Mud and Debris Modeling with HEC-RAS

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Abstract

High sediment concentrations (i.e. more than 5-10% solids) can affect fluid physics. High-concentration geophysical flows begin to diverge from the Newtonian assumptions of the shallow-water flow equations, applied in most flood risk studies. At high concentrations, particle interaction processes can change the depth, velocity, arrival time, damage, and floodplain extent associated with an event.

Debris flows are growing more common as wildfire frequency and intensity increases. Rainfall on high-gradient, recently burned watersheds can erode enough rock and sediment to develop flows with solid concentrations of greater than 50%. Mine tailing dam failures can also generate dangerous and destructive high-concertation flood waves. The risks associated with these structures are also increasing as the global, mine-tailings, dam portfolio ages. Accounting for the particle interactions in these mud and debris flows is critical to appropriately estimate downstream risks.

A multi-laboratory, US Army Corps of Engineers Team developed a non-Newtonian computational library to make single-phase, rheological, physics available for these simulations. This team integrated this library in the Hydrologic Engineering Center's River Analysis System (HEC-RAS). This presentation will describe the rheological models available in HEC-RAS and how they apply to mud and debris flows. The presentation will also survey the verification and validation tests the team used to evaluate these algorithms and several calibrated, field applications.

Newtonian vs Non-Newtonian Fluids

In a Newtonian fluid, the shear stress profile is proportional to the vertical gradient of the velocity (Garcia et al, 2008). The shear stress is the derivative of the velocity profile, which is linear with depth and proportional to the dynamic viscosity of the fluid (Figure 1).

$$\tau = \mu \frac{du}{dz}$$

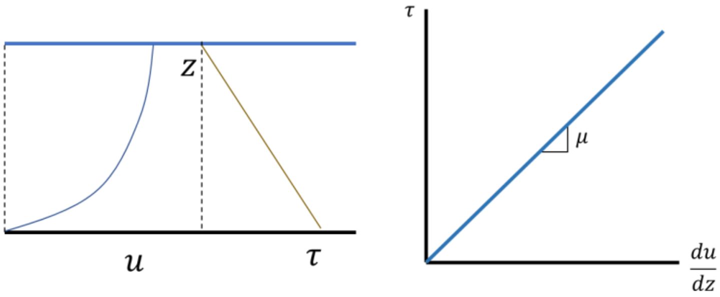

Figure 1. Equation for shear stress in a Newtonian fluid with illustration of the velocity and shear stress profiles and the shear-strain relationship for a Newtonian fluid.

The depth-derivative of velocity is also a measure of deformation, or strain. Therefore, a Newtonian fluid deforms immediately under the influence of any, small, shear stress (i.e. there is no range of non-zero shear stresses under which it is at rest) and deforms proportionally to the strain applied.

Non-Newtonian fluids violate one or more of those assumptions. The simplest Non-Newtonian fluid, the Bingham plastic, keeps the linear proportionality between stress and strain and the slope of that relationship is still the dynamic viscosity (though the viscosity of these fluids is often higher). But it has a range of shear stresses over which it resists motion. Therefore, a Bingham plastic takes an initial shear event to initiate motion and can come to rest if the shear stress drops below a threshold (Figure 2 – Left).

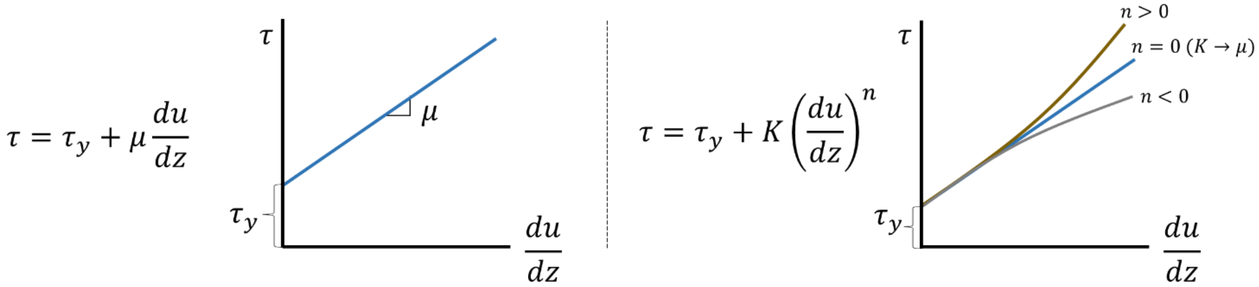

Figure 2. Equation and stress-strain relationship for a Bingham fluid (left) and idealized fluids with non-linear, non-Newtonian relationships.

Other Non-Newtonian fluids also depart from the linear assumption. Dilatant and pseudoplastic fluids raise the strain to powers less than or greater than one, which indicate that the fluid becomes more or less difficult to deform as it deforms (Figure 2-Right).

Rheological Simplifications for Mud and Debris Flows

Water is the most famous Newtonian fluid and most flood risk models are built on Newtonian assumptions. But mud and debris flows tend to carry enough sediment (and other solids) that the solid interactions introduce non-Newtonian effects. More sophisticated models take these effects into account with detailed two-phase mechanics (Iverson, 1997). But flood risk and emergency management modelers have been successful replicating these events with single-phase, non-Newtonian assumptions.

The simplest approach assumes that mud and debris flows are Bingham plastics, which only require users to define the viscosity of the material and a yield stress. But turbulent, dispersive, and inter-particle friction can add non-linearities to the stress-strain relationship. O'Brien *et al.* (1993) developed a quadratic model with terms that raise strain to the 0th power (yield strength), the 1st power (viscosity), and the 2nd power (turbulence and dispersion, estimated with a Bagnold term).

$$\tau = \tau_{yield} + \tau_{viscous} + \tau_{turbulent} + \tau_{dispersive}$$

$$\tau = \tau_y + \mu_m\left(\frac{3\bar{u}}{h}\right) + \rho_m l_m^2\left(\frac{3\bar{u}}{h}\right)^2 + 0.01\rho_s\left(\left(\frac{0.615}{C_v}\right)^{1/3} - 1\right)^{-2} d_s^2\left(\frac{3\bar{u}}{h}\right)^2$$

The Hershel-Bulkely (1926) (Figure 2 – Right) equation is a more empirical non-linear model that include the 0th order term (yield stress) but raise the strain to a single power that could be greater than or less than 1, but does not necessarily need to be quadratic, and collapses to the Bingham equation when the power is 1.

Non-Newtonian Mechanics in HEC-RAS

HEC-RAS (the Hydrologic Engineering Center's River Analysis System) is a popular flood risk model, widely applied to "clear water" flood studies. HEC-RAS has historically assumed fluids are Newtonian. Few alluvial flows carry enough solids to depart to change the physics of a flood risk simulation. Most alluvial flows – even big flood events that "look like chocolate milk" - carry less than 10% solids by volume. Therefore, and the vast majority of alluvial floods do not carry enough sediment that particle interactions change the fluid behavior. But post-wildfire events and mine-tailing dam removals can carry between 30 and 65% solids, by Volume. These concentrations require non-Newtonian physics.

HEC added fixed-bed non-Newtonian mechanics to HEC-RAS 6.0 and are enhancing these features in subsequent versions (Gibson *et al*., 2020, HEC, 2023). These functionalities will bulk the fluid to account for the solid volume, and change the fluid properties based on one of the non-Newtonian rheological models described above (e.g. Bingham, O'Brian quadratic, or Herschel-Bulkley). These features have improved the results of high-concentration flood risk management models including post wildfire and dam breach models (Gibson *et al*., 2022), but have also been applied to regular high gradient debris flows, paleoflood studies, and HEC-RAS includes a Bingham-cooling model (that adjusts the Bingham parameters based on fluid temperature) that can approximate some lava flow and cooling processes.

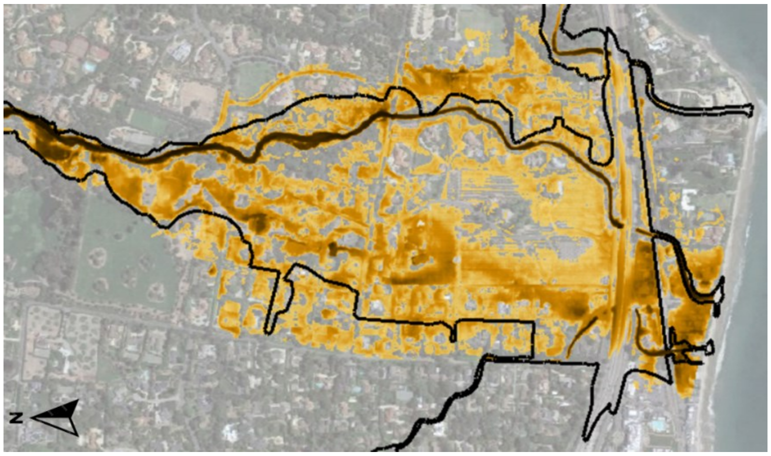

Figure 3. Example of a debris flow simulation with HEC-RAS. Observed mudplain extents (black line) are compared against a Bingham simulation.

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