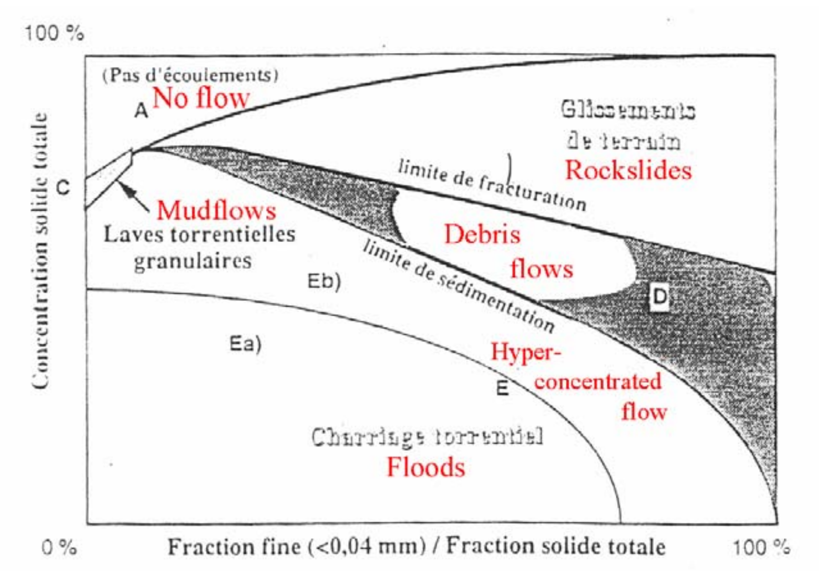
Debris flows

In the words of Iverson (1997), “debris flows occur when masses of poorly-sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction.” Coussot (below) describes them in terms of their grain-size distribution and concentration of solids.



Describing the physics of debris flows remains an active research topic. One of the fundamental questions is the characterization of the material that composes the flow. In other words, what is the **rheology** of debris flow material.

There are essentially two ways to investigate this:

1 – Consider the entire mass (fluid and solids) as one ‘fluid’ with particular properties. It has been found (e.g., Johnson,

1970) that a yield-strength fluid model works well for flows with considerable fines.

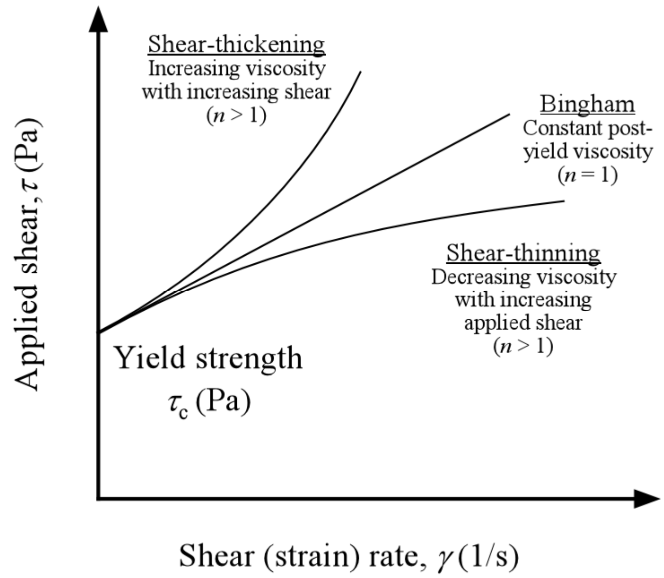
2 – The other possibility considers the water (and sometimes some of the fines) and coarser material separately. Often referred to as grain-flow models, these complicated models rely on an intimate knowledge of the particles and their size distribution.

Yield-strength models

Yield-strength models assume that the fluid has the properties

$$\tau - \tau_o = K\left(\frac{du}{dy}\right)^n; \quad \tau \geq \tau_o \tag{1}$$

where K is a linear coefficient, n is an exponent (both n and K are empirically determined), and τ_o is the yield strength of the material.



This model is often called a Herschel-Bulkley model. If $n = 1$, the fluid is said to be Bingham. In this case, K is the effective dynamic viscosity.

You can imagine that concentrated clay slurries have these characteristics.

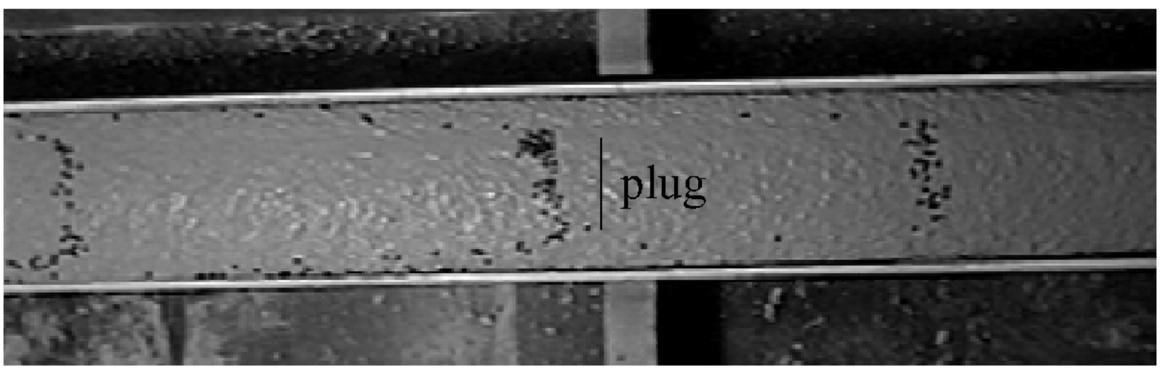
Well-sorted debris flow materials generally exhibit shear-thinning behavior, however. Regardless, the Bingham approximation is common. Because of the simplicity of the Bingham model, analytical solutions are often available (Johnson, 1970; Huang and Garcia, 1999). For instance, the plug velocity U_p can be related to known quantities for flow infinitely wide flow down a fixed slope S

$$U_p = \frac{\rho_d g S H^2}{\mu}\left[\frac{1}{2}\left(\frac{\tau_o}{\rho_d g H S}\right)^2 - \left(\frac{\tau_o}{\rho_d g H S}\right) + \frac{1}{2}\right] \qquad (2)$$

where ρ_d is the density of the debris flow (typically 2.2 g/cm^3), μ is the dynamic viscosity, and τ_o is the yield strength.

Flows having yield-strength will have the following properties:

- A plug forms in any region where shear is low. In channelized, debris flows have Bingham characteristics, the center portion of the channel is 'frozen', as shear there is below yield.



- The front proceeds in a 'rolling' fashion (sometimes referred to as conveyor-belt or caterpillar motion).
- Deposits will have a tendency to 'cake' sidewalls.
- Flows will have 'no-slip' at the sidewalls.
- 'Shear bands' will scale with the shear rate, not grain size.

Grain flows

Recent advances in numerical modeling of dry grain flows have produced a suite of models capable of characterizing grain-grain effects. Within these models, two types of effects are required to be accounted for: collisional and frictional.

Collisional forces

Bagnold (1954) realized that grain-grain interactions/collisions would affect particle transport rates. He used a series of experiments to describe what he referred to as dispersive pressure. This pressure is a result of collision between particles. Bagnold demonstrated that this increase in pressure has the result of inducing an additional shear stress τ_d to the fluid.

$$\tau_d \sim \alpha \left(\frac{du}{dy} \right)^2 \tag{3}$$

Also known as the 'Brazil-nut effect', **kinetic sieving** is the result of preferential motion of smaller particles 'falling through the cracks.' Middleton (1970) hypothesized that this was the explanation for large snouts on many debris flows. It also explains inverse grading – the top of a debris flow is generally coarser than the base.

To model these complementary, but distinctly different, phenomena, an analogy to ideal gas relations has been made.

Using the idea that the bouncing particles are similar to atoms in an ideal gas, Ogawa (1978) and others have used concept of a **granular temperature**

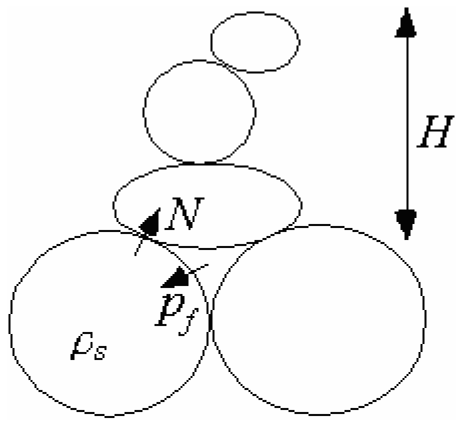
$$T = \left\langle \left(u_p - \bar{u}_p\right)^2 \right\rangle \qquad (4)$$

where u_p is the instantaneous particle velocity and $\bar{u}_p$ is the mean velocity of particles past that given point.

Like gases, places in a granular medium that have high granular temperatures will not support significant shear (i.e., they will flow easier). There is, of course, a feedback between the amount and location of shear, the granular temperature and the local grain-size distribution.

Frictional forces

One of the most important effects on natural debris flow runout is the frictional force exerted between particles. Friction in debris flow materials is also modulated by pore pressure. As the pore pressure increases, the normal force acting on any two grains is lessened. If the pore pressure increases beyond the overburden pressure, failure will necessarily occur. This is called **liquefaction**.



In a frictionally dominated flow, a plug will form. However, unlike a viscous flow, the shear-band width will be dependent on grain size. Flow runout cannot be modeled with yield-strength properties. As a result, frictional flows generally require considerably steeper slopes to generate flow than their muddy counterparts.

Acoustic energy can also act to liquefy a frictional mass.

Distinguishing between models and the messy middle ground

The best (but not necessarily, the easiest) way to discriminate between these different behaviors is dimensional analysis. Iverson (1997) proposed a set of dimensionless variables that would account for the various effects discussed above. He summarized these forces into four categories: collisional, viscous, frictional, and the effects due to pore pressure. The four dimensionless variables that can describe these

$$N_{BAG} = \frac{V_s \rho_s D^2 \gamma}{(1 - V_s)\mu}$$ Bagnold number (collision/viscous)

$$N_{SAV} = \frac{\rho_s D^2 \gamma^2}{(\rho_s - \rho_f) g H \tan\phi}$$ Savage number (collision/friction)

$$N_f = \frac{V_s(\rho_s - \rho_f) g H \tan\phi}{(1 - V_s)\gamma\mu}$$ friction number (friction/viscous)

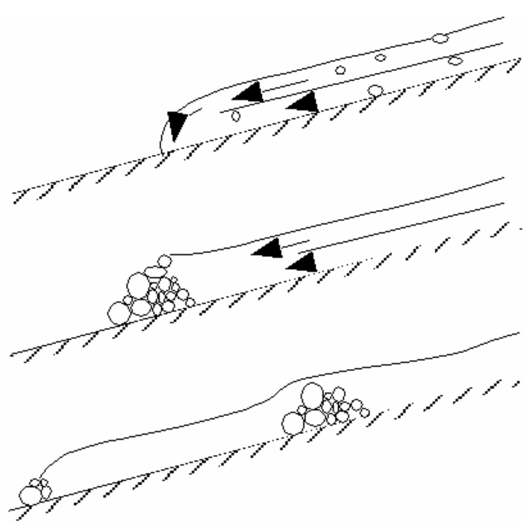
$$N_{DAR} = \frac{\mu}{V_s \rho_s \gamma k}$$ Darcy number (viscous/pore-pressure)

where V_s is the volume of solids, ρ_s is the density of solids, ρ_f is the density of interstitial fluid, γ is the strain rate (units: 1/T), k is the permeability of the mass while it is flowing, ϕ is the internal angle friction (angle of repose), H is the flow depth, μ is the dynamic viscosity of the interstitial fluid, and D is the mean diameter of the solids.

He also postulated, based on earlier simplified experiments, transitions for each of the variables. They are $N_f = 2000$, $N_{SAV} = 0.1$, $N_{BAG} = 200$, $N_{DAR} = 1000\text{-}6000$. Only one of these transitions (N_f) has been defined for realistic (poorly sorted) debris flows.

Complicating the simple picture of the dimensional analysis is the measurement of the each of the parameters. For instance, the shear rate affects both the rheology of interstitial slurry (and what constitutes the interstitial slurry) and as a variable in itself.

Spatial variability within a single flow also creates characterization problems. The conveyor belt motion at the front of these extremely poorly sorted flows collects the largest blocks due increased frictional effects there (among other causes). These snouts can build up and form dams (as in the famous Ansel Adams photograph below).

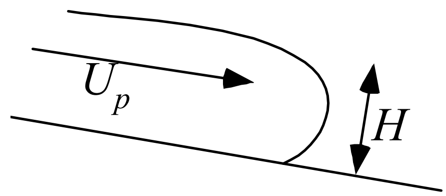


Submarine debris flows

Submarine debris flows are fundamentally the same as subaerial flows. Their constituent grain-size distribution, however, generally tends to be finer than their subaerial counterparts. As a result, the Bingham approximation generally works well.

Hydroplaning

The motion of submarine debris flow has the appearance of a car tire. The conveyor belt, if it is moving fast enough, will cause the flow to ride on a 'cushion' of water.



Mohrig et al. (1998) hypothesized that if the 'dynamic pressure' p_d associated with the moving flow

$$p_d = \rho U_p^{\,2} / 2 \tag{5}$$

exceeds the static pressure p_s associated with the loading from the debris

$$p_s = (\rho_d - \rho_f) g H (1 - S) \tag{6}$$

then the water will not have a chance to 'get out of the way.' The result is a dimensionless variable H_p that should regulate the ability of the flow to hydroplane.

$$H_p = \frac{(\rho_d - \rho_f) g H (1 - S)}{\rho_f U_p^{\,2}} \tag{7}$$

Mohrig et al. (1998) suggest that for $H_p < 10$, flows will begin to hydroplane.

Association with and production of turbidity currents

Every submarine debris flow generates a turbidity current.

The significance of these currents is still a matter of debate. Recent work (Maar et al., 2001) has indicated that it is difficult to convert a debris flow into a turbidity current.

Based on these experiments, a physical argument could be made as follows…

Fine material is required for low-yield-strength, low-viscosity flows (i.e., fast flows). However, the addition of fines (in particular, clay) binds the flow together and causes less material to be lost to suspension. The result is that it is impossible to generate enough kinetic energy to rip a debris flow apart.