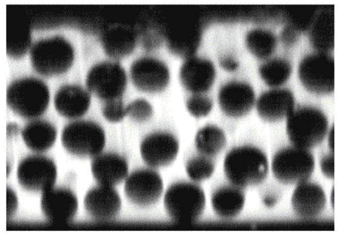
Investigation of Dense Dry and Wet Granular Flows with Internal Imaging



Ashish Orpe, Salome Siavoshi and Arshad Kudrolli

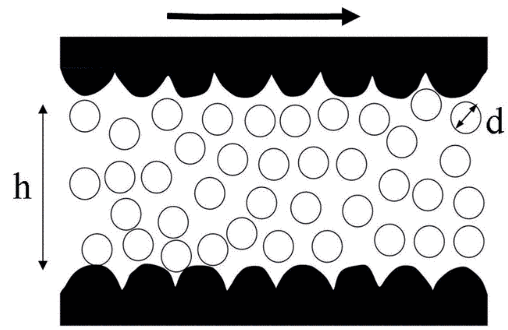
Department of Physics, Clark University

Funded by the National Science Foundation

Outline

- Experiments with index matching to visualize dense granular flows
- Slider on a granular bed: Friction Measurements
- Shear profiles in thin layers and the effect of boundary conditions
- Gravity driven grain flow *inside* a silo

Friction of sliding surfaces



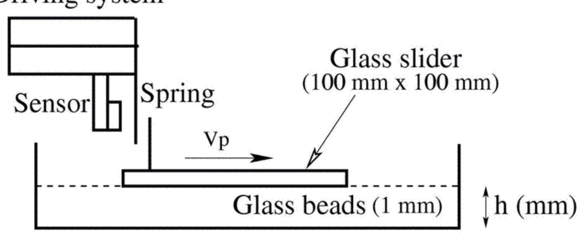
eg: Walking on sand, braking on pebble strewn road

- ❑ *Friction force required to start the motion ?*
- ❑ *Friction encountered during motion ?*
- ❑ *Friction dependence on **h** ?*

Previous studies for deep beds (h >> d)

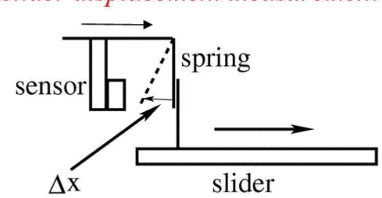
Nasuno *et al.*, 1997, 1998, Losert *et al.*, 1999, Coste 2004

Experimental System



(Nasuno *et al.*, 1997)

Slider displacement measurement



Measurements

- Mean friction as function of ***h***
- Visualization of particle motion

Friction coefficient

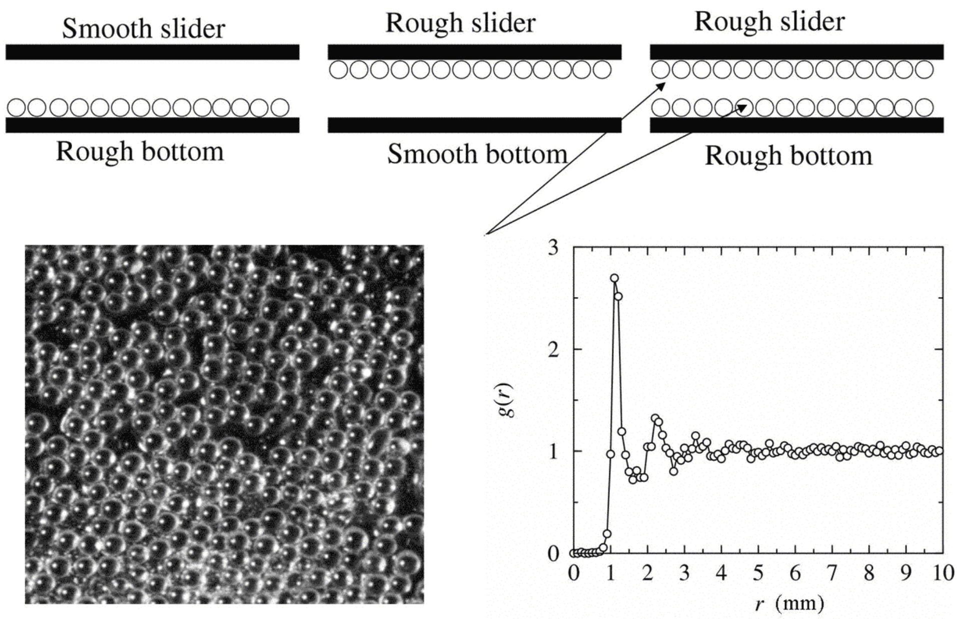
$$\boxed{F = \mu_k mg = k\Delta x}$$

Slider weight

Spring constant

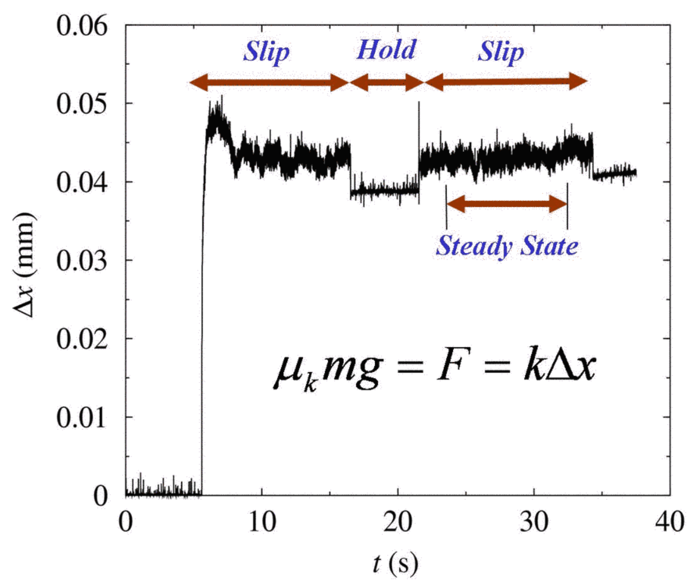
Slider displacement

Boundary conditions

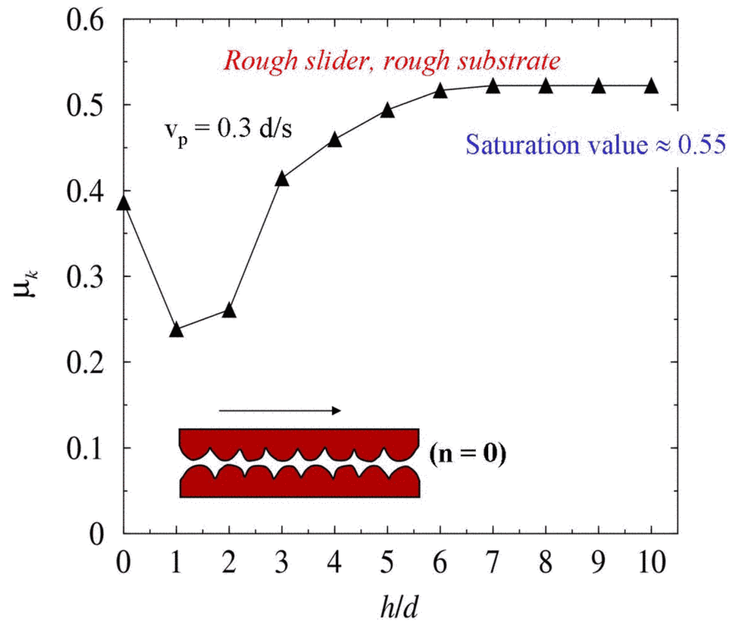


Friction measurement

(Rough slider, rough substrate, $v_p = 1.3$ d/s, h/d = 6)



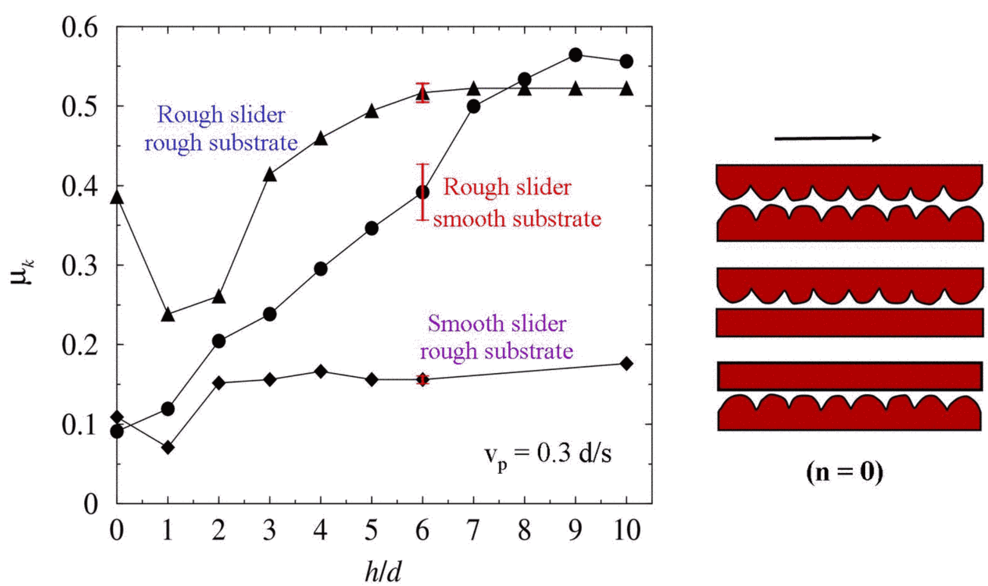
Mean friction coefficient



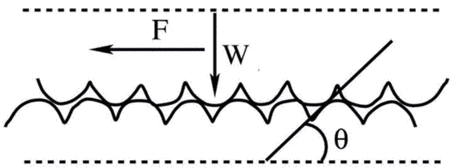
Friction coefficient increases and saturates for deep beds

Minimum friction for 1-2 layers

Effect of surface boundary



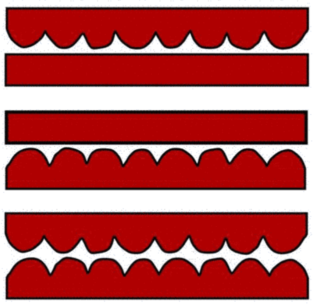
Effective friction coefficient



$$\mu_{eff} = \frac{F}{W} = \frac{\mu\cos\theta + \sin\theta}{\cos\theta - \mu\sin\theta}$$

$\mu_{kinetic}$(glass) : (≈ 0.2)

Surface boundaries studied



$\theta = 0^o \longrightarrow \mu_{eff} = \mu \approx 0.1$

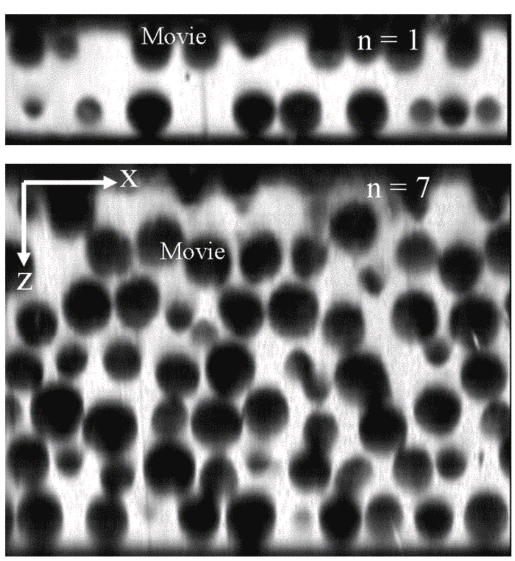
$\theta = 0^o \longrightarrow \mu_{eff} = \mu \approx 0.1$

$0^o \leq \theta \leq 30^o \longrightarrow \mu_{eff} \approx 0.5$

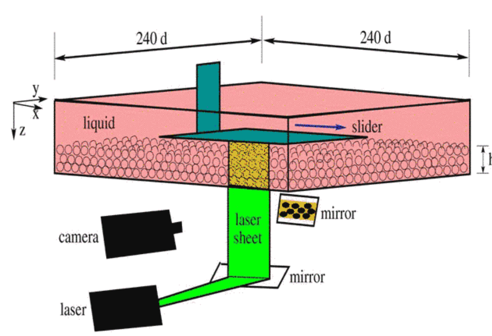
(n = 0)

Index matching experiments

Observation of the particle motion in the bulk



Rough slider, smooth substrate,
$v_p = 1.3$ d/s, 30 fps



System is immersed in a liquid with the same refractive index as particles

$\nu = 25$ cS

Particle identification (Tsai et al, 2003)

Experimental details

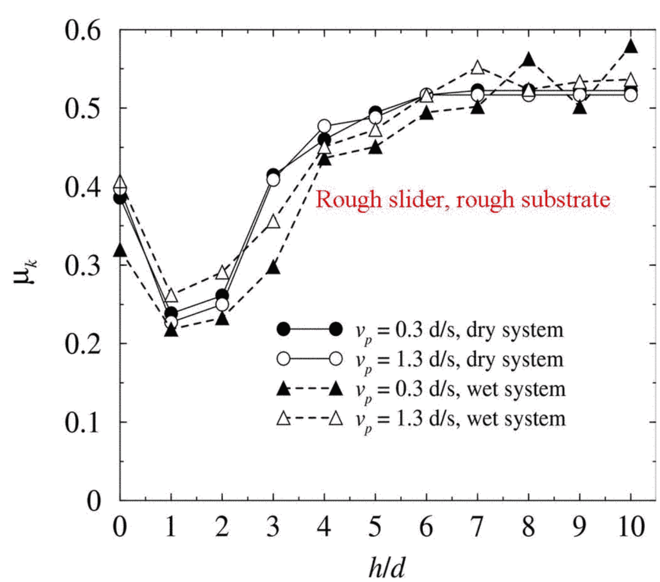
- Liquid : Aliphatic/Alicyclic hydrocarbons (RI: 1.460 & 1.600).
  Effective viscosity: 22.67 cS at 25c
  Effective RI : ~ 1.520 (matched to 3rd decimal place)

- Glass beads: Soda-lime (RI ~ 1.520)

- Dye: Pyromethene 597 λ_max for fluorescence: 565 nm
  λ_max for absorption: 525.5 nm,
  (both values in Ethanol)

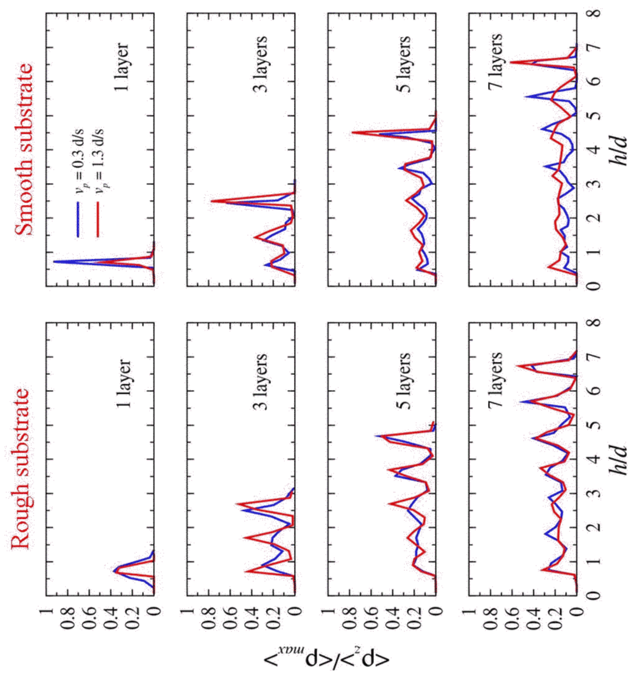
- Laser: Green Laser (Diode pumped solid state, DPSS,
  λ: 533.4 nm and Power: 48.73 mW)
  fan angle for line generator: 15 deg.

Interstitial liquid has negligible effects



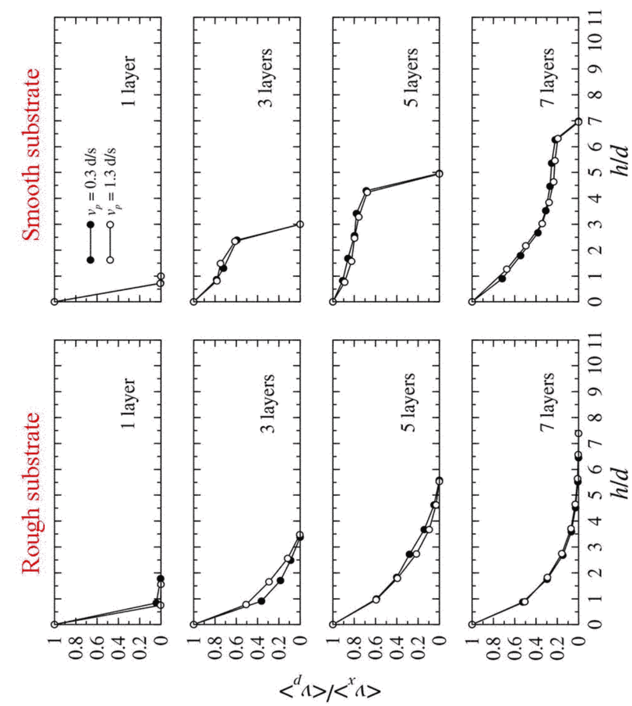
Number density (ρ_z) profiles

Effect of the slider driving velocity

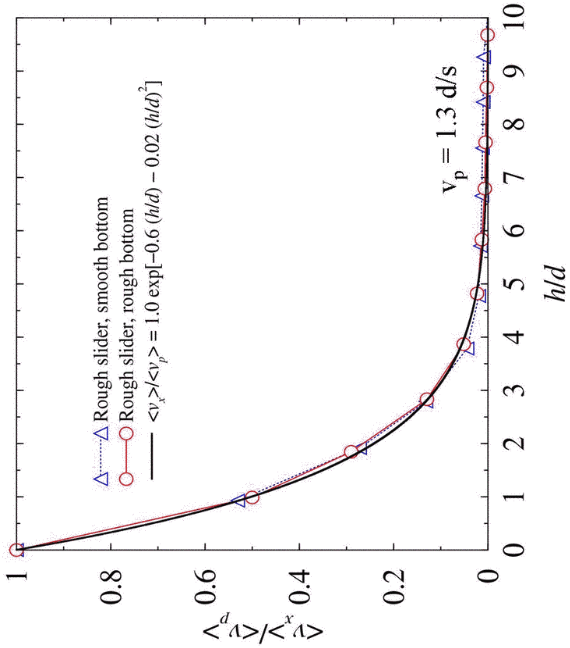


Mean velocity (v_x) profiles for various layer thicknesses

Effect of the slider driving velocity



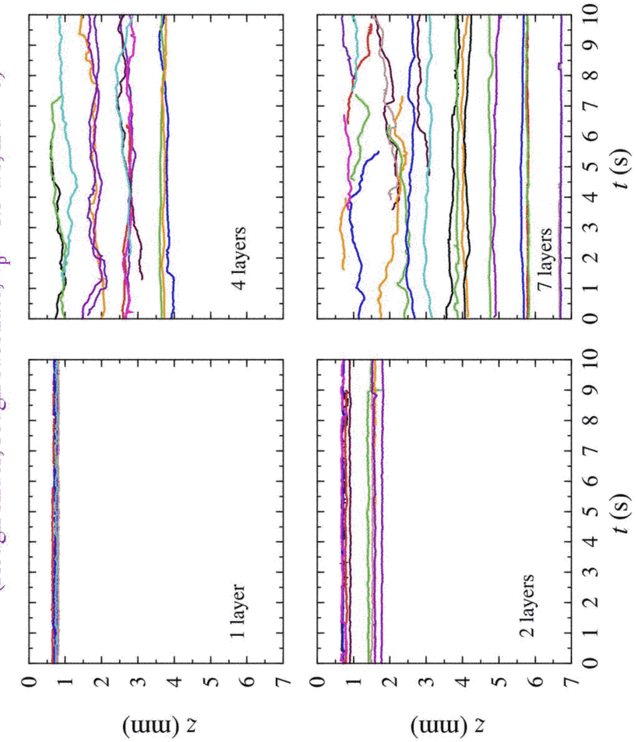
Mean velocity (v_x) profiles



Profiles are independent of substrate roughness for h/d ~ 10

Time series of vertical motion of grains

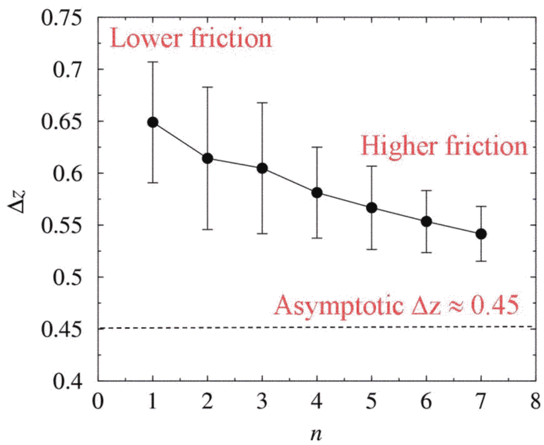
(Rough slider, rough substrate, $v_p = 1.3$ d/s, h/d = 6)



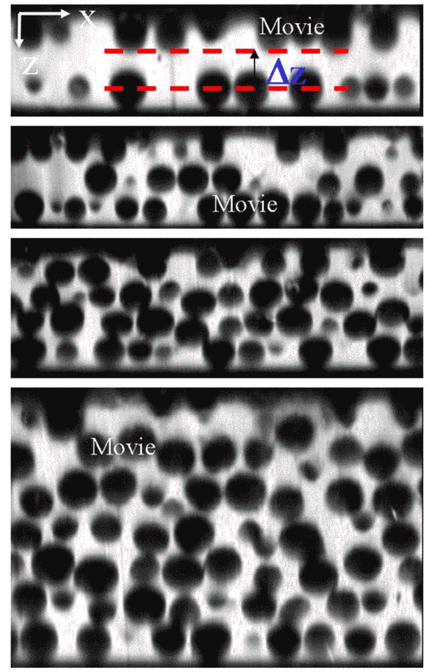
Shear Confinement

Rough slider, smooth substrate, $v_p = 1.3$ d/s

Average over all boundary conditions & slider speeds



Higher friction coefficients for deep beds owing to confinement of flowing particles against slider



n = 1

n = 2

n = 4

n = 7

Conclusions

➢ Friction coefficient increases with layer thickness before saturating for deep beds.

➢ Friction coefficient shows minimum for single particle layer.

➢ Higher friction coefficient obtained for rough surfaces.

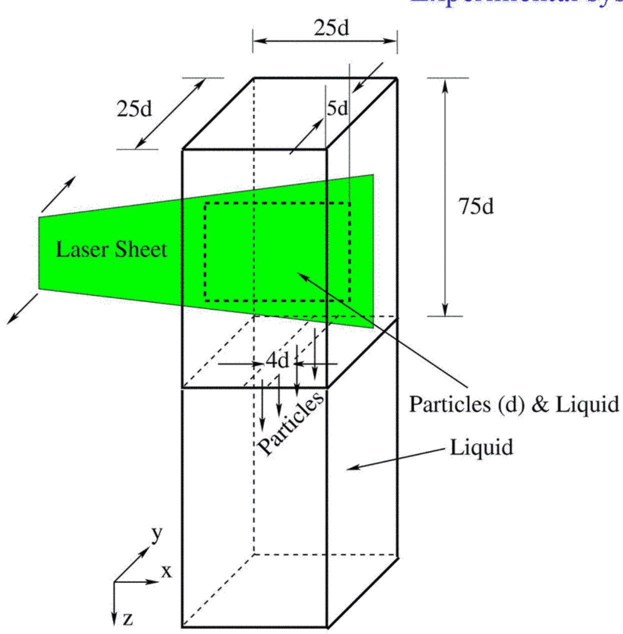
➢ Values for the friction coefficient governed by the confinement of the sheared particles.

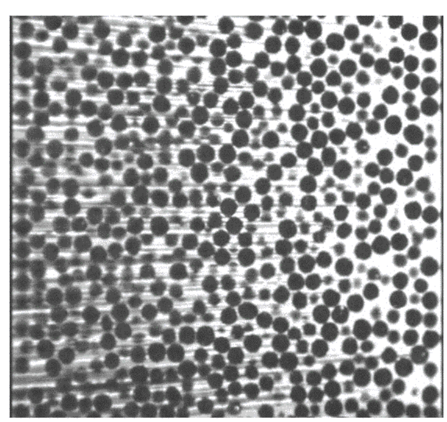
Dense granular flow inside a silo

- Use index matching to measure the particle motion away from side walls
- Measure diffusion and particle rearrangements in regions with and without shear
- Previous experimental measurements on particle diffusion carried out near the side walls

Particle tracking away from side-walls inside a silo

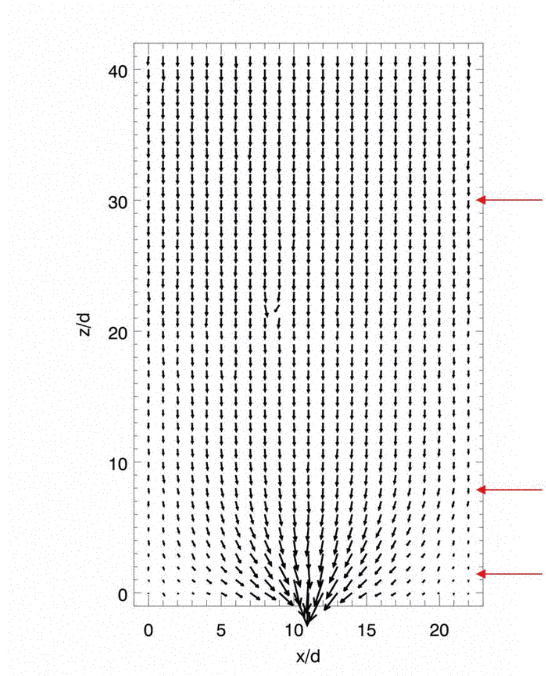
Experimental system





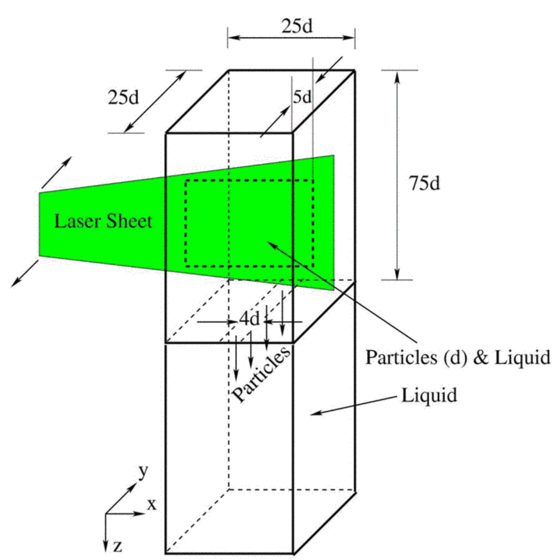
Flow depth = 5d, 60 fps

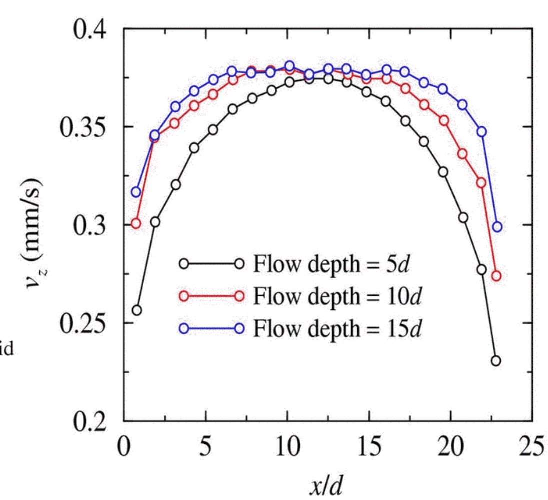
Velocity field inside silo



Mean flow velocities

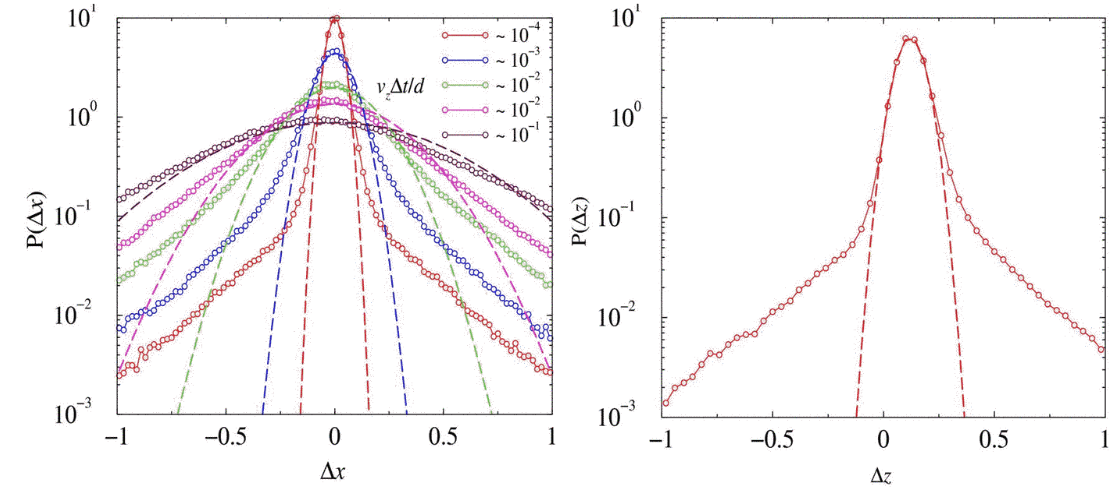
Plug flow region





Particle displacement distributions

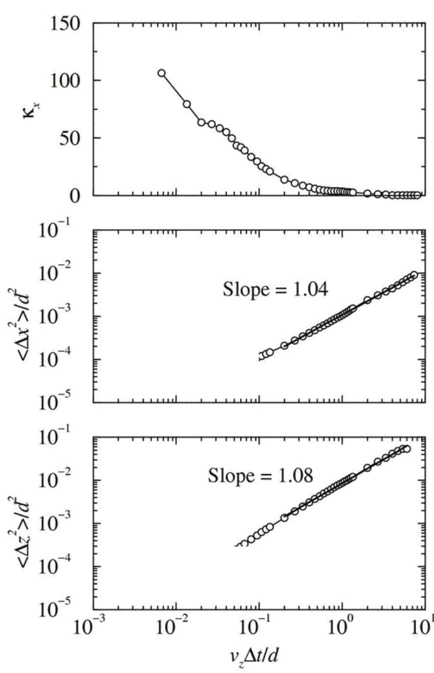
Flow depth = 5d



$\Delta t = 1/60$ s

Mean square displacements

Flow depth = 5d



Summary

- Visualized particle motion in 3D
- Side walls affects the flow to at least 15 grain diameters from surface
- Kurtosis of distributions may show possible cage breaking

Further information:
http://physics.clarku.edu/~akudrolli

[also on “Dynamics of a bouncing dimer” PRL (to appear)]