The physics of debris flows:

Making the Montecito mudslides

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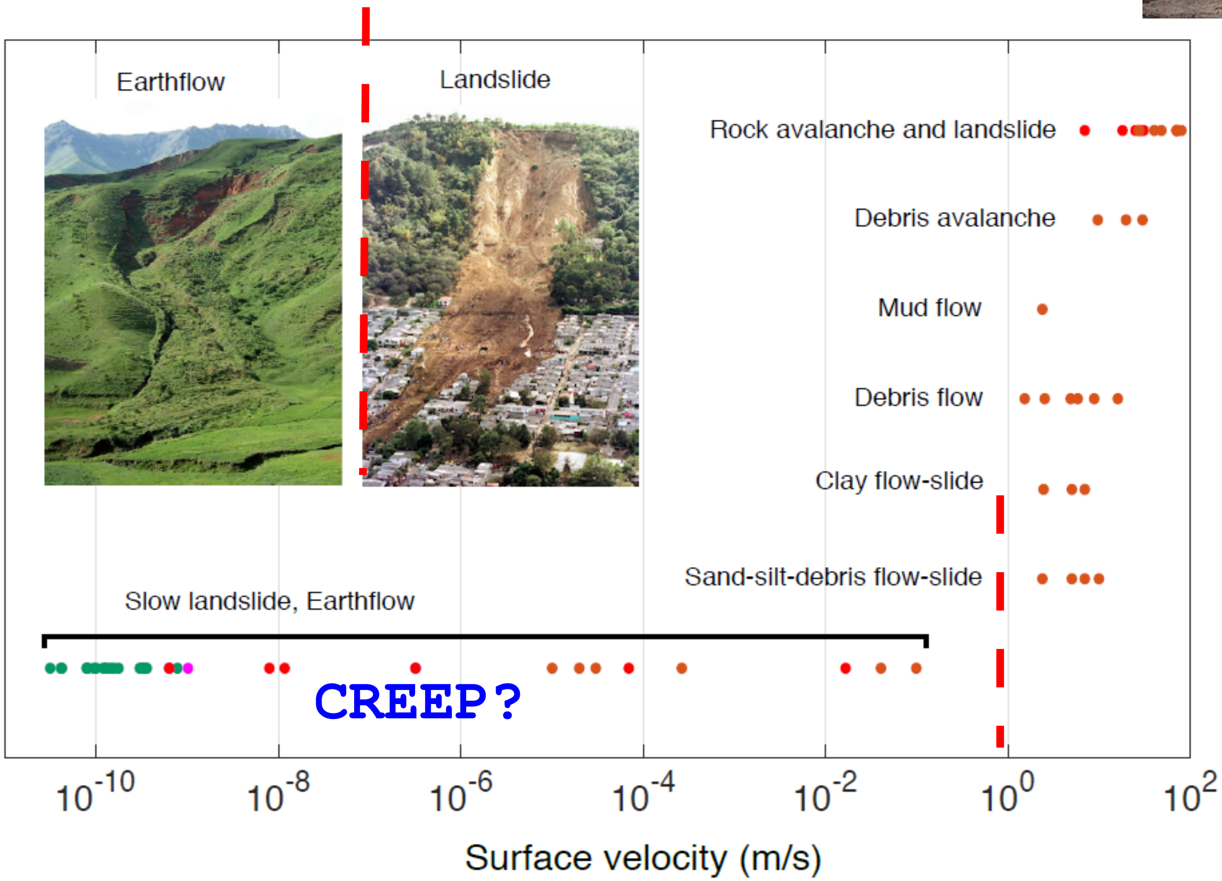
Landscapes:: creeping ↔ flowing



Montecito – 3x vertical exaggeration

Fans: deposits at the mouths of canyons

A landscape built by debris flows

Flow struck early morning: limited direct observation

https://youtu.be/JNl2wUIynvY

0 – 0:40

Boulder-mud debris flow.

"The patrol vehicle was elevated off the road by the mudflow and was spinning without traction. The car was spun 180 degrees after fifteen seconds and was able to gain traction."

https://youtu.be/dDSAwM1nf_c

0:21 – 0:30.
3:39 – 4:16

Viscous suspension
High concentration silt/clay

Debris flow – Ilgraben

https://youtu.be/Fsh5E9m3PrM?list=PLrBn8y0HF3J0XjJt4l2N3BFQdDtjhAGr3

Boulder-rich “dam” front, up to car-sized.

Dense, viscous mud ponded behind

Headwaters – burned hills

Looking upstream at trib. entry to San Ysidro Creek. 12 February, 2018

Source material – mud → gravel

Rills cut into ash and mud, down to unburned soil.

Cold Spring Creek, 26 March 2018. Trib to San Ysidro Creek, 12 Feb.

Source material - boulders

Boulders tumble down valley walls, accumulate in channels.
Looking upstream, bedrock headwater trib. to San Ysidro Creek.
12 February, 2018

The aftermath – canyon

Looking downstream in Cold Spring Creek canyon.

Flow in picture is result of ruptured water line.

Note blown out channel, with boulders and debris.
Many trees were cleared out.

The aftermath – top of fan

A new “boulder field” left behind by the debris flow.

Glen Oaks neighborhood, Montecito.

2 February, 2018.

The aftermath – top of fan

Glen Oaks neighborhood,
Montecito.

2 February, 2018.

The aftermath - down fan

An avocado grove on San Leandro Drive.
San Ysidro Creek.

2 February, 2018.

~20 cm mud drape, still wet 3 weeks after deposition.

Estimating flow depth

Mudline on trees.

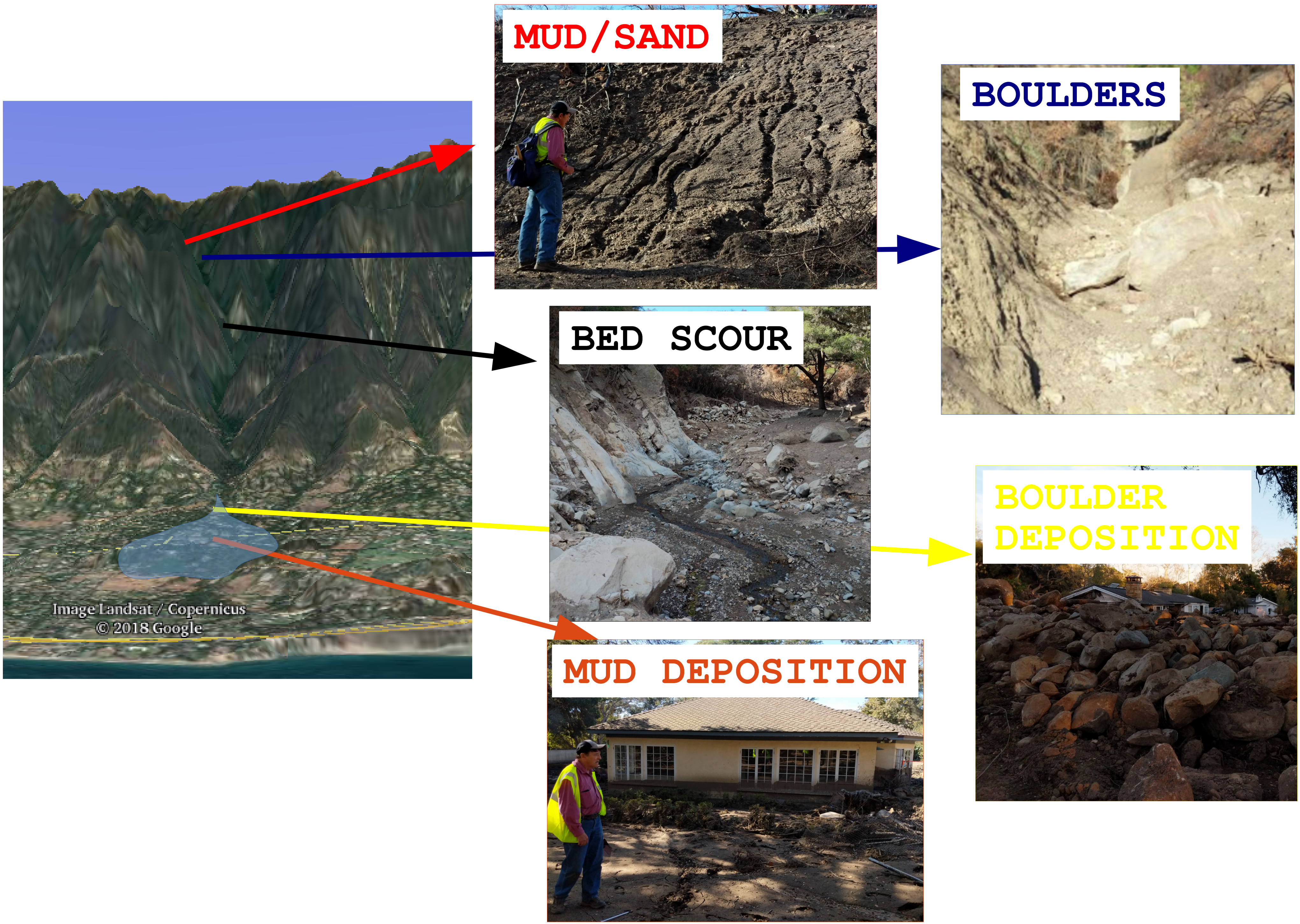
San Ysidro Creek,2 February 2018

Damage on bridge bottom.

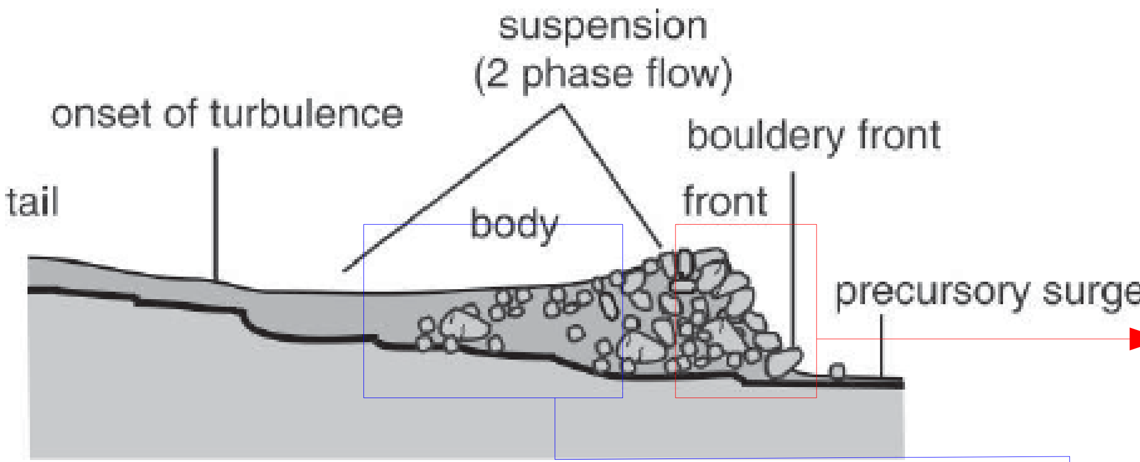
~4 m flow depth

Mud/gravel mix on
~1.5m boulder
~3m above channel

Montecito debris flow zones

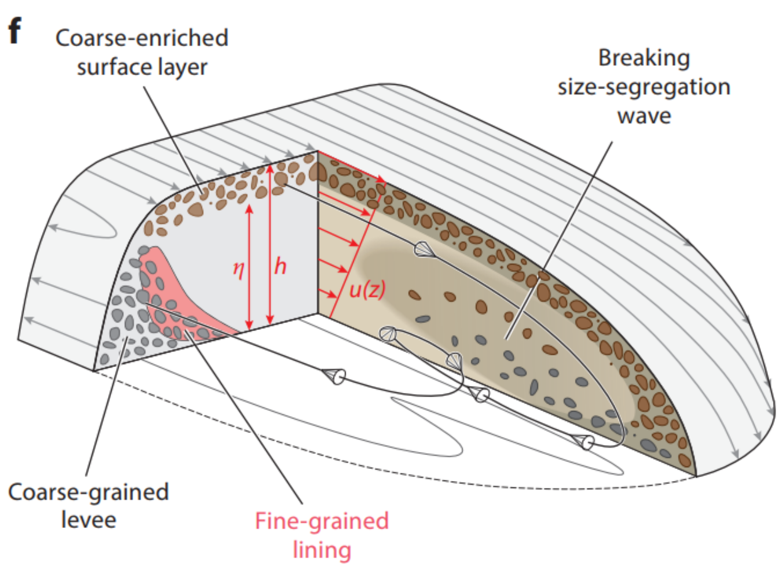


Debris flow – conceptual model



<u>Dense granular flow:</u>
Diameter, $D \sim 1$ m
Depth, $h \sim 1\text{–}4$ m
Velocity, $u \sim 5\text{–}10$ m/s
Stress carried by grains

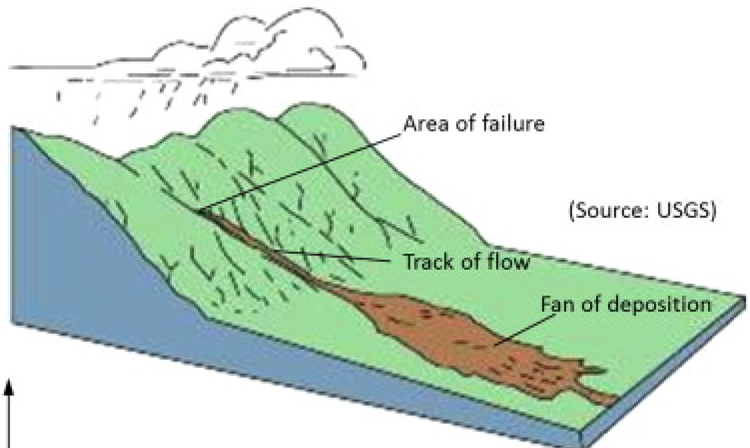
<u>Dense, sedimenting suspension (mudflow):</u>
Diameter, $D < 10^{-3}$ m
Depth, $h \sim 1\text{–}4$ m
Velocity, $u \sim 5\text{–}10$ m/s
Stress carried by fluid
Mud/sand
High concentration → laminar

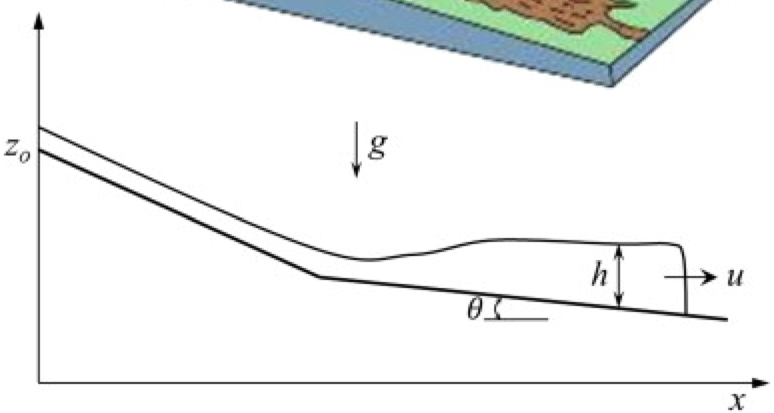


A fluid-granular flow that makes its own boundary.

How do we create this flow?

Montecito debris flow – NOT a landslide

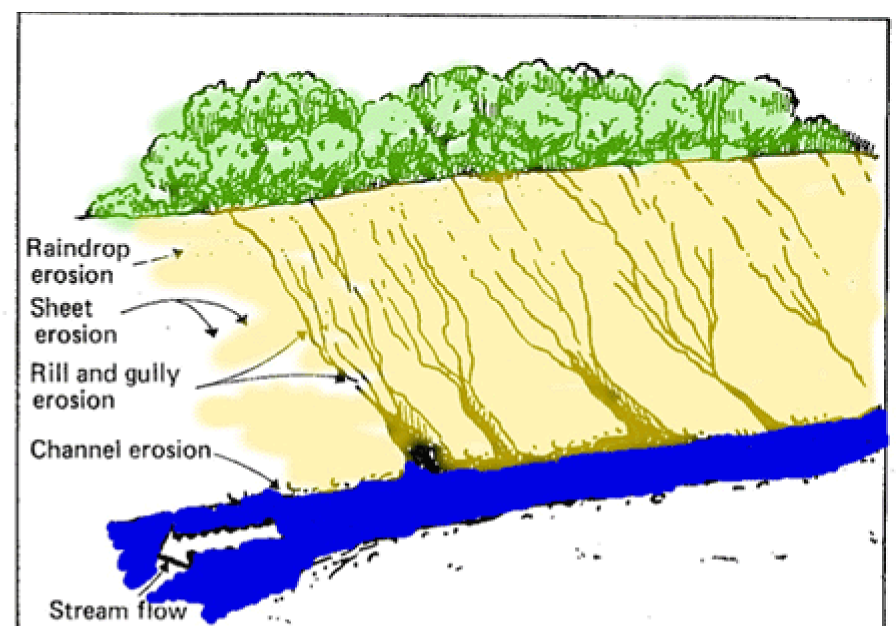




[Paik, *J. Hydro-env. Res.* 2015]

[science-art.com]

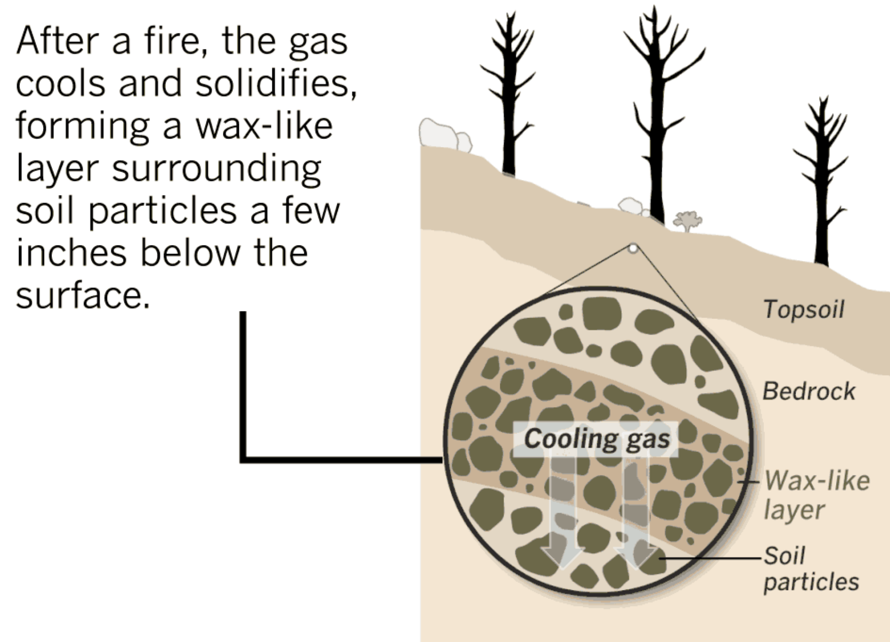
Mud-sand-gravel suspension formed from hillslope runoff.



[http://www.civil.ryerson.ca/Stormwater/menu_5/index.htm]

Mudflow setup: Thomas fire

[Noozhawk.com]



[latimes.com]

[Cerda, *Fire effects on soils and restoration strategies* 2009]

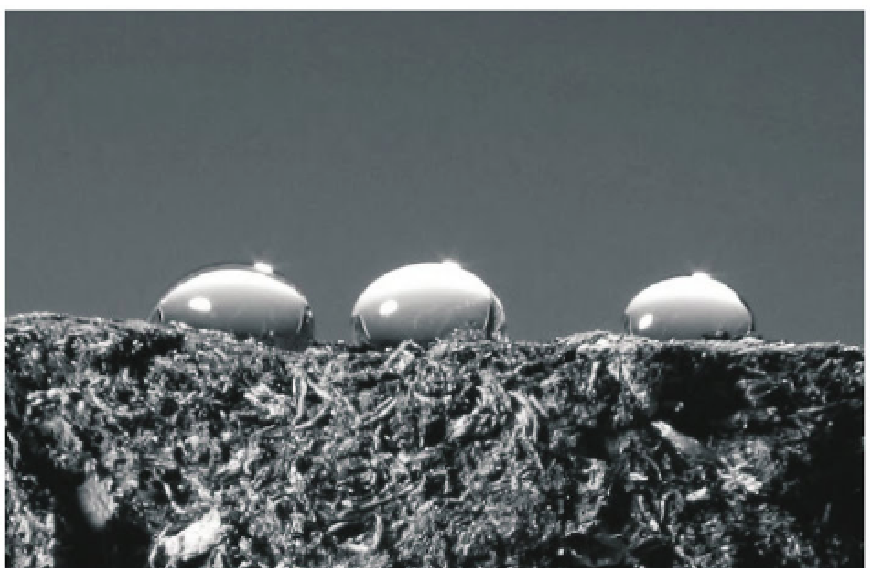
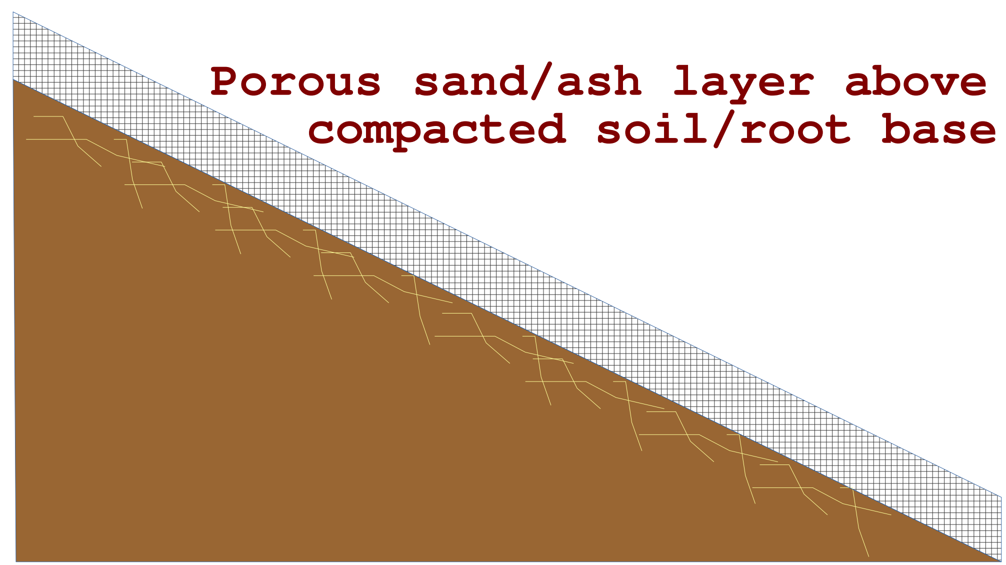
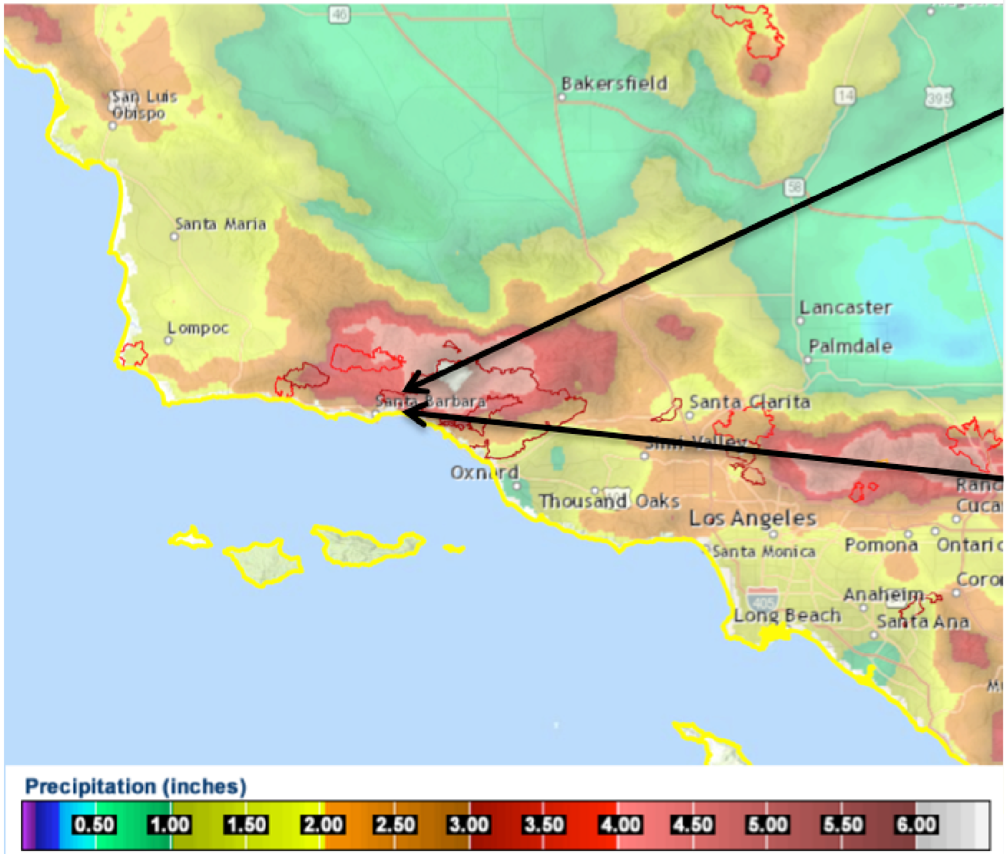
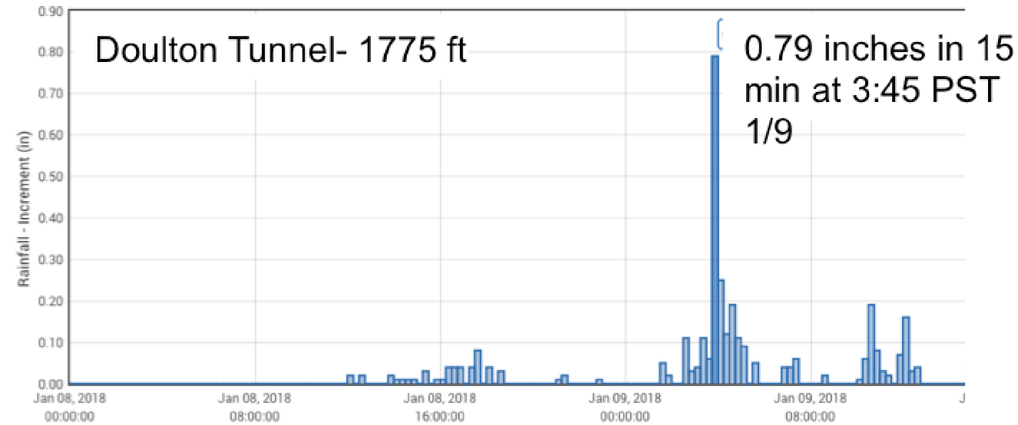


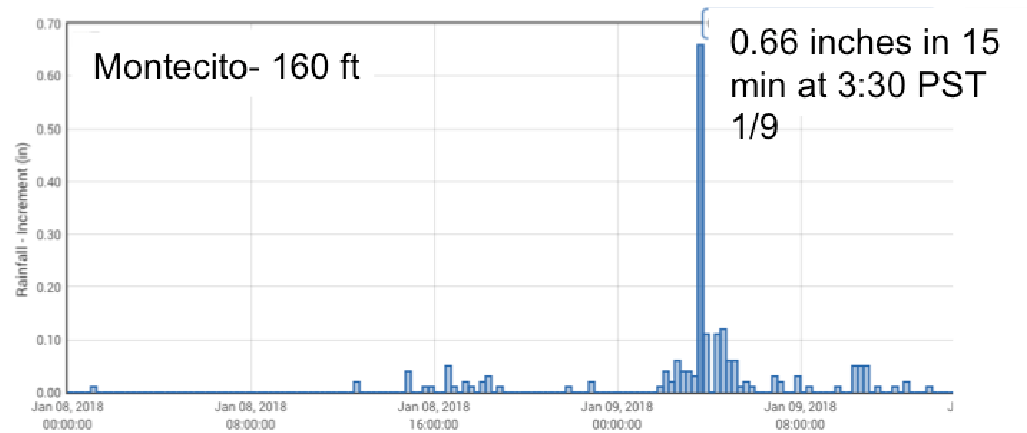
Fig. 1 Water drops resting on a highly repellent organic-rich soil (photo by Erik van den Elsen).



Mudflow trigger: intense rain





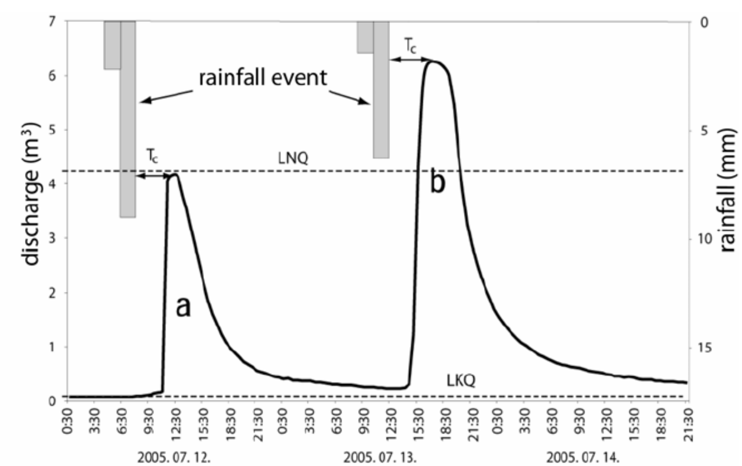


[http://cw3e.ucsd.edu/category/precipitation-event/]

Rainfall: almost delta function

Flash flood: shallow wave

To do: determine hydrograph (Tom Dunne), IC for mudlow

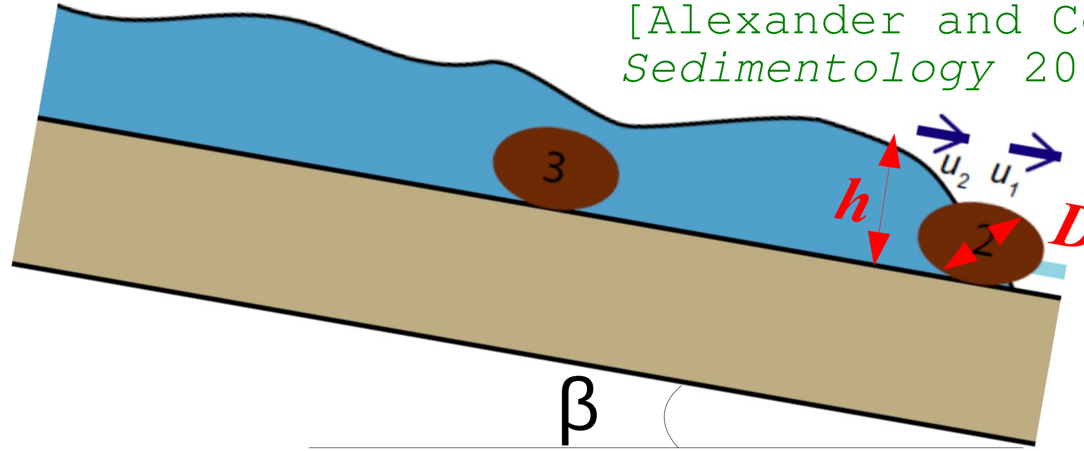


[Loczy et al., *Flash flood hazards* 2012]

Making mudflows on hillsides

Rills cut *almost all the way to ridge*
→ *required very little water accumulation*
Some lobe and mild levee features
→ *viscous flow deposits*
Laboratory experiments:
→ *sediment concentration = f(slope)*
[Aksoy et al., *Hydro. Sci. J.* 2013; Chen et al., *PLoS ONE* 2014]

Boulder entrainment



[Alexander and Cooker, *Sedimentology* 2016]

Force balance on a boulder at initiation of motion:

Drag + Downslope gravity + Impulse + Lift = Friction

Density of boulders, sand and clay, $\rho_s = 2600\ \mathrm{kg/m^3}$

Density of clear water, $\rho_f = 1000\ \mathrm{kg/m^3}$

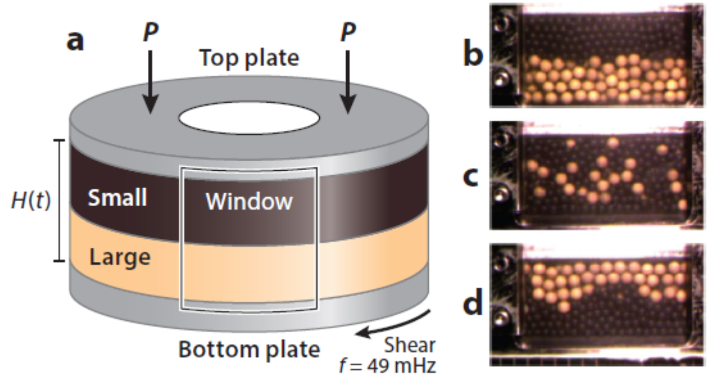
Density of mudflow, ~60% solids, $\rho_f = 2000\ \mathrm{kg/m^3}$

→ Mud reduces h_{crit} 3x compared to water, **due to density**.
→ Lubrication reduces friction, μ_f 2x or more.
→ Flow depth to move boulders as small as *D*/10!

→ Lift force on boulders is doubled in mudflow.

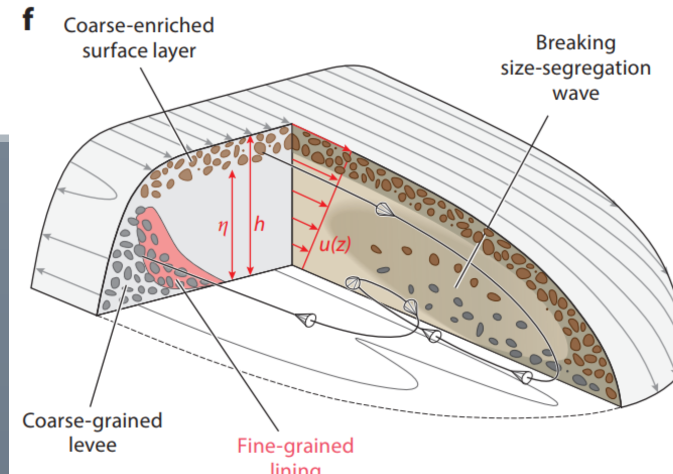
Creating a boulder dam: Granular segregation(?)

[*Wikipedia*]

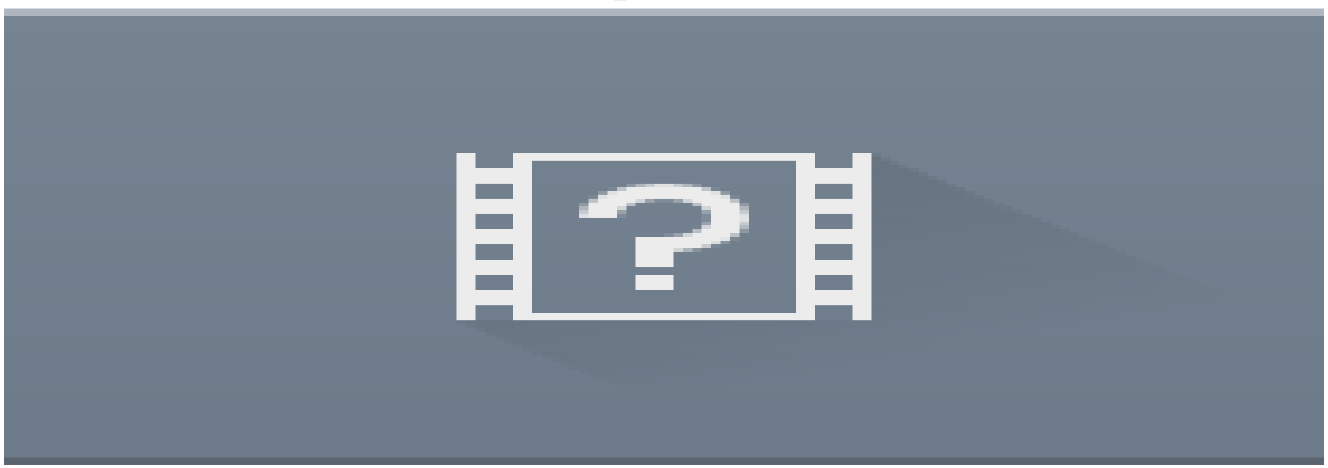


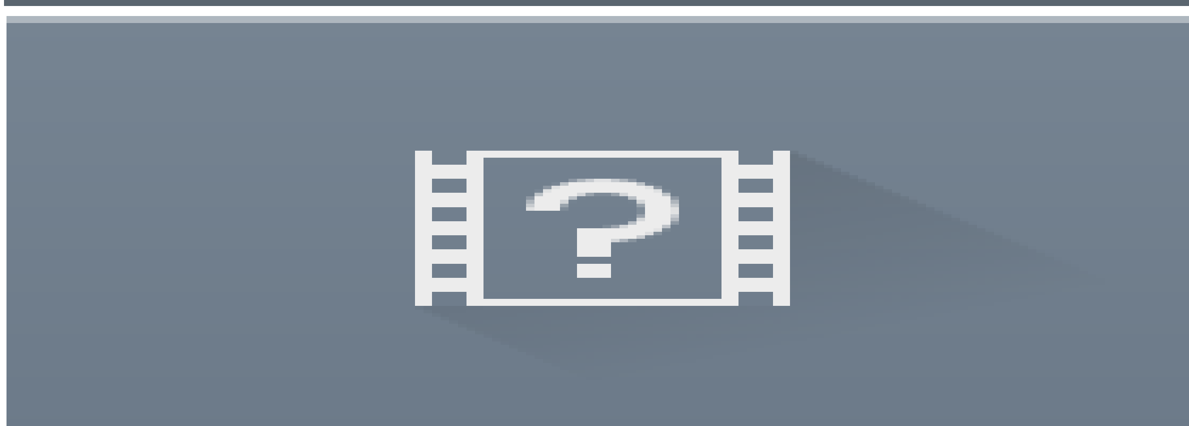
[Golick & Daniels, *Phys. Rev. E* 2009]

Vibrated and sheared granular systems size segregate
→ Large grains "float"



[Gray, *Ann. Rev. Fluid Mech.* 2017]





Produces fronts and levees of large grains.

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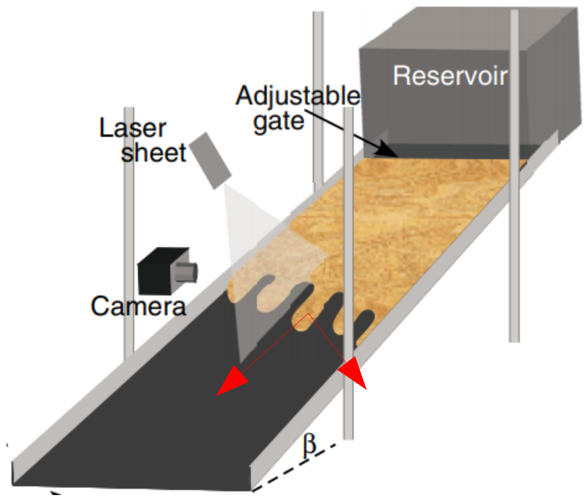
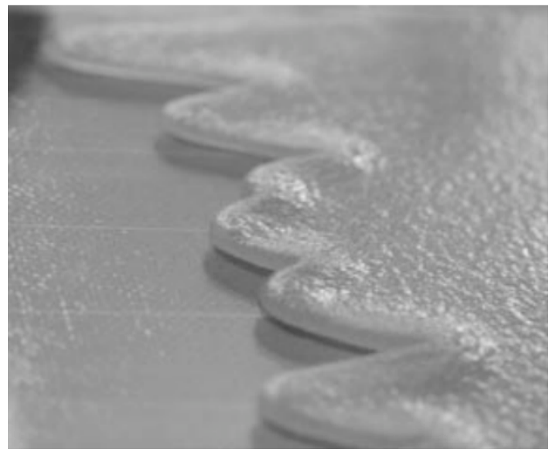
But granular fronts form in fluids...

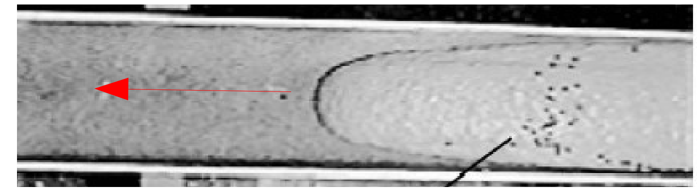
PRL 94, 117803 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

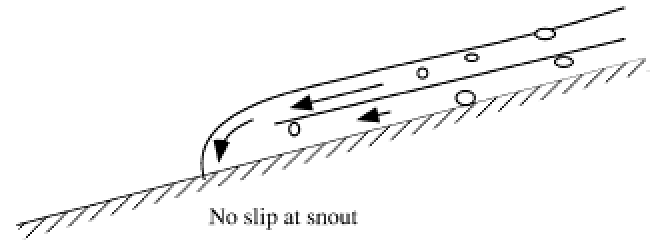
Theory for Shock Dynamics in Particle-Laden Thin Films

Junjie Zhou,[1] B. Dupuy,[1] A. L. Bertozzi,[2] and A. E. Hosoi[1]

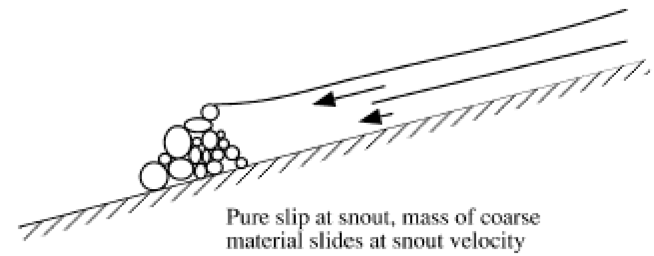






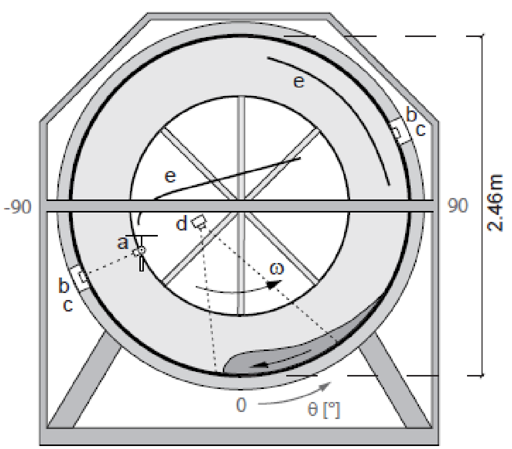


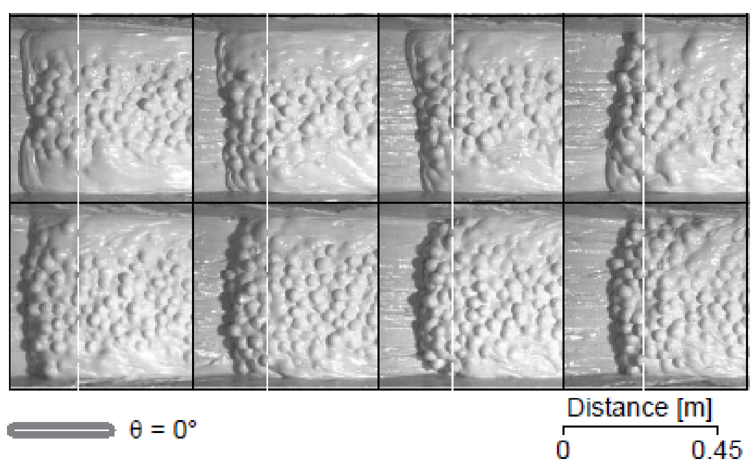
Debris flow without or prior to snout effect. Conveyor belt driven by body motion constantly and consistently lays down a new front from behind.

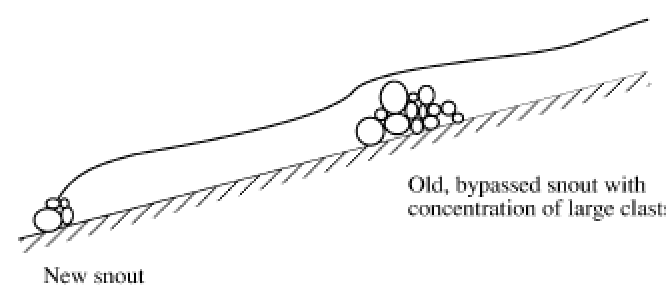


Snout effect. Larger clasts collect at front, shutting off the conveyor. Freezing of body occurs from front backward. Backwater also forms.

Drag + gravity > settling

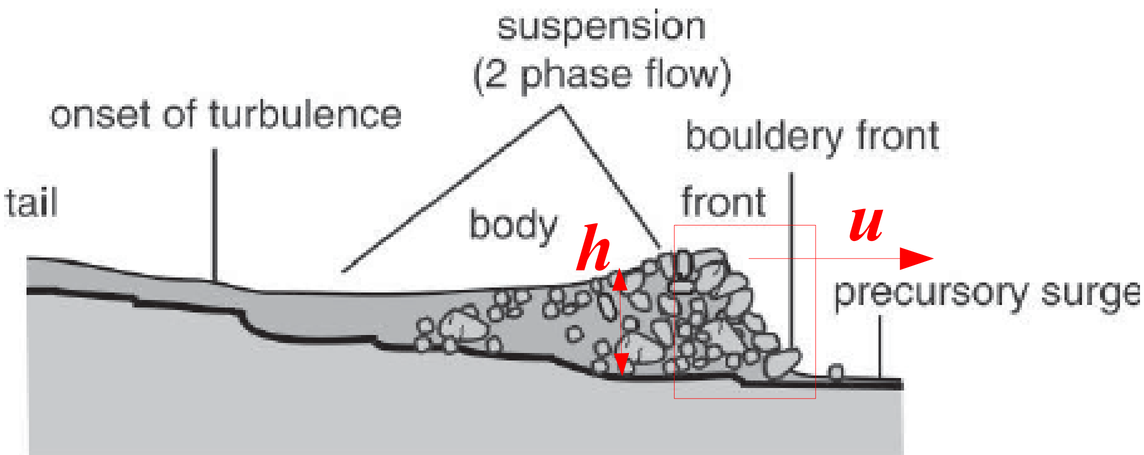






[Leonardi et al., *Phys. Rev. E* 2015] [Parsons et al., *J. Geology* 2001]

Boulder front: relevant scales



Front moves as wave:

$$Fr = \frac{u}{\sqrt{gh}} \approx 1$$

h = 1-4 m
u = 5-10 m/s

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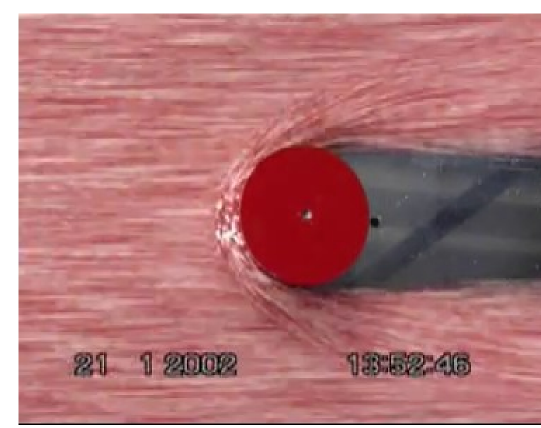
Collisions >> viscosity

$$St = \frac{(\rho_s - \rho_f) D u}{\eta_f} \sim 10^6$$

$$\frac{\text{Particle inertia}}{\text{Fluid viscosity}}$$



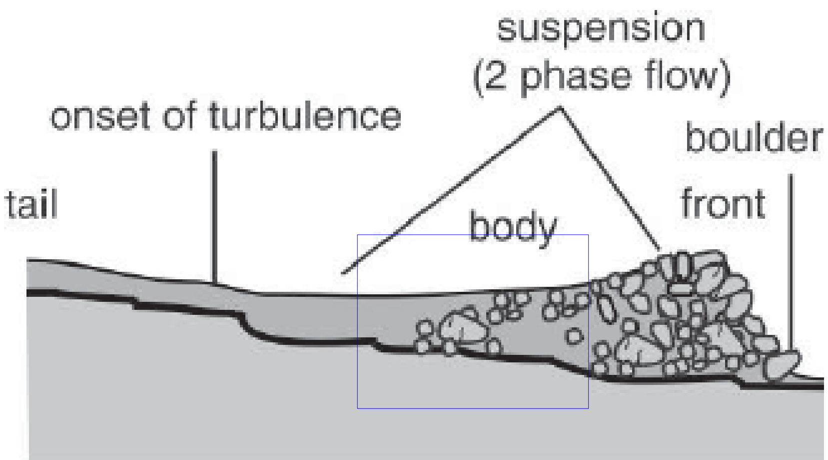
Fast, collisional flow

$$I = \frac{\dot{\gamma} d}{\sqrt{P/\rho}} \sim 1$$

$$\frac{\text{Shear (flow)}}{\text{Confining pressure}}$$

[Cui and Gray., *J. Fluid Mech.* 2013]

Mud phase: scales



Viscous: collisions strongly damped

$$St = \frac{(\rho_s - \rho_f)Du}{\eta_f} \sim 10 \qquad << 10^2$$

Frictional: slowly deforming

$$I = \frac{\dot{\gamma} d}{\sqrt{P/\rho}} \sim 10^{-4} \qquad << 10^{-3}$$

Consider mud as viscous fluid with yield stress:

$$(\tau_b - \tau_o)/\dot{\gamma} = \eta_{eff} \approx 300 \text{ Pa} \cdot \text{s} \qquad Re = \rho_f h u / \eta_{eff} \sim 10^{2}$$

→ ***viscosity > 10^5 water*** → ***transitional flow***


Reports on Progress in Physics

Video Abstract

Shear thickening in concentrated suspensions: phenomenology, mechanisms and relations to jamming

Eric Brown and Heinrich M Jaeger 2014 Rep. Prog. Phys. 77 046602

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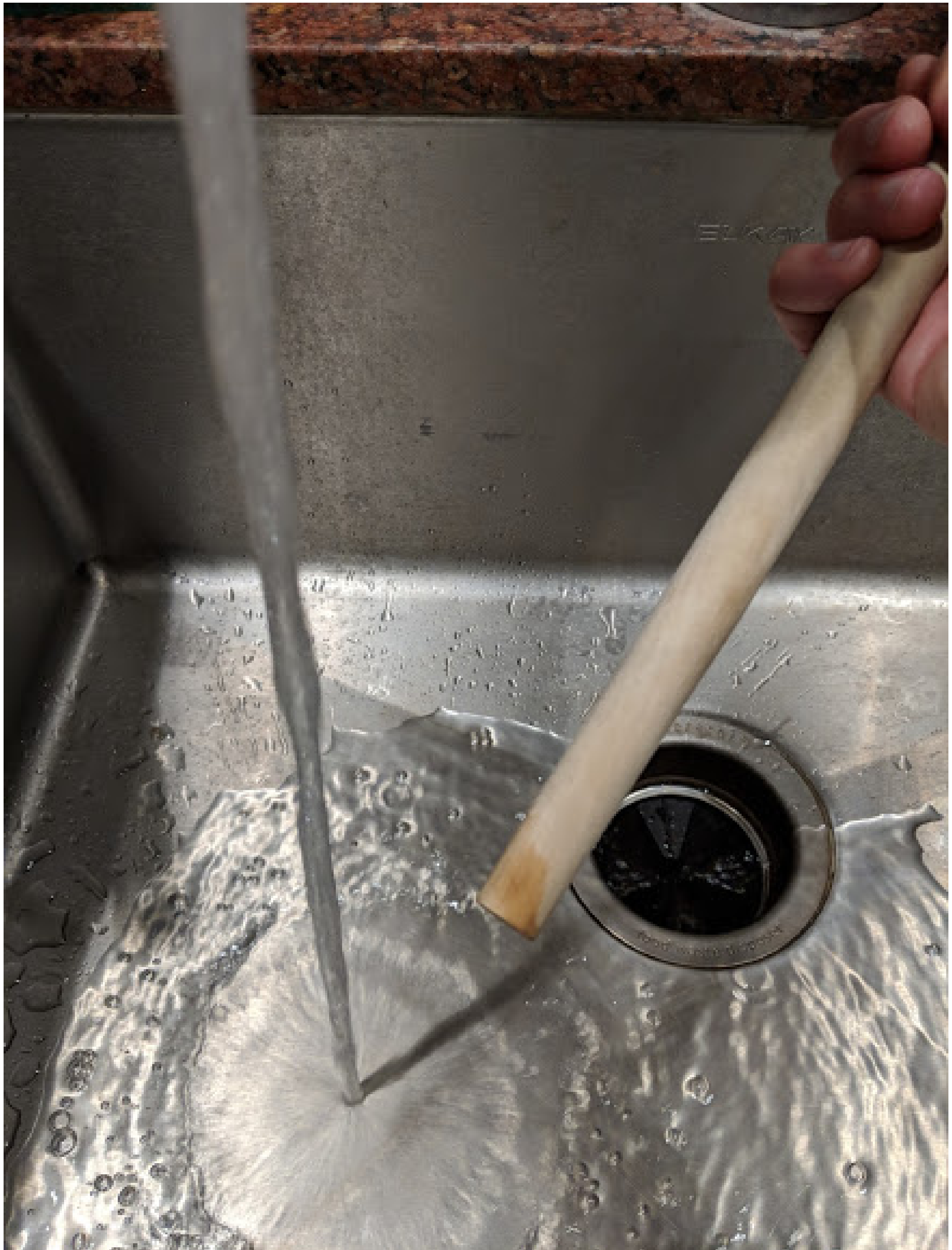
Shear thickening suspensions

Mud phase comparison: your sink



Froude number

$$Fr = \frac{u}{\sqrt{gh}} \quad \geq 1$$

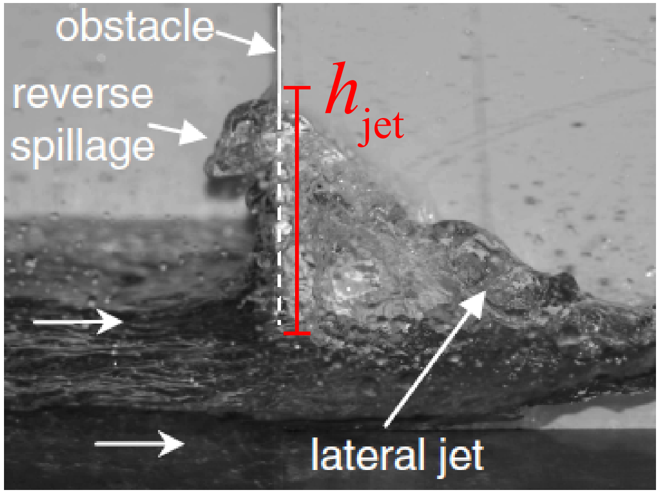
$h \sim 0.001$ m

$\rightarrow u \sim 0.1$ m/s

Reynolds number

$$Re = \rho_f h u / \eta_{eff} \sim 10^2$$

Mud phase: scales



[Riviere et al., *J. Hydraulic Eng.* 2017]

Energy balance argument for wall jet height (no backwater):

$$h_{jet} \approx \frac{u^2}{2g}$$

$u = 10\,\mathrm{m/s} \rightarrow h_{jet}$ up to 5 m!

High mud runup (splash) on trees consistent with flow estimates.

Mud phase: rheology

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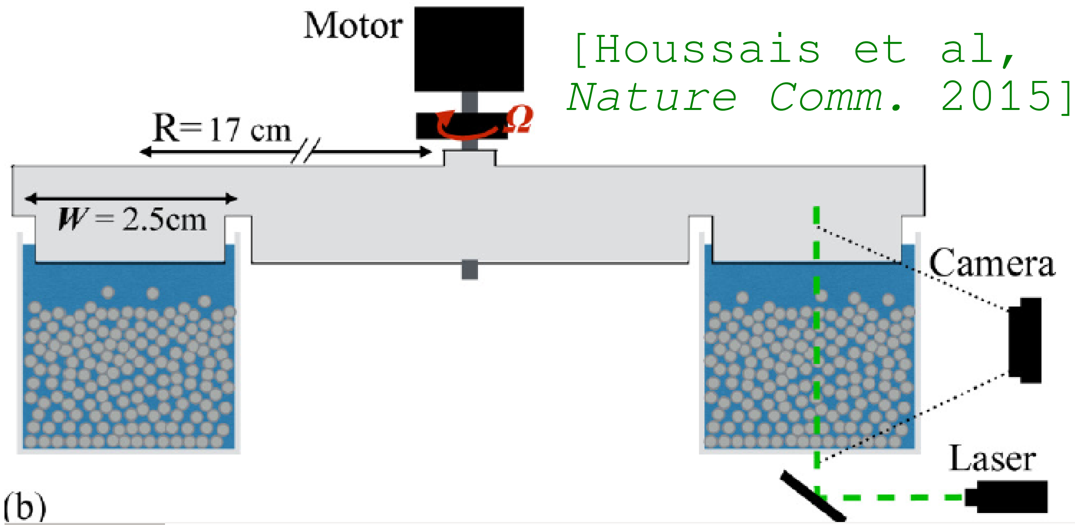
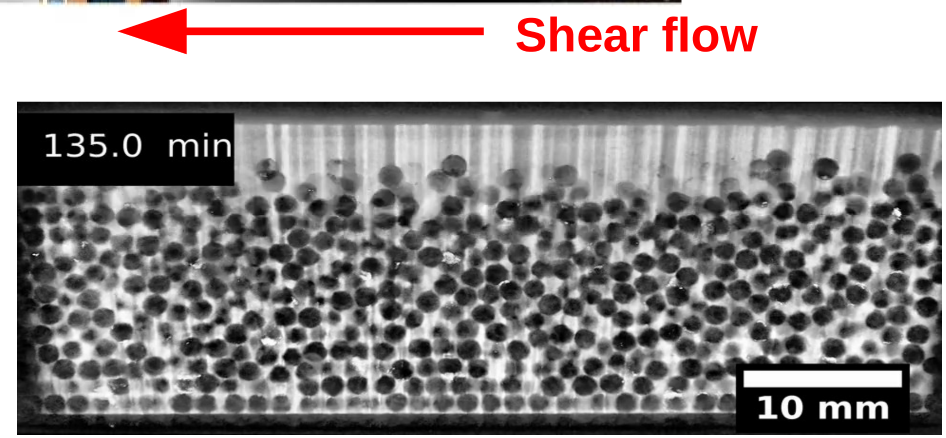
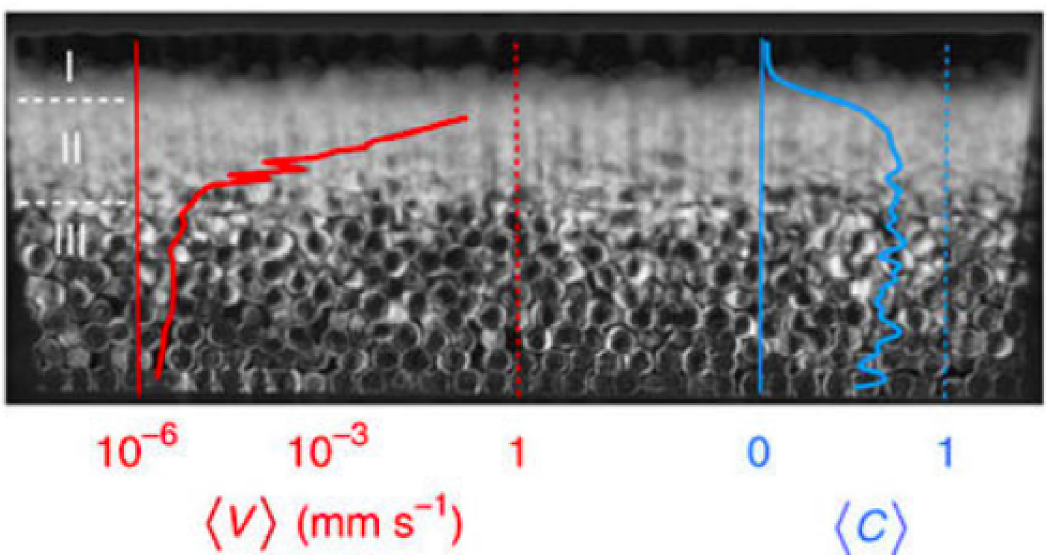
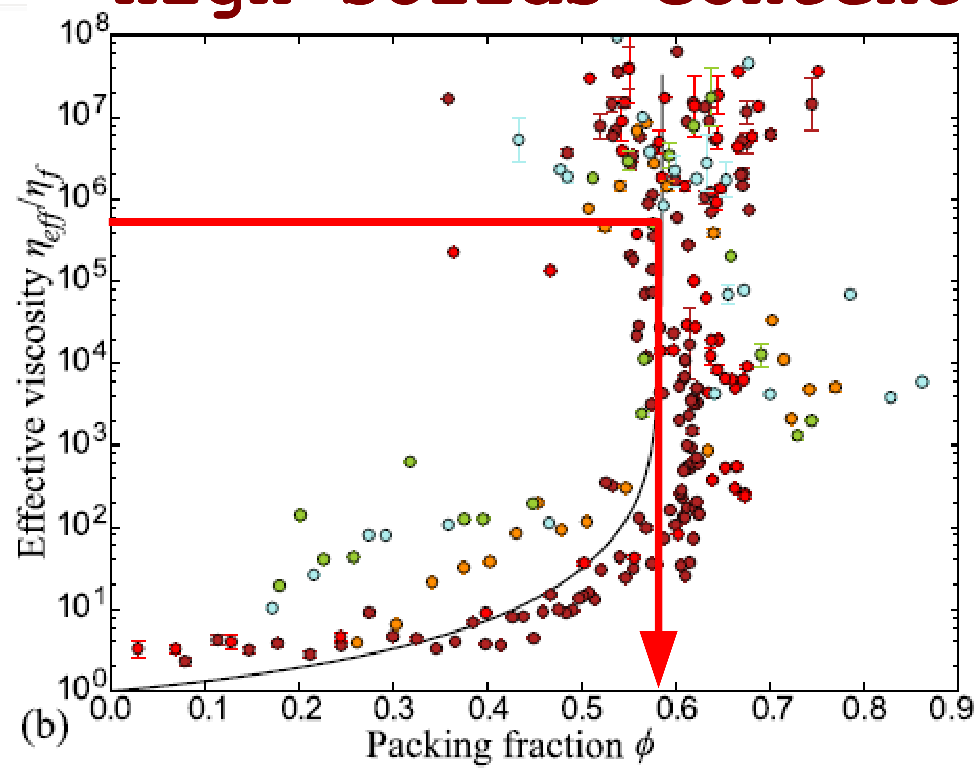
[Houssais et al, *Nature Comm.* 2015]





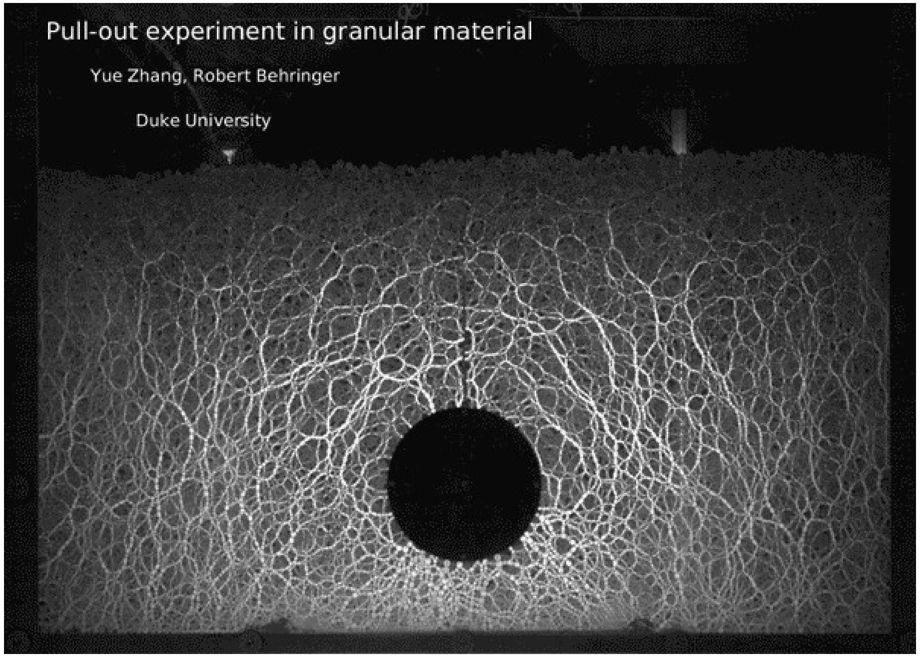


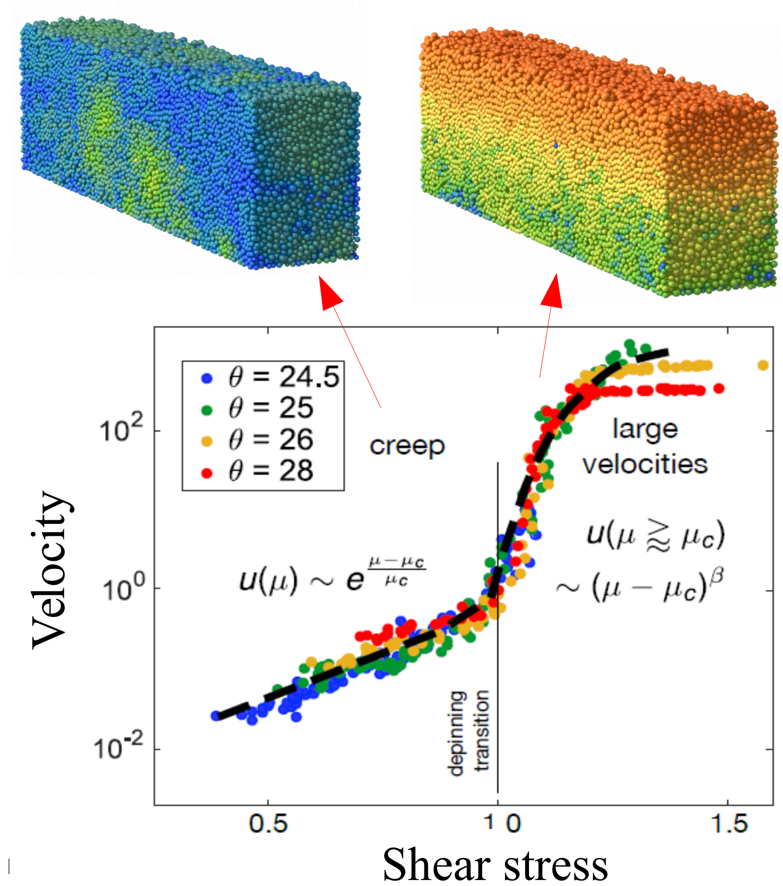
High solids content



~60% solids by volume

Outstanding problem: "liquefaction", creep → flow transition





[Ferdowsi, Ortiz and Jerolmack, *PNAS 2018*]

Creep → flow transition: Glassy dynamics?

Shear-thickening (or thinning), force chains, cohesion...

Gradual, viscous failure: physics are un(der)studied
→ Pore pressure vs. lubrication, material controls