The physics of debris flows: Making the Montecito mudslides

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Landscapes:: creeping ↔ flowing

Santa Barbara, 9 January 2018
Montecito – 3x vertical exaggeration

Fans: deposits at the mouths of canyons
A landscape built by debris flows
Flow struck early morning: limited direct observation

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/JNl2wUIynvY
0 – 0:40

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

San Ysidro Creek, 2 February 2018

Damage on bridge bottom.

~4 m flow depth

Mudline on trees.

Mud/gravel mix on ~1.5m boulder ~3m above channel
Montecito debris flow zones

- MUD/SAND
- BOULDERS
- BED SCOUR
- BOULDER DEPOSITION
- MUD DEPOSITION
Debris flow – conceptual model

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

Dense, sedimenting suspension (mudflow):
- Diameter, $D < 10^{-3} \text{ m}$
- Depth, $h \sim 1-4 \text{ m}$
- Velocity, $u \sim 5-10 \text{ m/s}$
- 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

Mud–sand–gravel suspension formed from hillslope runoff.
Mudflow setup: Thomas fire

After a fire, the gas cools and solidifies, forming a wax-like layer surrounding soil particles a few inches below the surface.

[Noozhawk.com]
[Cerda, Fire effects on soils and restoration strategies 2009]

Porous sand/ash layer above compacted soil/root base.

[latimes.com]

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

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

Force balance on a boulder at initiation of motion:

Drag + Downslope gravity + Impulse + Lift = Friction

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

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

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

→ Mud reduces $h_{crit}$ 3x compared to water, due to density.
→ Lubrication reduces friction, $\mu_f$ 2x or more.
→ Flow depth to move boulders as small as $D/10$!
→ Lift force on boulders is doubled in mudflow.

[Alexander and Cooker, Sedimentology 2016]
Creating a boulder dam: Granular segregation (?)

Vibrated and sheared granular systems size segregate → Large grains “float”

Produces fronts and levees of large grains.

But granular fronts form in fluids...

Theory for Shock Dynamics in Particle-Laden Thin Films

Junjie Zhou,1 B. Dupuy,1 A.L. Bertozzi,2 and A.E. Hosoi1

Drag + gravity > settling

Boulder front: relevant scales

Front moves as wave:

\[ Fr = \frac{u}{\sqrt{gh}} \approx 1 \]

\[ h = 1-4 \text{ m} \]
\[ u = 5-10 \text{ m/s} \]

Collisions >> viscosity

\[ St = \frac{(\rho_s - \rho_f)Du}{\eta_f} \sim 10^6 \]

Fast, collisional flow

\[ I = \frac{\gamma d}{\sqrt{P/\rho}} \sim 1 \]

[Particle inertia] [Fluid viscosity]

Particle inertia

Fluid viscosity

Shear (flow)

Confining pressure

[Cui and Gray., J. Fluid Mech. 2013]
**Mud phase: scales**

Viscous: collisions strongly damped

\[ St = \frac{(\rho_s - \rho_f)Du}{\eta_f} \sim 10 \ll 10^2 \]

Frictional: slowly deforming

\[ I = \frac{\dot{\gamma}d}{\sqrt{P/\rho}} \sim 10^{-4} \ll 10^{-3} \]

Consider mud as viscous fluid with yield stress:

\[ \frac{(\tau_b - \tau_o)}{\dot{\gamma}} = \eta_{eff} \approx 300 \text{ Pa} \cdot \text{s} \]

→ viscosity > $10^5$ water

→ transitional flow

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Reports on Progress in Physics

**Video Abstract**

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


Shear thickening suspensions
Mud phase comparison: your sink

Froude number

\[ Fr = \frac{u}{\sqrt{gh}} \geq 1 \]

\[ h \sim 0.001 \text{ m} \]

\[ \rightarrow u \sim 0.1 \text{ m/s} \]

Reynolds number

\[ Re = \frac{\rho_f h u}{\eta_{eff}} \sim 10^2 \]
Mud phase: scales

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

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

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

High mud runup (splash) on trees consistent with flow estimates.
Mud phase: rheology

[Image of experiment setup with a motor, radius R=17 cm, width W=2.5 cm, and a camera and laser]

High solids content

~60% solids by volume

[Houssais et al, Nature Comm. 2015]

Shear flow

135.0 min

Effective viscosity $\eta_{\text{eff}}$/[Pa s] vs Packing fraction $\phi$

$\langle V \rangle$ (mm s$^{-1}$)

$\langle C \rangle$
Outstanding problem: “liquefaction”, creep → flow transition

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

[Ferdowsi, Ortiz and Jerolmack, PNAS 2018]