Fun in the Sand: Some Experiments in Granular Physics

Peter Schiffer
Pennsylvania State University

Collaborators
T. Vicsek, A.-L. Barabási, B. Kahng

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OUTLINE OF TALK

1. Introduction to Granular Materials: Why physicists might want to think about them

2. Various Experimental Studies
   a. Wet Granular Materials
   b. Thermal Effects on Granular Materials
   c. Drag Force and Local Jamming in Granular Materials
What is a granular medium?

**Definition:** large collection of classical solid particles, interacting only through contact forces
Granular media are everywhere!
Granular media have vast practical importance ~ 100 G$/yr in U.S. in handling.
Improved understanding of granular media could save a lot....
Why Study Physics of Granular Media?

- Simple interactions $\rightarrow$ complex dynamics and non-equilibrium states (analogous to glasses/spin glasses/colloids…)

- Relatively easy to probe with experiment
  \[ T_{\text{effective}} = 0 \] (no dilution fridge needed!!)

Like Liquid: Conform to container shape and flow when poured

Like Solid: Can support object on top (even if object is denser)

ALL SORTS OF SURPRISES IN THEIR BEHAVIOR!
Novel physics in dynamics of grains

Shake a thin layer on a vibrating plate and get all sorts of patterns

Images From P. Umbanhowar et al.
Novel physics in dynamics of grains

Drop a ball into loose grains and get a jet of grains to pop out

Images from Heinrich Jaeger group website
http://jfi.uchicago.edu/~jaeger/granular2/jets.html
Novel physics in statics of grains

Stress propagates through inhomogeneous concentrated "force chains"

Images from R. Behringer et al.
Part 1: Slopes of wet granular media

Interstitial liquid adds new dimensions to granular physics:
- capillary forces – cohesion
- lubrication – decrease of static friction
- viscous forces

Like adding new terms to the Hamiltonian!

One of the most obvious effects is an increase in stability of a wet granular pile compared to a dry one....
Initial experiments

Measure repose angle ($\Theta_R$) by draining crater method

- Glass spheres (available for bead-blasting at $3/\text{lb}$)
- Add controlled small amounts of pump oil -- low vapor pressure

**VERY SIMPLE EXPERIMENT**

Three regimes of behavior reflected in repose angle

- **Granular Regime**: Individual grains flow down surface matches theory for individual grain motion
- **Correlated Regime**: Correlated clumps flow down surface matches theory for continuum model with cohesion
- **Viscoplastic Regime**: Coherent surface flow (like viscous liquid) data not modelled
Study Dynamics: Rotating Drum Apparatus

Video to study dynamics of flow in drum (especially avalanches)

Glass beads (0.9 mm, 0.5 mm, 0.35 mm diameter) + oil (0.001%-5%)
Drum diameter = 22 cm, width = 3 cm

Try to get a quantitative measure of developing intergrain correlations

Avalanches in rotating drum

granular
correlated
viscoplastic
Different types of avalanches in different regimes

Dry 0.04% 0.12% 5.00% LIQUID CONTENT

Local angle (degrees)
Data are very rich in detail

Avalanche front

Kink

Block size

Granular: $\tau = 0.04\%$

Correlated: $\tau = 0.12\%$

local vertical velocity

local vertical velocity

Piles of experimental results….no theory yet!

Much other recent work on wet grains:

Part 2: Thermal Cycling and Granular Packing

• Packing of grains is random and not unique. It depends on the mechanical history of the sample.

• Changes all physical properties. Even a few percent change makes a big difference.

• Active topic of theoretical research.

Strong analogy to glassy materials/spin glasses: grains are in a metastable state in a complex and random arrangement.
But…what if container and grains expand/contract by different amounts?

Usually temperature cycles are uninteresting for bulk materials: Expand and contract

True for grains also: Energy scale of grain motion is much larger than accessible thermal energies

But…what if container and grains expand/contract by different amounts?
Temperature variation will change packing of granular samples

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

Irreversible change in packing changes granular properties, maybe even burst containers.
Thermal effects can be very serious

- Metallic silo wall expanded more than grains during the hot day
- Grains settled and compacted
- Silo wall contracted at night...and failed!
Relatively little systematic study of thermal effects on granular media

- Work on silos at very large scale (Blight et al.)
- Work on “stone heave” with liquid effects (Viklander and many others)
- Pressure induced by temperature change (Puri et al.)

- How do thermal effects depend on temperature change?
- What is the impact of repeated thermal cycling?
Simple thermal packing experiment

0.9 mm glass beads, coefficient of thermal expansion = $9 \times 10^{-6}/K$

PMP plastic cylinders, coefficient of thermal expansion = $117 \times 10^{-6}/K$

Clear effect from even a single thermal cycle

Change in Packing Fraction (%)

Room temperature (22 °C)

0.9mm beads, initial PF 58.8%

0.5mm beads, initial PF 58.9%
Little or no sample size dependence

The relaxation of packing fraction is a bulk effect

0.5 mm glass beads in PMP (plastic) cylinders, initial PF = 58.9 %, cycle temperature 107 °C
Thermal packing dependence on repeated cycles

\[ T = 107 \, ^\circ \text{C} \]

\[ T = 41 \, ^\circ \text{C} \]
Two-component model for compaction

\[ PF = PF_{\text{max}} - A_1 e^{-\frac{n}{\tau_1}} - A_2 e^{-\frac{n}{\tau_2}} \]

Barker and Mehta

Individual grains rearrange \((A_1)\) and larger groups of grains also rearrange \((A_2)\)

Cycle temperature of 107 °C
\[
A_1 = 1.8 \pm 0.1 \quad \tau_1 = 1.7 \pm 0.3 \\
A_2 = 3.2 \pm 0.1 \quad \tau_2 = 58 \pm 6.5
\]

Cycle temperature of 41 °C
\[
A_1 = 0.90 \pm 0.07 \quad \tau_1 = 2.7 \pm 0.5 \\
A_2 = 4.11 \pm 0.06 \quad \tau_2 = 131 \pm 10
\]
Thermal effects to look at next

• What are the microscopic motions during thermal cycling?

• How do thermal effects depend on grain/container properties?
  Grain morphology
  Relative thermal expansion coefficient
  Initial packing

• What other effects might be associated with thermal cycling? Segregation? Cracking of grains?
Part 3: Local Jamming

When a stress is applied to a dense collection of grains, the grains form a rigid "jammed" structure to resist the stress.
Local Jamming is Manifested in Drag Force

Drag is force required to reorganize grains to allow motion
Force is transmitted through force chains of jammed grains
Drag force in air is well-known and has been studied in detail
Drag force in granular media is also well-known, but less well studied -- at least by scientists....
Dragging something through the sand is qualitatively different from dragging through fluids!
Principles of granular drag at low velocities

Grains jam, and then jammed state breaks

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

where:
- \( \eta \) = dimensionless constant (grain surface/morphology/packing)
- \( \rho \) = density of grain material
- \( d_c \) = cylinder diameter
- \( H \) = depth of insertion

\( F_{\text{drag}} \) should be velocity independent -- akin to friction
Measure Drag Force at Low Velocities

Rotating Bucket of Glass Spheres, Cylinder Dipped In

Measure Force to Keep Cylinder Fixed

Vary grain size, velocity, depth, cylinder diameter
Details of Drag Force Apparatus

Cross-Sectional View

Top View
Average Drag Properties

Phys. Rev. Lett. 82, 205 (1999)

\[ F_{\text{drag}} = \eta \rho d_c H^2 \]

in agreement with theoretical expectations

independent of velocity and grain size

\[ F = \eta \frac{g \rho d_c H^2}{d_c} \]

\[ \eta = \frac{F}{d_c^2 \rho g H^2} \]
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

0.9 mm beads
19.1 mm rod
50 mm depth
0.06 mm/s velocity

Aluminium Rod C = 19.1 mm, Bead C = 0.9 mm, Depth = 70 mm
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: effects of finite size

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


- 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
Height dependence of penetration force

- Initial linear force distribution with subsequent rollover
- 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, $F_{\text{bulk}}$

Measure of stress at bucket bottom, $F_0$

0.9 mm beads
25.4 mm plate
Subtraction of background yields surprising minimum in force

\[ \Delta F (N) \]

0.9 mm beads
25.4 mm plate
Why is there a minimum in $\Delta F$?

Forces in bulk need to rearrange ensemble of grains

Near the bottom, grains can slide along surface

Penetration Force (N)

$\Delta$ Penetration Force (N)

$z$ (mm)

Bottom Type
- Smooth
- Rough
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?

Exponential behavior observed in $\Delta F$ approaching bottom boundary for all textures, grain sizes, and real sand

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

Exponential behavior observed in $\Delta F$ approaching bottom boundary for all textures, grain sizes, and real sand

Implies the existence of an intrinsic length scale!
What controls length scale of jammed state?

Length scale of jammed state depends on ambient pressure and plate size ($\lambda \sim [Pr]^{1/2}$) -- but not on grain diameter.

Drag force also independent of grain size (Albert et al., PRE 2001)
Initiating motion through grains: how hard is it to start motion?


How much force is needed to lift the coffin lid?

Of great interest to “taphephobics”!
New apparatus: penetrating grains from below

- Bucket is filled with glass beads
- Plunger begins flush with container’s base
- Plunger is pushed upwards from below through low-friction bearing
Details of apparatus

- Careful and reproducible filling
- Plate is much larger than grains
- Controlled elasticity through spring

Diagram:
- Filling tube
- Plunger
- Spring Joint
- Load Cell
- Stepper Motor
- Transducer
Raw Data: force vs. upward displacement

- Complex behavior associated with emergence of plate
- Focus on force needed to initiate motion
Grain diameter dependence of upward penetration force

- Clear dependence of phenomena on grain size
- Not seen in previous measures of granular drag
Breakout force grows linearly with grain size

- Effect holds over wide range of grain and plate sizes
- Better to be buried under sand than rocks!
- Grain size matters only in terms linear in plate diameter
- Suggests perimeter of plate is where grain size matters
- Presumably related to creation of shear zone to allow motion
Conclusions: Lots of interesting physics in grains

- Jamming leads to unusual drag
- Temperature can have interesting non-linear effects
- Wetting leads to interesting cohesive effects – yet another different type of matter
- Many open issues: the field will be active for years to come!

As scientists, we should spend more time on the beach!
Question & Answer 1
Question & Answer 3