The dambreak problem revisited

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Outline

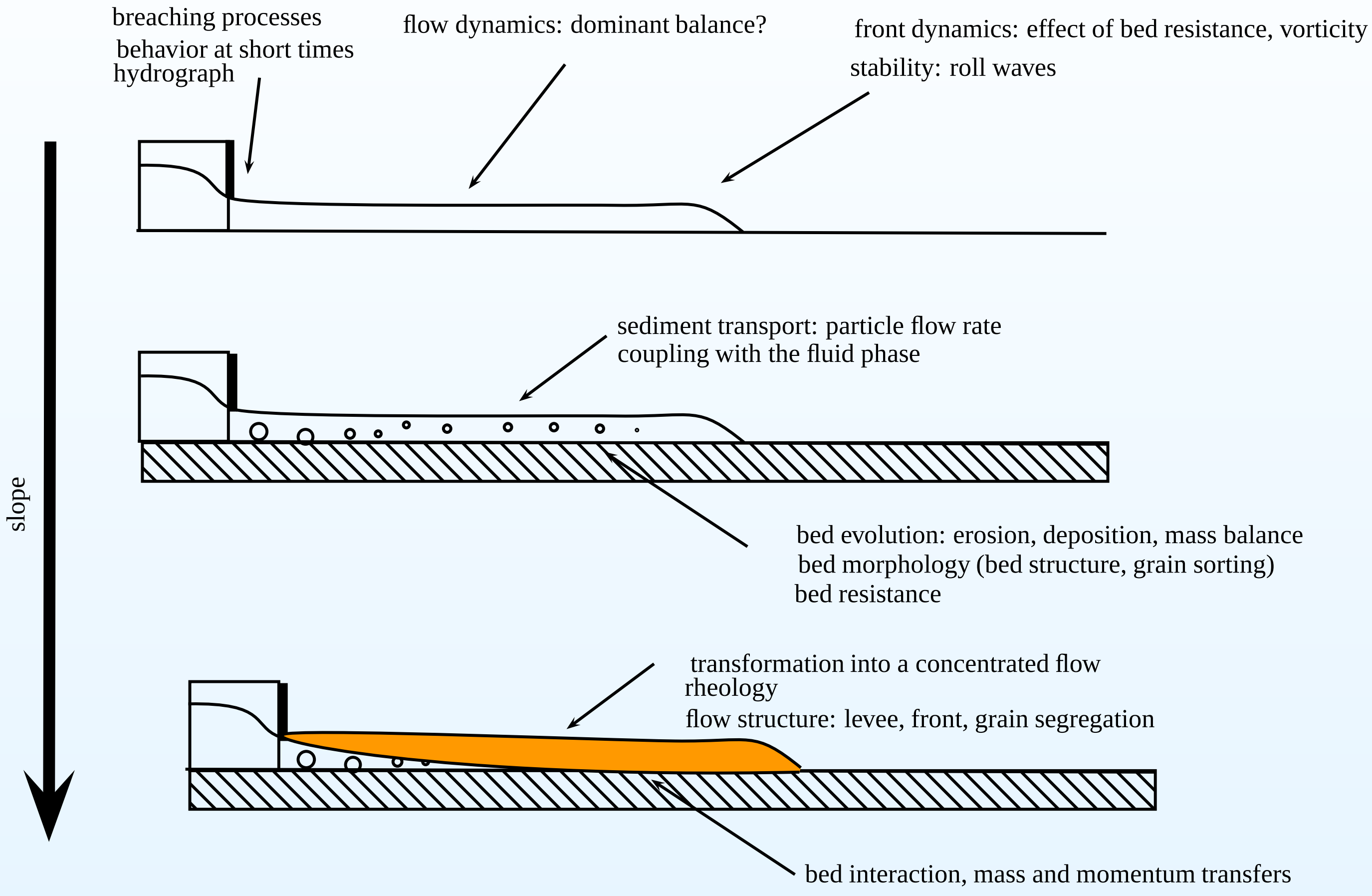
- Context : dam-break flows and related phenomena
- Laboratory insight : flow visualization
  - The Newtonian paradigm
  - Viscoplastic flows
  - Viscoplastic flows

Dam break problem

Dam break: sudden release of a fixed volume of water.

Teton dambreak (Idaho, 1976)

Scientific issues



breaching processes
behavior at short times
hydrograph

flow dynamics: dominant balance?

front dynamics: effect of bed resistance, vorticity

stability: roll waves

sediment transport: particle flow rate
coupling with the fluid phase

bed evolution: erosion, deposition, mass balance
bed morphology (bed structure, grain sorting)
bed resistance

transformation into a concentrated flow
rheology
flow structure: levee, front, grain segregation

bed interaction, mass and momentum transfers

Induced sediment transport

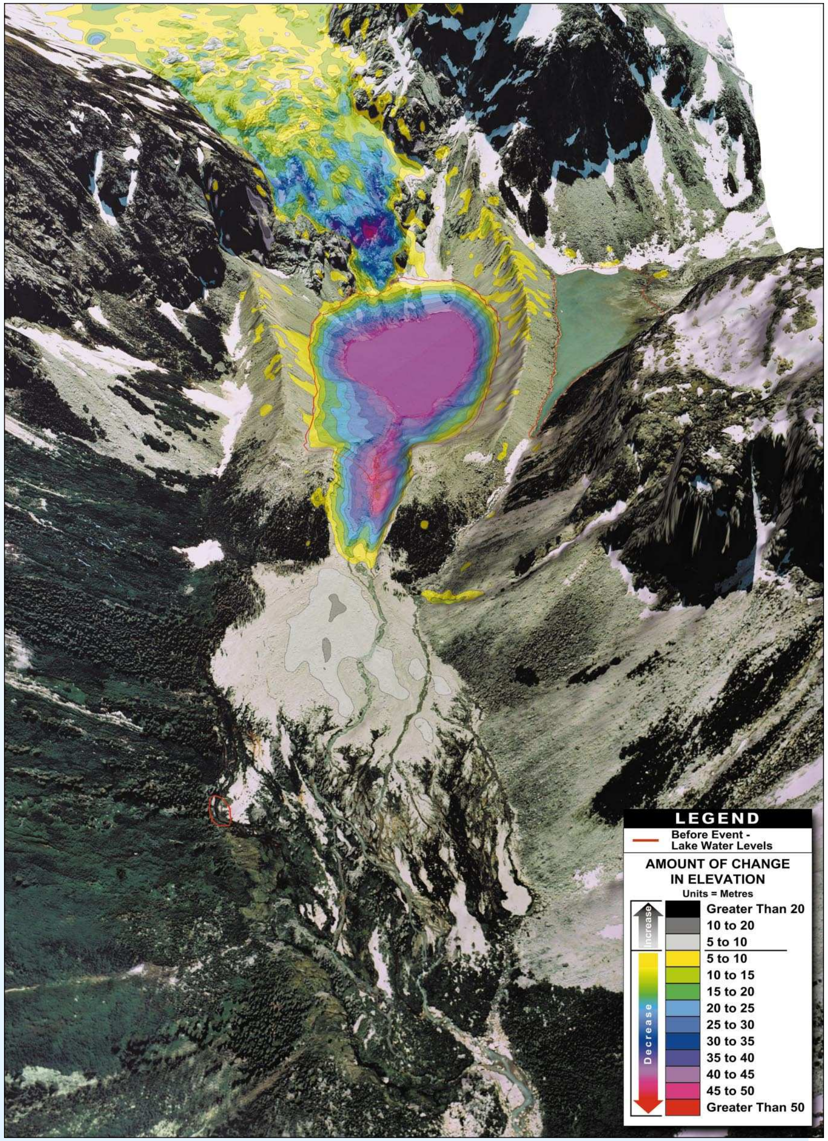
Taum Sauk dam break (Missouri, Dec. 2005) intense erosion of the bed (down to the bed rock) and sediment transport

Related phenomena

Slush and wet-snow avalanche (dambreak flow inducing a snow avalanche) Pelvoux (France) March 2006

Outburst flood from moraine-dammed lake

Lake Nostetuko (British Columbia, Canada) July 1983



Muddy debris flow

Lahar

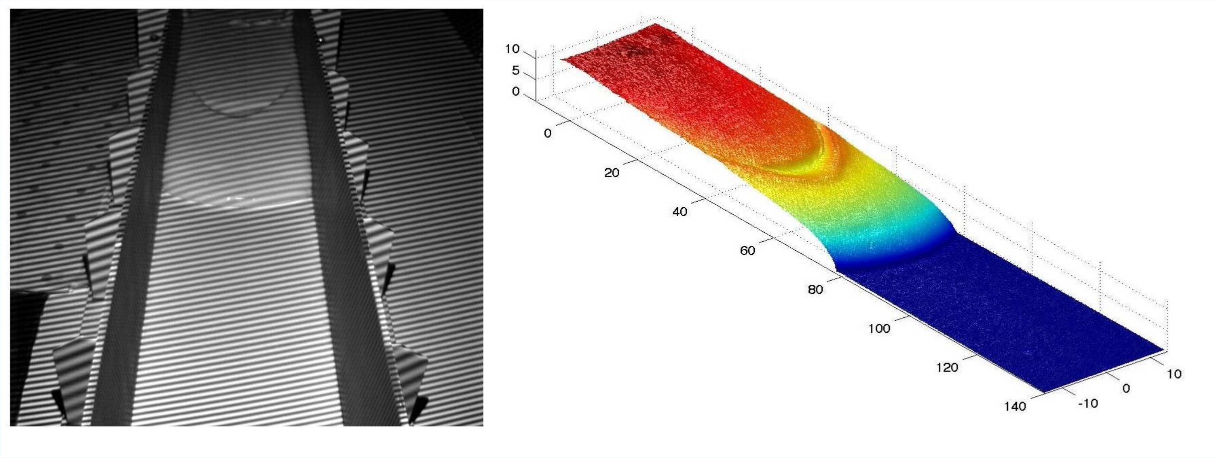
Dambreak in the lab: massive erosion

Gaël Epely-Chauvin's thesis (slope: 3° and 10°, particles: 3-mm glass beads, fluid: alcohol with viscosity 5×10^{-3} Pa s, bottom: mobile bed)

Dambreak in the lab: viscoplastic flow

Steve Cochard’s thesis

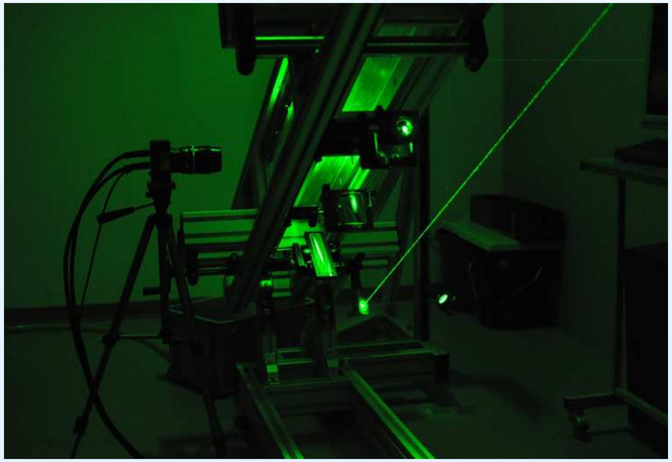
Surface reconstruction



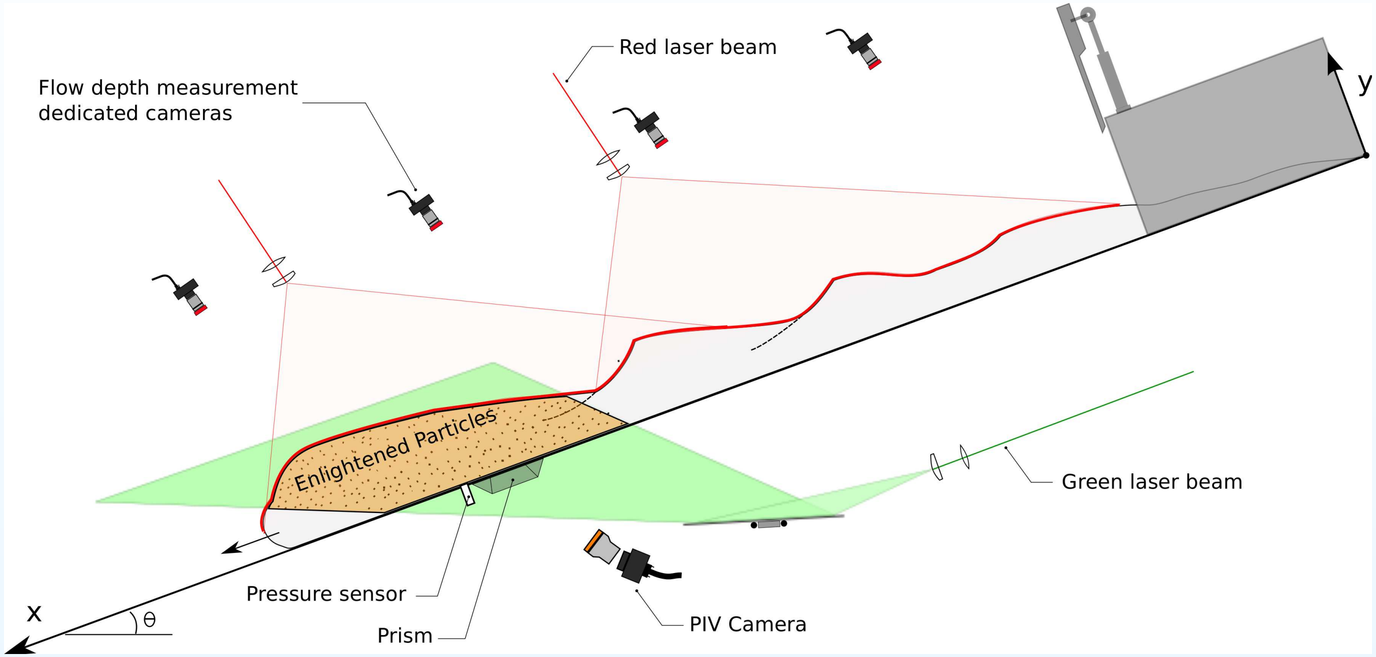
Pattern projection and image processing to reconstruct the free surface

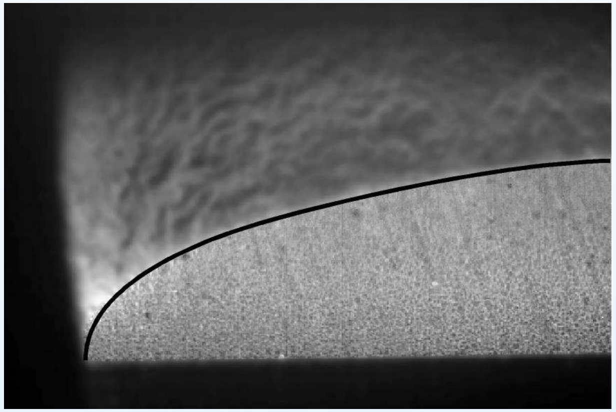
Steve Cochard’s thesis (EPFL, 2007) ; *J. Non-Newtonian Fluid Mech.* **142** (2007) 4–35 ; *Exper. Fluids* **44** (2008) 59–71 ; *J. Non-Newtonian Fluid Mech.* **158** (2009) 18–35; *J. Fluid Mech.* **624** (2009) 1–22

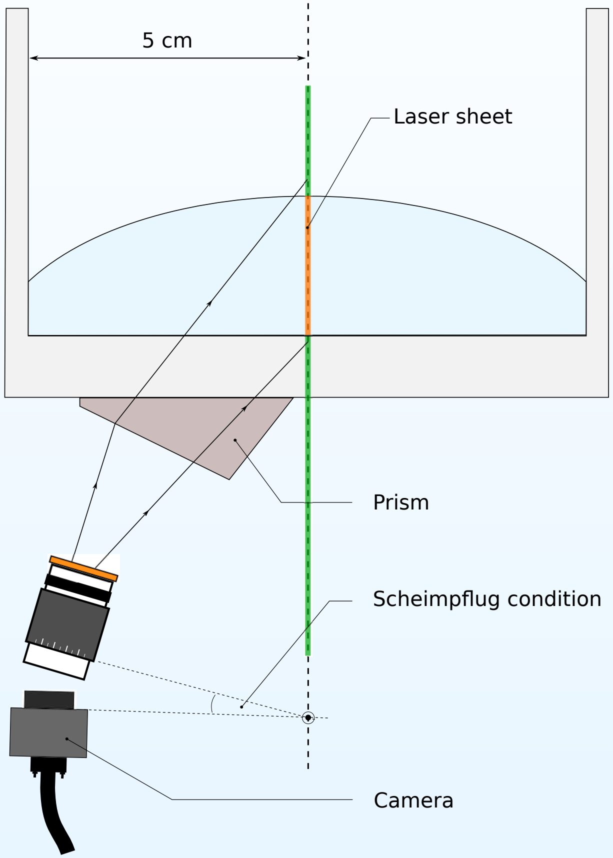
Dambreak in the lab: avalanche of particle suspension



Experimental facility

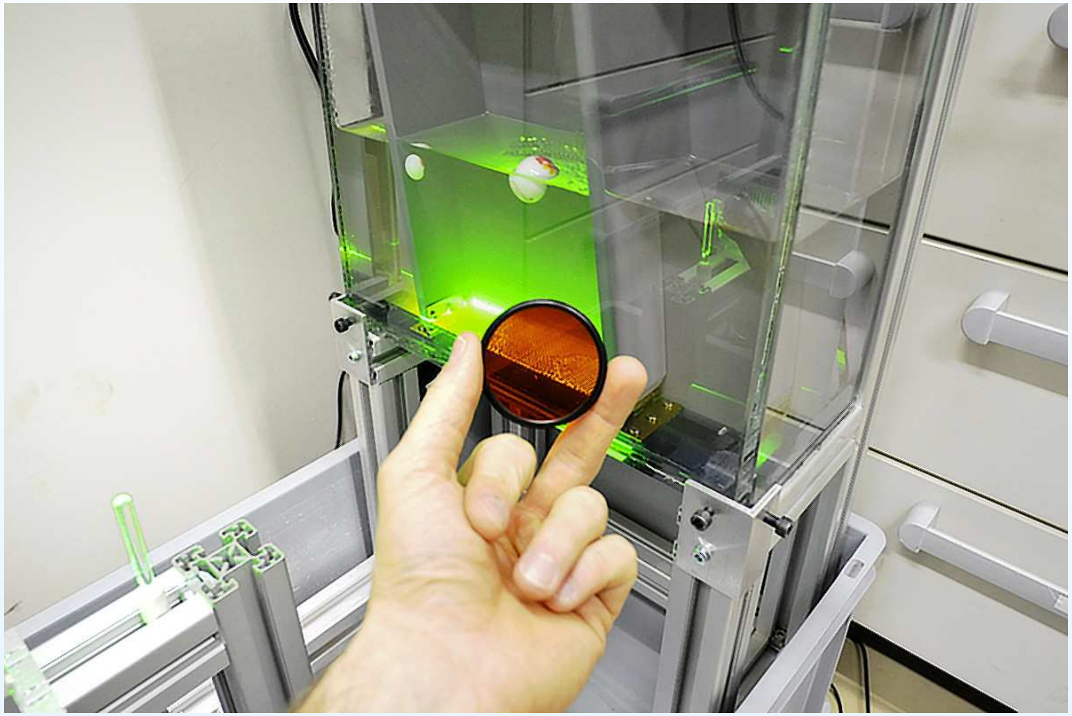





5 cm
Laser sheet
Prism
Scheimpflug condition
Camera

Three-dimensional scanning

Shearing box: oscillating plates shearing a bimodal mixture



Epely-Chauvin's thesis (3-mm and 6-mm particles)

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Experiments with borosilicate beads of 1 and 2 mm in diameter in alcohol
Reconstruction of the beads' trajectory using image processing

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A bit of theory

For thin elongating flows (sheet flow), the Navier-Stokes equation can be simplified a great deal. Pressure distribution is found to be 'hydrostatic'

$$p = \rho g \cos\theta (h - y), \tag{1}$$

while the streamwise velocity component is given by the momentum balance equation

$$\mu \frac{d^2 u}{dy^2} + \rho g \sin\theta = \rho g \cos\theta \frac{\partial h}{\partial x}, \tag{2}$$

A bit of theory

Integrating twice leads to the depth-averaged velocity

$$\bar{u}(x,t) = \frac{1}{h}\int_0^h u(x,y,t)\,dy = \frac{1}{3}Kh^2\left(1 - \cot\theta\frac{\partial h}{\partial x}\right), \tag{3}$$

with $K = \frac{\rho g \sin\theta}{\mu}$. The governing equation for h is

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} = 0. \tag{4}$$

We end up with a nonlinear advection-diffusion equation

$$\frac{\partial h}{\partial t} + Kh^2\frac{\partial h}{\partial x} = Kh^2\cot\theta\left(\frac{\partial h}{\partial x}\right)^2 + \frac{Kh^3}{3}\cot\theta\frac{\partial^2 h}{\partial x^2} \tag{5}$$

A bit of theory: outer solution

Seeking similarity solutions in the form

$$h(x,t) = t^{-n} H(\xi, t), \tag{6}$$

with $\xi = x/t^n$ the similarity variable and $n = 1/5$ (short time behavior) or $n = 1/3$ (long time behavior). We pose

$$h(x,t) = t^{-1/3} H(\xi,t) \text{ with } H(\xi,t) = H_0(\xi) + t^{\nu_1} H_1(\xi) + \cdots\ , \tag{7}$$

with $\nu_i > 0$ and H_i functions of ξ alone. In the $t \to \infty$ limit, the leading-order function H_0 satisfies

$$-H_0 - \xi \frac{dH_0}{d\xi} + 3KH_0^2 \frac{dH_0}{d\xi} = 0, \tag{8}$$

whose integration yields

$$H_0(\xi) = \sqrt{\xi/K} \text{ for } 0 \le \xi \le \xi_f = \left(9KV^2/4\right)^{1/3} \tag{9}$$

A bit of theory: inner solution

For the inner solution, we introduce

$$\xi = \xi_f - \eta t^\sigma,$$

with $\sigma) = -2/3$. We pose $H(\xi, t) = H_0^* + t^{\chi_1} H_1^*(\xi) + \cdots$. To leading order

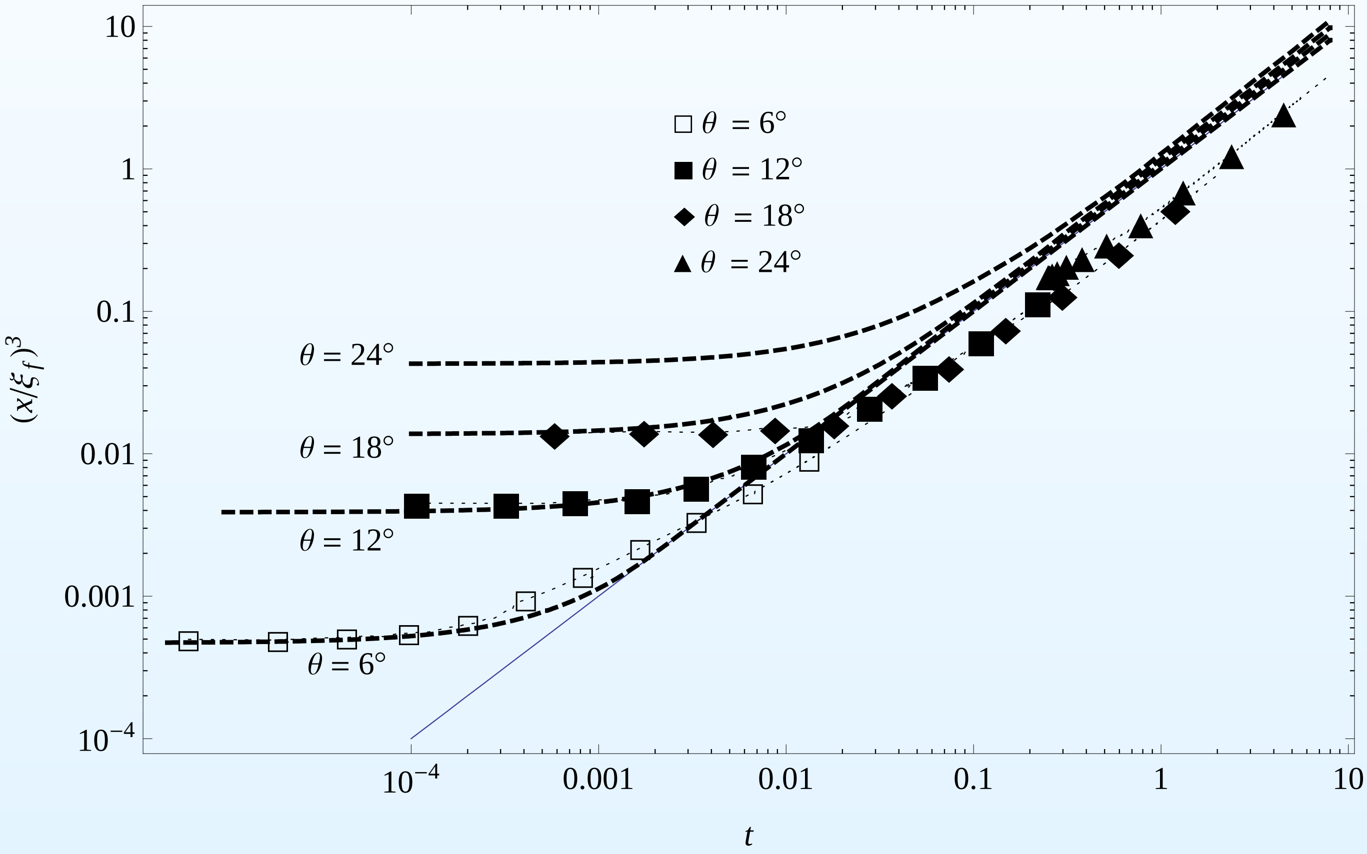
$$\frac{1}{3}\xi_f \frac{dH_0^*}{d\eta} = K\cot\theta\left[\left(H_0^{*2}\frac{dH_0^*}{d\eta}\right)^2 + \frac{1}{3}H_0^{*3}\frac{d^2H_0^*}{d\eta^2}\right] + K H_0^{*2}\frac{dH_0^*}{d\eta}$$

whose implicit solution is

$$\eta - \eta_f = \eta_s(H_0^*) = \cot\theta\left[H_0^f \tanh^{-1}\left(\frac{H_0^*}{H_0^f}\right) - H_0^*\right].$$

Viscous flow: glycerol solution

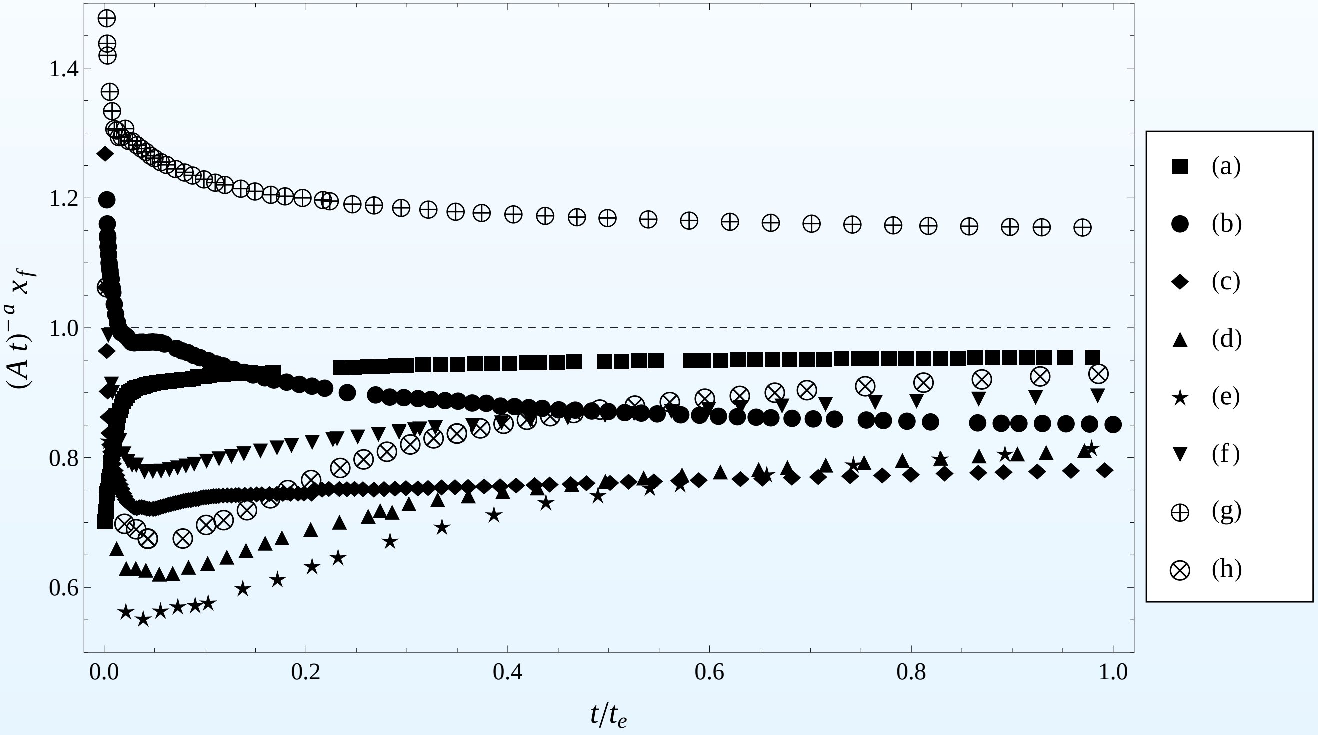
Position of the front as a function of time for various inclinations ($\mu = 345$ Pa·s)



Ancey *et al.*, The dam-break problem for viscous fluids in the high-capillary-number limit, *J. Fluid Mech.*, **624**, 1-22, 2009.

Viscous flow: glucose solution

Position of the front as a function of time for various inclinations ($\mu = 1.1$ Pa·s)



Andreini *et al.*, submitted to *Phys. Fluids.*

Introduction

Lab experiments

Newtonian flows
- A bit of theory
- Viscous flow: glycerol solution
- Viscous flow: glucose solution
- Flow depth profile
- Contact line profile
- Velocity profile

Viscoplastic flows

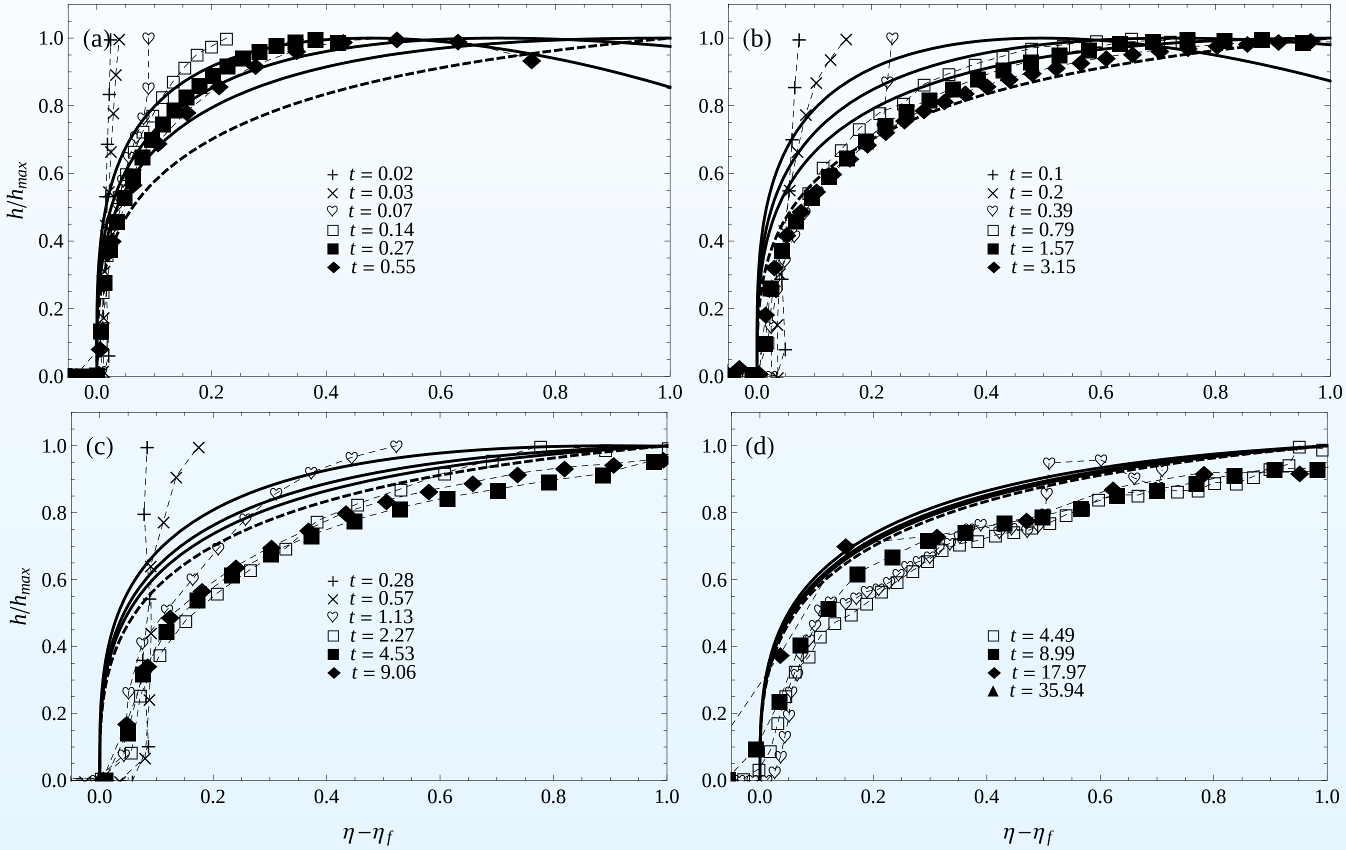
Concentrated flows

Flow structure

Perspectives

Flow depth profile

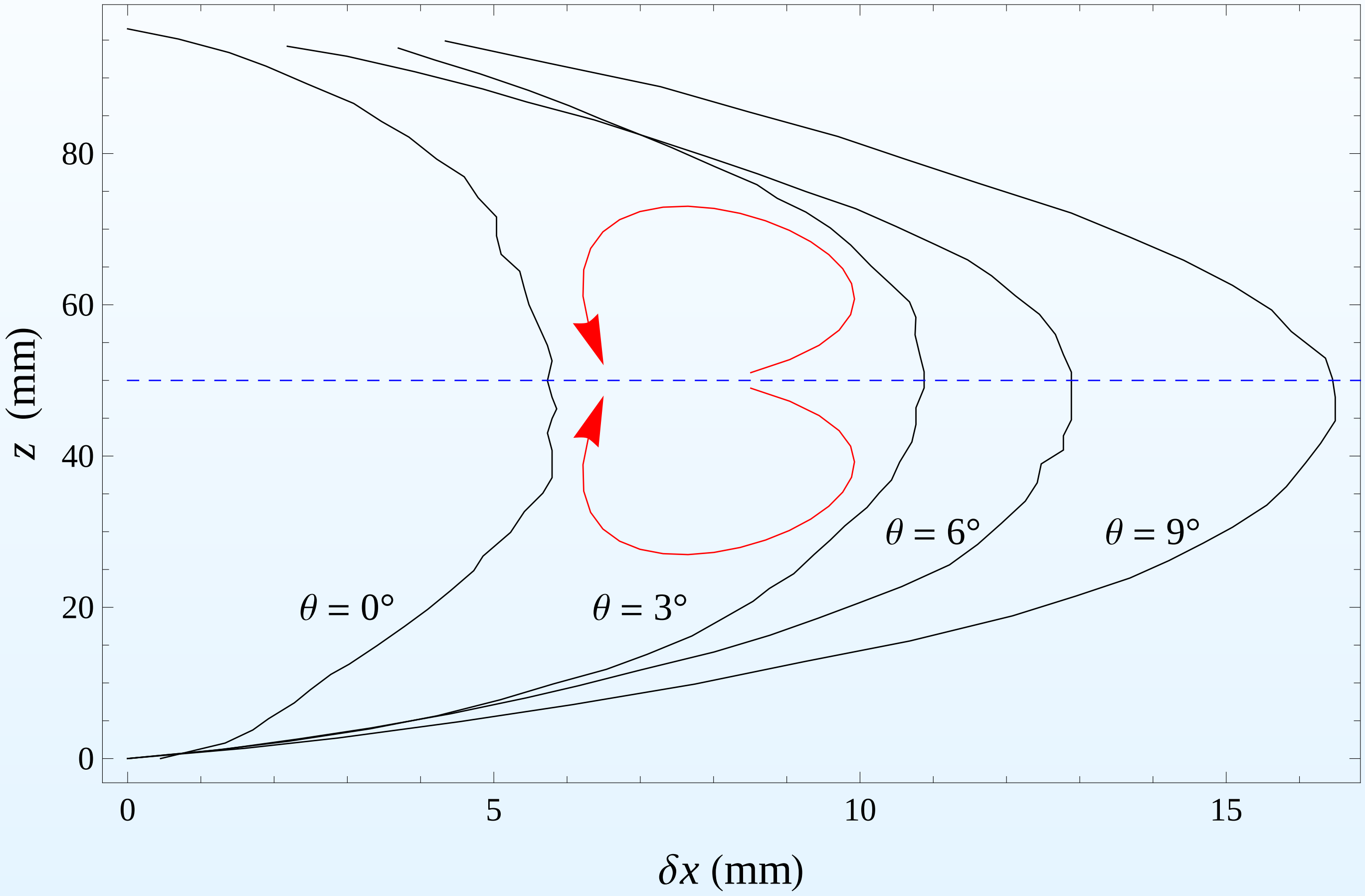
Scaled flow depth profiles h as a function of distance to front $\eta - \eta_f$



Comparison theory vs experiment for various inclinations and (dimensionless) times

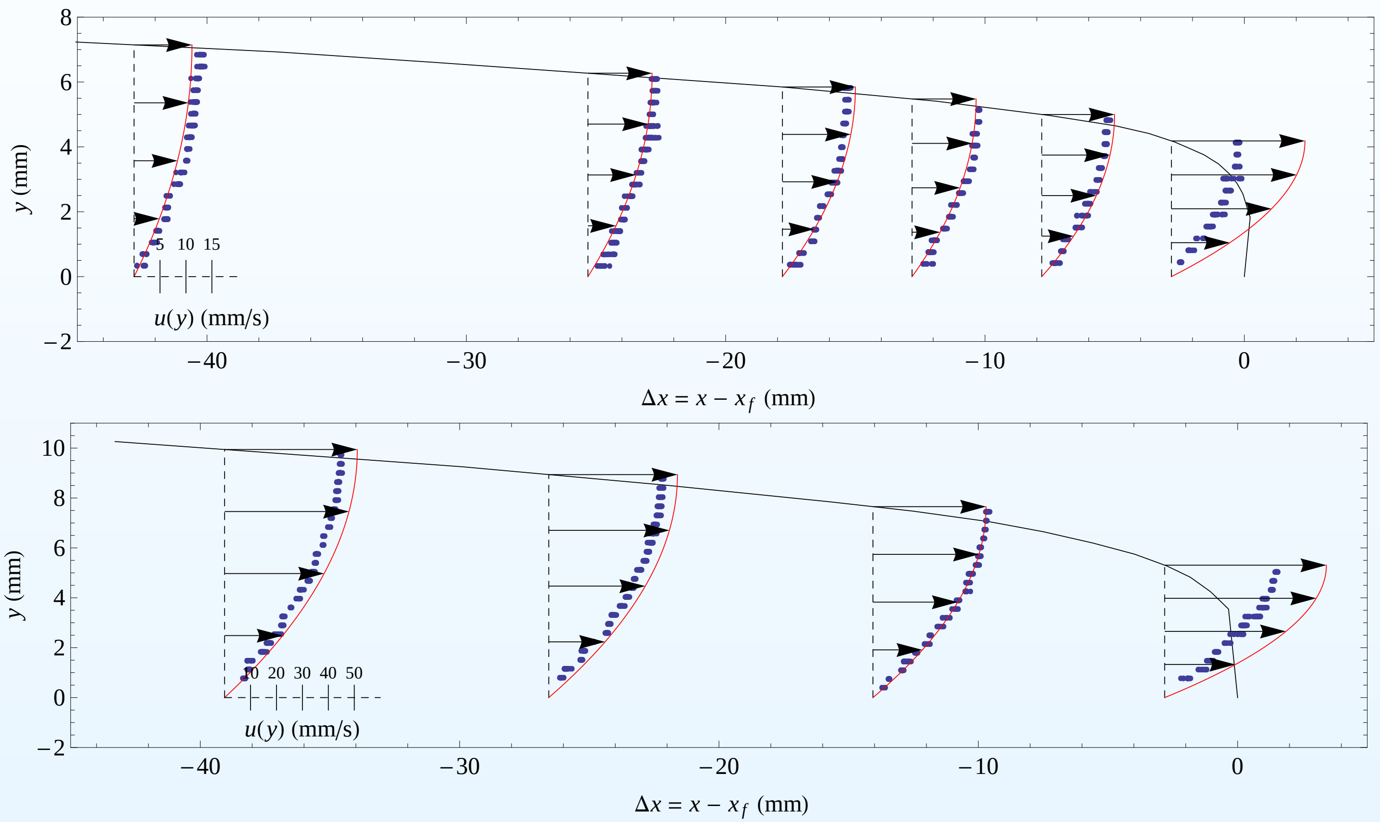
Contact line profile

Contact line profile



Comparison of experiments for various inclinations

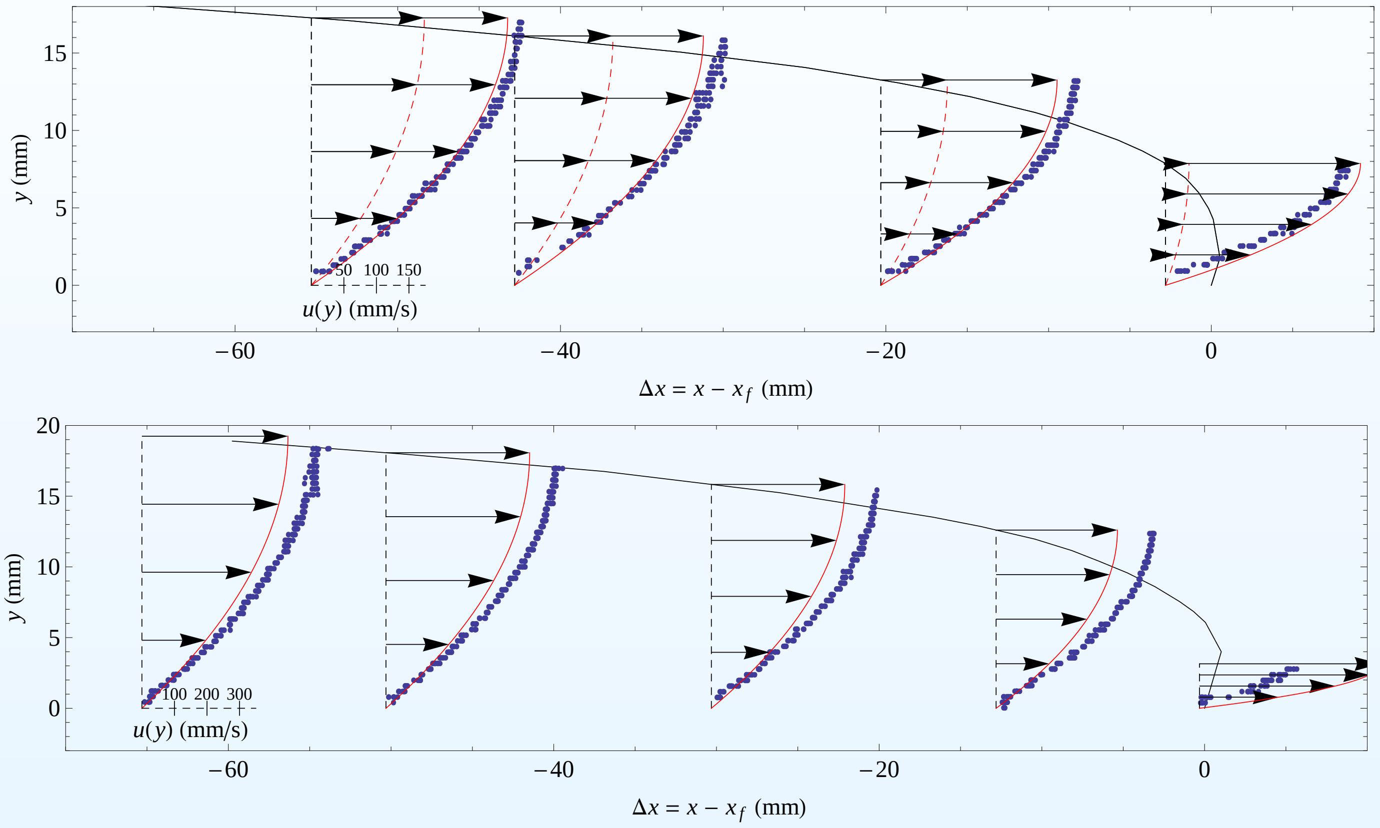
Velocity profile



Slope: 0 et 3 deg

Andreini *et al.*, submitted to *Phys. Fluids.*

Velocity profile



Slope: 6 et 9 deg

Andreini *et al.*, submitted to *Phys. Fluids.*

Viscoplastic avalanches

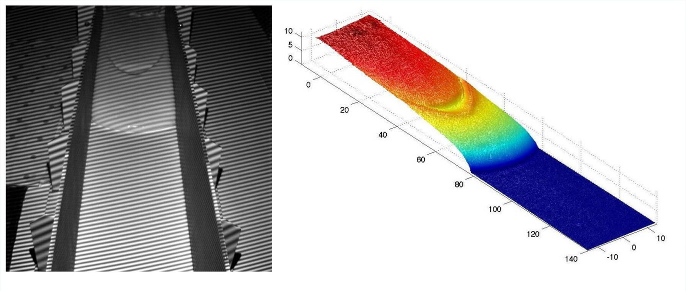
The same techniques as for Newtonian flows can be applied to viscoplastic materials.

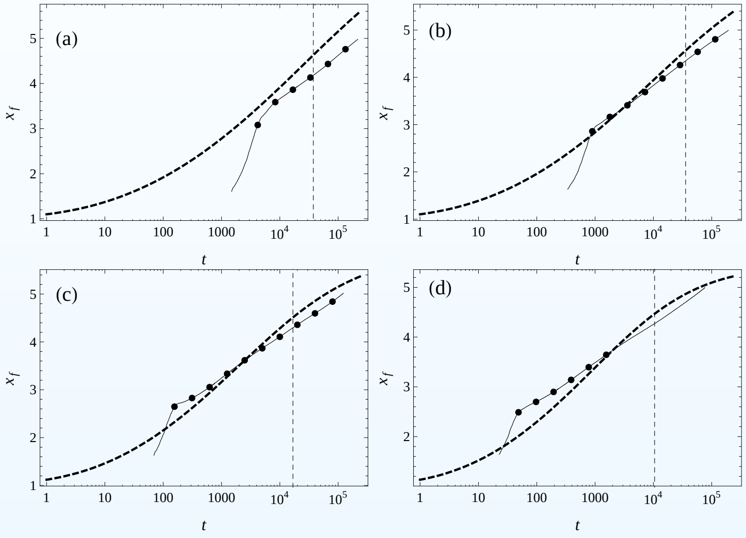
$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}F(h)=0,$$

with $Y=\max\left(h-Bi,0\right)$ and

$$F(h)=nY^{1+1/n}\frac{(2n+1)h-nY}{(2n+1)(n+1)}\text{ and }Bi=\frac{\tau_c}{K\left(\frac{U_*}{H_*}\right)^n}.$$

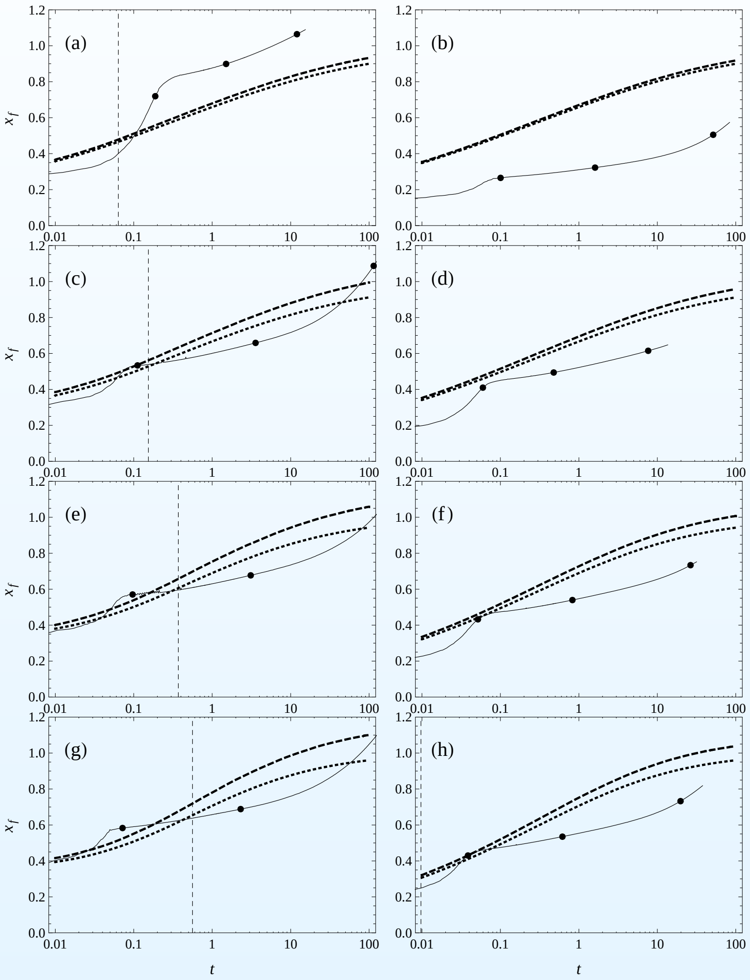
Comparison with data





Variation in the front position with time for $\theta = 24^\circ$. Experiments done with Carbopol at various concentrations. Dashed curves: theoretical prediction given by a zero-order nonlinear convection equation (modelling the behavior of an avalanching mass of Herschel-Bulkley fluid).

Comparison with data (continued)



Variation in the front position with time for $\theta = 12^\circ$. Experiments done with Carbopol at various concentrations. Dashed curves: theoretical prediction given by a zero-order nonlinear convection equation (modelling the behavior of an avalanching mass of Herschel-Bulkley fluid).

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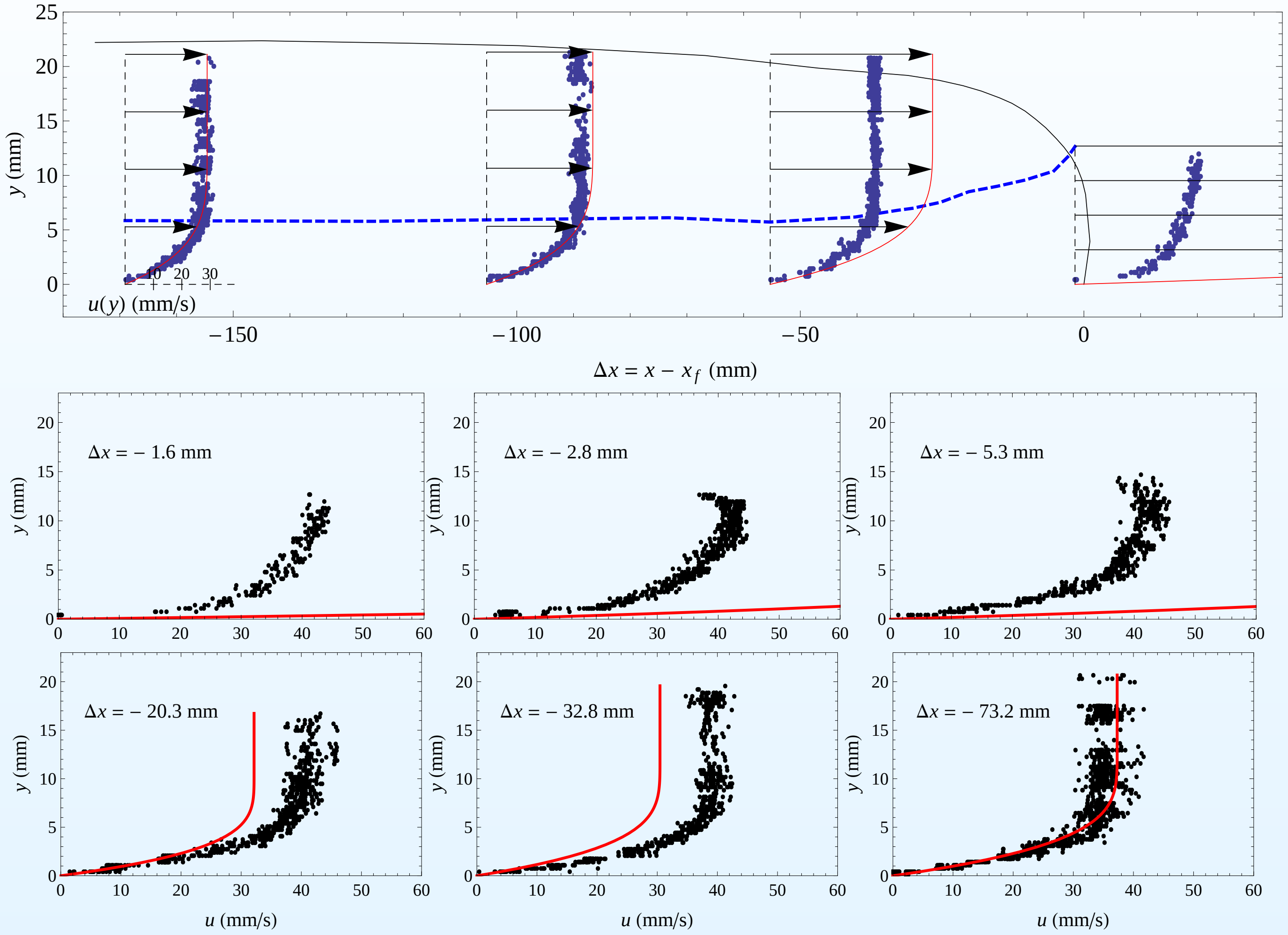
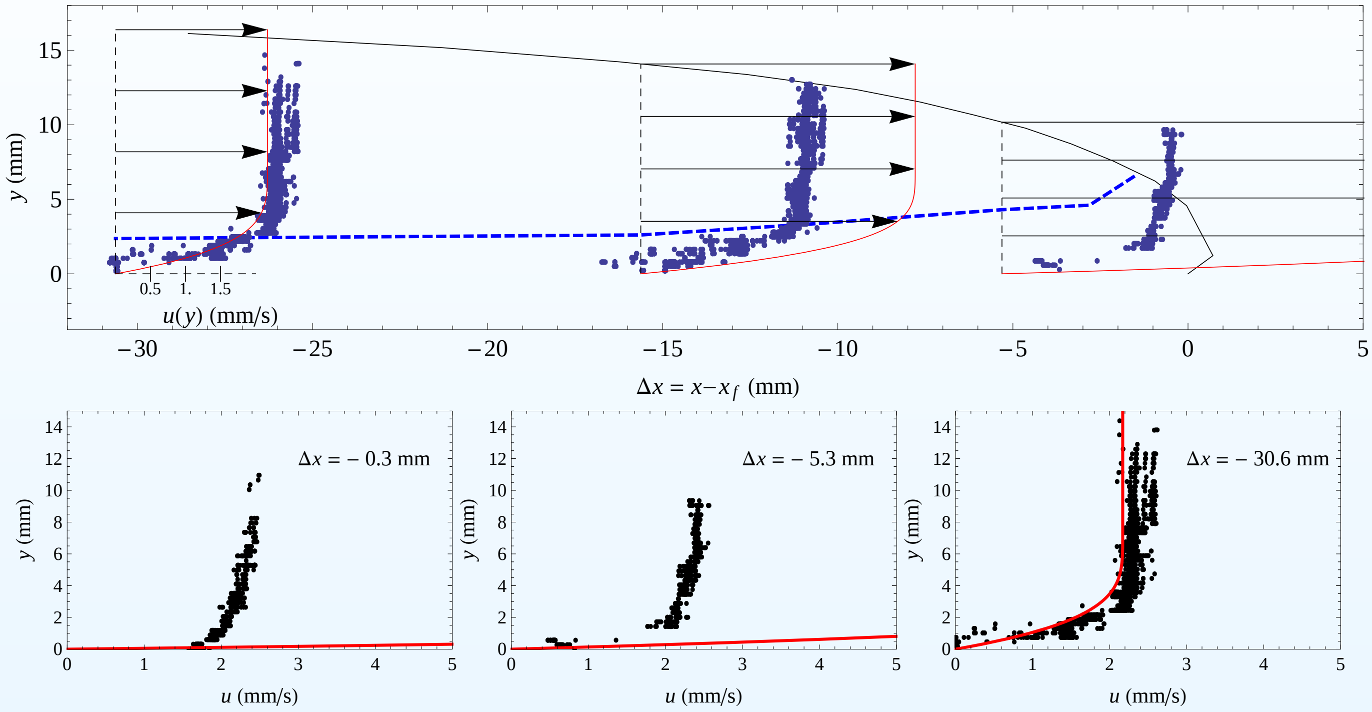
Velocity profile



Slope: 25 deg

Andreini *et al.*, submitted to *Phys. Fluids.*

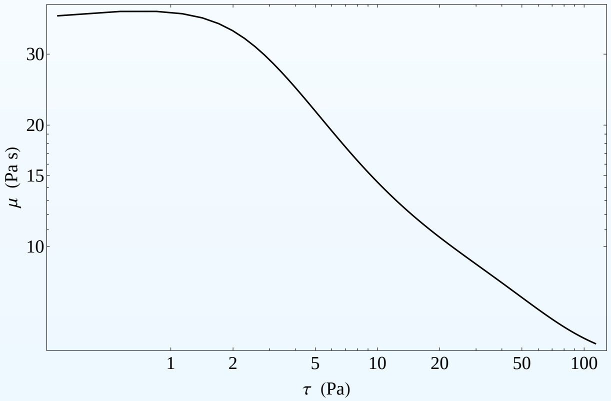
Velocity profile



Slope: 15 deg

Andreini *et al.*, submitted to *Phys. Fluids.*

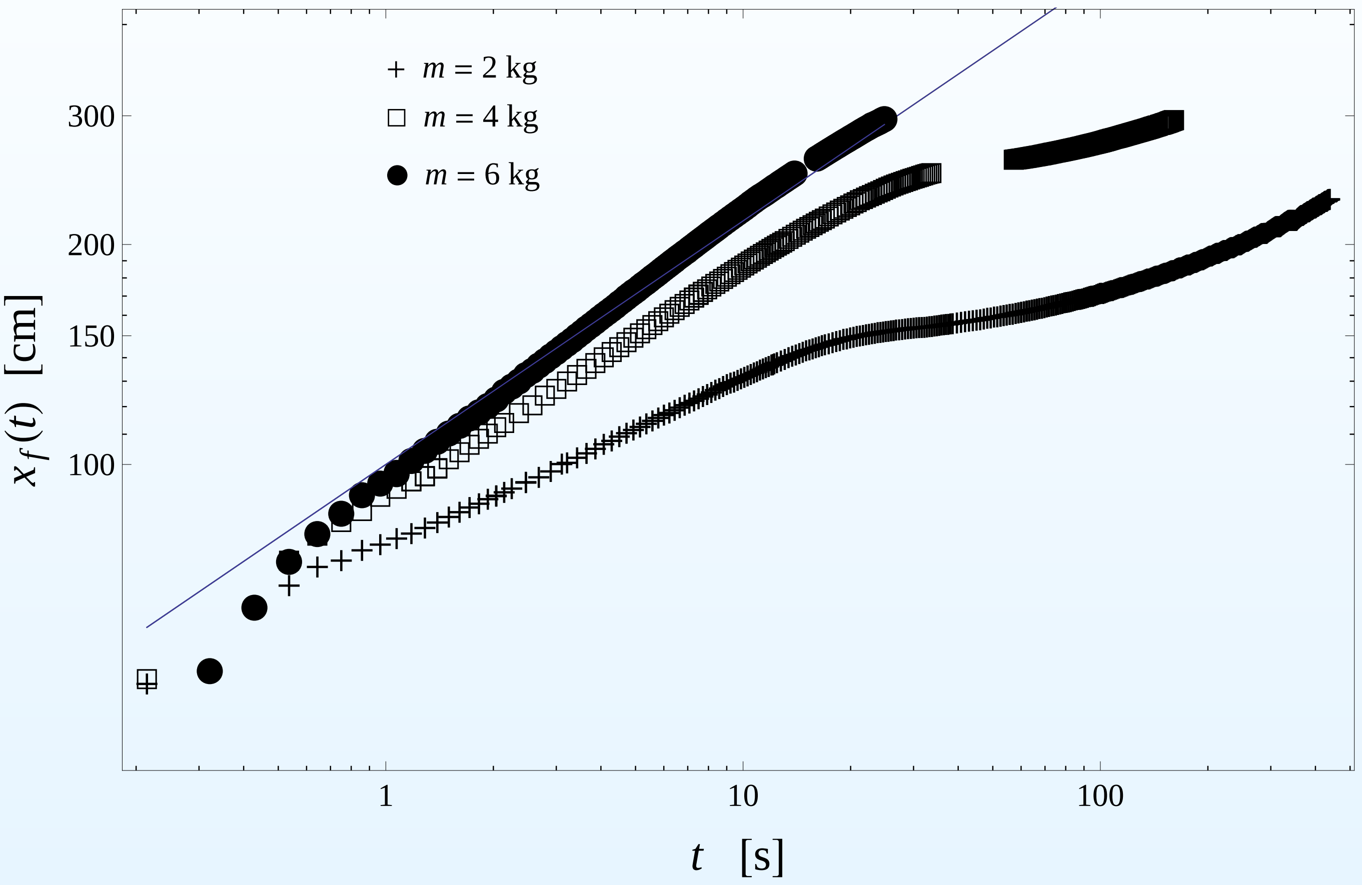
Viscous flow: particle suspension



0.1-mm PMMA particles suspended in a Trimix solution (DBG, Triton, UCON oil), density matched: shear-thinning fluid with no plastic behavior

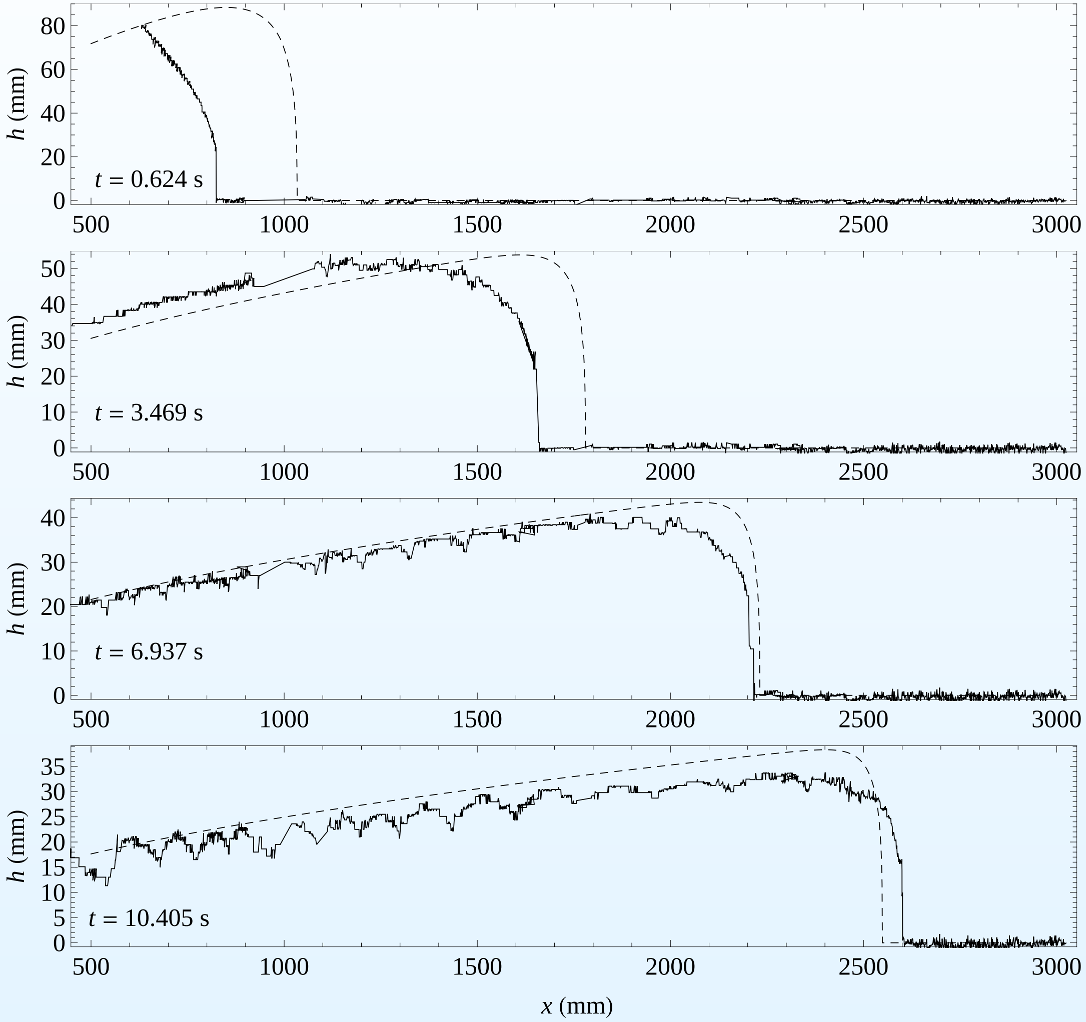
Andreini *et al.*, submitted to *Phys. Fluids*

Evolution of the front position

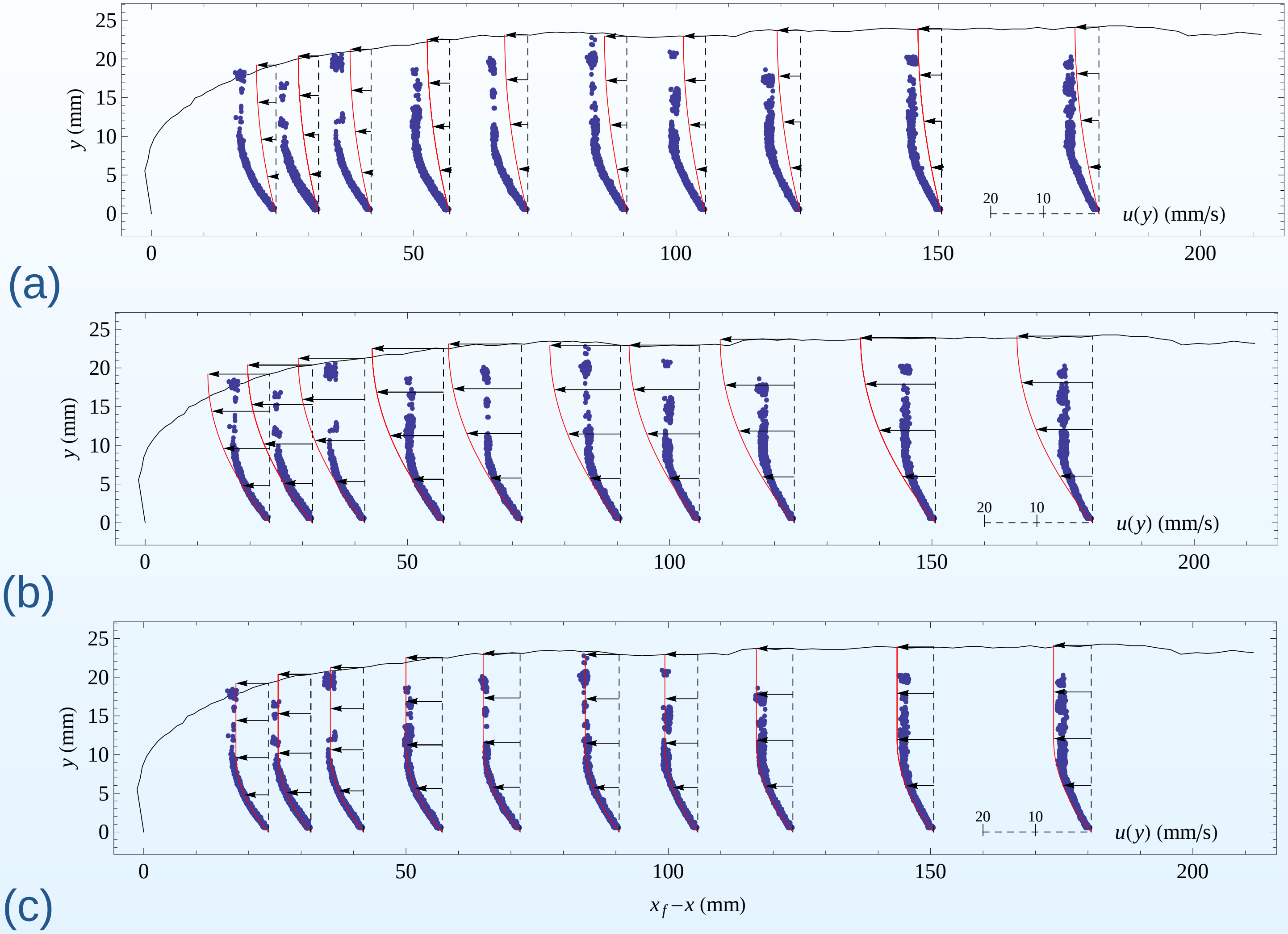


Position of the front as a function of time (for various masses)

Evolution of the flow depth profiles

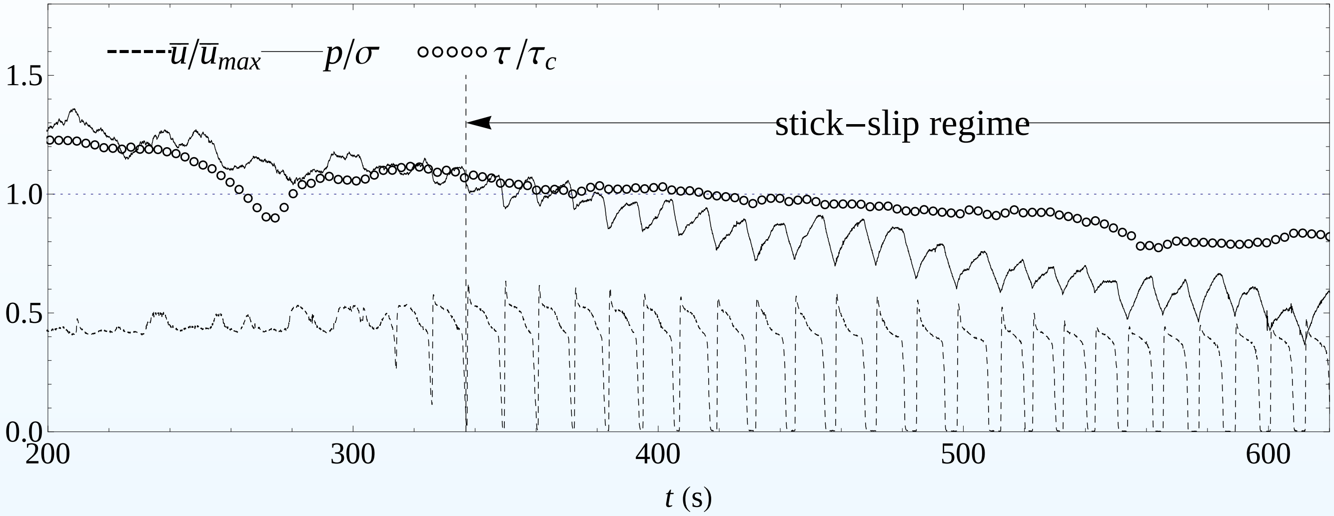


Velocity profiles



(a) Newtonian model with $\mu = 31.65$ Pa s. (b) Newtonian model with $\mu = 10$ Pa s. (c) Bingham model with $\tau_c = 65$ Pa and $\mu_b = 5$ Pa s.

Occurrence of a plastic regime



- $\bar{u}$ depth averaged velocity ($\bar{u}_{max}$ maximum of the time series)
- $\tau = \rho g h \sin\theta$ bottom shear stress, $\tau_c = 65$ Pa estimated yield stress if viscoplastic model used
- p pore pressure, $\sigma = \rho g h \cos\theta$ normal stress (normal to the bottom)

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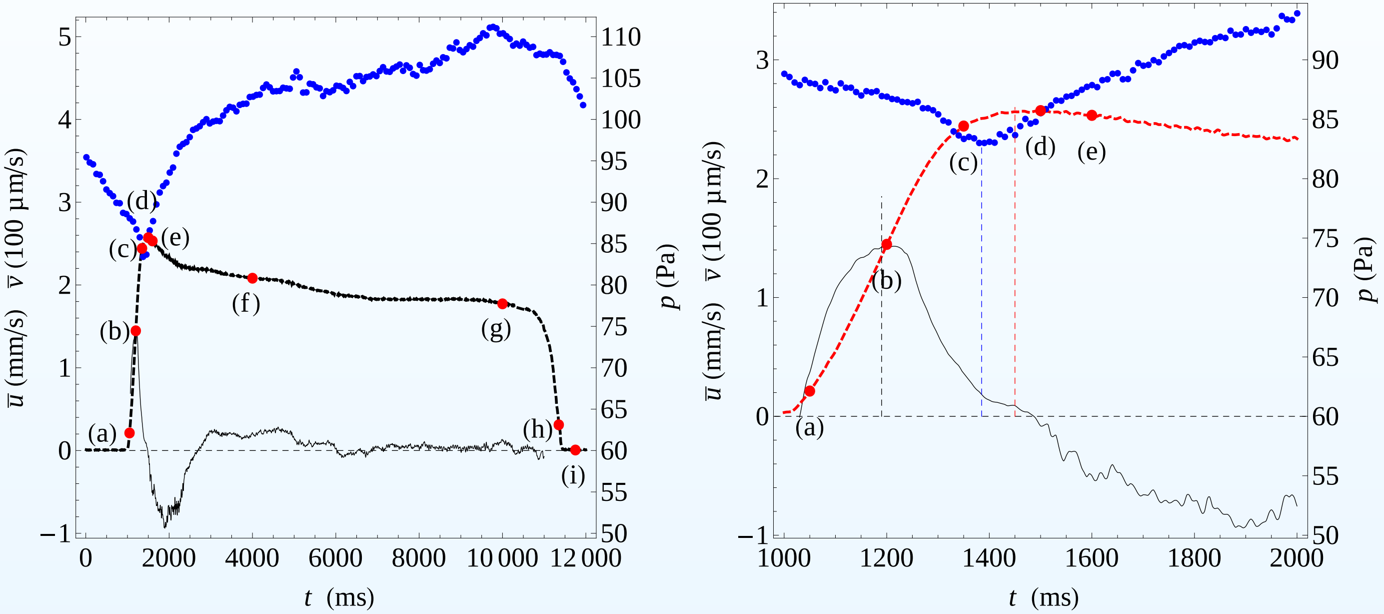
Stick-slip regime

Velocity profiles



Evolution of pore pressure and depth-averaged velocities (streamwise and normal components)

Interpretation

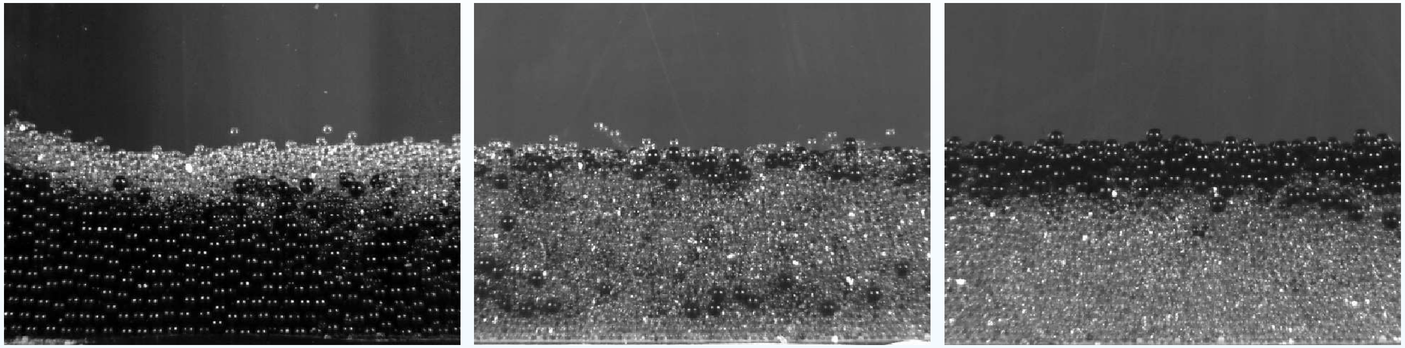
Terzaghi's decomposition

$$\sigma = p + \sigma_p \Rightarrow \sigma_p = \sigma - p = \sigma\left(1 - \frac{p}{\sigma}\right),$$

which shows that :

- the effective stress is compressive when $p/\sigma < 1$, it generates a frictional shear stress, which satisfies the Coulomb law.
- the effective stress is tensile (negative) when $p/\sigma > 1$. Particles are fluidized.

Segregation



Snapshots showing particles segregating down a flume. Initially, when the particles enter the chute (image on the left), the mixture is normally graded, with all the small particles (1-mm diameter glass beads, colored) on top of the coarse grains (2-mm diameter glass beads in black). Segregation leads to a grading inversion, in which the smallest particles percolate to the bottom of the flow, while the largest rise toward the free surface (image in the middle). In the final state (in this experiment, approximately 1 m downward of the flume entrance), the particles separate out, with the large particles on top and small particles next to the bottom (image on the right).

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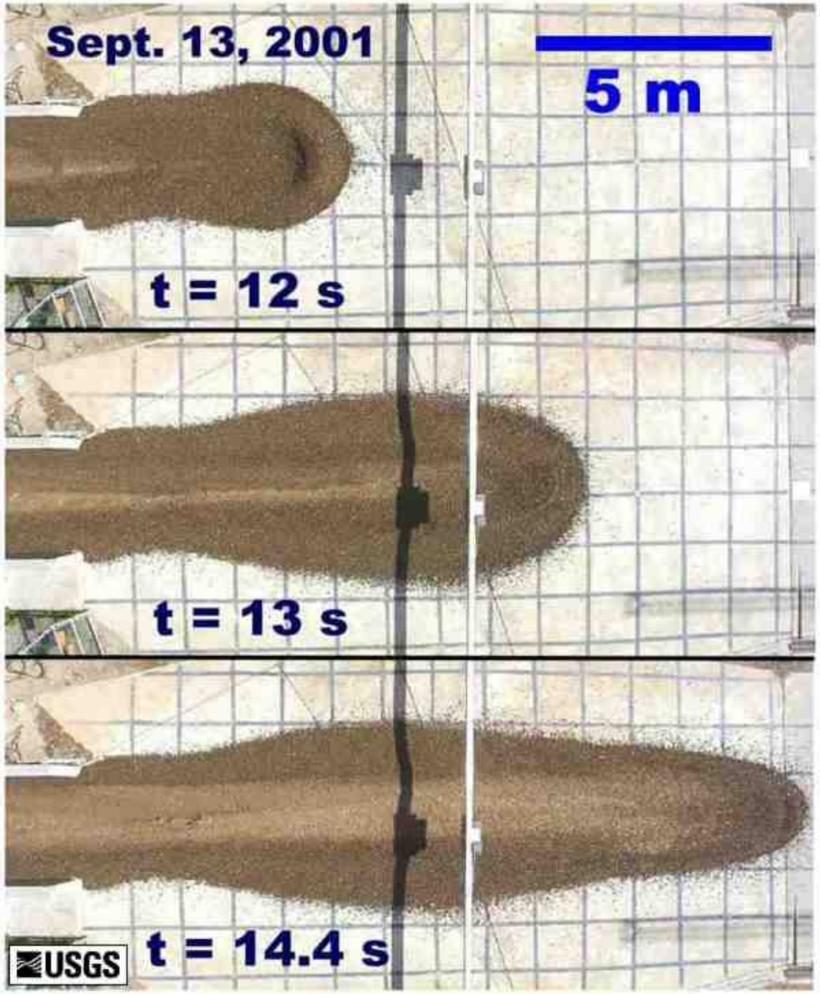
Consequences on flow dynamics

Snapshots showing slurry flow discharging from the U.S. Geological Survey Debris-flow Flume and crossing the unconfined, nearly horizontal runout zone. The dark-toned material around the perimeter of the flow was predominantly gravel, while the light-toned material in the center of the flow was liquified mud.



Courtesy of R.M. Iverson

Introduction

Lab experiments

Newtonian flows

Viscoplastic flows

Concentrated flows

Flow structure

- Segregation
- Consequences on flow dynamics
- Simple theory

Perspectives

Courtesy of J.M.N.T Gray. C. Johnson *et al.*, submitted to *J. Geophys. Res.*

Simple theory

Using simple arguments, Gray and coworkers showed that for bimodal distribution, the variations in the concentration (in small particles) can be described using a ‘simple’ advection-diffusion equation

$$\frac{\partial \phi}{\partial t} + \mathrm{div}(\phi \mathbf{u}) - \frac{\partial}{\partial z}\Big(q\phi(1-\phi)\Big) = \frac{\partial}{\partial z}\left(D\frac{\partial \phi}{\partial z}\right),$$

Gray & Chugunov, Particle-size segregation and diffusive remixing in shallow granular avalanches, *J. Fluid Mech.*, **569**, 365–398, 2006; Thornton *et al.*, A three-phase mixture theory for particle size segregation in shallow granular free-surface flows, *J. Fluid Mech.*, **550**, 1–25, 2006; Gray & Ancey, Multi-component particle size segregation in shallow granular avalanches, *J. Fluid Mech.*, in press, 2011.

Ongoing and future research

- mass balance: how material is incorporated and deposited?
- shallow flows: do the flow-depth-averaged equations perform well when used to modelling unsteady fixed-volume surges?
- flow structure: particle flows, segregation, two-phase aspects, etc.
- stochastic modelling: coupling deterministic and stochastic models (MCMC models).