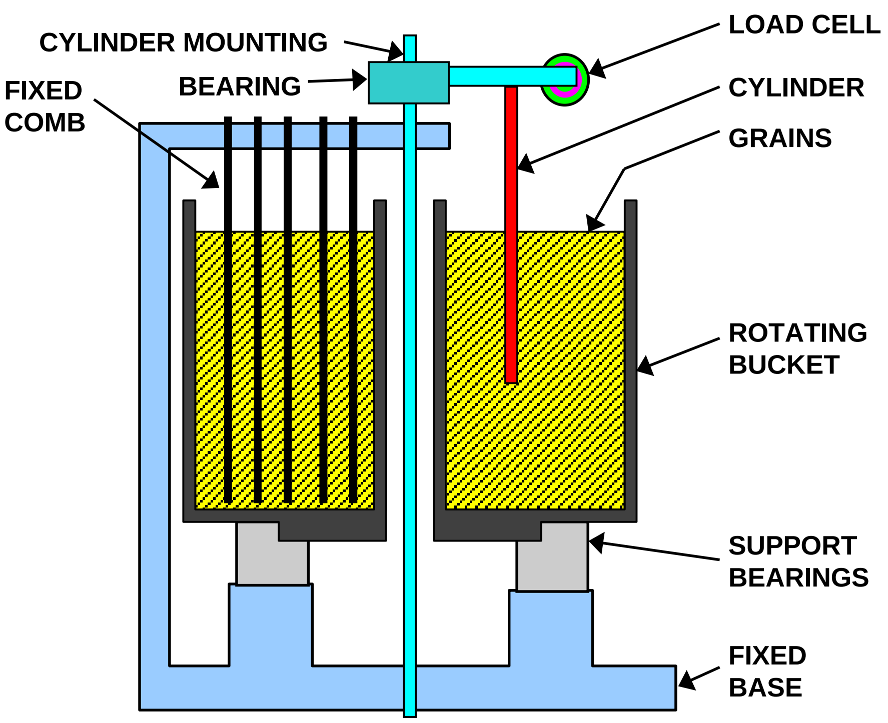
Rotating Bucket of Glass Spheres, Cylinder Dipped In

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

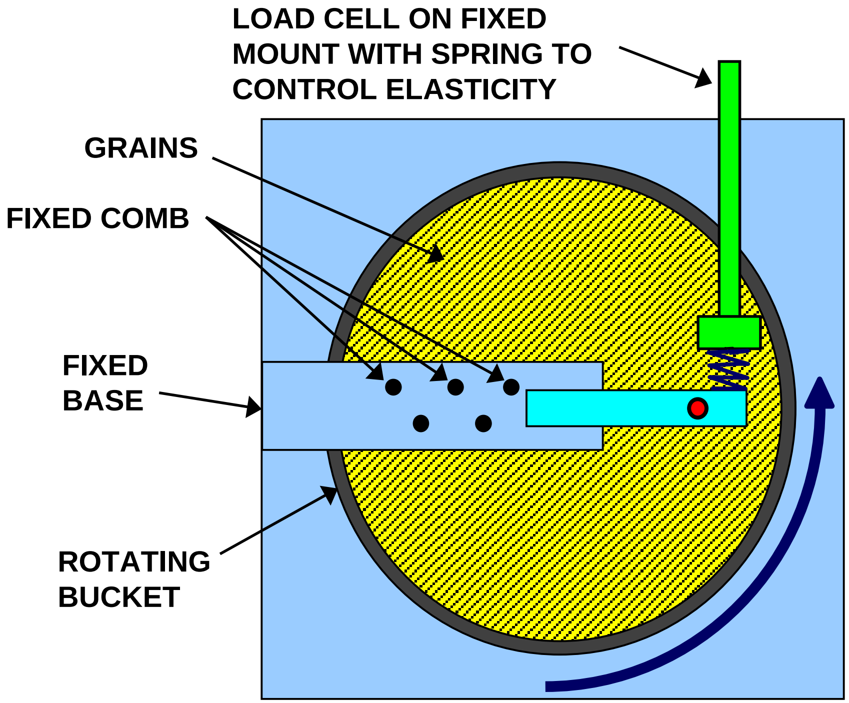


Vary grain size, velocity, depth, cylinder diameter

Details of Drag Force Apparatus



Cross-Sectional View



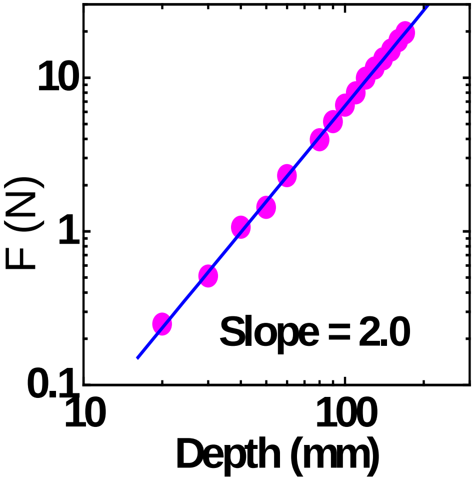
Top View

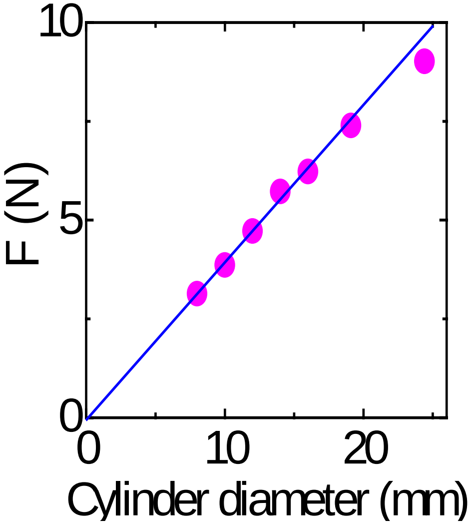
Average Drag Properties

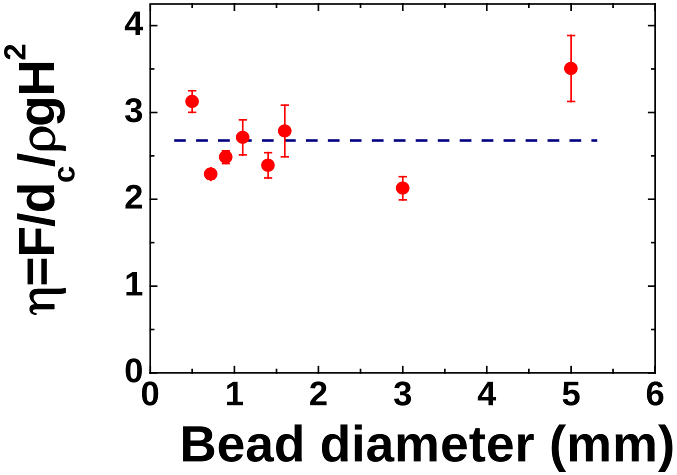
<u>Phys. Rev. Lett.</u> **82,** 205 (1999)

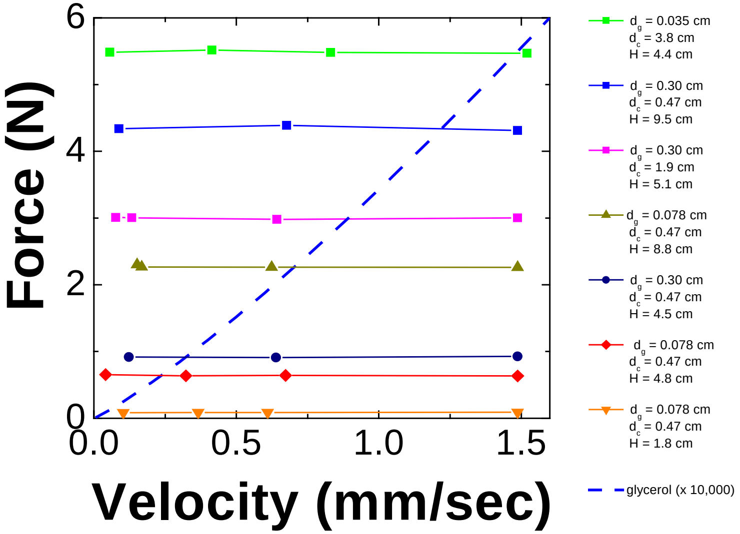
$F_{drag} = \eta g \rho d_c H^2$ in agreement with theoretical expectations

independent of velocity and grain size



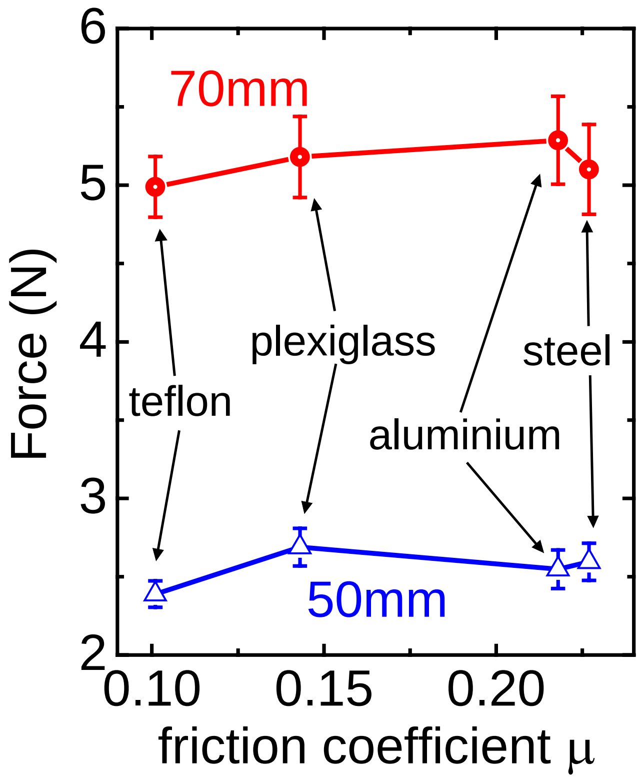


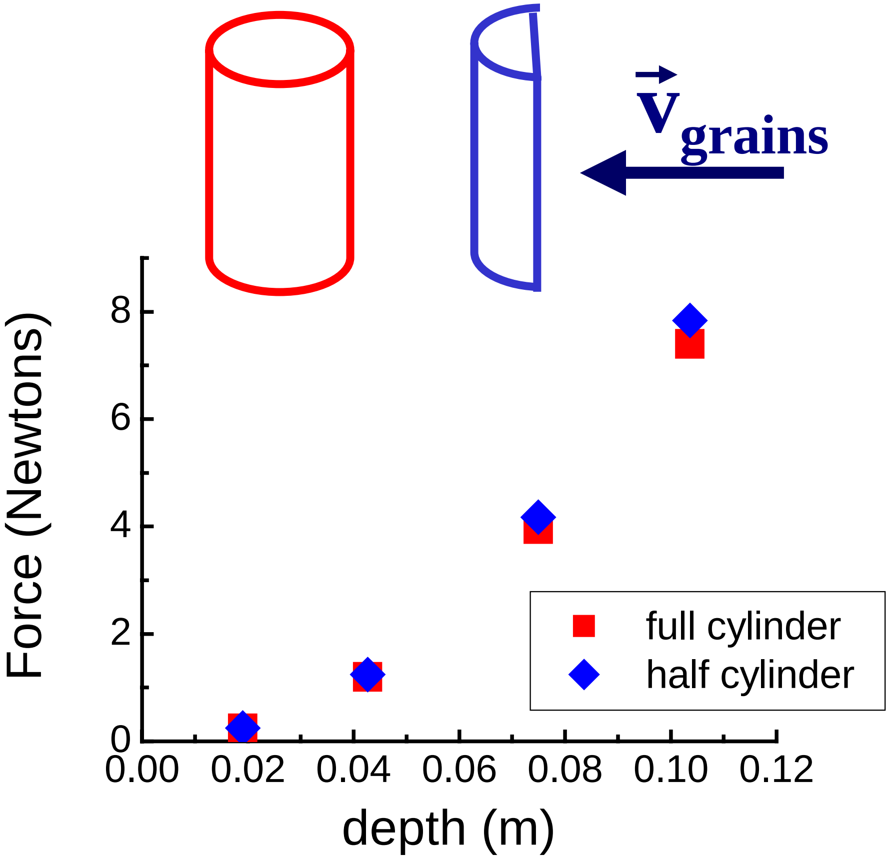




Average drag does not depend on cylinder surface

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

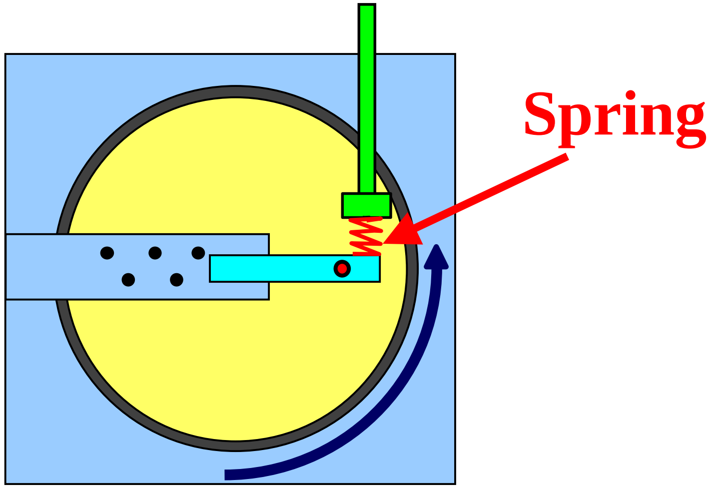


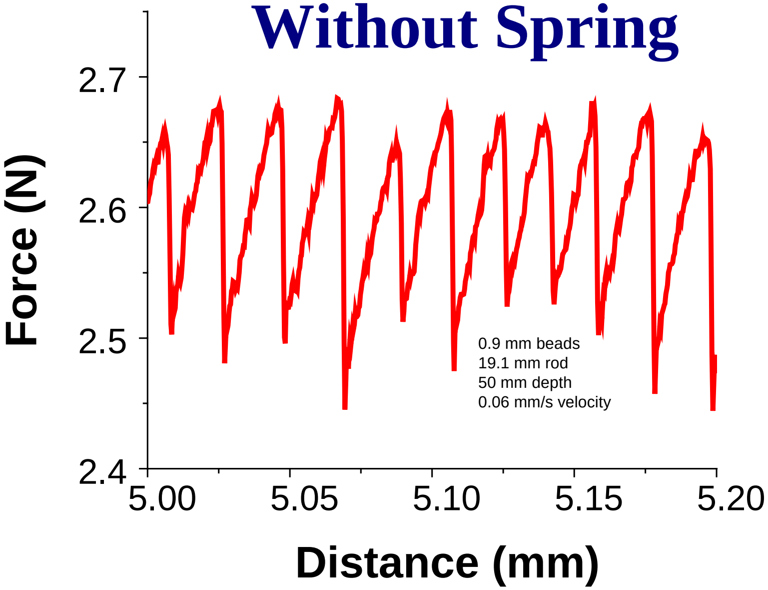


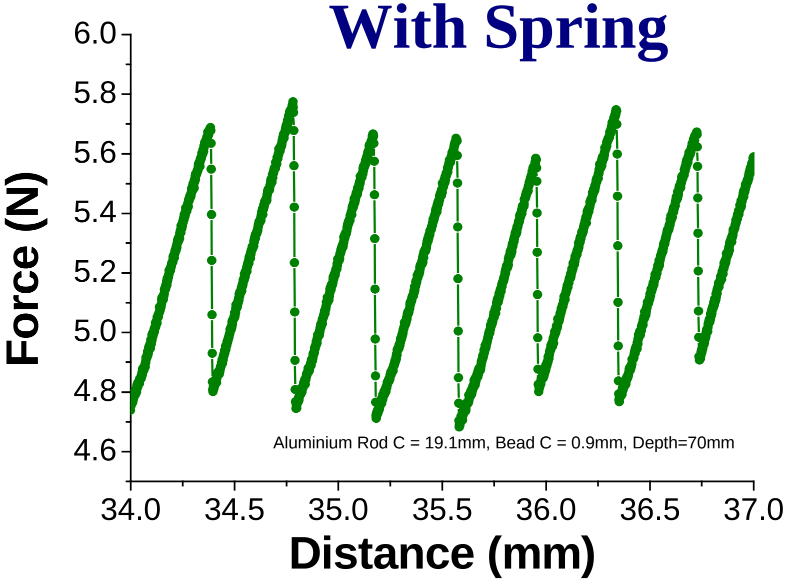
Drag determined by the force needed to collapse the bulk jammed state

Fluctuations in drag force: jammed states breaking

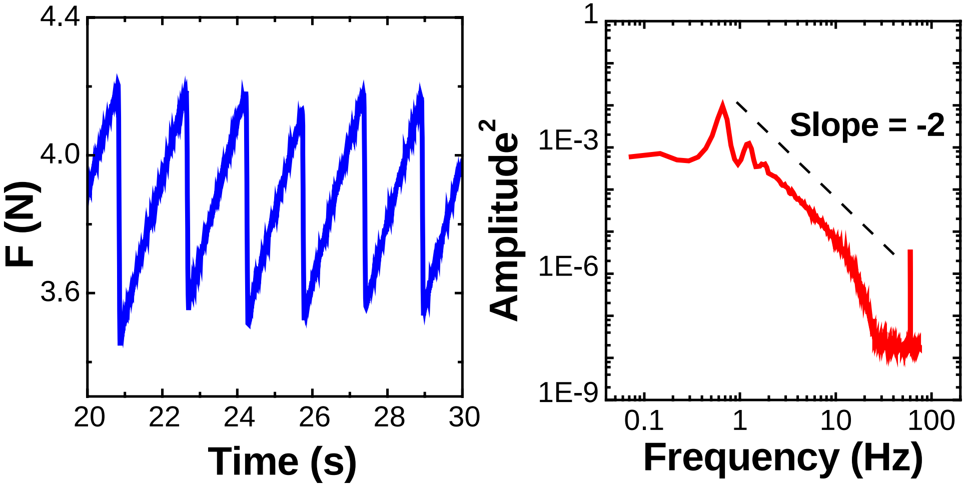
Add spring to control elasticity




Without Spring


With Spring

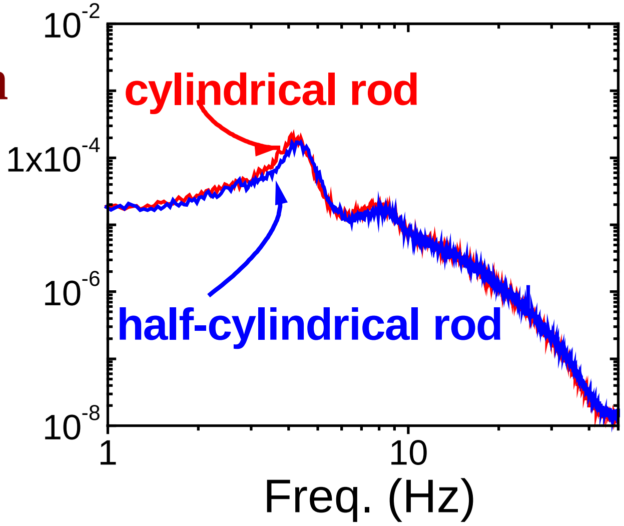
Fluctuations are periodic at low depths



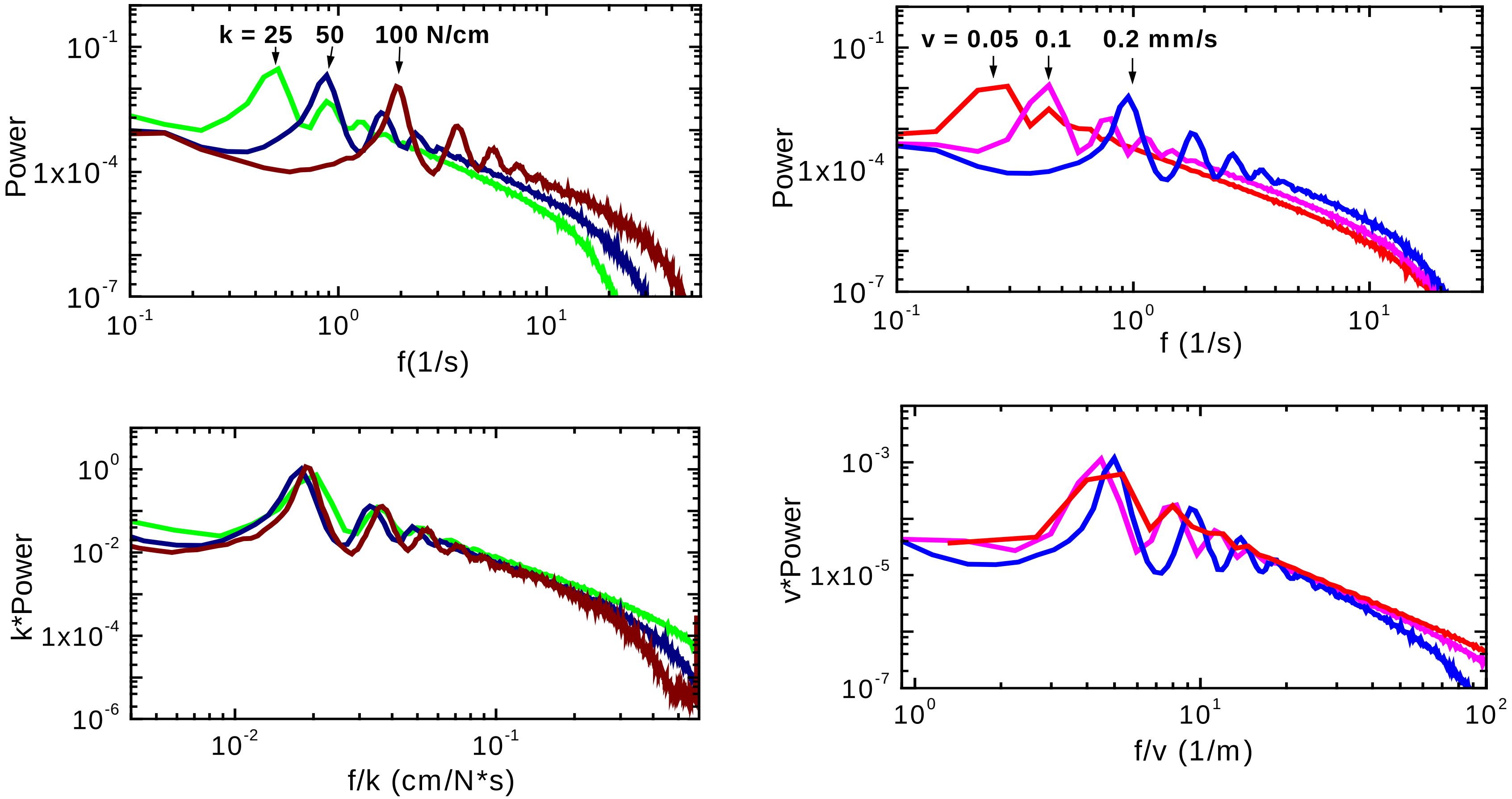
Can be reproduced by model of coupled springs

Phys. Rev. E **64** 051303 (2001)

Fluctuations do not depend on rod shape or surface friction: result from bulk failure of the jammed grains



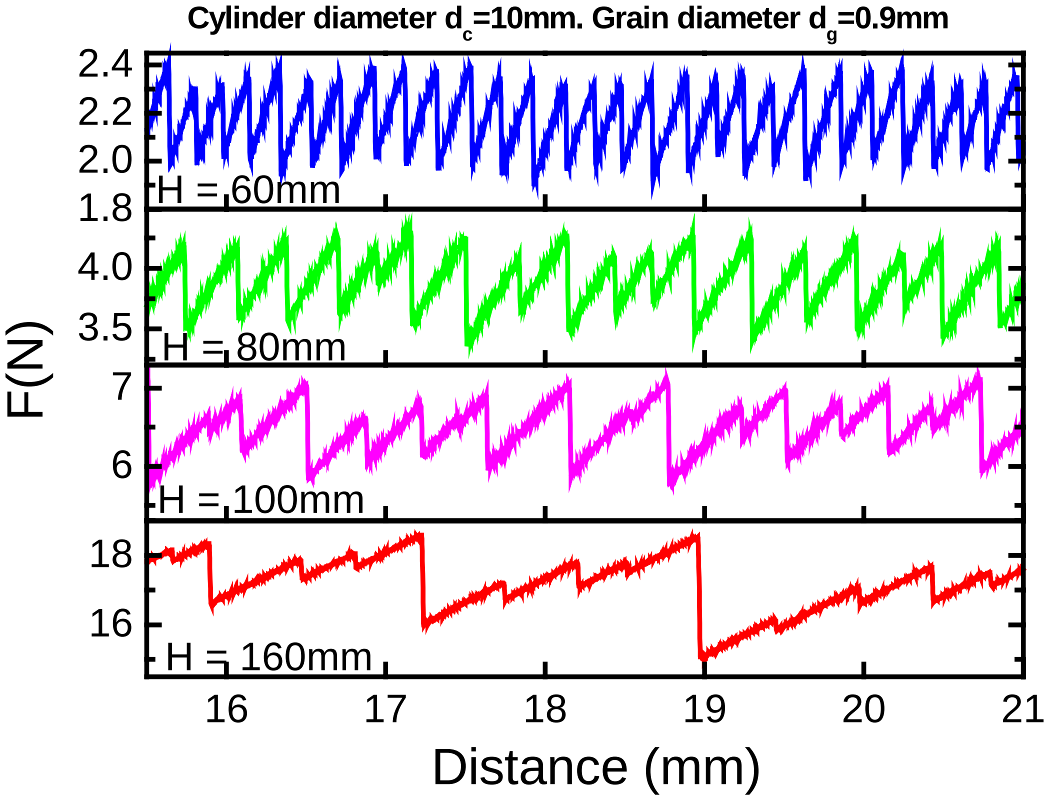
Fluctuations scale with velocity and elasticity



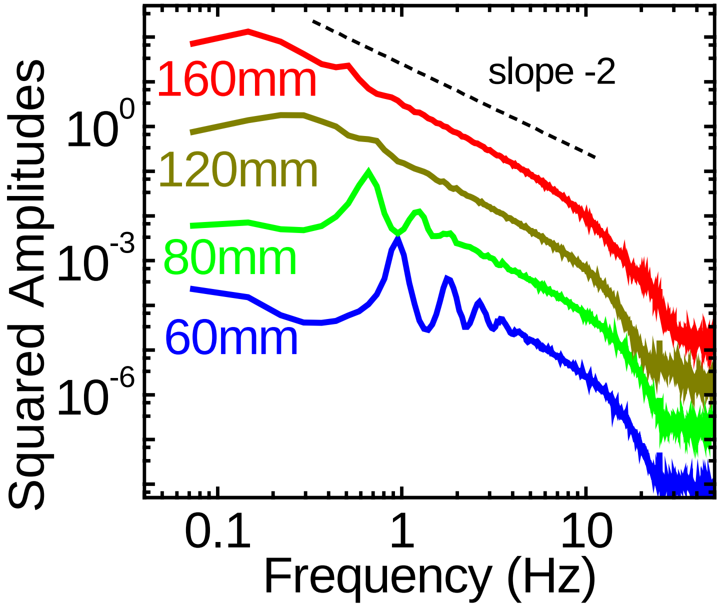
Stick slip reflects properties of grains, not apparatus

Fluctuations change in character with depth of insertion

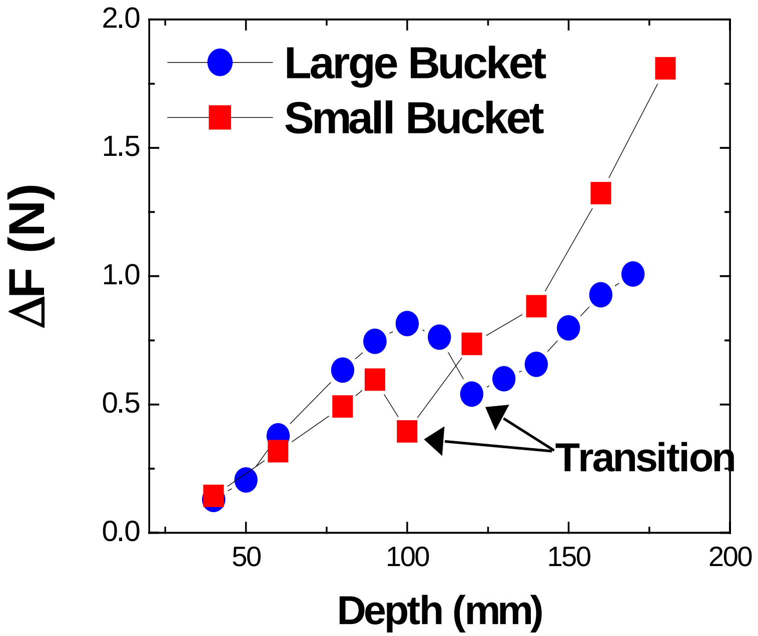
__Phys. Rev. Lett.__ **84** 5122 (2000)



Cylinder diameter d_c=10mm. Grain diameter d_g=0.9mm



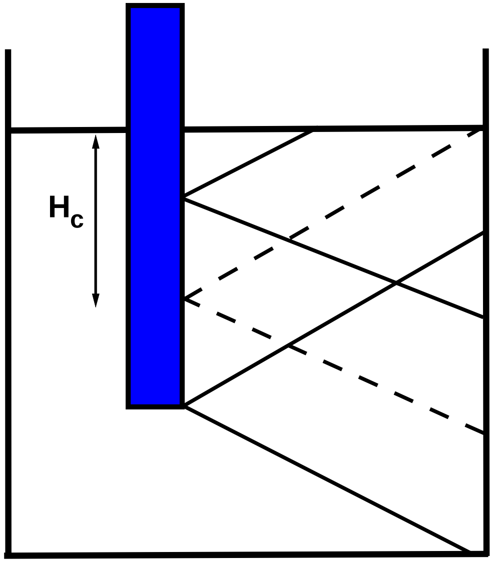
Fluctuation transition is finite size effect?



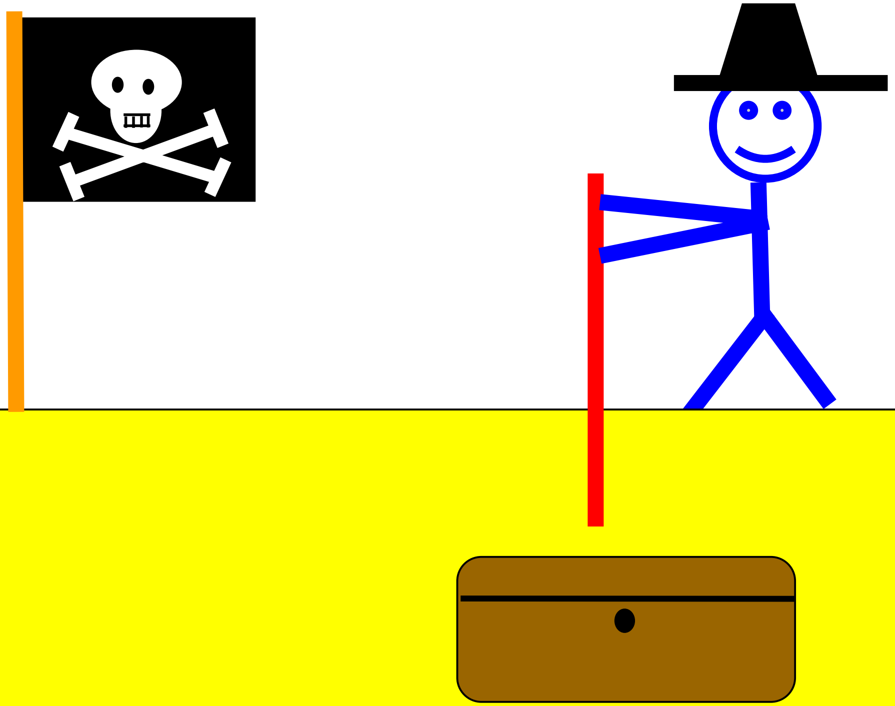
Force chains are long range →

Below certain depth the container walls prevent relaxation of the jammed state →

More frequent reorganizations

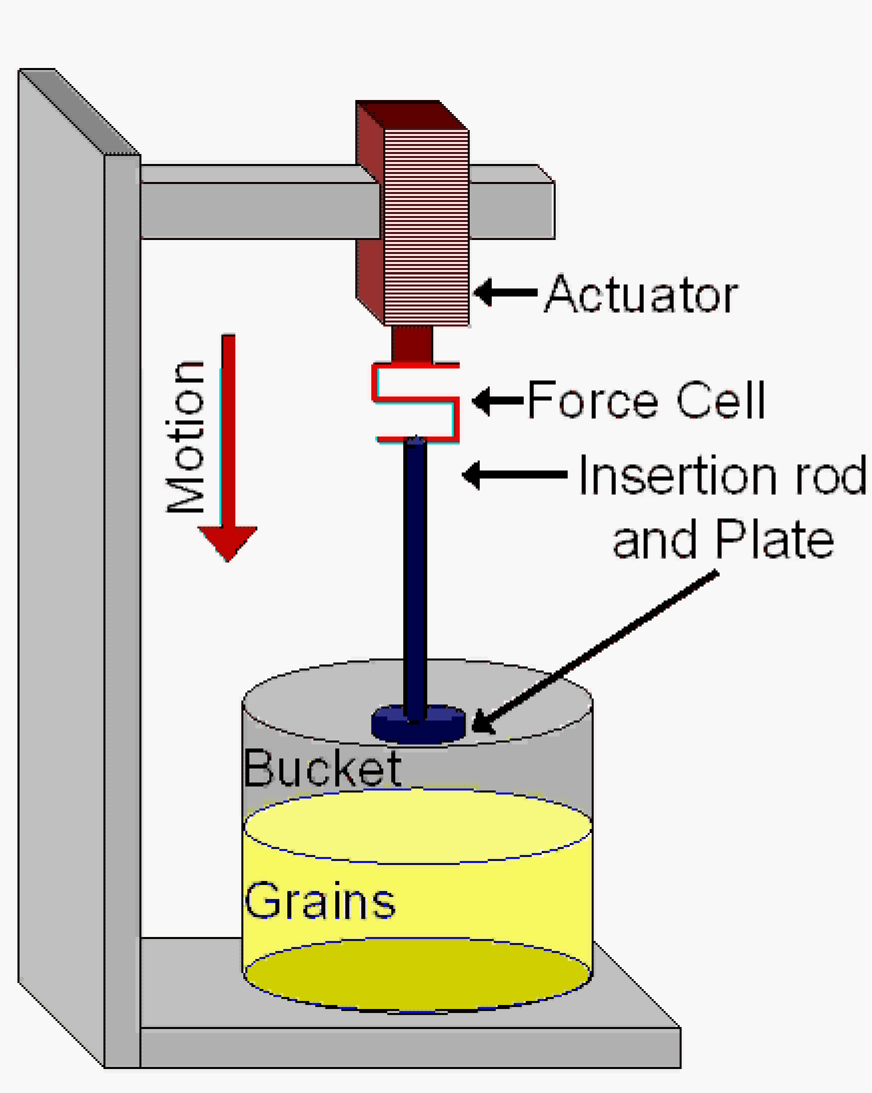


More direct measure of finite size effect on granular drag: penetration force near boundary



How close to the treasure chest does the pirate feel its presence under the sand?

Look at finite size effect with penetrometer



Nature **427**, 503 (2004)

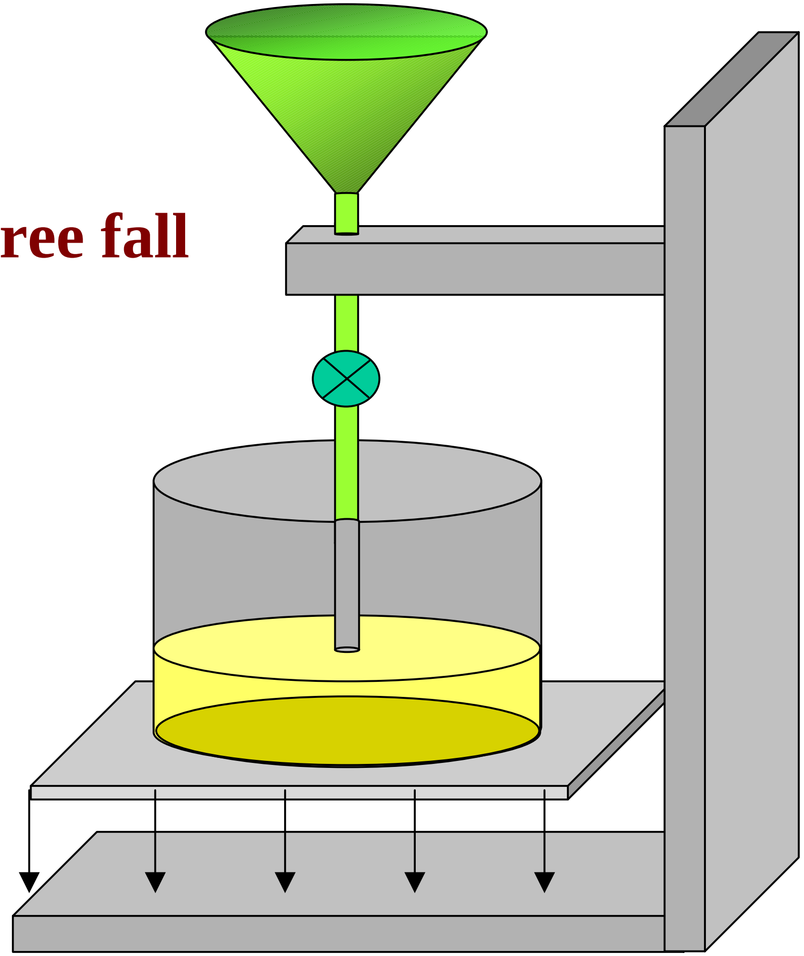
Phys. Rev. E **70**, 041301 (2004)

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

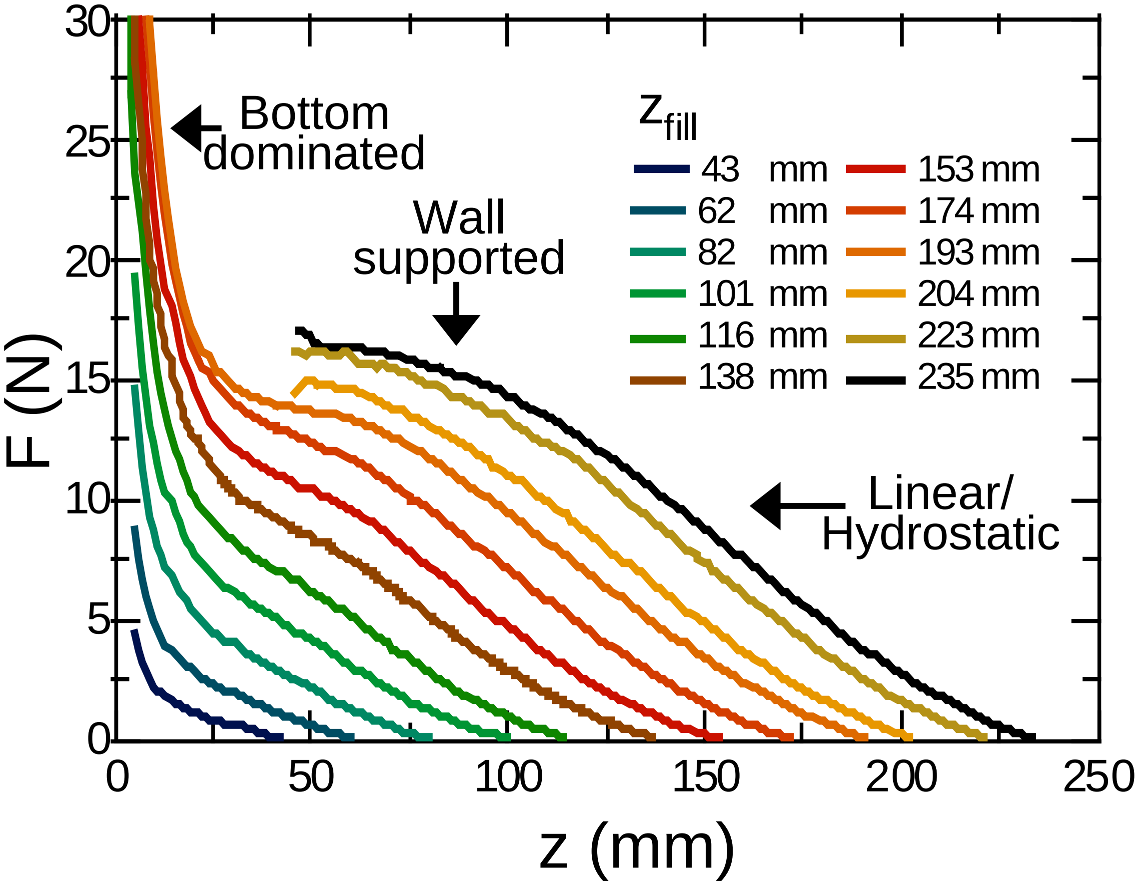
- **Vary:**
  bead diameter
  bucket size
  diameter of plate
  velocity,
  texture of bottom surface

Careful filling procedure required

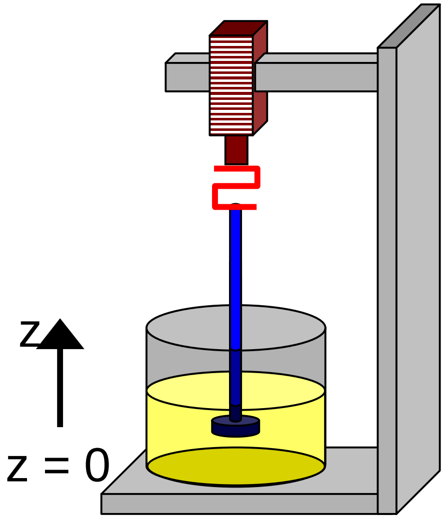
Slowly lower bucket
so grains fill without free fall



Height dependence of penetration force



0.9 mm beads
25.4 mm plate

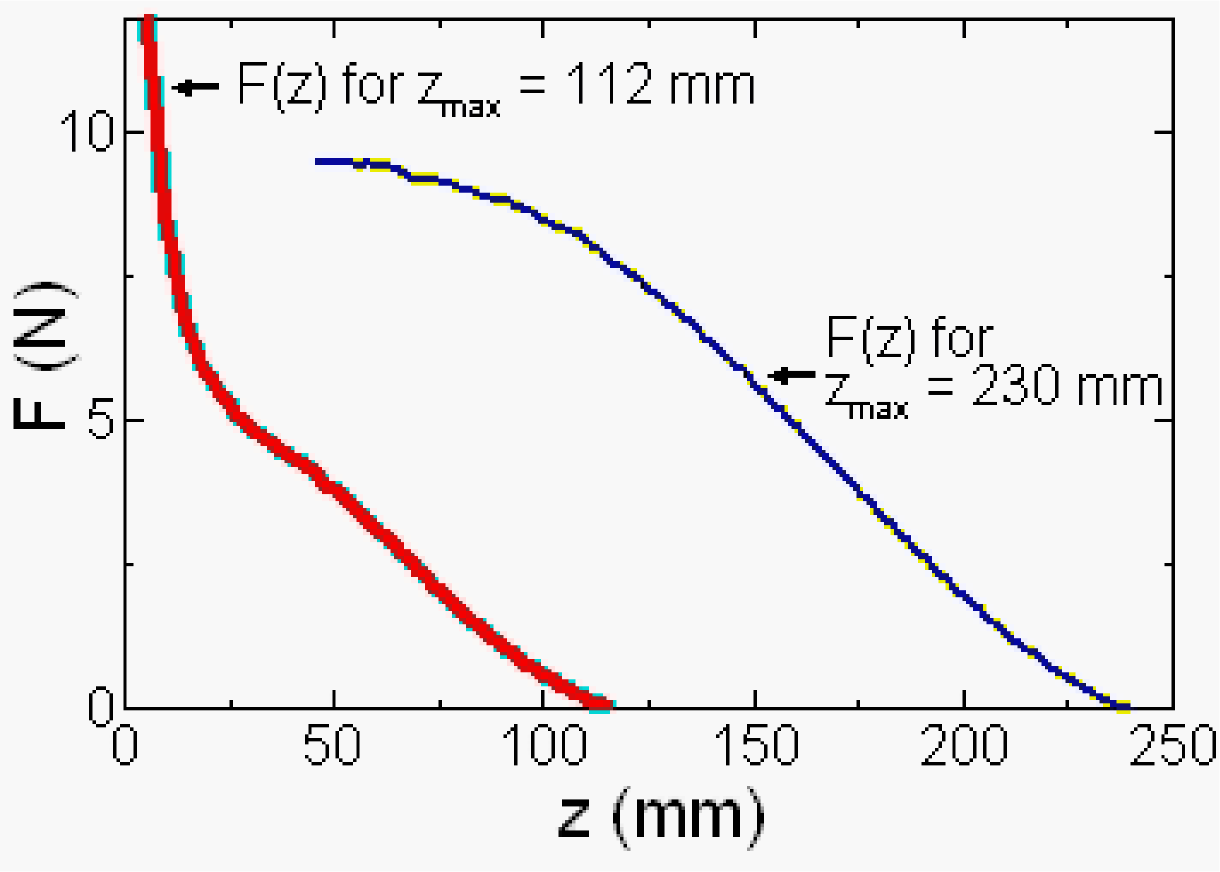


- **Initial linear force distribution with subsequent rollover**

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



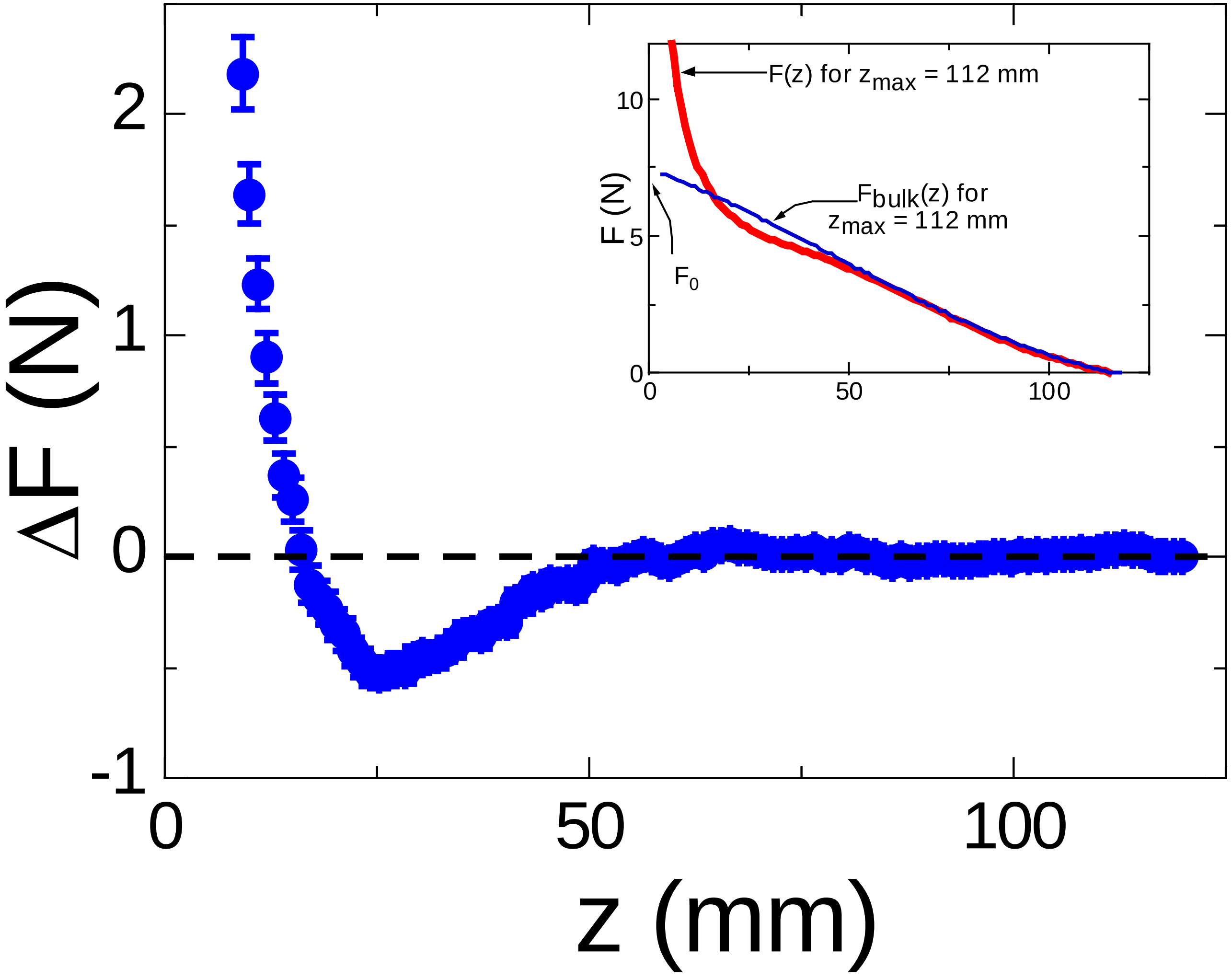
Obtain:

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

Measure of stress at bucket bottom, F_0

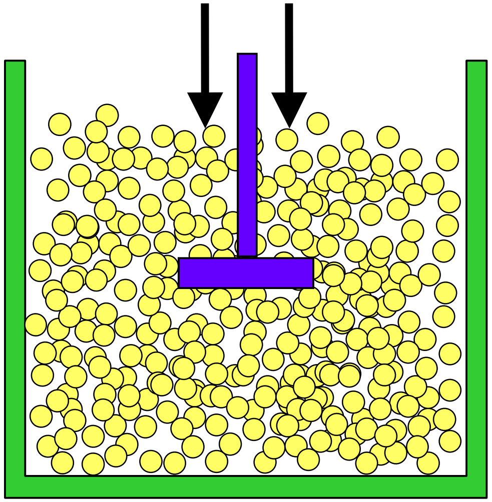
0.9 mm beads
25.4 mm plate

Subtraction of background yields surprising minimum in force

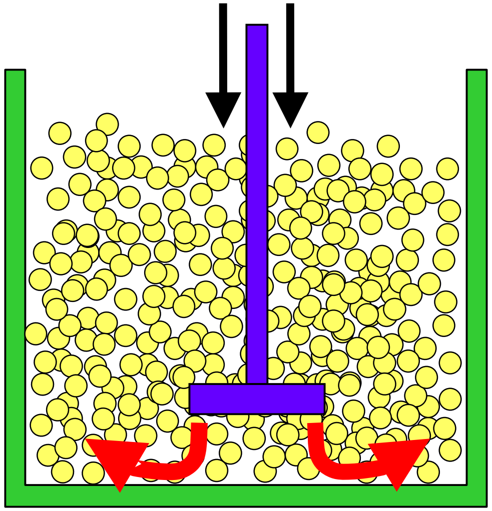


0.9 mm beads
25.4 mm plate

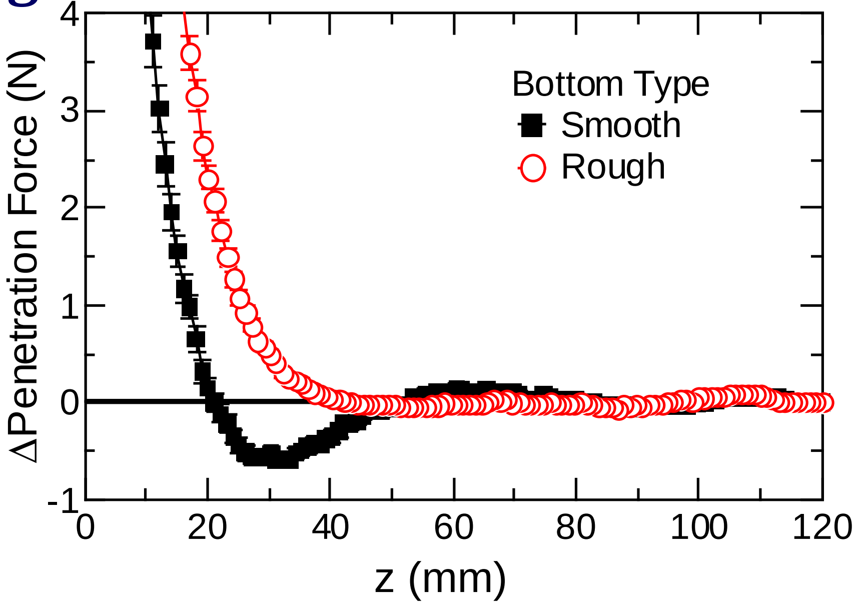
Why is there a minimum in ΔF?



Forces in bulk need to rearrange ensemble of grains

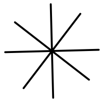


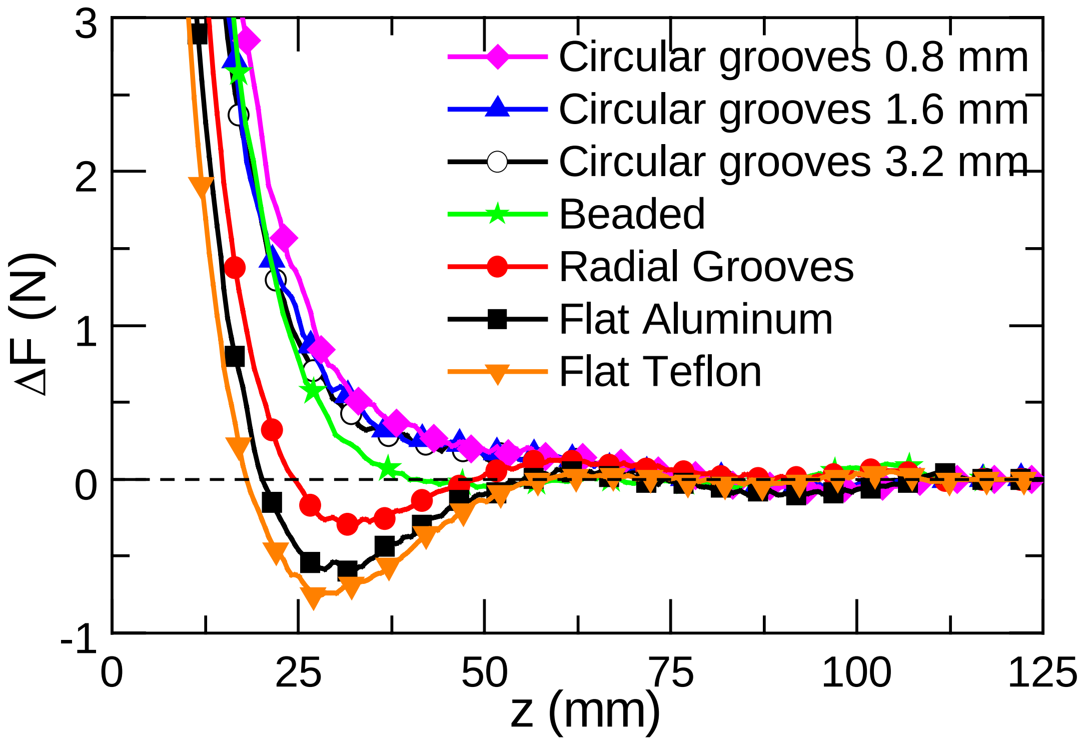
Near the bottom grains can slide along surface



Remote sensing of boundary texture through penetration

Texture of bucket bottom

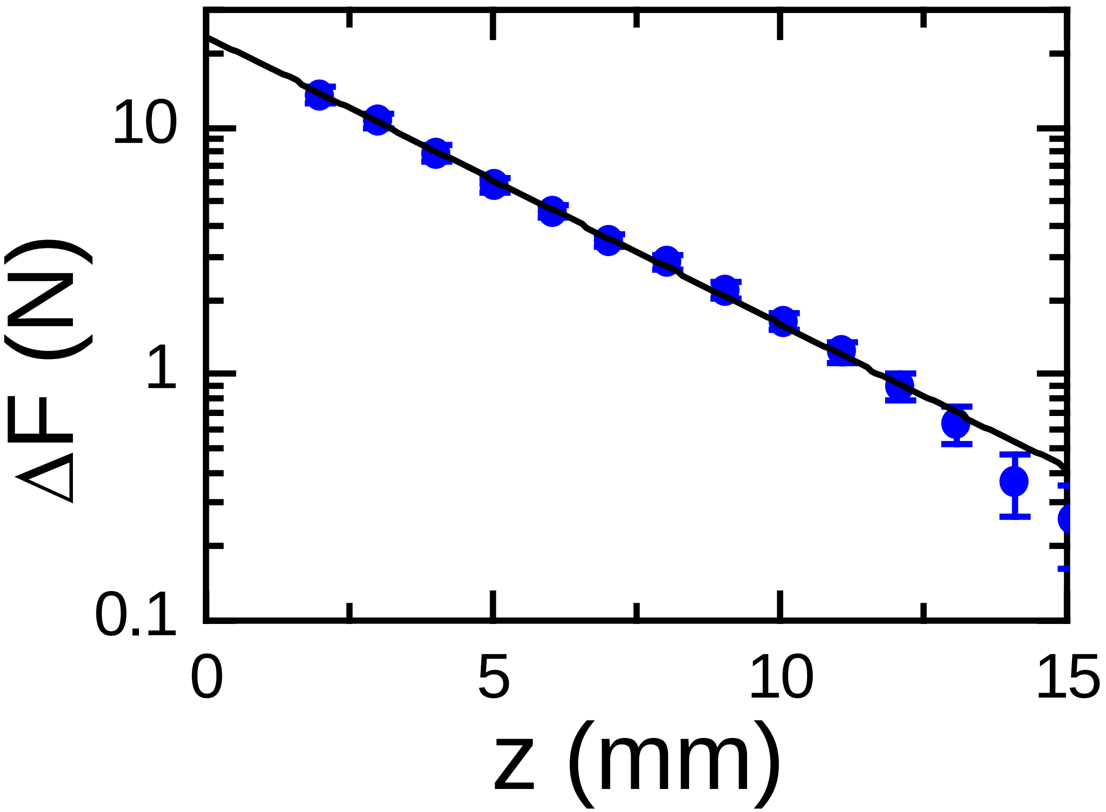
- Flat/Smooth
- Circularly grooved 
- Radially grooved 
- Rough/Beaded



Sliding along boundary surfaces reduces penetration force.

→ Texture affects the nature of the local jammed state.

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



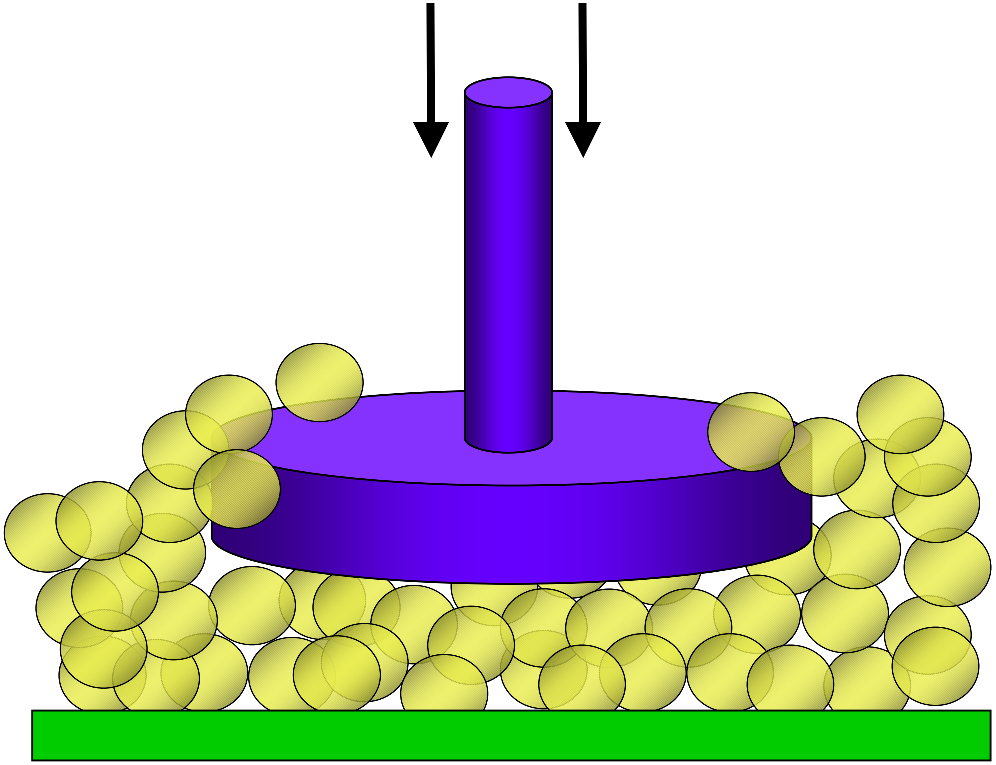
$$\Delta F \propto e^{-z/\lambda}$$

Exponential behavior observed in ΔF approaching bottom boundary for all textures, grain sizes, and real sand

Implies the existence of an intrinsic length scale!

What sets the length scale for sensing the bottom?

Length scale defines the size of the locally jammed state



Fill Depth?   Plate Diameter?   Grain Diameter? Something else?

Grain diameter appears not to affect length scale

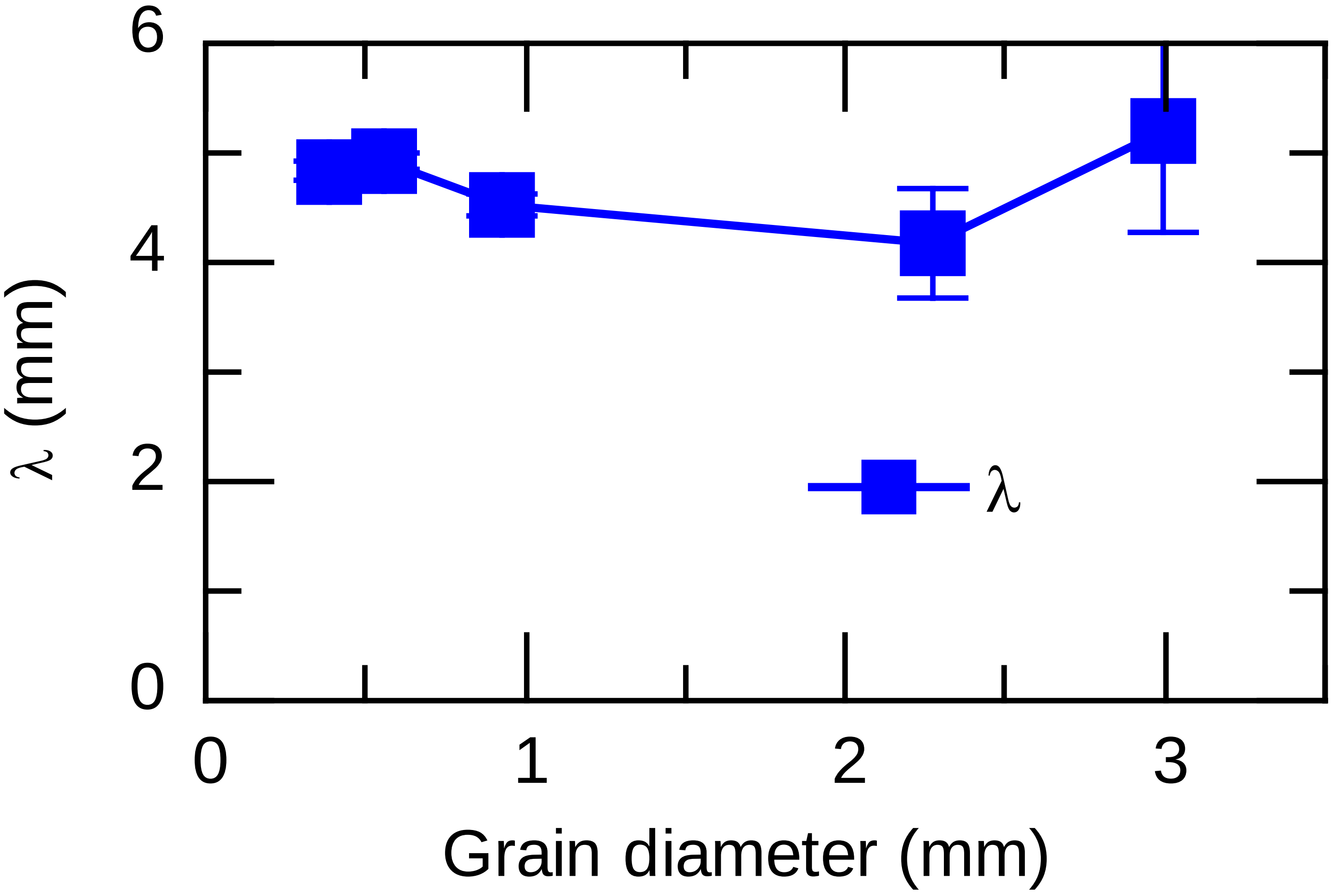
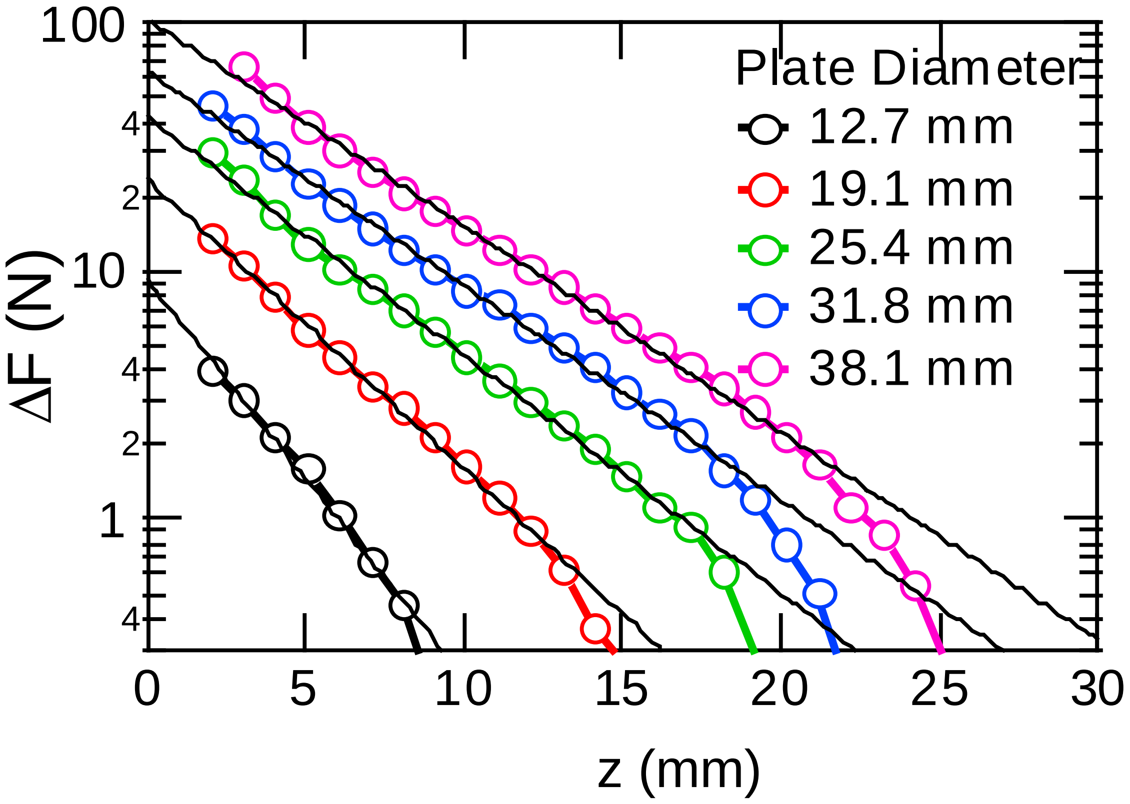


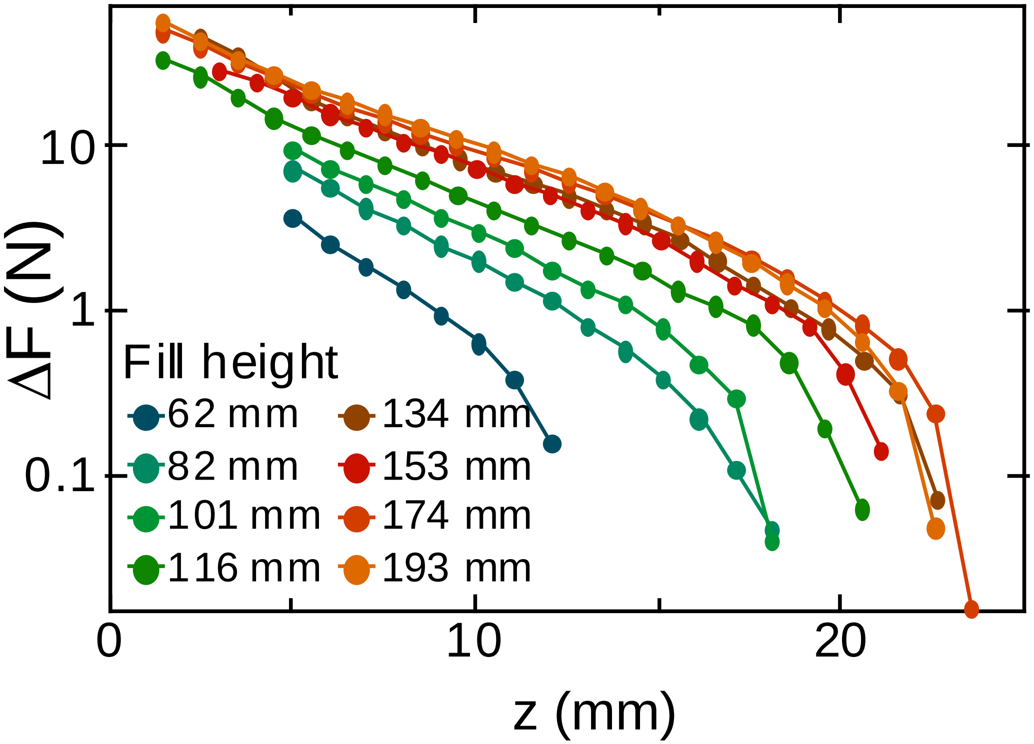
Plate diameter dependence of length scale



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

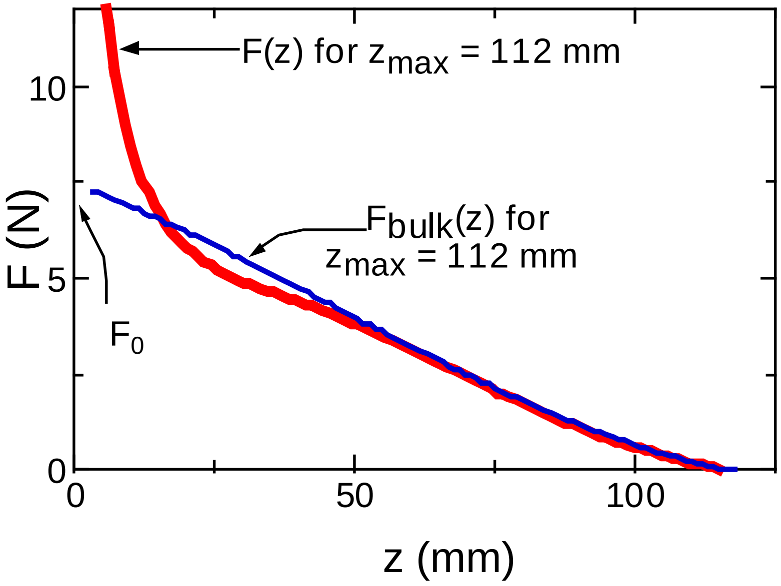
- λ increases with penetrating plate size
- Larger penetrating object detects bottom earlier

Fill height dependence of length scale



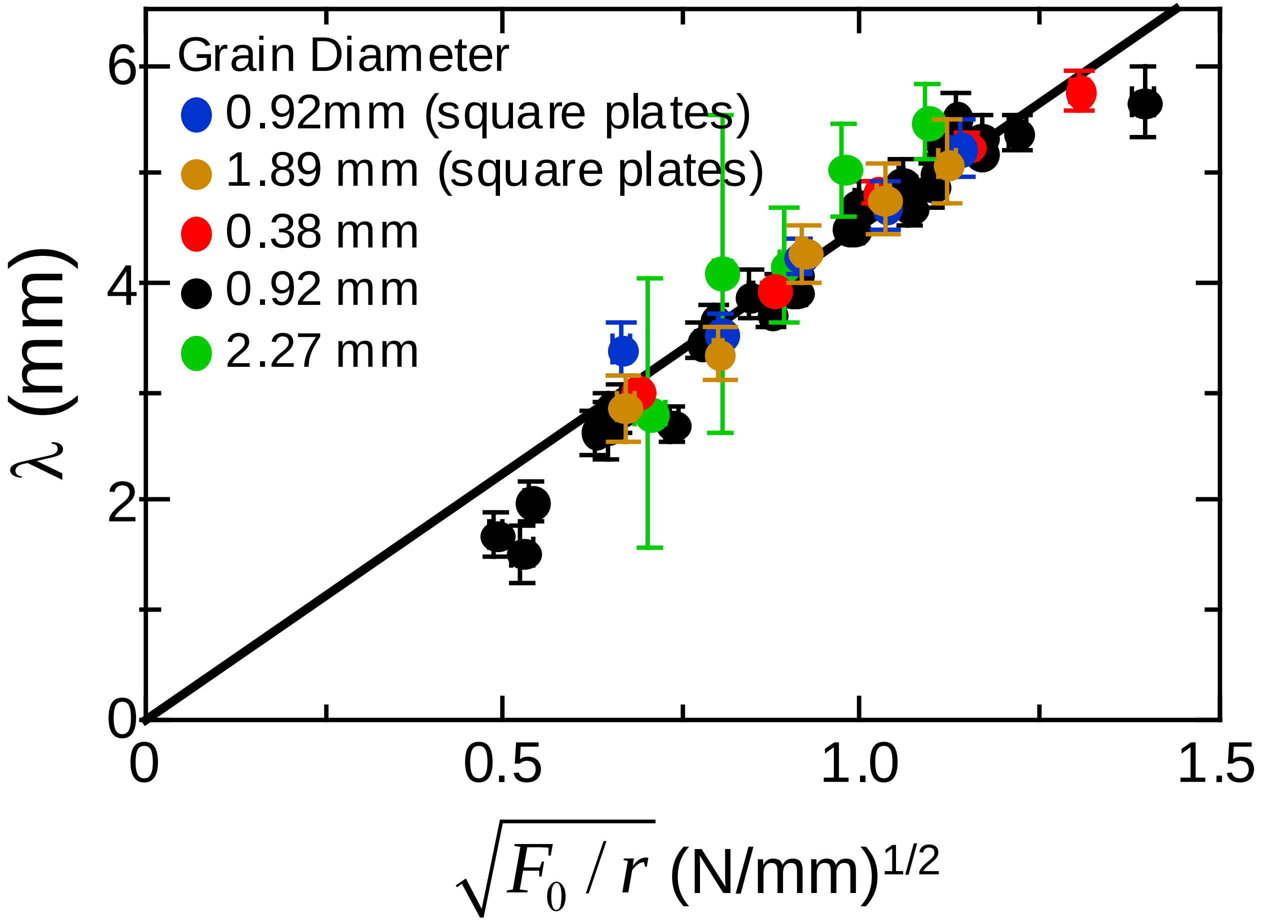
Fill height affects λ through ambient stress

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



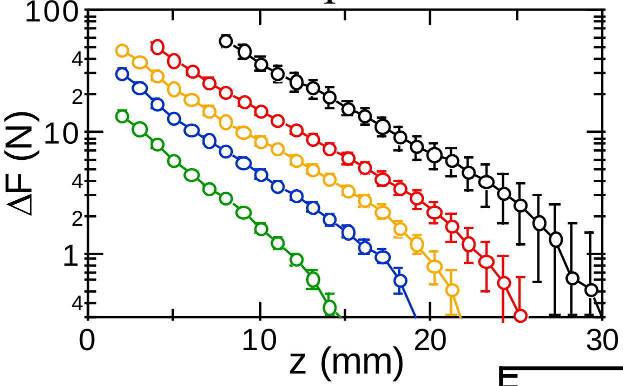
Dependence of length scale on system parameters

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



Scaling of length scale

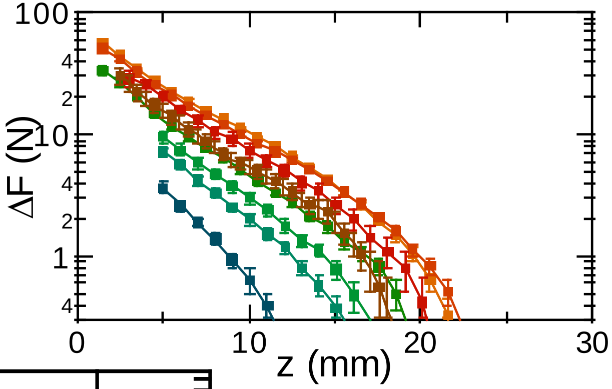
Plate size dependence

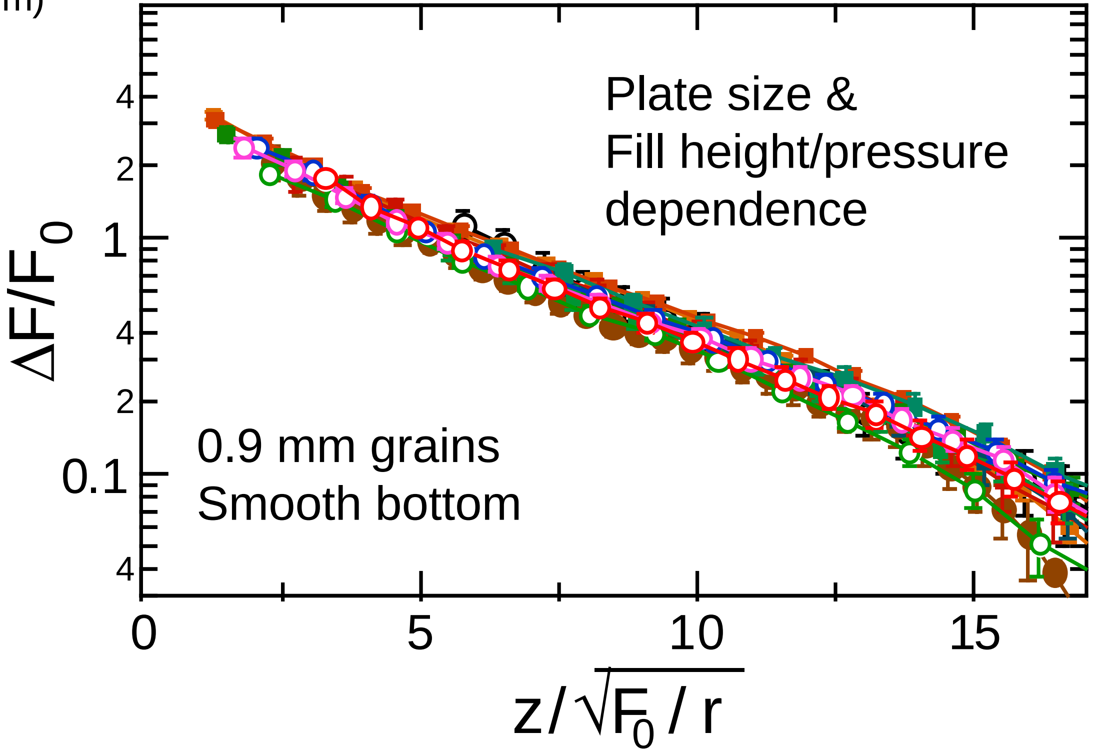


$$\Delta F \Rightarrow \Delta F / F_0$$

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

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!!!

Conclusions: Jamming in drag

- **Jamming leads to unusual drag in granular materials**
  - **Velocity independent**
  - **Stick slip fluctuations**
  - **Only weakly shape dependent**
- **Boundary effects on jamming result in rich behavior**
- **Many open issues**
  - **What defines the length scale for the jammed state?**
  - **What are the microscopic dynamics of the collapse process?**