Granular Flows From the Laboratory to the Ski Jump

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Acknowledgments

THE ROYAL SOCIETY

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Plan of Talk

- Introduction to Avalanches
- Granular Levees
- Direct Numerical Simulations
- Integral Models and Field Obervations
- Shallow Models and Field Obervations
- Mars

Powder Avalanche on K2

Pierre Beghin

Head of Powder Snow Avalanche

Cemagref

Slab Avalanche Fracture Line

Skier in Slab Avalanche Debris

Cemagref

Patreksfjörður 1983, a Slush Flow Killed 3 People

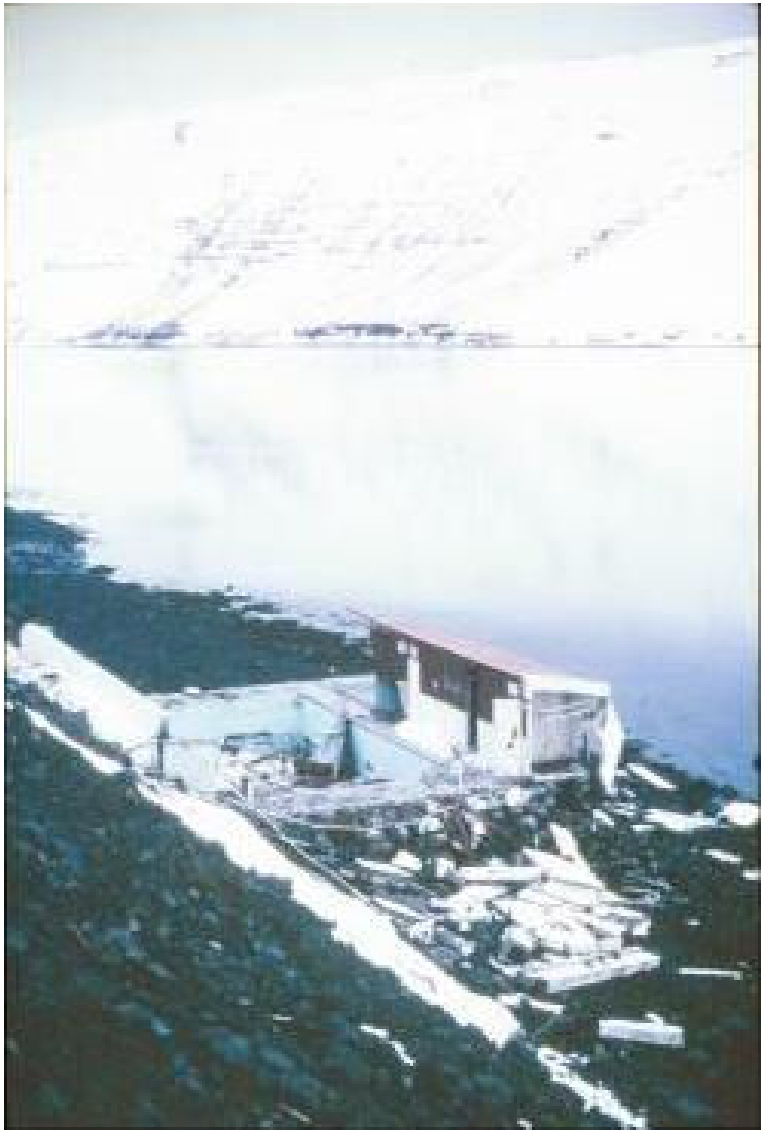
Destroyed House at Saint Colomban Les Villars

Test Chute in Davos film

Destroyed Buildings at La Morte

Cemagref

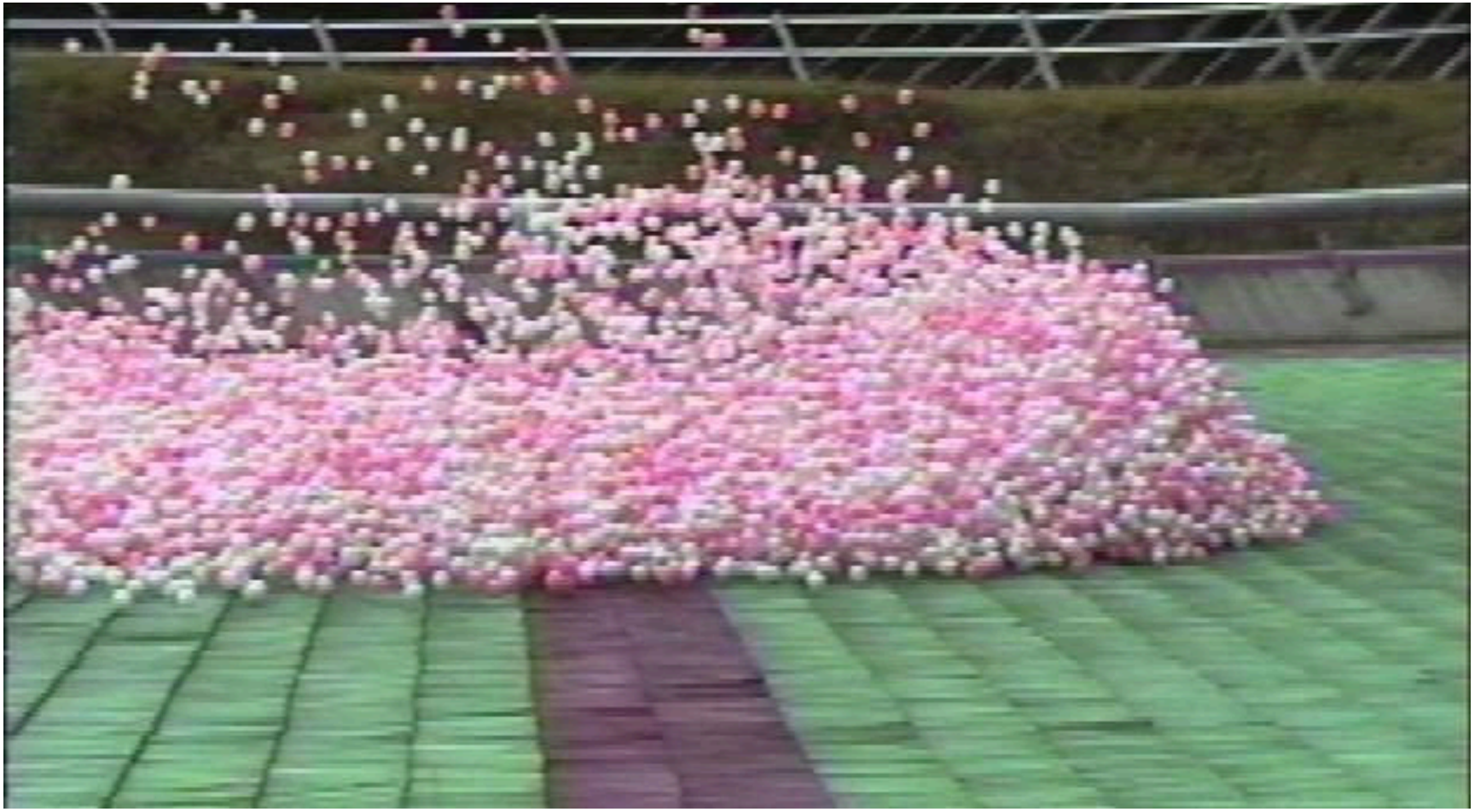
Damage by a flood wave at Súgandafjörður



Current Avalanche Research

- Huge variety:
  - speeds 25–250 $\mathrm{km/h}$
  - densities 5–500 $\mathrm{kg/m^3}$
  - masses 10^2–10^9 kg
- Three dimensional terrain and structure
- Snow properties are complicated and ill-defined
- Unpredictable, destructive, unreproducible
- Current theories are phenomenological
- Genesis of powder snow avalanches not understood

Ping-Pong Avalanches



Levee Formation in Natural Flows

Phys. Rev. E 83:031306 (2011)

Types

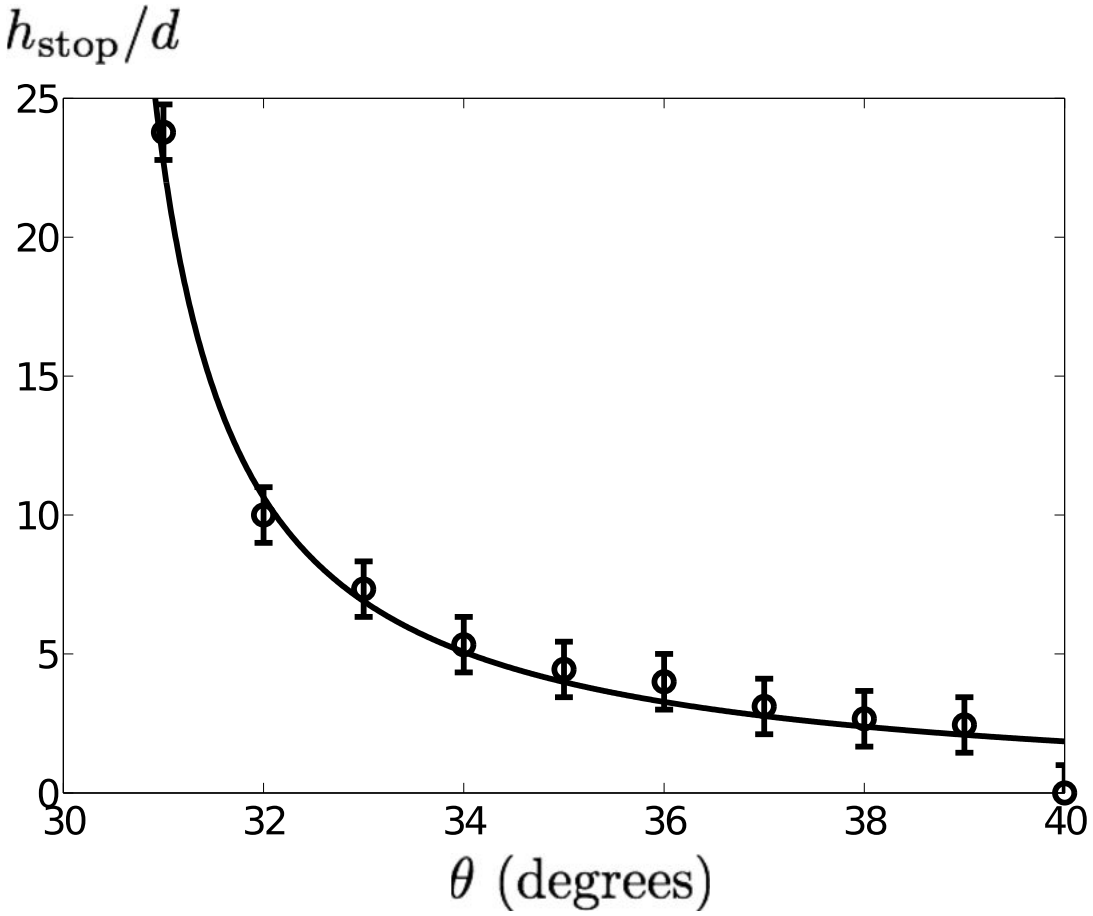
- Avalanches
- Rock Slides
- Debris Flows

Effects

- Increased Runout
- Changed Hazard Zones

Levee Formation at Vallée de la Sionne film

Deposit thickness hstop as a function of slope angle θ



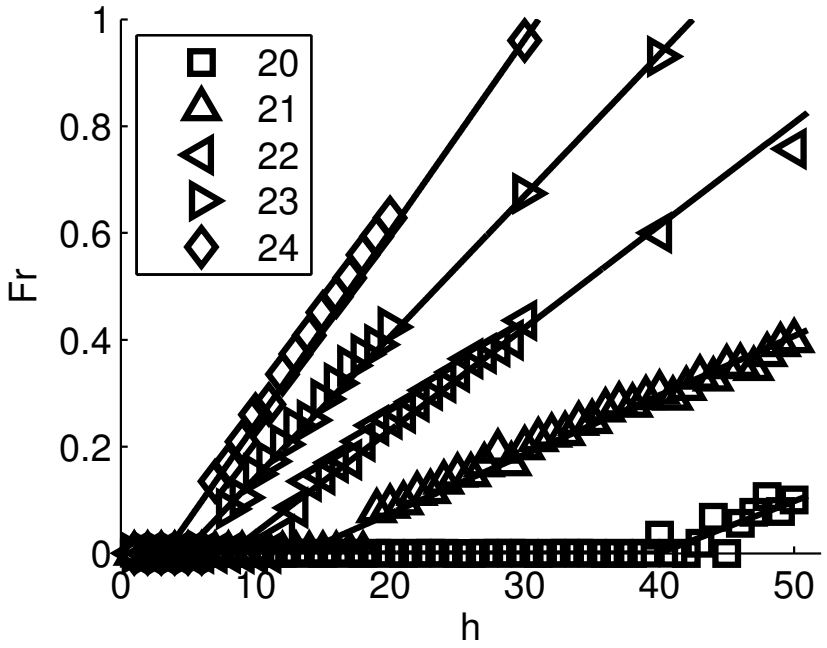
$$\frac{h_{\mathrm{stop}}}{d} = \frac{a}{\tan\theta - \tan\theta_1}$$

Theoretical Motivation

An empirical law for the steady granular flow from experiments and simulations

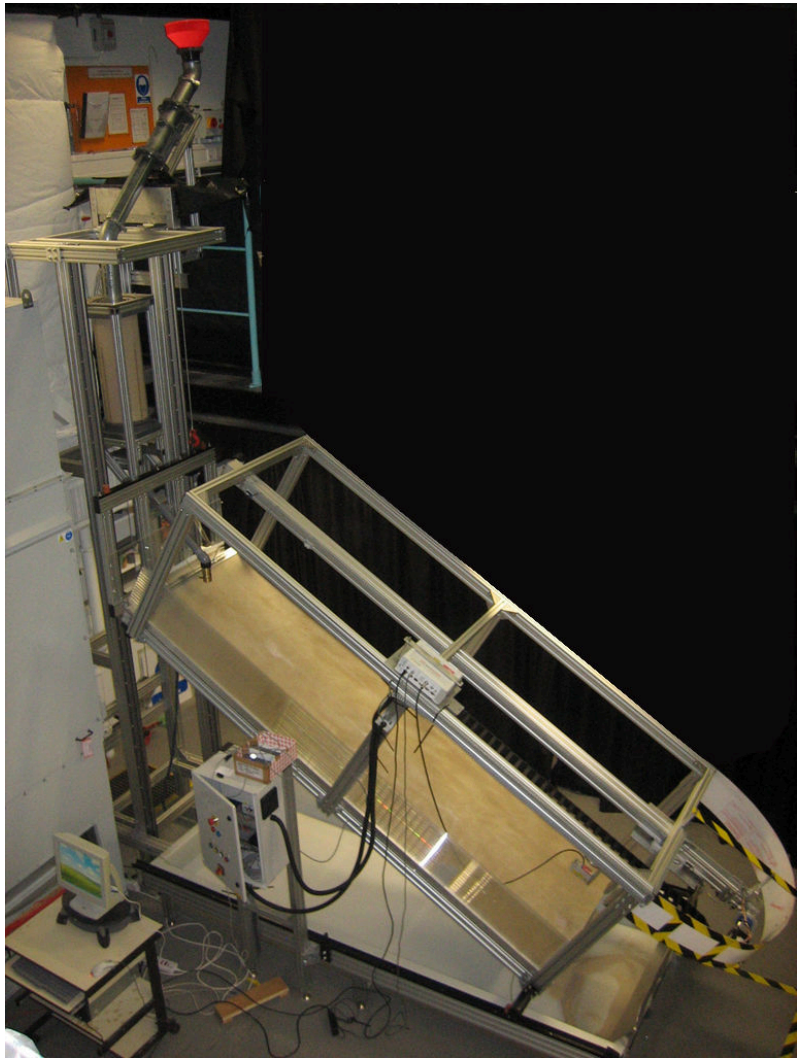
$$\mathrm{Fr} = \frac{u}{\sqrt{gh\cos\theta}} = \alpha + \beta\frac{h}{\mathrm{hstop}(\theta)},$$

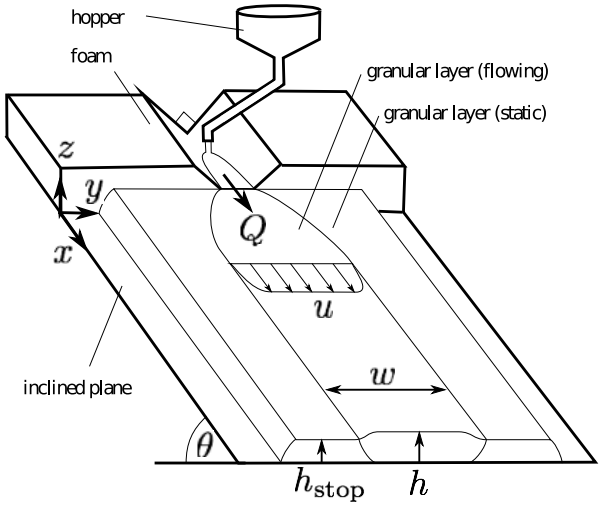
- u velocity
- h flow depth
- hstop deposit depth
- g gravity
- θ slope angle



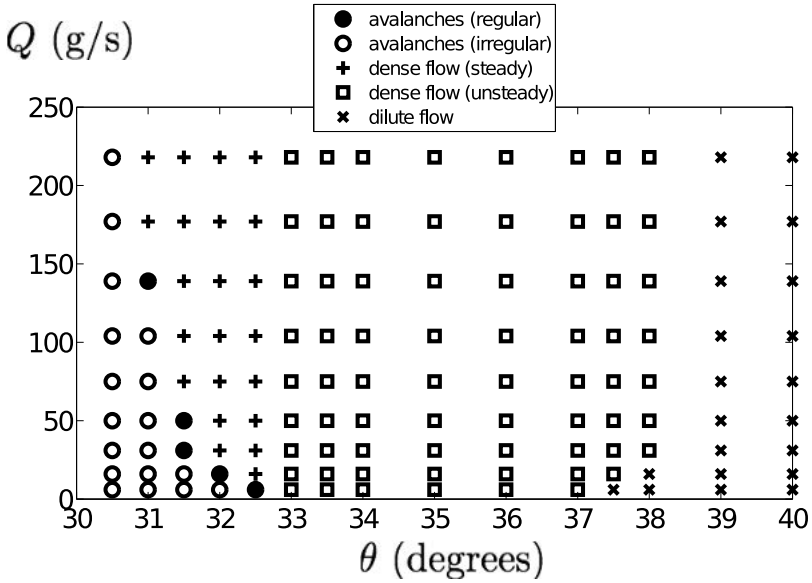
Experimental setup film

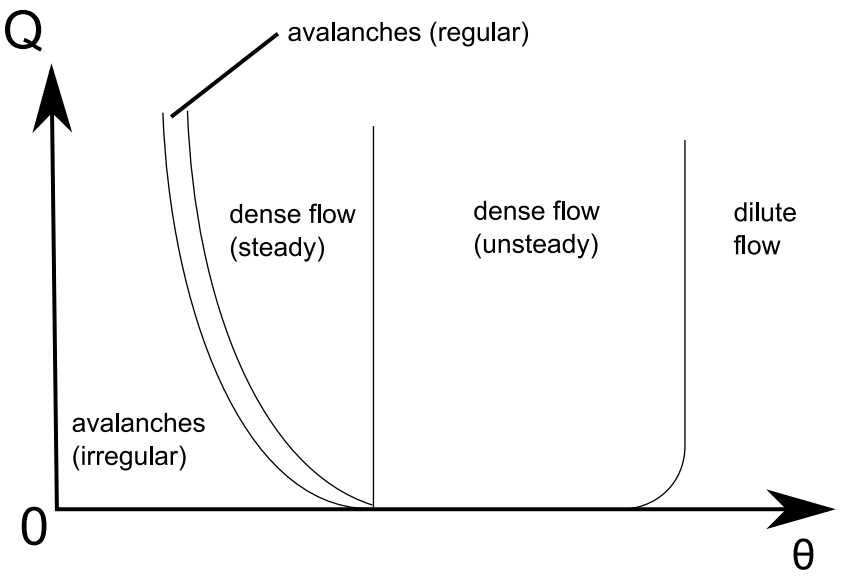
Phys. Rev. E **(83)**:031306, 2011. Gran. Mat. (2012)





Regime diagram for Sand

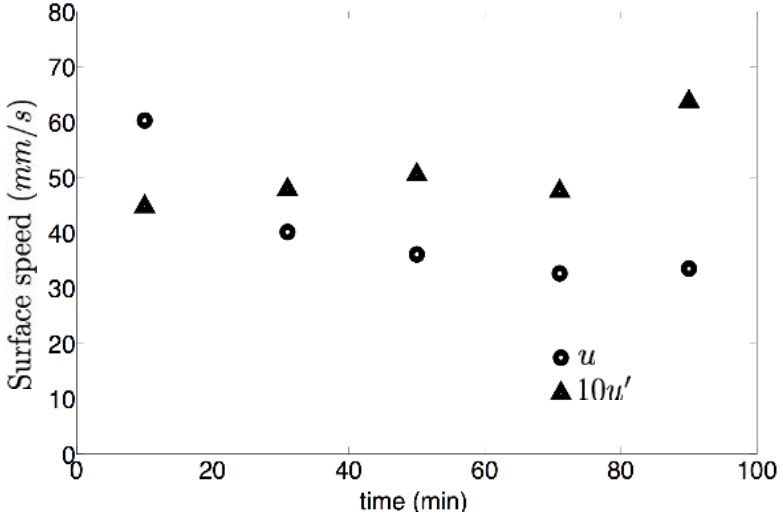




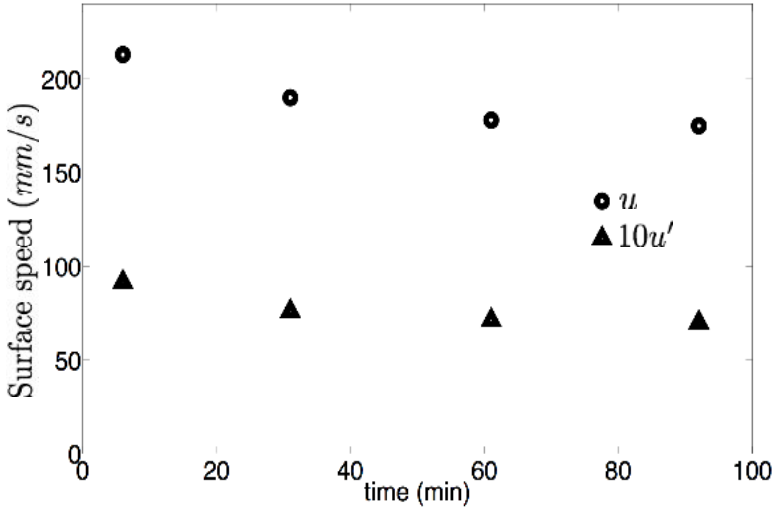
Q mass flow rate

Evolution of the surface velocity

Ballotini $Q = 10\,\mathrm{g/s}$, $\theta = 25°$

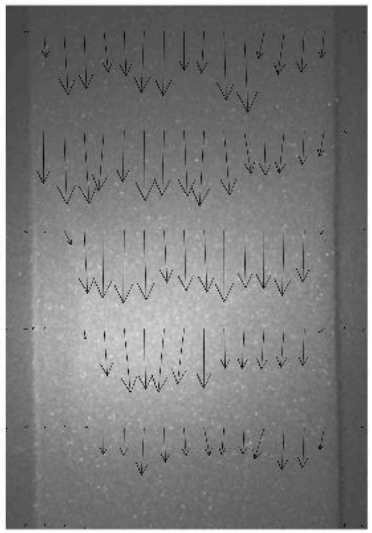


Sand $Q = 104\,\mathrm{g/s}$, $\theta = 32°$

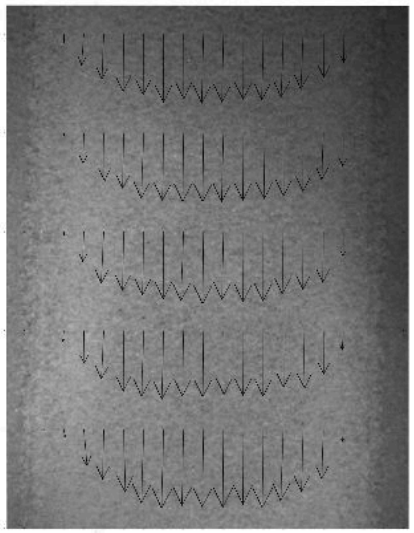


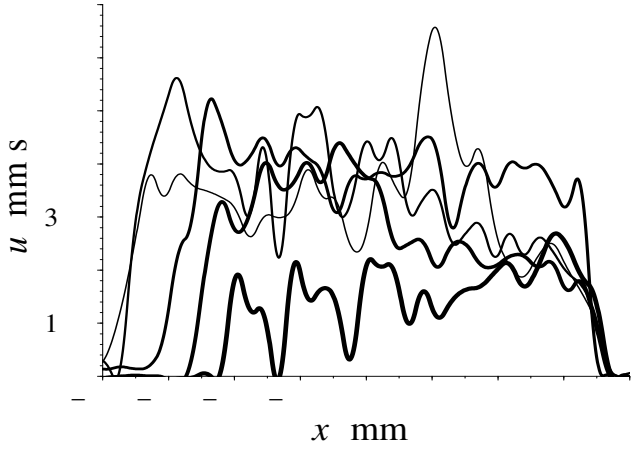
Surface Measurements with Particle Image Velocimetry (PIV)

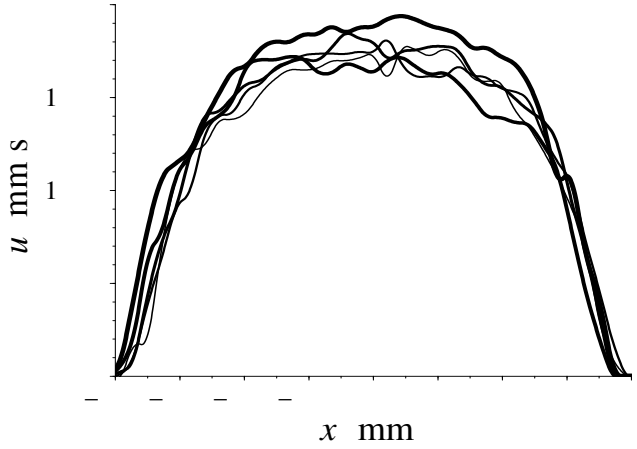
Ballotini



Sand

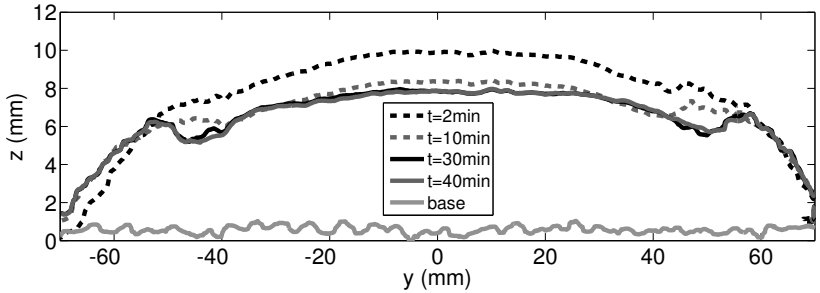




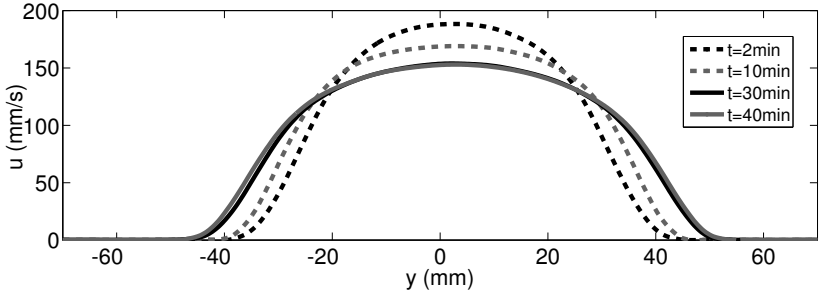


Surface height and velocity of sand

Clear Surface

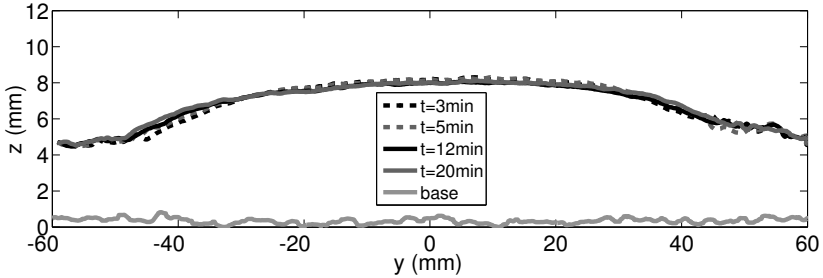


Surface Height

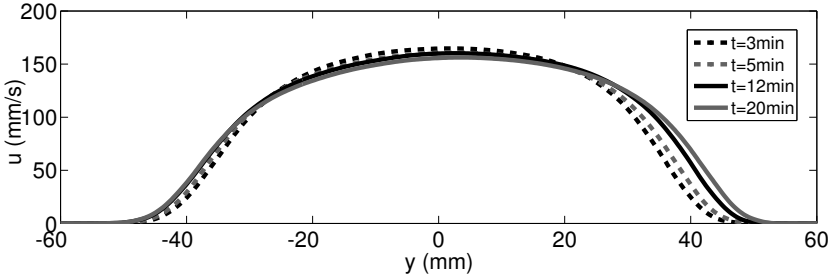


Surface Velocity

Covered surface



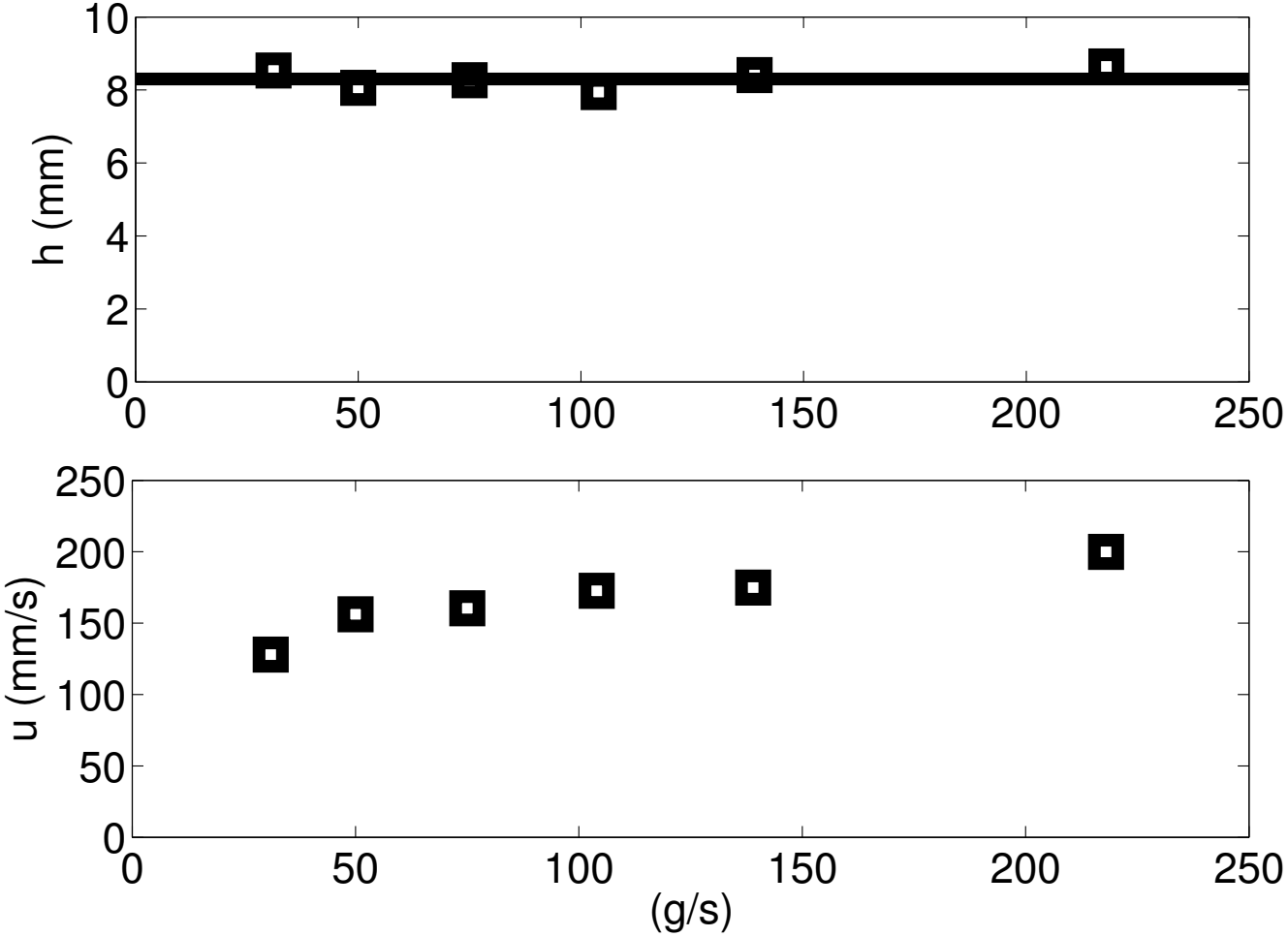
Surface Height



Surface Velocity

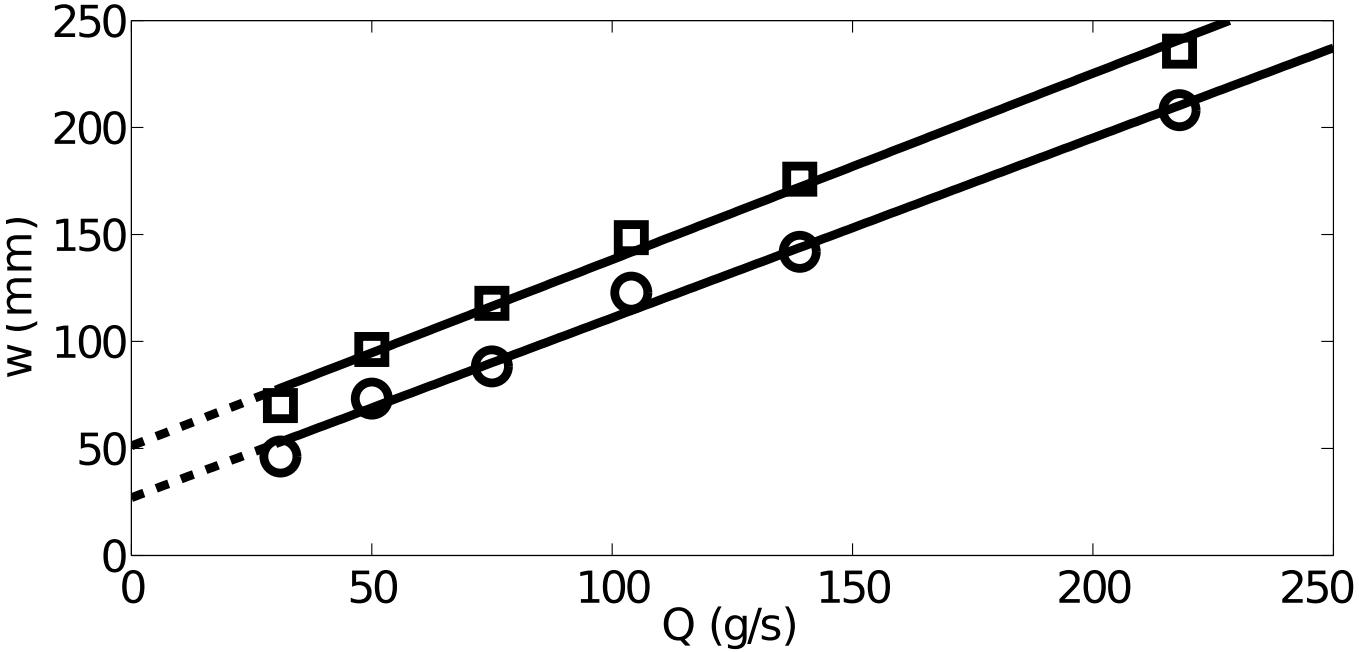
Covered surface Speeds up convergence, steady states are identical

Centre height and velocity against flow rate



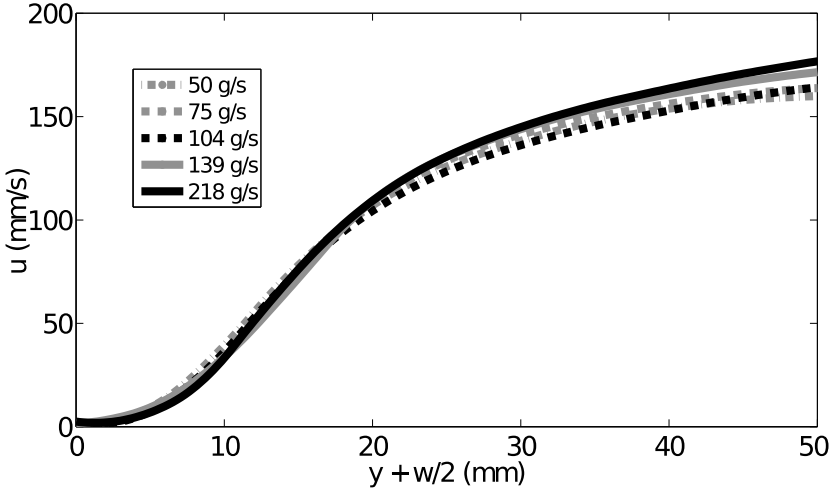
Characteristic width of the flowing region

$$Q = \rho h U (W - W_0) \quad \Rightarrow \quad W = W_0 + \frac{Q}{\rho H U}$$

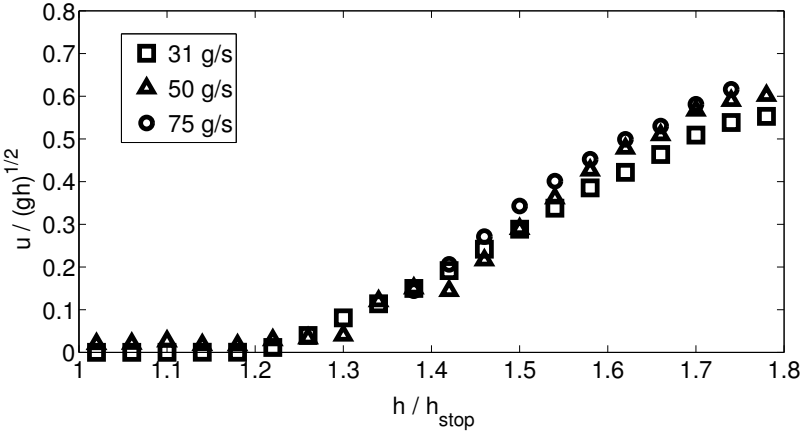


ρ density, H depth, U velocity, Q mass flux, W width

Speed against height



Speed against position

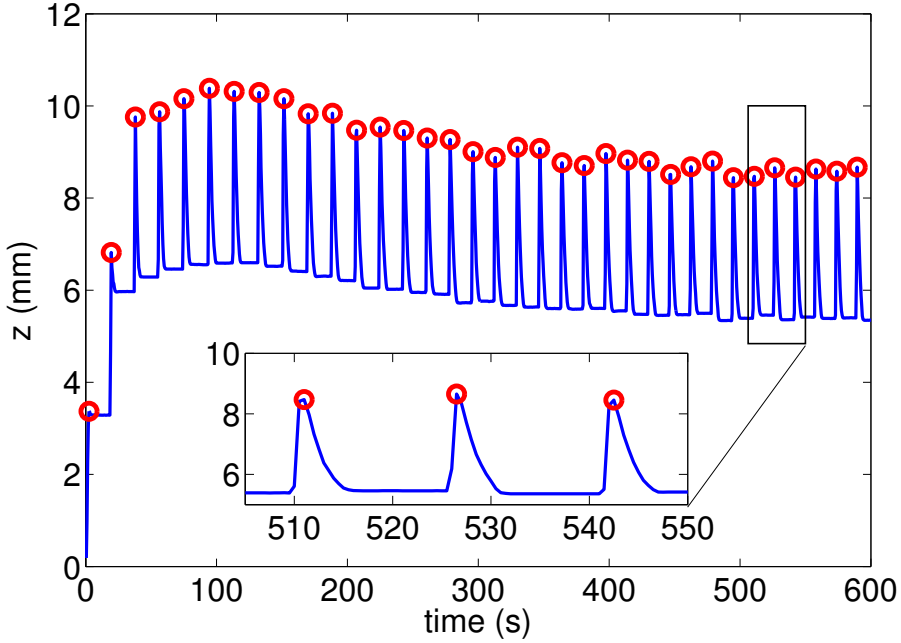


Speed against height

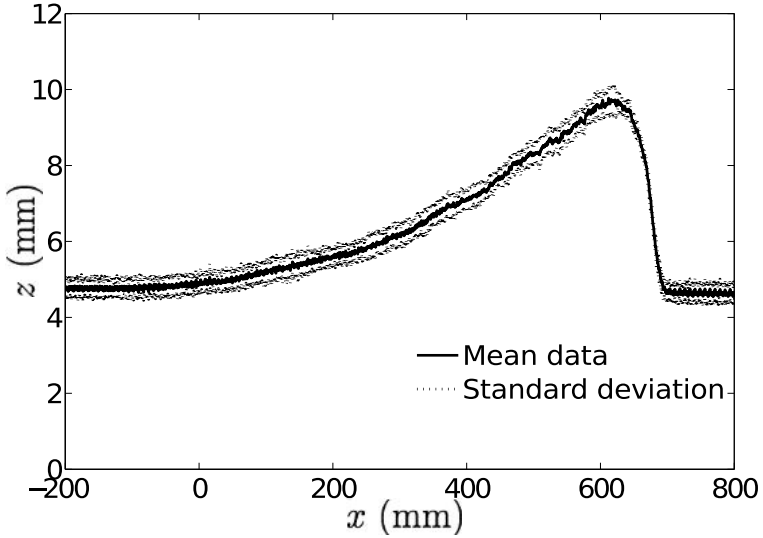
$$\frac{u}{\sqrt{gh\cos\theta}} = \alpha + \beta\frac{h}{\mathrm{hstop}(\theta)} + \nu\frac{h^2}{\sqrt{gh\cos\theta}}\frac{\partial^2 u}{\partial z^2}$$

Granular Solitons

film



Surface height Measured in the middle of the slope



Avalanche profiles

Dry-mixed avalanche artificially released at the Vallée da la Sionne

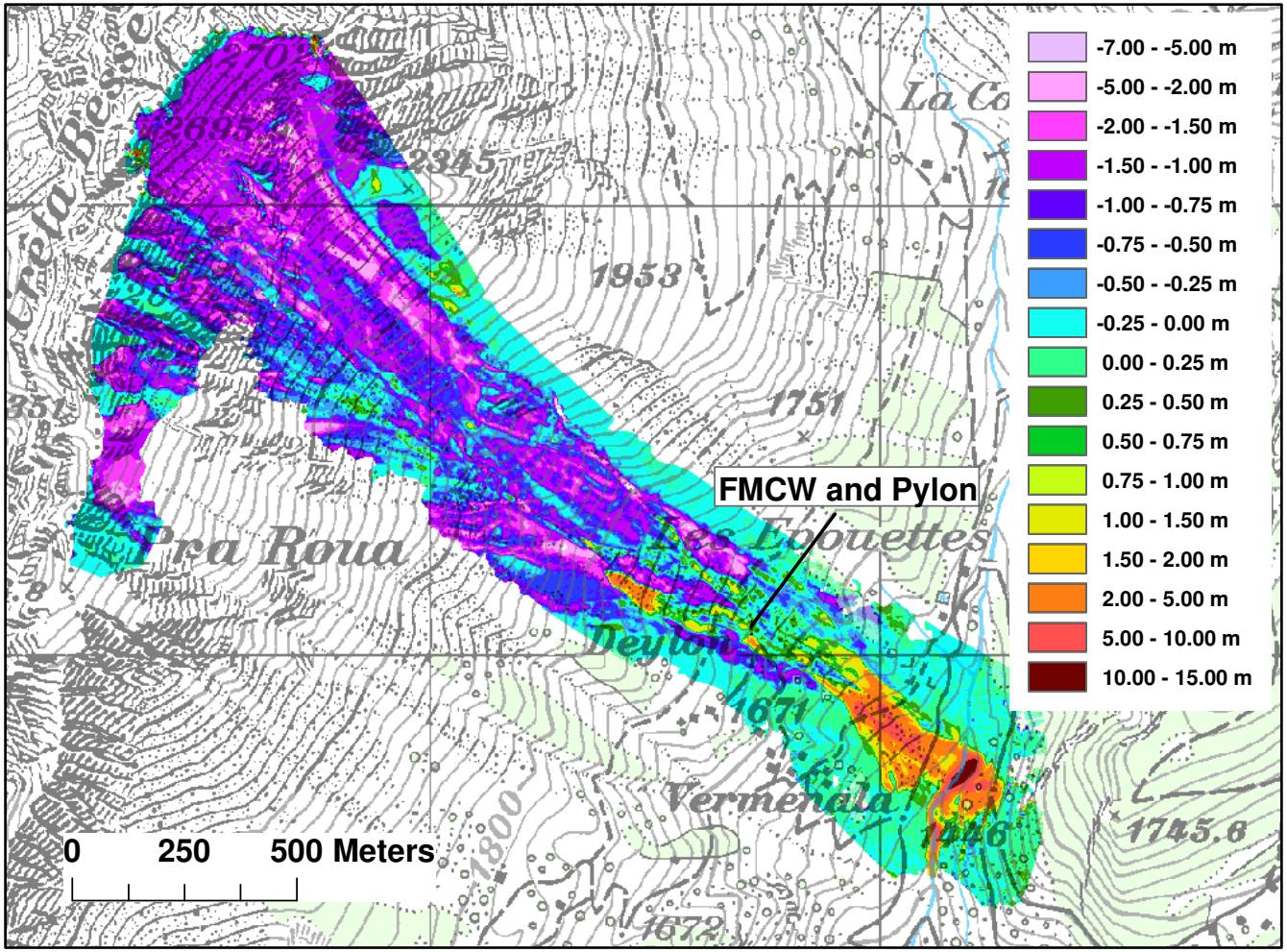
Deposit showing a homogeneous snow depth distribution

Riegl LMS-Q240i laser scanner

Specs

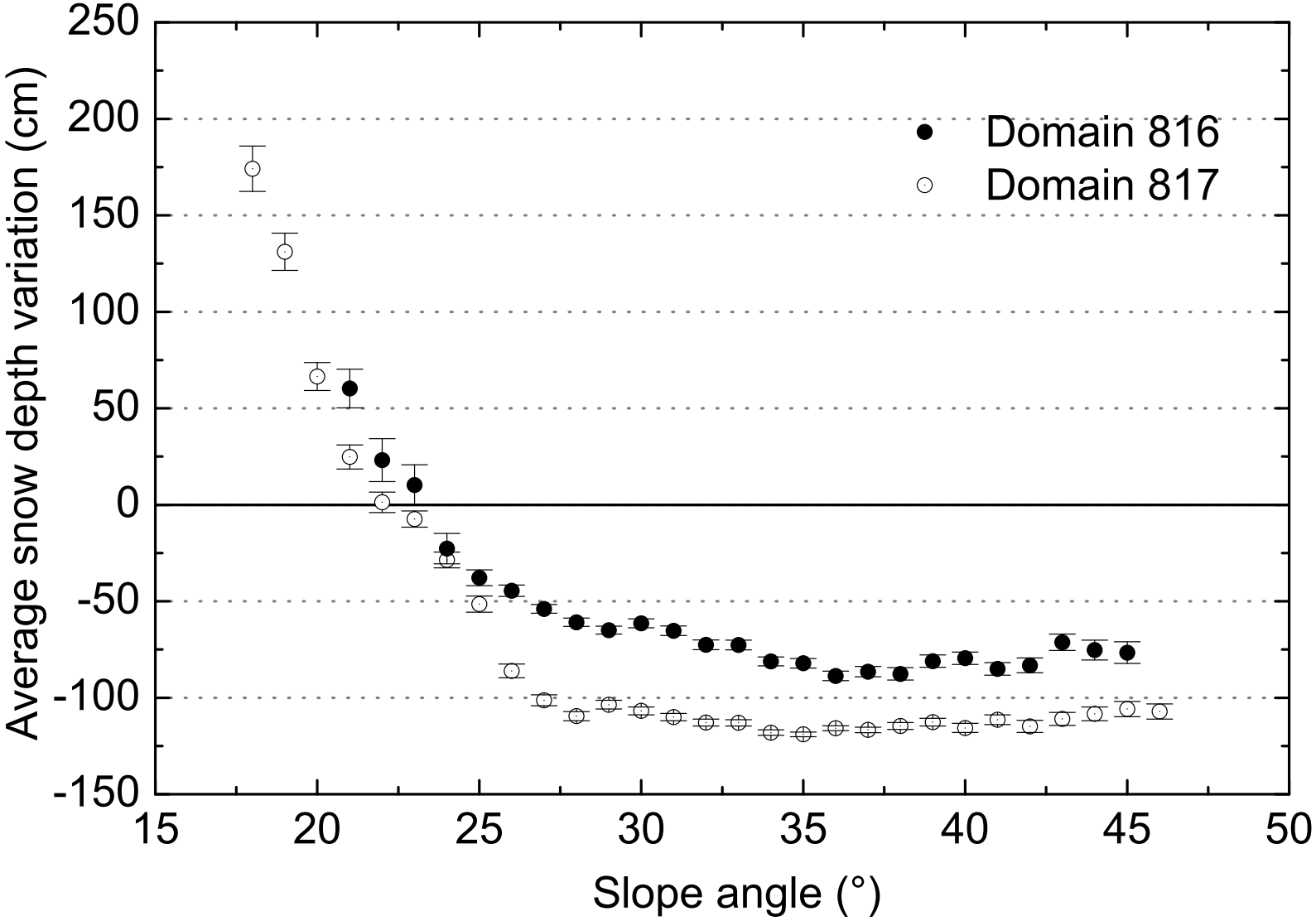
- time of flight principle
- 10 000 points per second
- horizontal resolution 500 mm
- vertical resolution 100 mm
- high density of points
- inertial measurement
- GPS

Snow depths variations h_δ



Bunker Rescue

Average snow depth variation $\overline{h}_\delta$



Cohesion-Frictional Model

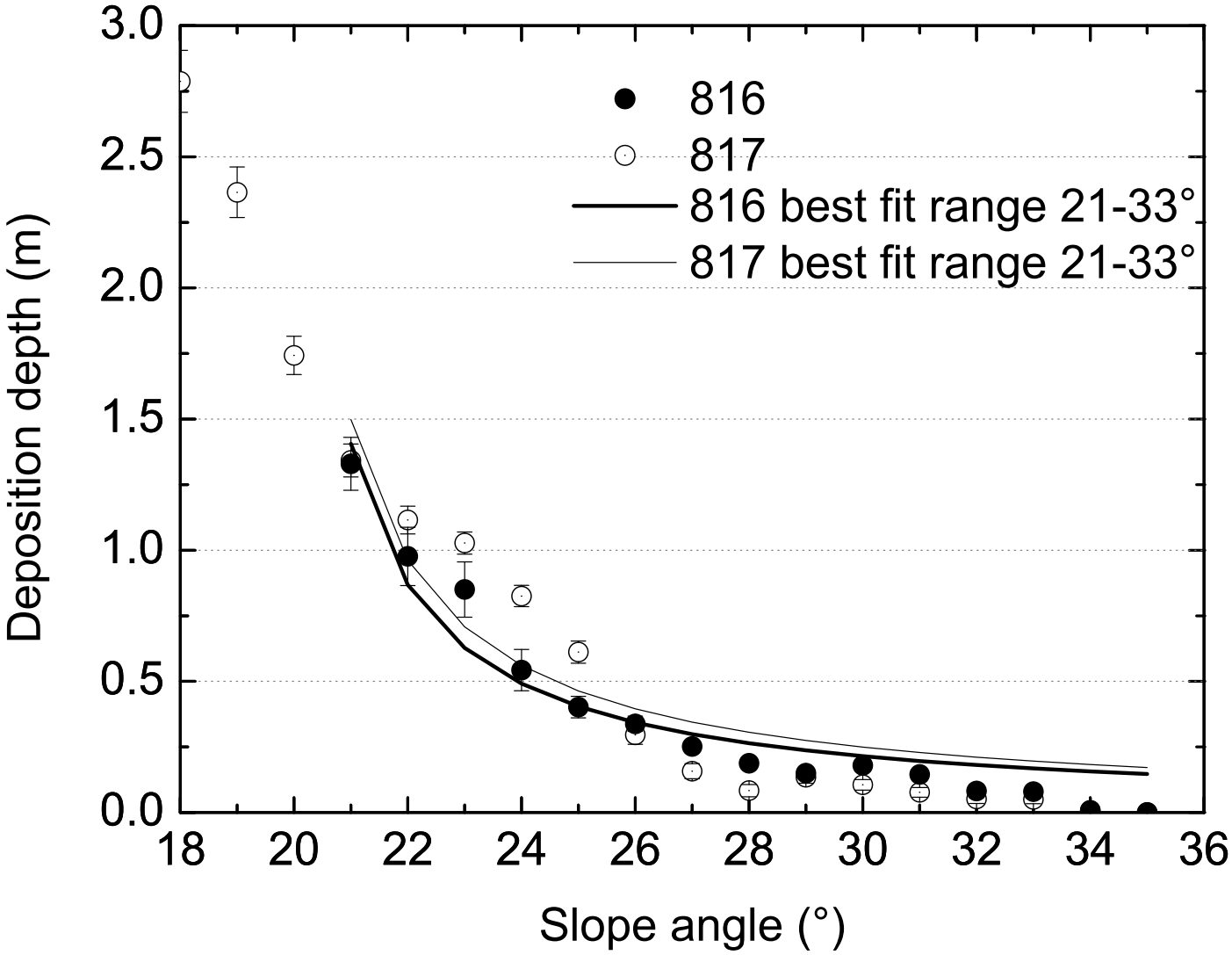
$$\rho g d_f \sin\theta = c + \mu \rho g d_f \cos\theta$$

$$d_f = \frac{c}{\rho g(\sin\theta - \mu\cos\theta)}$$

ρ density	g gravity	d_f flow depth
θ slope angle	c cohesion	μ friction

#816	$c = 123 \pm 25\,\mathrm{N\,m^{-2}}$	$\mu = 0.35 \pm 0.02$
#817	$c = 146 \pm 26\,\mathrm{N\,m^{-2}}$	$\mu = 0.36 \pm 0.02$

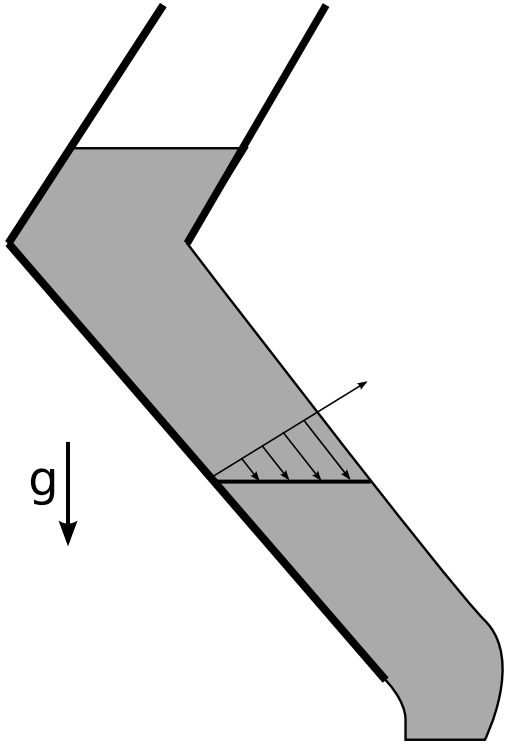
Deposit depth $d_f = h_d \cos\theta$ #816



Chutes — A Granular Rheometers J. Fluid. Mech. 710:35 (2012)

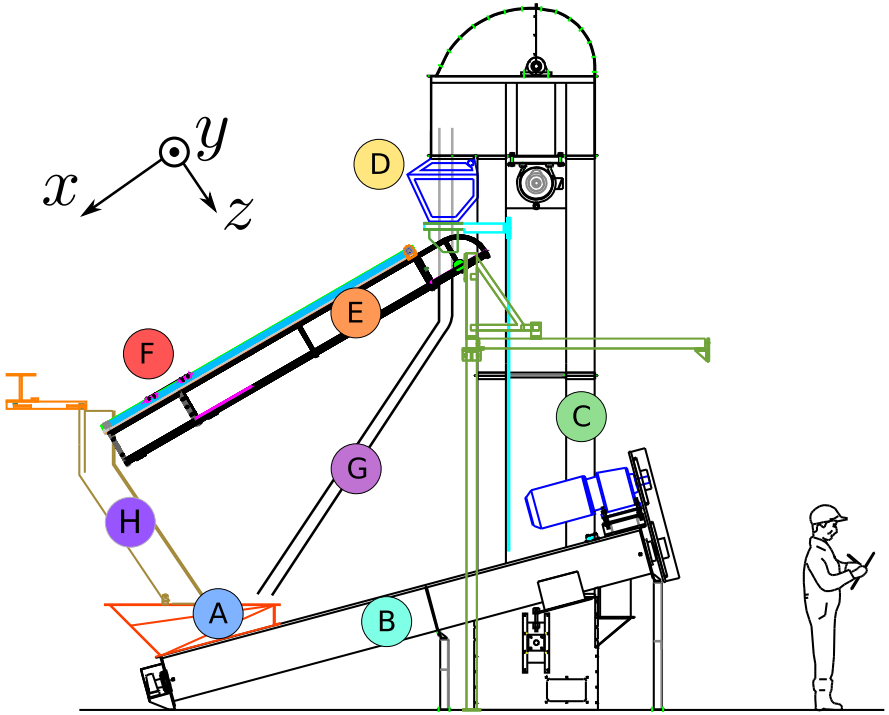
Previous chutes have been built but

- low mass fluxes
- only steady flows studied
- limited slope angles
- limited boundary conditions
- limited measurement systems



Our Chute

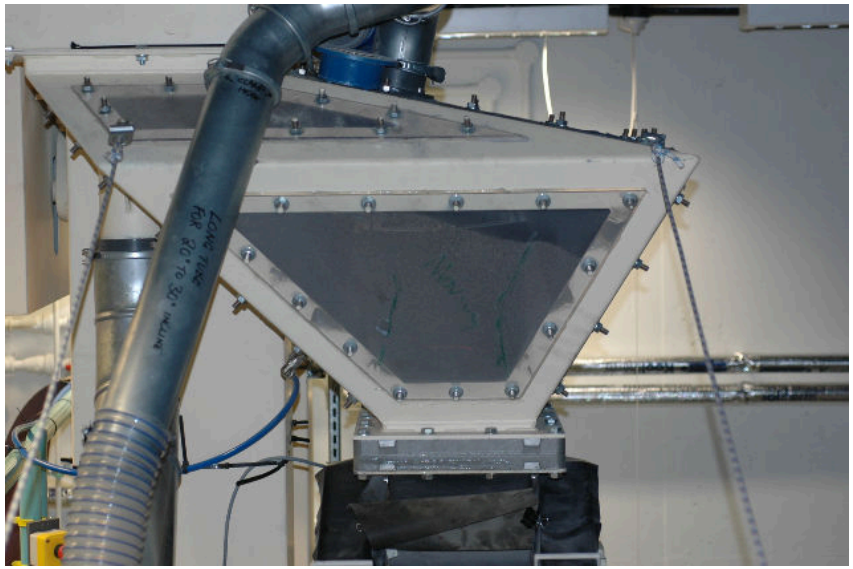
- A Return Chute
- B Screw Conveyor
- C Bucket Lift
- D Feed Hopper
- E Chute
- F Equipment Traverse
- G Overflow Chute

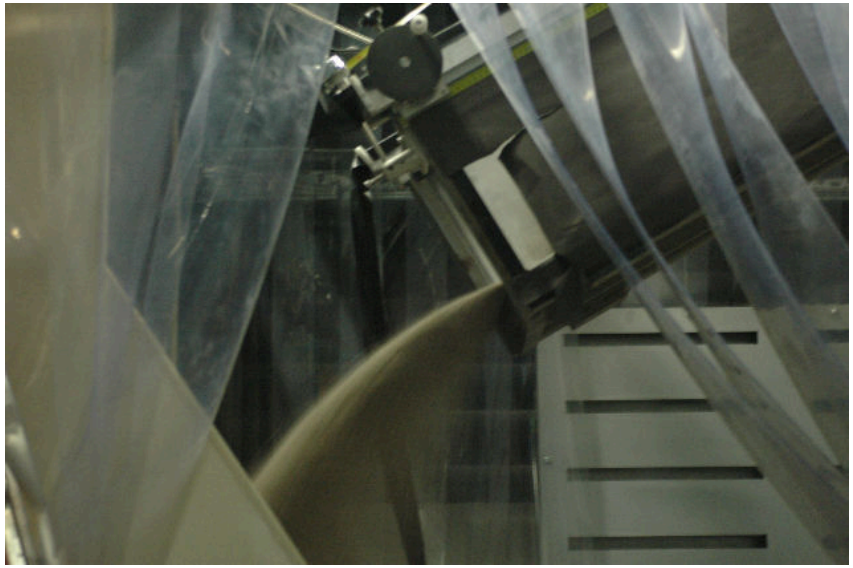


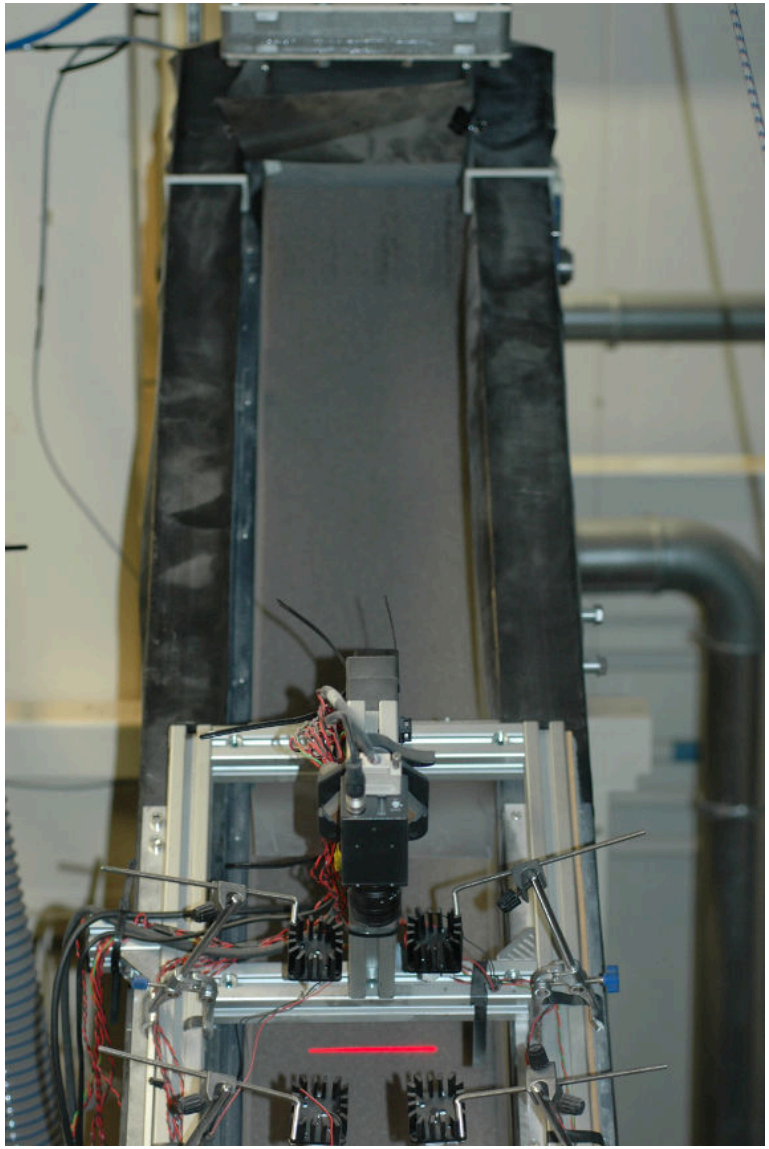
Our Chute

- $20\,\mathrm{kg\,s^{-1}}$ Flux rate
- $2000\,\mathrm{kg}$ Capacity
- $0.25\,\mathrm{m}$ Chute width
- $4\,\mathrm{m}$ Chute length
- 0–60° slope angle
- instrumentation traverse complete surface velocity and height

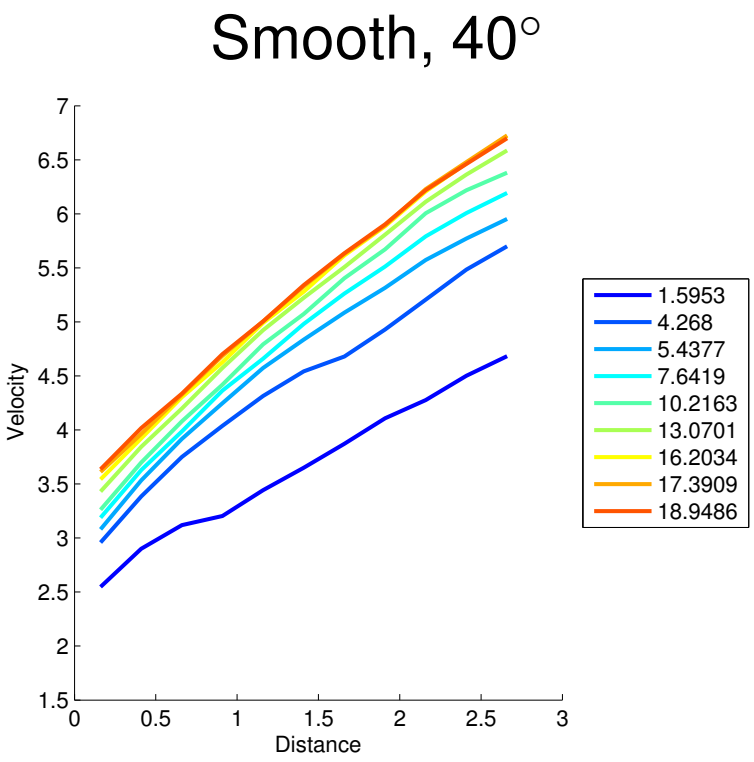
Chute Components

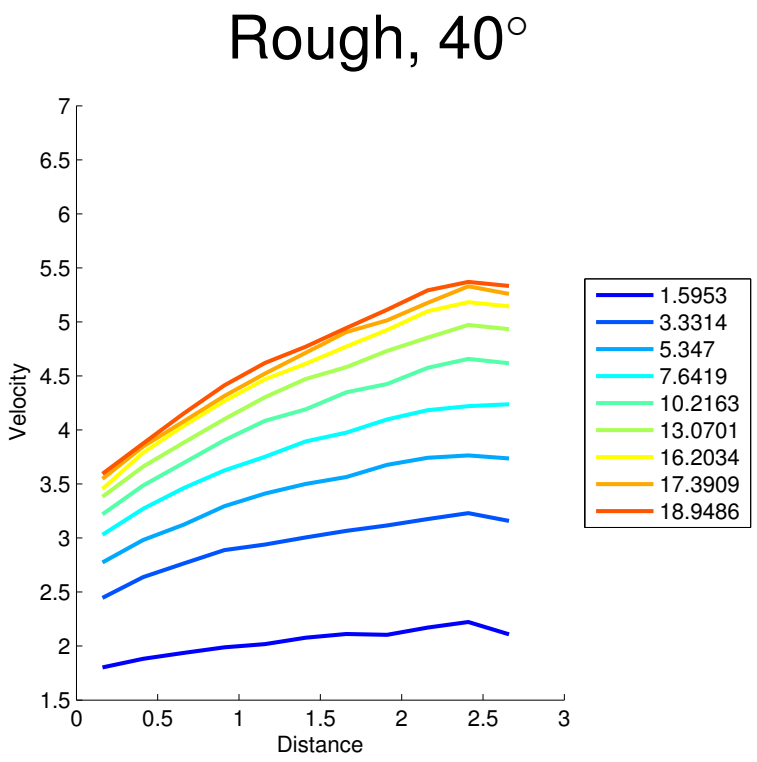




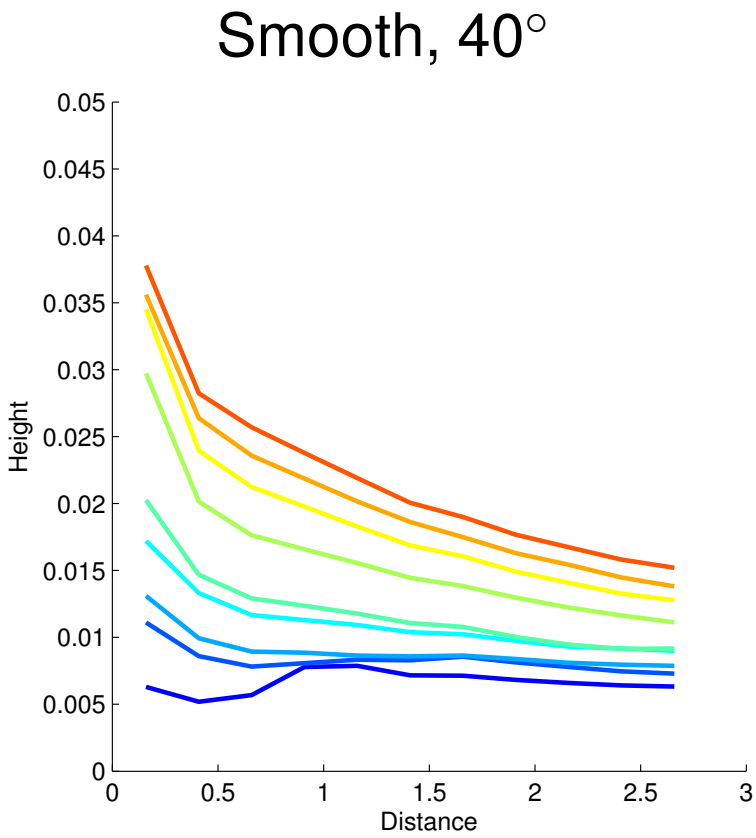


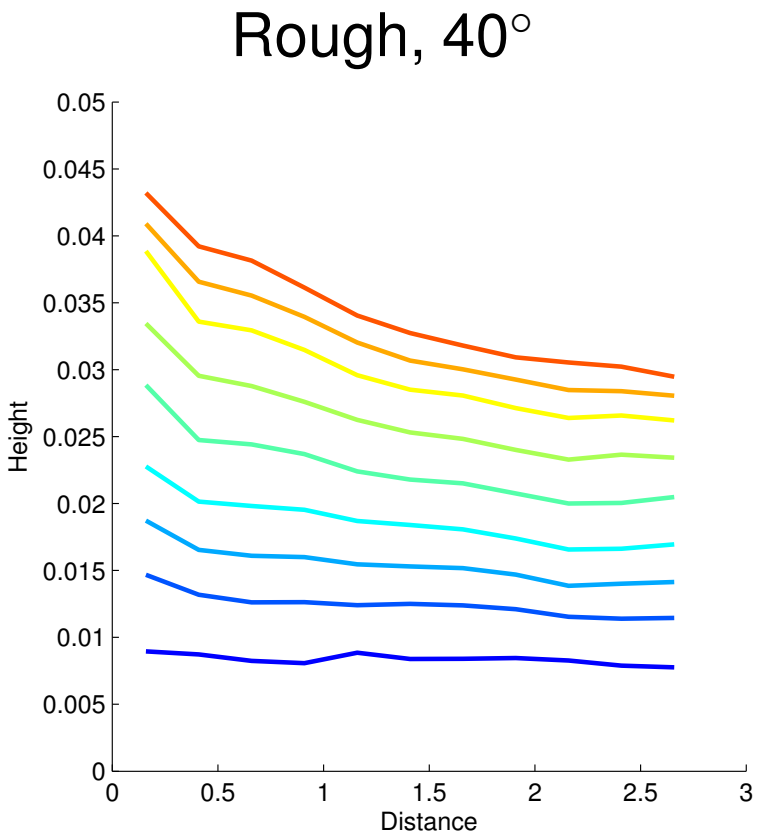
Velocity for Rough and Smooth Bases



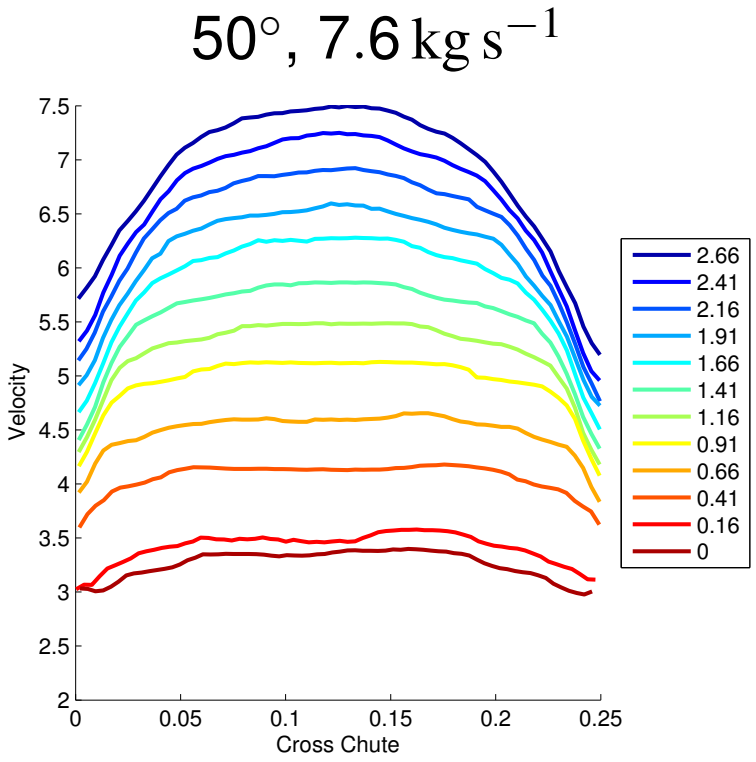


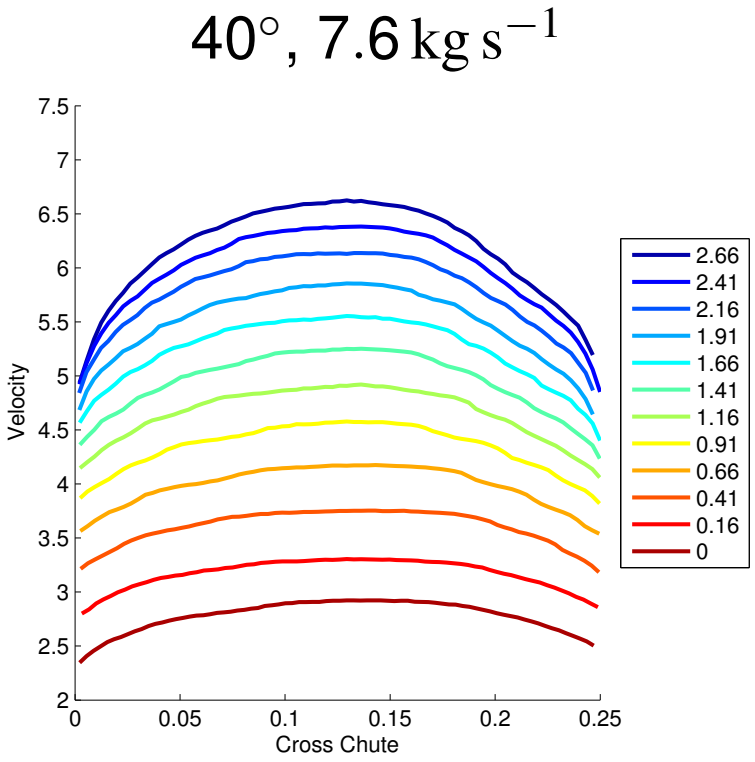
Height for Rough and Smooth Bases



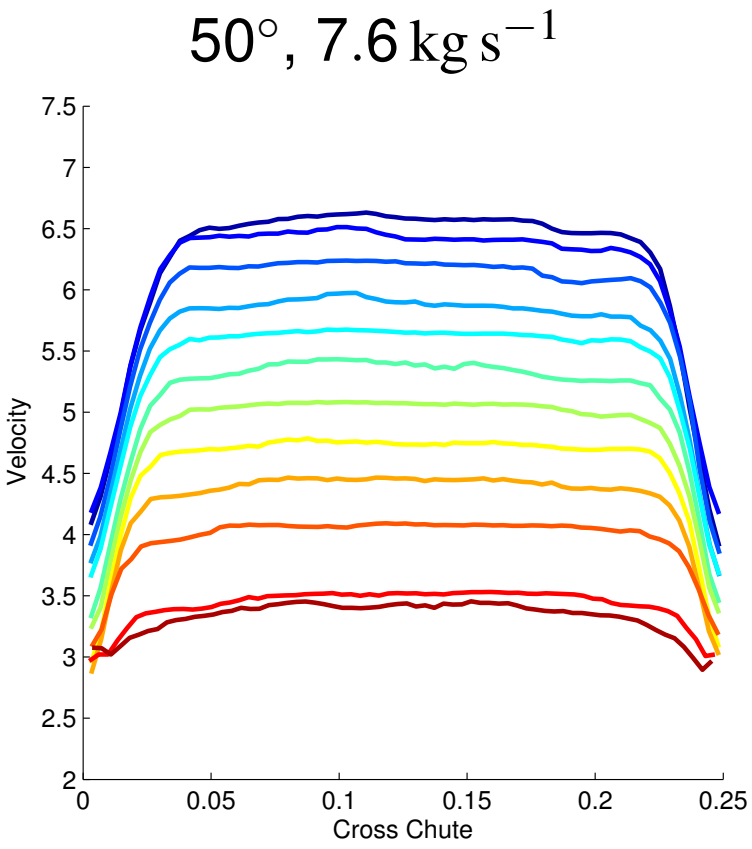


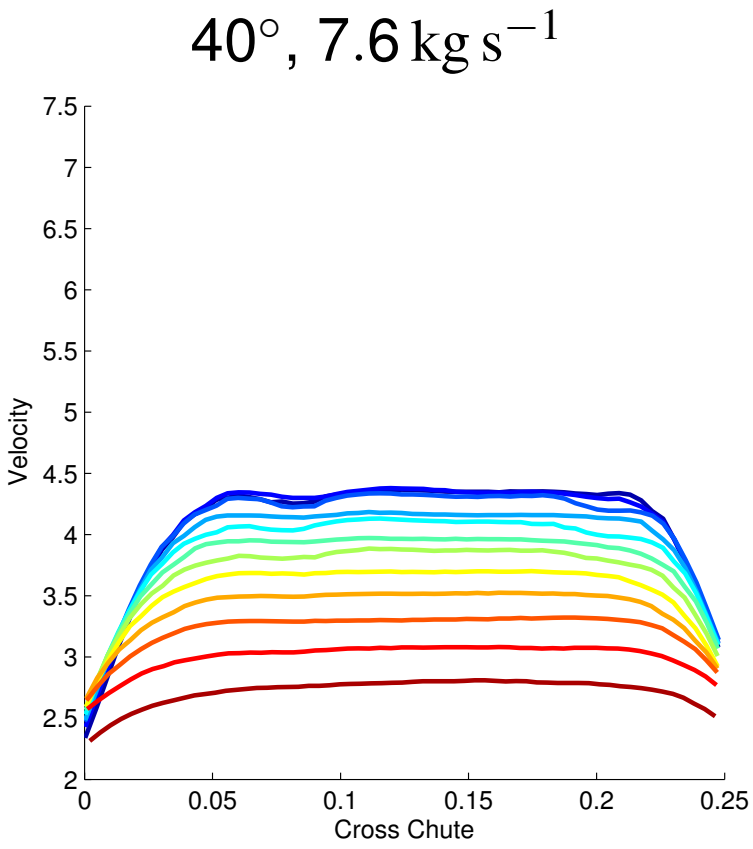
Transverse Velocity Profiles — Smooth Base





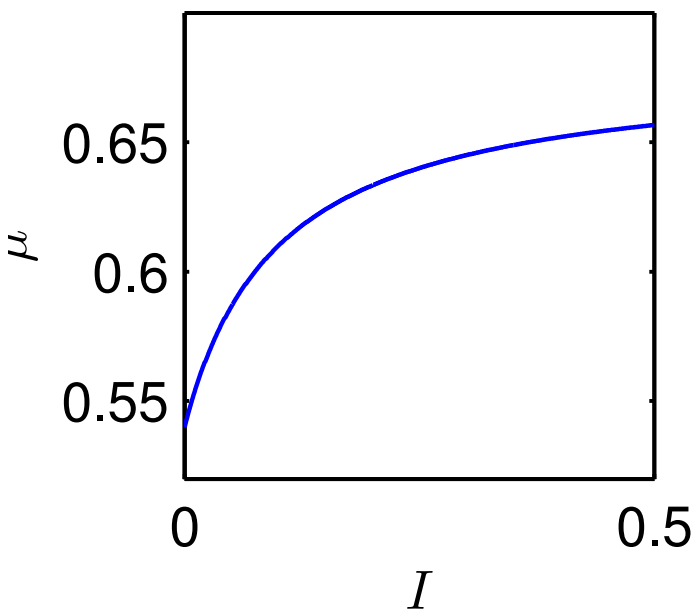
Transverse Velocity Profiles — Rough Base

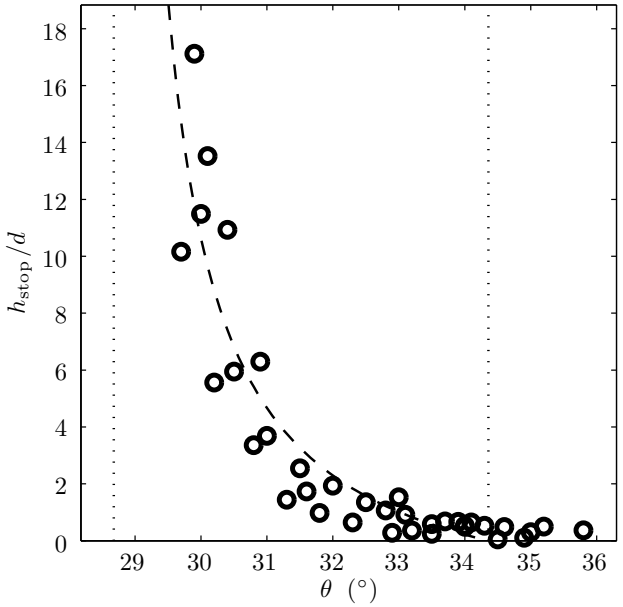




$\mu(I)$ Friction Law

$$\mu(I) = \frac{\mu_1 I_0 + \mu_2 I}{I_0 + I}$$

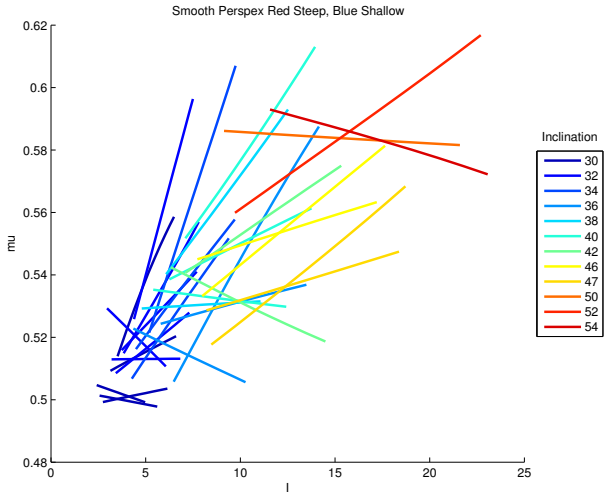




h_{stop}/d as a function of the inclination over the bumpy base. Fitting gives $\mu_1 = 0.54$ and $\mu_2 = 0.68$.

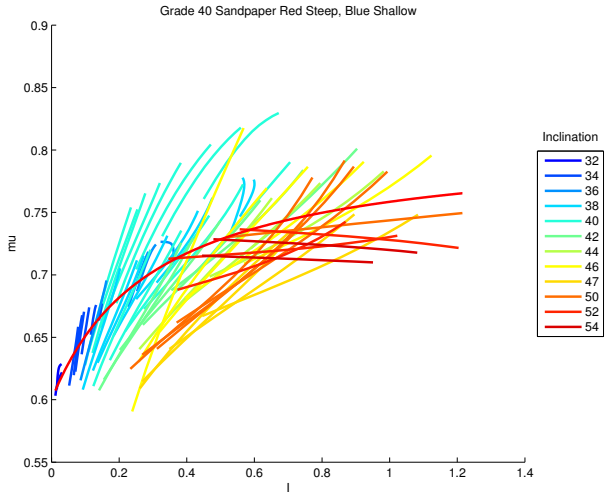
Macroscopic Friction coefficient (μ)

$\mu(I)$ Smooth Base



$$\dot{\gamma} \sim \frac{u}{d} \implies I = \frac{u}{\sqrt{gh\cos\theta}}$$

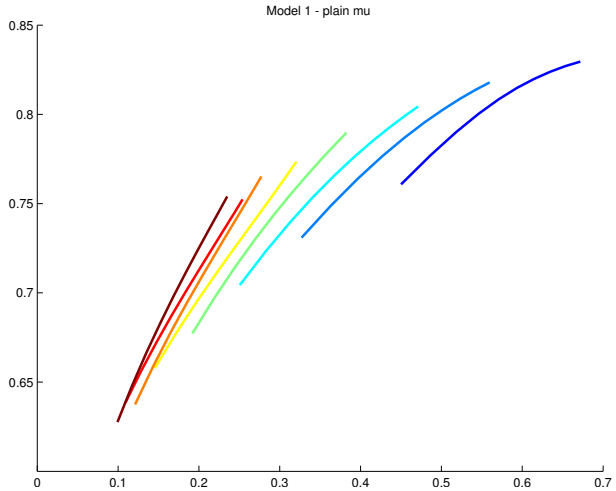
$\mu(I)$ Rough Base



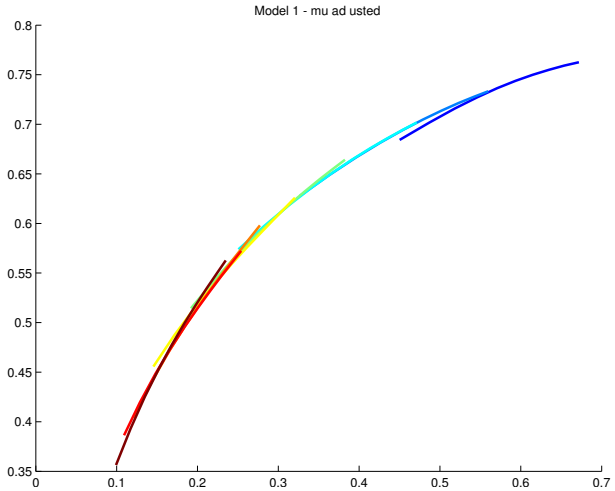
$$\dot{\gamma} \sim \frac{u}{h} \implies I = \frac{ud}{\sqrt{gh^3\cos\theta}}$$

$\mu(I)$ at fixed inclination (40°)

Plain data



Wall contribution subtracted



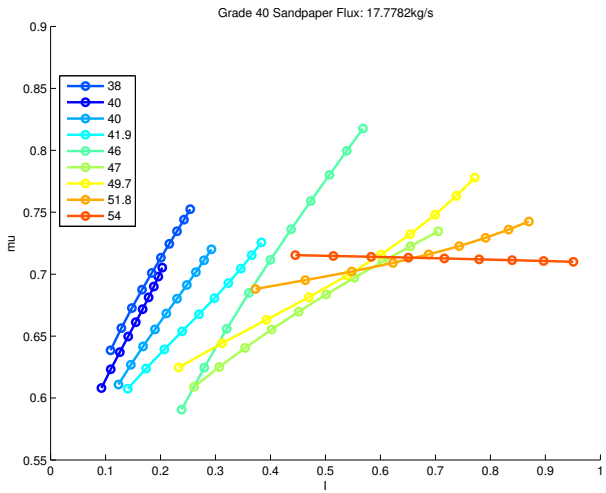
$$u\frac{\mathrm{d}u}{\mathrm{d}x} = g\sin\theta - \left(\mu(I) + \mu_w\frac{h}{2w}\right)g\cos\theta$$

Constant wall friction

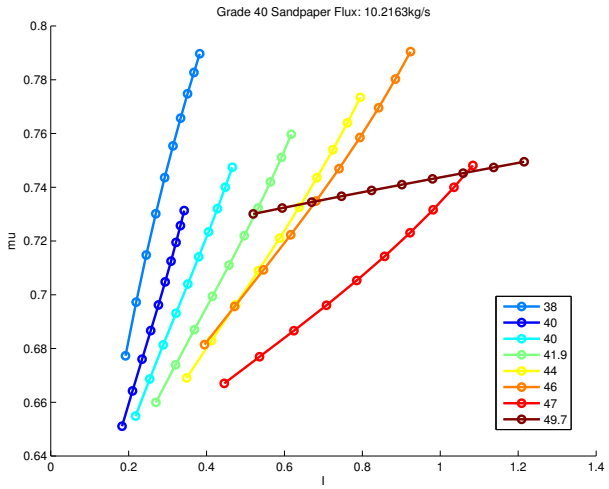
$$\mu_1 = 0.05 \ \ , \mu_2 = 0.93 \ \ , I_0 = 0.16 \ \ \mu_w = 2.6$$

$\mu(I)$ at fixed flux

High flow rate 17.8 $\mathrm{kg\ s^{-1}}$

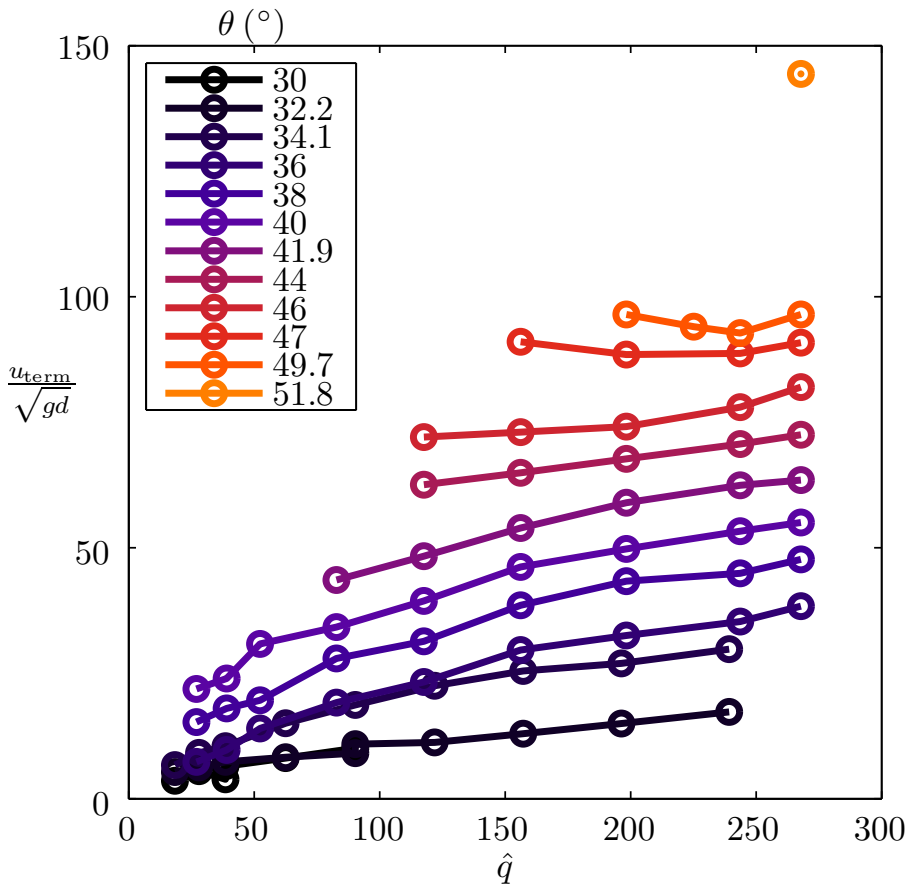


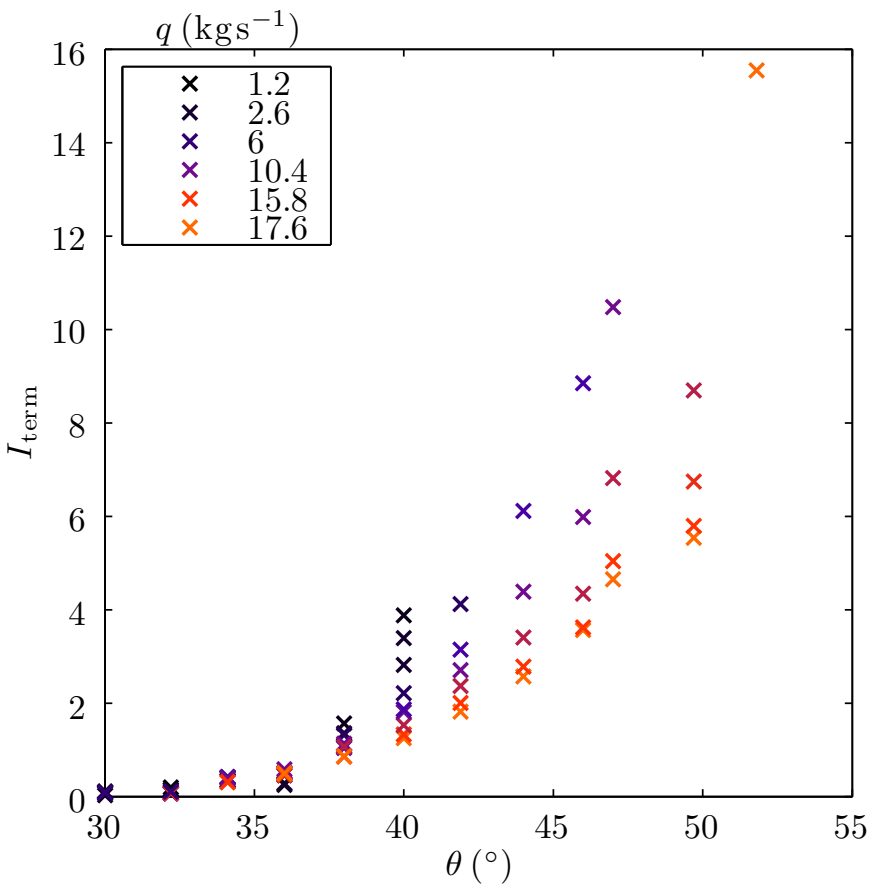
Medium flow rate 10.2 $\mathrm{kg\ s^{-1}}$



$$\left.\frac{\mathrm{d}\mu}{\mathrm{d}I}\right|_{I=0} = \frac{\mu_1 - \mu_2}{I_0}$$

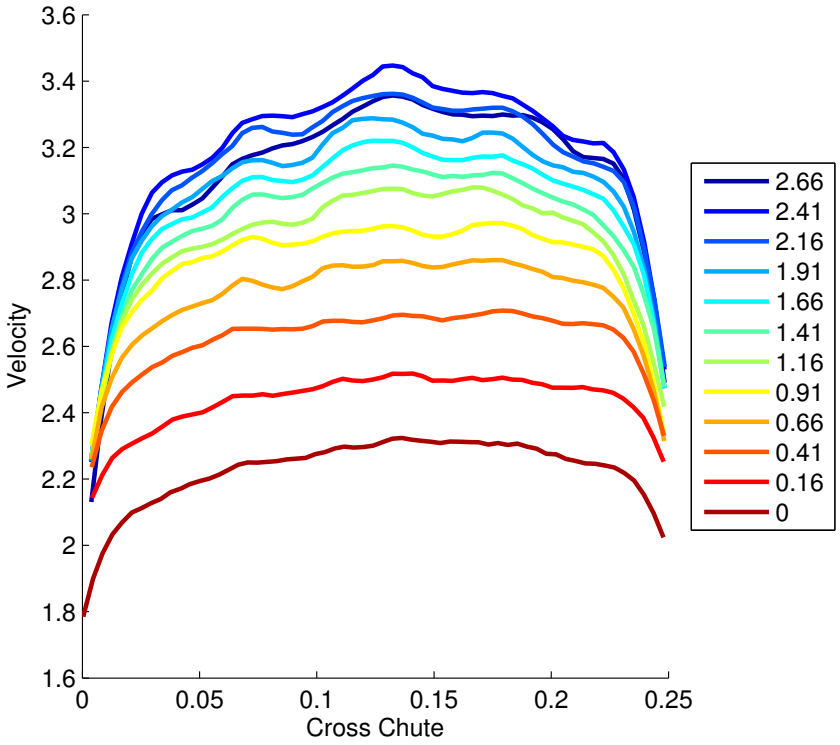
Terminal velocity on a bumpy surface

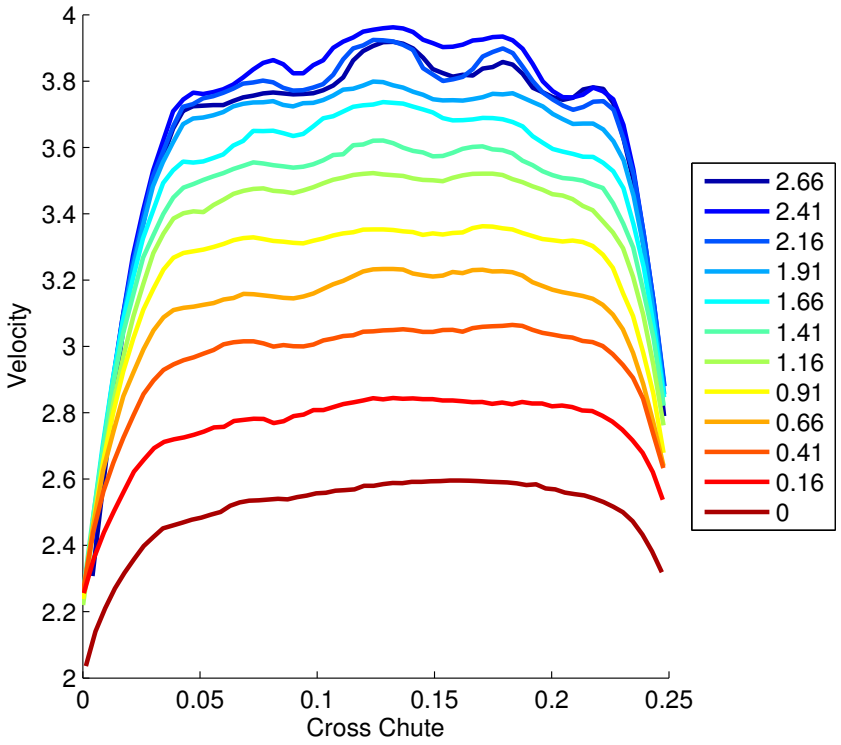




Each line represents the terminal velocities at a given inclination as the flux varies.

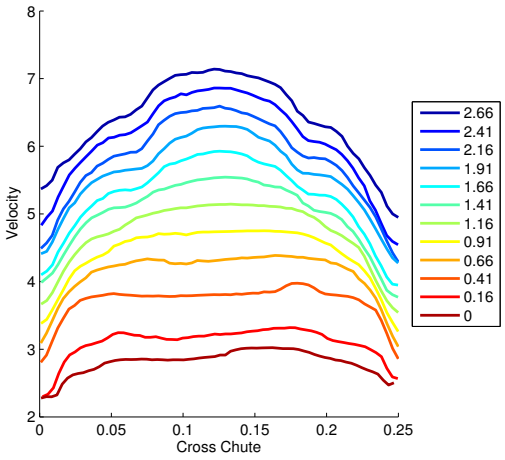
Onset of Turbulence

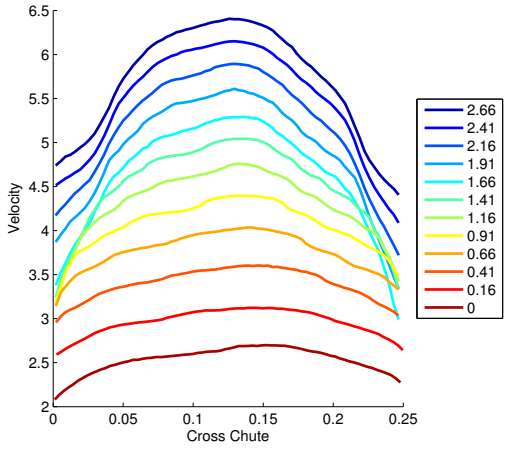


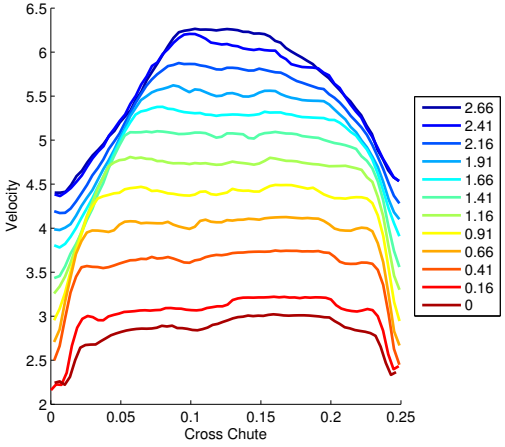


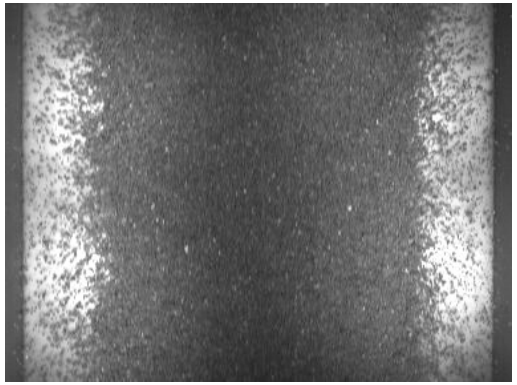
40° at 3.3 $\mathrm{kg\,s^{-1}}$ and 5.3 $\mathrm{kg\,s^{-1}}$

Lateral Instability

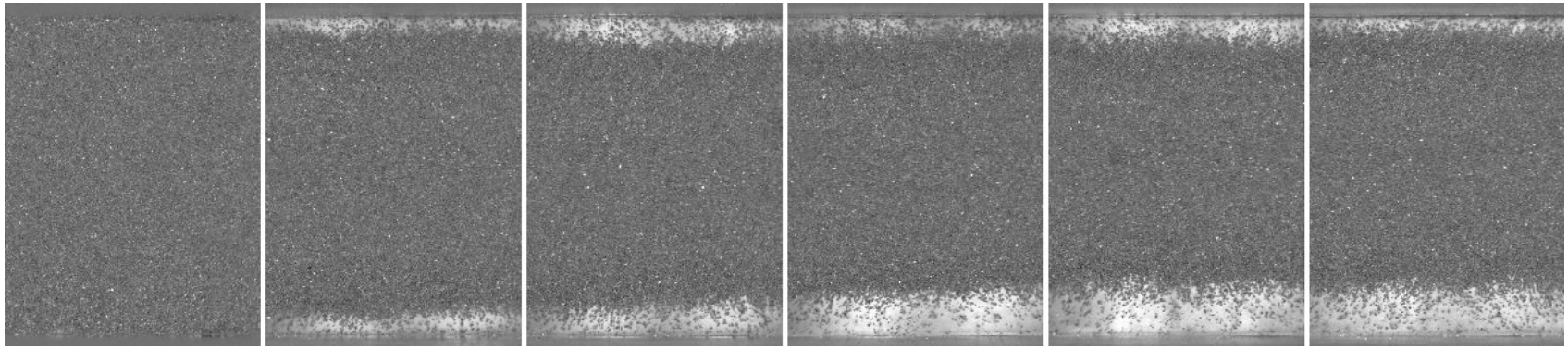






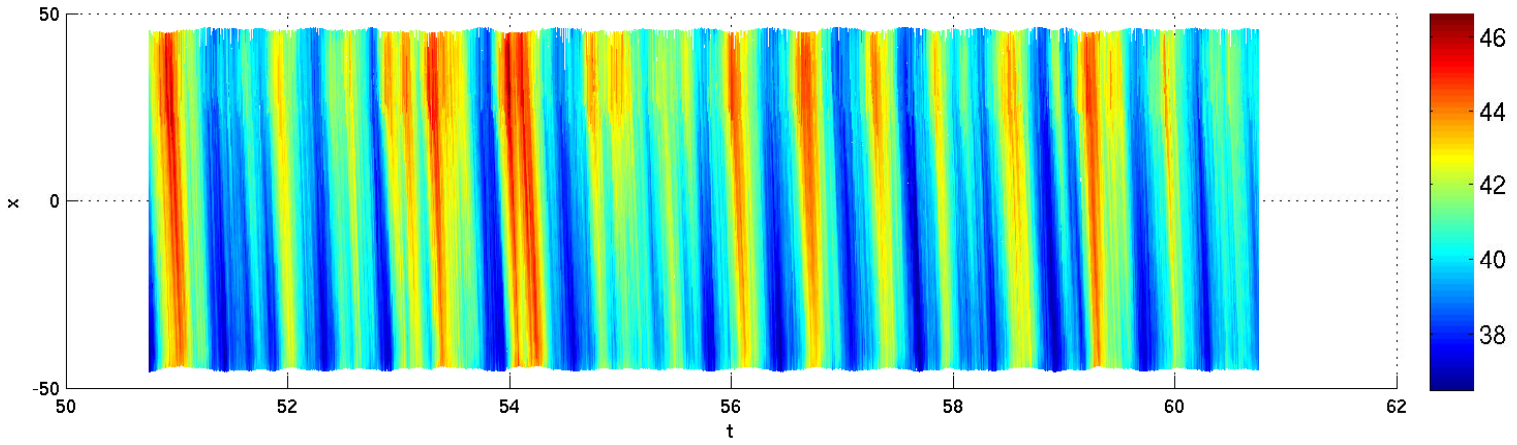


Lateral Instability Develops Down the Chute



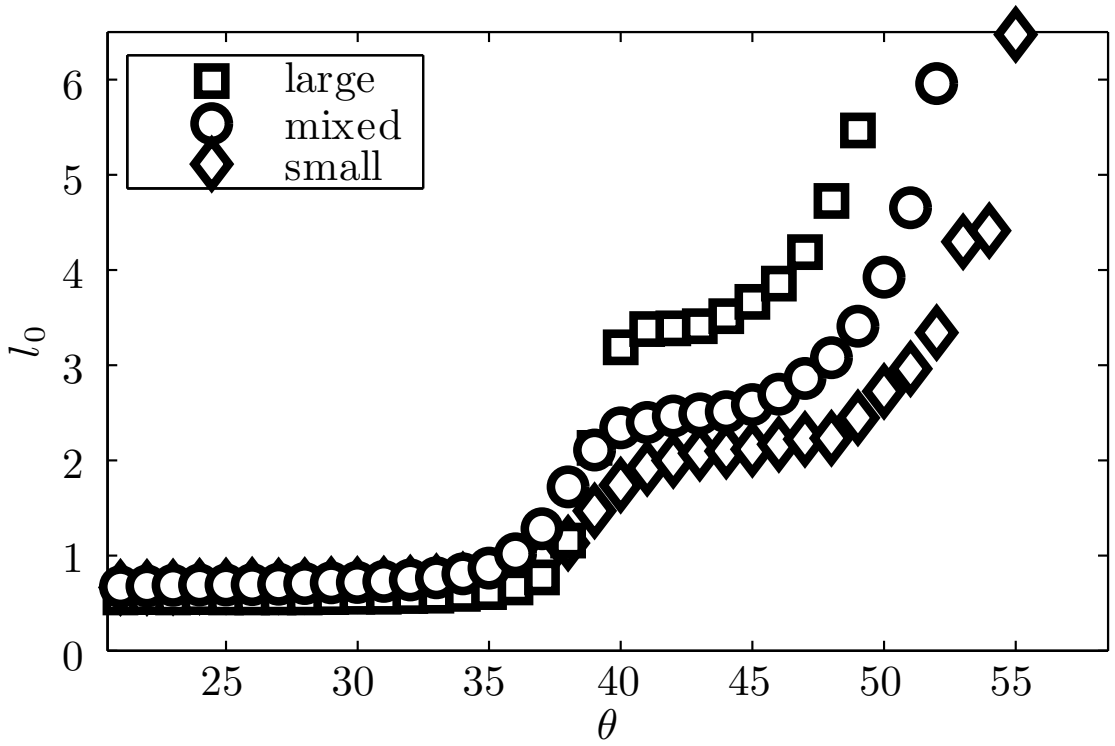
Inelastic collapse ?

Roll Wave Instability



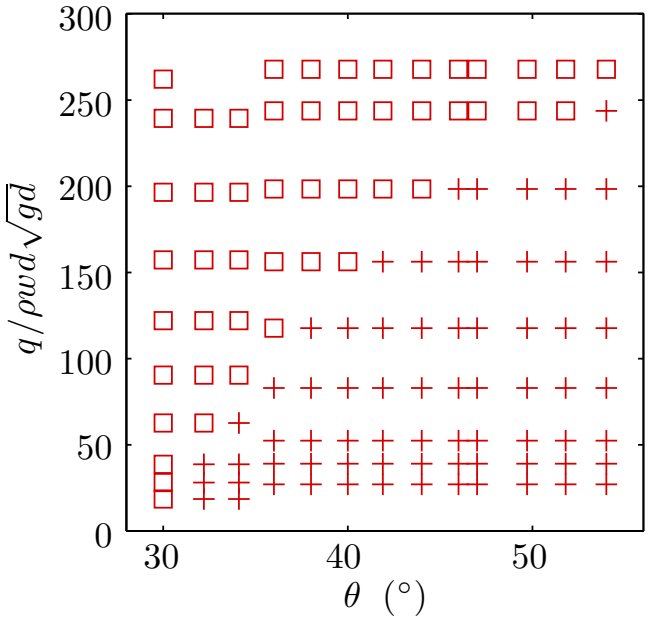
Spacetime plots of surface height

Leidenfrost effect

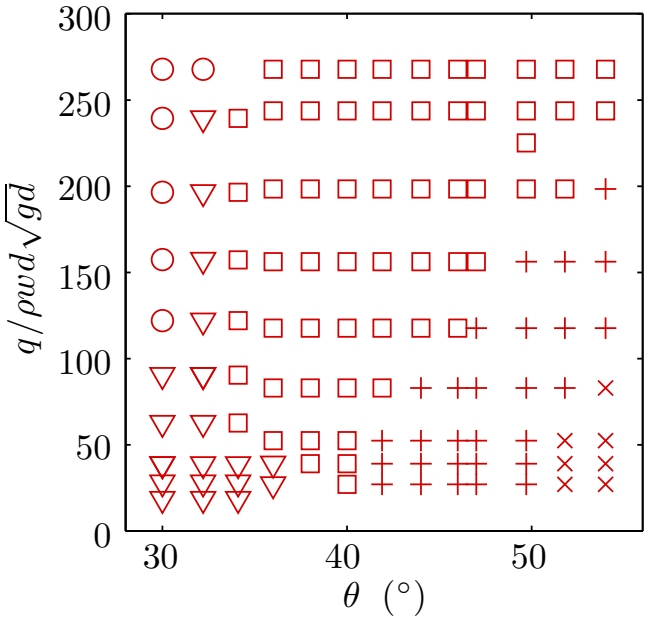


Height of the low density layer at the basal surface in DEM simulations

Conclusions — Phase diagram



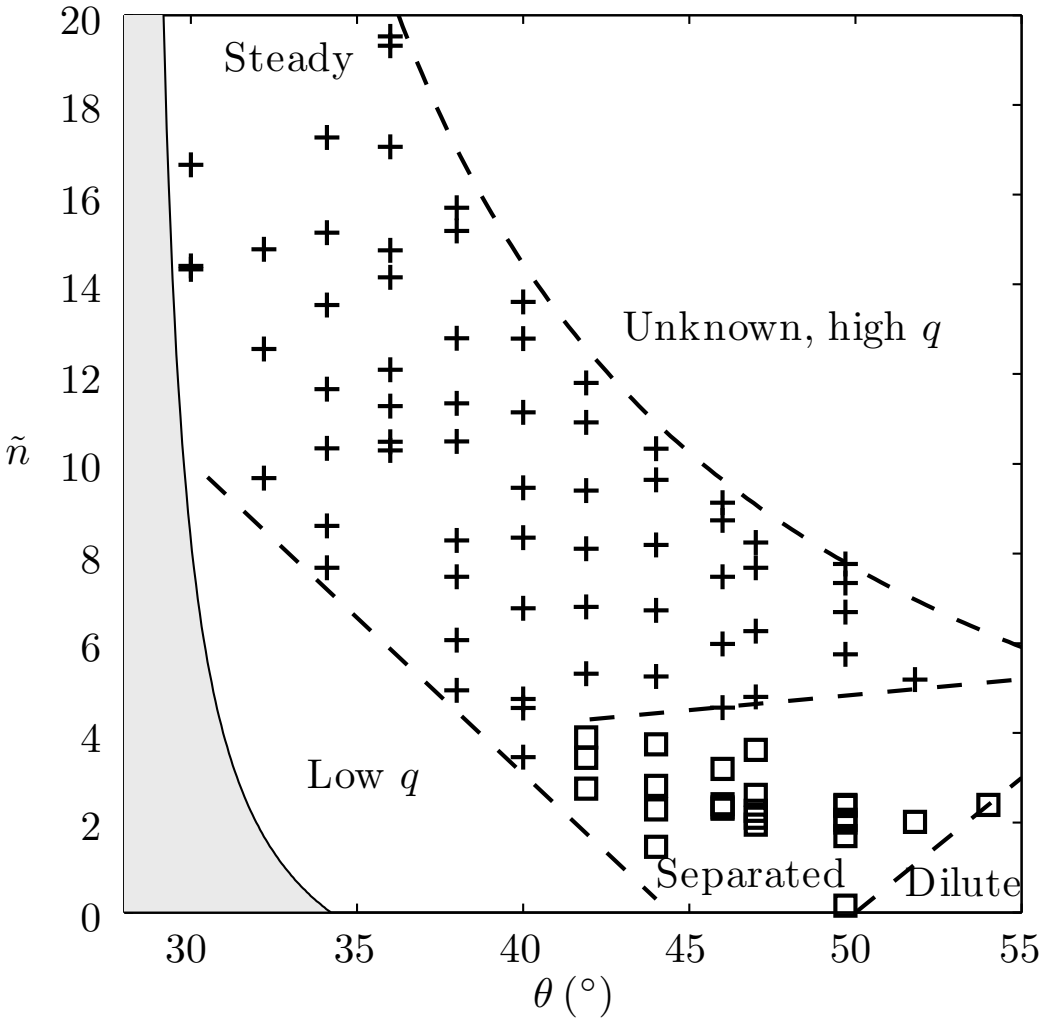
Flat Base



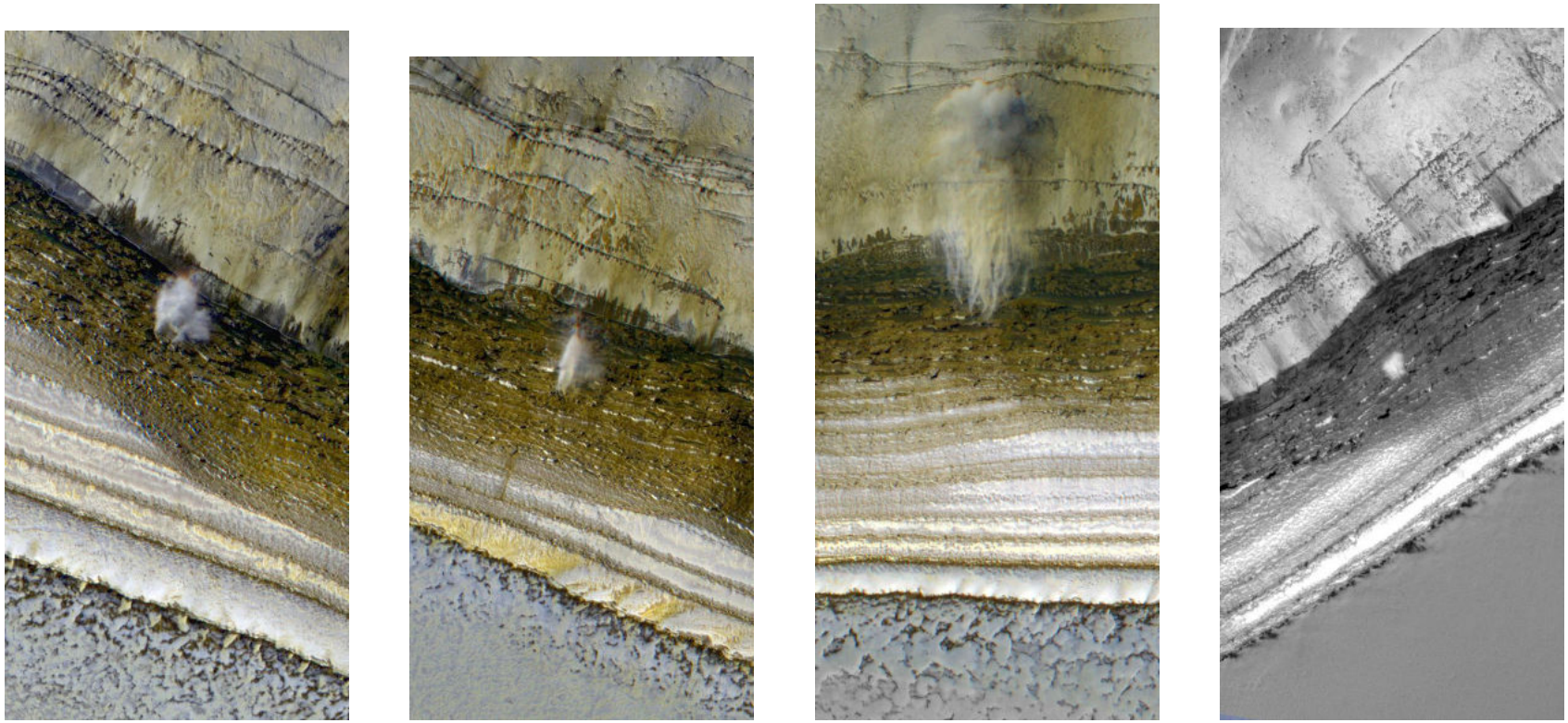
Bumpy Base

($\bigtriangledown$) Constant velocity flows, ($\square$) Accelerating, Dense Flows, ($+$) Flows with separation at walls, ($\times$) Low density flows, ($\circ$) Superstable heap formation

Conclusions — Extrapolated Phase diagram



CO_2 Avalanche on Mars from HiRise



Aspect: W WSW SW S

Four simultaneous avalanches with a range of Slope azimuths south is up and left Speeds measured in ten of $m\,s^{-1}$

Helene — moon of Saturn

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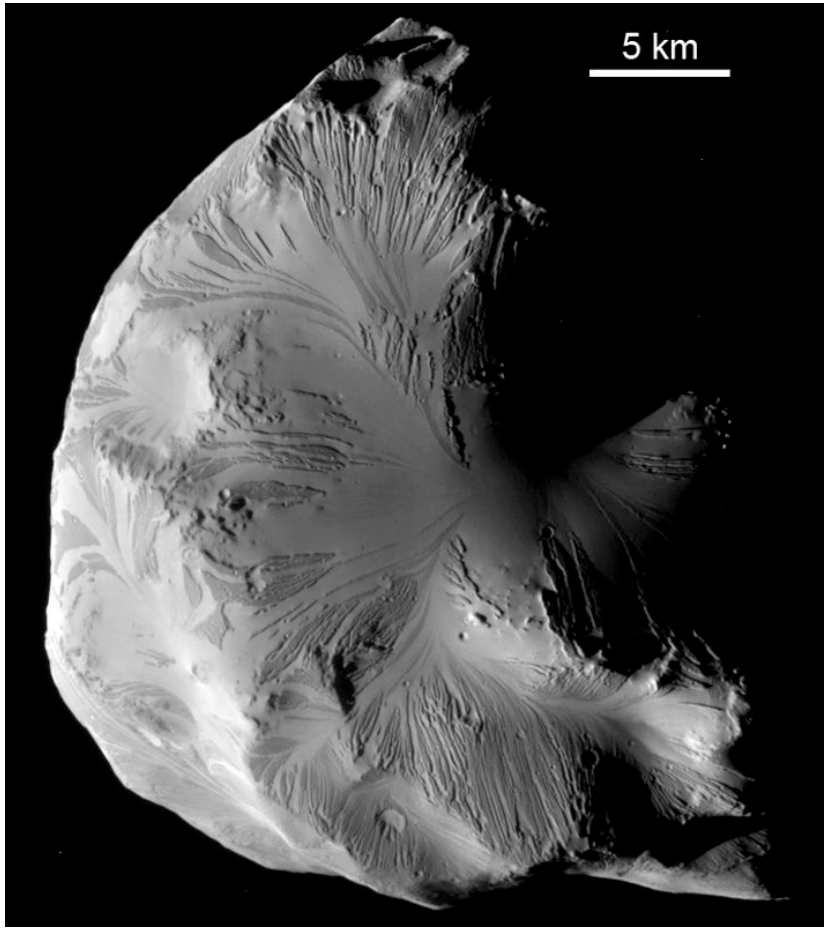
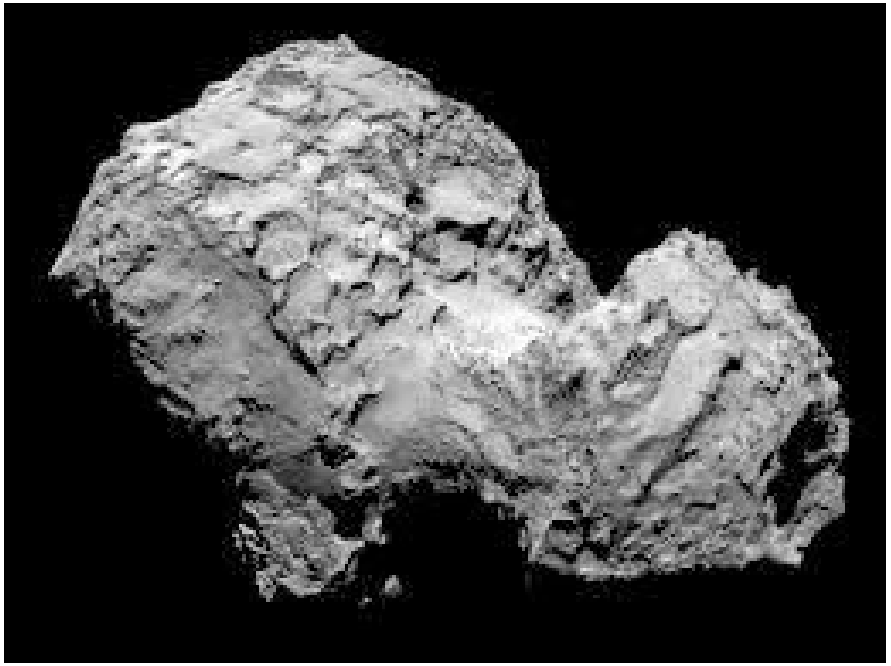


7P Churyumov — comet



Thanks !

Publications

- Turnbull, B. and J.N. McElwaine, 2008. Experiments on the non-Boussineq Flow of Self-Igniting Suspension Currents on a Steep Open Slope., *J. Geophys. Res.*, **113**(F01003), doi:10.1029/2007JF000753.
- Turnbull, B., J.N. McElwaine and Ancey, C., 2007. The Kulikovskiy–Sveshnikova–Beghin Model of Powder Snow Avalanches: Development and Application, *J. Geophys. Res.*, **112**(F01004), doi:10.1029/2006JF000489.
- Turnbull, B., and J.N. McElwaine, 2007. A Comparison of Powder Snow Avalanches at Vallée de la Sionne with Plume Theories, *J. Glaciol.*, **53**(30)
- J.N. McElwaine, and Turnbull, B.,2006. Plume Theories Versus Compact Models for Powder Snow Avalanches, *Sixth International Symposium on Stratified Flows, Perth, December 11-14*,
- McElwaine, J.N., 2005. Rotational flow in gravity current heads, *Phil. Trans. R. Soc. Lond.*, **363**, 1603–1623, 10.1098/rsta.2005.1597.
- McElwaine, J.N. and Turnbull, B., 2005. Air Pressure Data from the Vallée de la Sionne Avalanches of 2004, *J. Geophys. Res.*, **110**(F03010), doi:10.1029/2004JF000237.
- McElwaine, J.N. and Nishimura, K. 2001. Particulate Gravity Currents, Blackwell Science, chap. Ping-pong Ball Avalanche Experiments, no. 31 in Special Publication of the International Association of Sedimentologists, 135–148.