Making the Montecito Mudslides:
Unpacking the (relevant) physics of debris flows

Douglas Jerolmack\textsuperscript{1,2}, Thomas Dunne\textsuperscript{3}
1. PennSeD, Earth & Environmental Science, Univ. Pennsylvania
2. Mechanical Engineering & Applied Mechanics, Univ. Pennsylvania
3. Bren School, UC Santa Barbara

[sediment@sas.upenn.edu]
Landscapes:: creeping ↔ flowing

Santa Barbara, 9 January 2018

CREEP?
Montecito – 3x vertical exaggeration

A landscape built by debris flows
Flow struck early morning: limited direct observation

0 – 0:40.
3:10 – end

https://youtu.be/JNl2wUlynvY

3:10 – end

https://youtu.be/dDSAwM1nf_c

0:21 – 0:30.
2:07 – 2:21

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.”

Viscous suspension
High concentration silt/clay
Surges continued for hours
(cf. Nico Gray’s talk)

https://youtu.be/HALHkKcFbg8

~1m deep, mud-rich flow pushing ~1m boulders. Speed is ~5 m/s.

“2 phases”: boulder-rich front → dense granular flow, makes a “dam”. Mud-rich flow behind: a visco-plastic (non-Newtonian) fluid(?)
Debris flow - Ilgraben

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

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

Dense, viscous mud ponded behind
Looking upstream at trib. entry to San Ysidro Creek. 12 February, 2018
Source material – mud → gravel

Dry ravel moving into channel.  Rills cut into ash and mud.

Cold Spring Creek, 6 February 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
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

Mudline on trees.

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

Damage on bridge bottom.

~4 m flow depth
Montecito debris flow zones

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

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

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

How do we create this flow?
Montecito debris flow – NOT a landslide

Mud-sand-gravel suspension formed from hillslope runoff.

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

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

[latimes.com]

[Cerda, *Fire effects on soils and restoration strategies* 2009]
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 all the way to ridge → no water accumulation
Some lobate and mild levee features → viscous flow deposits
Laboratory experiments:
→ sediment concentration = f(slope)
Boulder entrainment

[Alexander and Cooker, Sedimentology 2016]

Force balance on a boulder at initiation of motion:

\[
\frac{1}{2} C_D \rho_f A_s u^2 + F'_g \sin(\beta) + k u \frac{\partial u}{\partial x} V_s \rho_f - F'_g \cos(\beta) \mu_f = 0
\]

Drag  Downslope-g  Impulse  Friction  \( F'_g = (\rho_s - \rho_f) g D \)

\( a \sim gh/D \)

(Neglect lift force since \( h \sim D \):)

Front moves as wave: \( Fr \approx 1 \rightarrow h_{\text{crit}} \approx \left( \frac{\rho_s}{\rho_f} - 1 \right) \frac{\mu_f D}{0.5 C_D + k} \)

Mud reduces \( h_{\text{crit}} \) 3x compared to water, due to density.
Lubrication reduces \( \mu_f \) 2x or more.

Condition for lift: \( (u_i^2 - u_b^2) \approx \frac{2gD}{C_L} \left( \frac{\rho_s}{\rho_f} - 1 \right) \)

\( h_{\text{crit}} \) as small as \( D/10! \)
Mud reduces \( u_{\text{crit}} \) 2x compared to water.
Creating a boulder dam: Granular segregation (?)

*Annual Review of Fluid Mechanics*

Particle Segregation in Dense Granular Flows

John Mark Nicholas Timm Gray

(cf. Nico Gray’s talk)

But granular fronts form in fluids too...

\[ \text{Theory for Shock Dynamics in Particle-Laden Thin Films} \]

\[ \text{Junjie Zhou, B. Dupuy, A.L. Bertozzi, and A.E. Hosoi} \]

\[ \text{Department of Mechanical Engineering, Hatsopoulos Microfluids Laboratory, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA} \]

\[ \text{UCLA Mathematics Department, Box 951555, Los Angeles, California 90095-1555, USA} \]

\[ \text{(Received 20 July 2004; published 23 March 2005)} \]

We present a theory to explain the emergence of a particle-rich ridge observed experimentally in a thin film particle-laden flow on an incline. We derive a lubrication theory for this system which is qualitatively compared to preliminary experimental data. The ridge formation arises from the creation of two shocks due to the differential transport rates of fluid and particles. This parallels recent findings of double shocks in thermal-gravity-driven flow [A. L. Bertozzi et al., Phys. Rev. Lett. 81, 5169 (1998); J. Sun et al., ibid. 90, 126105 (2003); A. Münch, ibid. 91, 016105 (2003)]. However, here the emergence of the shocks arises from a new mechanism involving the settling rates of the species.

“Intuitively, we expect the large ridge to arise if the particle settling velocity along the plate exceeds that of the front.”

\[ \rightarrow \text{Invokes hindered settling in high concentrations} \]

\[ \text{[Suwa, Dissertation, Kyoto University 1988]} \]

\[ \text{Clear-water flood waves over gravel} \]

“[A] larger boulder attains a higher terminal velocity on a steep slope and focuses faster to the front.”

\[ \text{[Image showing a diagram of a flood wave experiment]} \]
Granular fronts in mud

Sedimentation + shear...

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

Pure slip at snout, mass of coarse material slides at snout velocity.

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

[Parsons et al., J. Geology 2001]

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 \textit{if fluid is clear water...}

\[ St = \frac{(\rho_s - \rho_f)Du}{\eta_f} \sim 10^6 \]
\[ N_b = \frac{\phi_s(\rho_s - \rho_f)D^2\frac{\partial u}{\partial h}}{(1 - \phi_s)\eta_f} \sim 10^6 \]

\textit{...but collisions \sim viscosity for concentrated muds.}

Inertial \sim Confining/normal stress

\[ N_s = \frac{\rho_s D^2 \left(\frac{\partial u}{\partial h}\right)^2}{(\rho_s - \rho_f)gh} \sim 1 \]
\[ I = D \left(\frac{\partial u}{\partial h}\right) \sqrt{(\rho_s - \rho_f)/P^p} \sim 1 \]
Mud phase: scales

Boundary shear stress: \[ \tau_b = \rho_f ghS \]
\[ S \approx 0.1 \]
\[ \rho_f \approx 2000 \text{ kg/m}^3 \]

Flow resistance estimate of \( u \):

\[ u = C_f \sqrt{ghS} \log(h/D) \approx 10 \sqrt{ghS} \approx 10 \text{ m/s} \]


Mud phase: viscous, frictional flow

**Viscous**

\[ N_b = \frac{\phi_s (\rho_s - \rho_f) D^2 \frac{\partial u}{\partial h}}{(1 - \phi_s) \eta_f} \sim 1 \]

**Frictional**

\[ N_s = \frac{\rho_s D^2 (\frac{\partial u}{\partial h})^2}{(\rho_s - \rho_f) gh} \sim 10^{-6} \]

**Herschel-Buckley rheology:**

\[ \tau = \tau_0 + k \dot{\gamma}^n \]

Yield stress  Viscosity (if \( n = 1 \))

\[ h \sim 0.2 \text{ m mud} \]

‘frozen’ on \( S \sim 0.04 \)

\[ \tau_0 = \rho_f g h S \]

**Yield stress:**

\[ \tau_0 \sim 200 \text{ Pa} \]

**VISCOSITY: Bingham:** \( n = 1 \) for high shear rates (??)

\[ \left( \tau_b - \tau_0 \right) / \dot{\gamma} = \eta_{eff} \approx 300 \text{ Pa} \cdot \text{s} \]

\( \rightarrow \) viscosity \( > 10^5 \) water

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

\( \rightarrow \) transitional flow

[Phillips & Davies, Geomorphology 1991]
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

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

\[ h_{jet} \approx \frac{u^2}{2g} \]

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

\[ Fr \geq 1 \]

Mudlines indicate \( h_{jet} \) up to \(~4\, \text{m} (!!!)\)

\[ \rightarrow u = 9\, \text{m/s} \]

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

[Phillips & Davies, Geomorphology 1991]
Mud phase: rheology and solids content

$\tau = \mu P_p = \eta_{\text{eff}} \dot{\gamma}$

$I_v = \frac{\eta_f |\dot{\gamma}|}{P_p} \sim 10^{-6}$

$\phi = \frac{\phi_c}{1 + I_v^{1/2}}$

High solids content

Friction coefficient $\mu$

Viscous number $I_v$

Effective viscosity $\eta_{\text{eff}}/\eta$

Packing fraction $\phi$
Inferred debris flow properties similar to Iverson experiments/theory:

\[ \phi \approx 0.6 \rightarrow \rho_f \approx 2000 \text{ kg/m}^3 \]

\[ u = 10 \text{ m/s} \quad \tau_y \approx 100\text{ Pa} \cdot \text{s} \]

Darcy #:

\[ N_{Dar} = \frac{\eta_f}{\phi \rho_s \gamma\kappa} \approx 10^5 \]

Significant fluid pressures

[Iverson, Rev. Geophys. 1997]
Outstanding problems 1: rheology/tribology of polydisperse suspensions

Sand breaks contact networks of clay/silt?
Clay/silt lubricates sand?

[Ancy, J. Rheology 2001]

A direct application of the present results concerns the physics of debris flows in mountain areas. To explain the striking mobility of these natural flows involving a wide range of materials (fine sediment, boulders, etc.), geologists usually evoke the pore-fluid pressure as the key mechanism. In this article it was shown that a fluid-like state is reached for very concentrated slurries when contact between coarse particles is lubricated by the interstitial fluid. Such an explanation appears to the author to be better founded. Moreover, it should be possible to predetermine bulk behavior of natural slurries depending on its composition, at least in simple cases. This would be a result of primary importance in engineering.

(cf. Sarah Hormozi talk)

Debris flow: dense non-colloidal suspension in yield stress fluid? → Grain polydispersity is challenging!
Outstanding problems 2: phase separation/segregation of particles and fluids

Unsaturated boulder front:
- Very destructive
- Enhances flood levels behind

Formation depends on:
- Shear rate
- Fluid viscosity (?)
- Fines content (?)


[Kaitna et al., Int. Conference, 2011]
Outstanding problems 3: gradual liquefaction and continuous failure by wetting

Shear-induced liquefaction is reasonably well studied.

Rainfall-induced landslides commonly reported.

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

https://youtu.be/Rd6W2aP2dkA

[Wijdenes & Ergenzinger, Catena 1998]

Conclusions: how do we make this flow?

Current models that include **pore pressure**, **compressibility** and **granular rheology** reproduce important features of debris flows.

**Limitations:**
1. Do not include grain-size/phase segregation → no boulder front.
2. Sensitivity to initial conditions: “...a fundamental bifurcation of behaviour (runaway acceleration versus slow, regulated motion) can result from rather minor differences in the initial state.”

**Our objectives:**
1. Determine how initially-dry hillslopes “liquified” → rills, mud.
2. Understand entrainment of boulders and front formation.

**How?**
Materials characterization, rheology, surveying.