

Dense avalanches hitting structures: demarcating depth-dependent impact pressures from velocity-squared impact pressures

Thierry Faug

Univ. Grenoble Alpes, INRAE, UR ETNA*, Grenoble, France

*Unité de recherche Erosion Torrentielle Neige & Avalanches

thierry.faug@inrae.fr

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Motivation: destructive power of avalanches



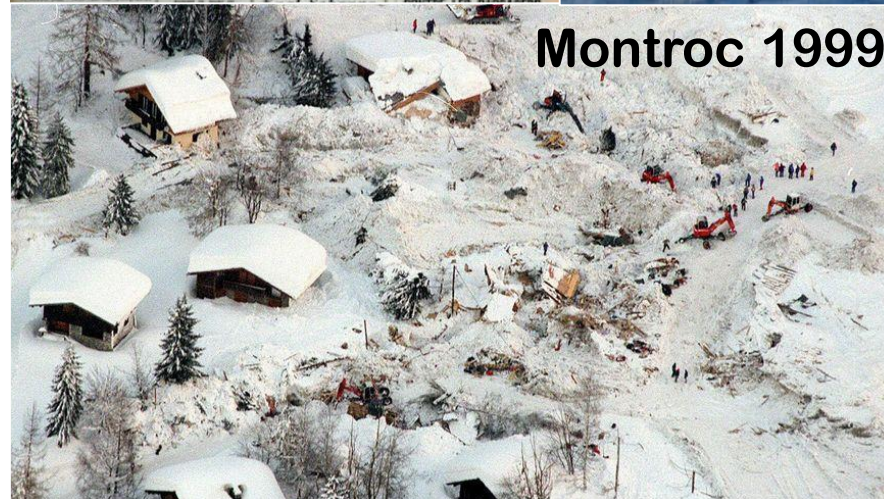
France 1970



Galtur 1999



Neelum valley 2020



Montroc 1999



Iceland



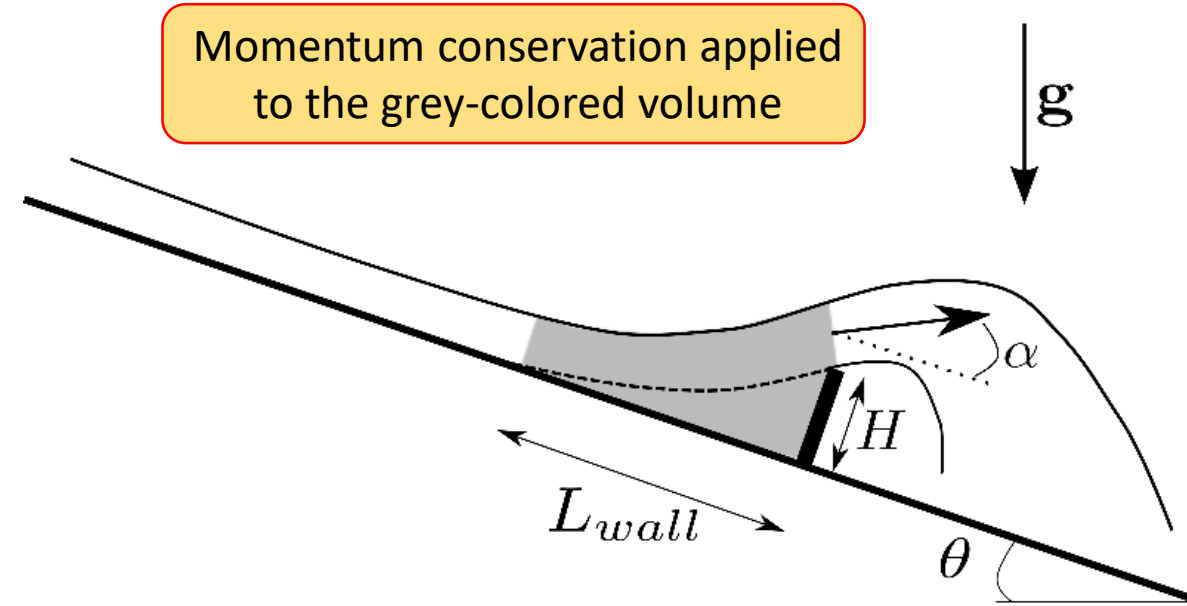
Rigopiano 2017

Outline

- Examples of granular flow-obstacle problems:
 - *A granular flow overtopping a wall (of small height H)*
 - *A slender obstacle (of width/diameter D) immersed in a granular flow*
 - *Granular avalanche impact on a wall (no overflow) with a propagating jump*
- Towards a generic formula for the (granular) avalanche force
 - A criterion to demarcate depth-dependent impact forces from velocity-squared impact forces

Granular flow-obstacle problems

I. A granular flow overtopping a wall



$$F_{wall} = F_u + F_h + F_{aw} + F_{mv}$$

$$F_u = \beta \mathfrak{I}_W(\alpha, \kappa, \mu_{dz}) \bar{\phi} \rho_P \bar{u}^2 h \ell$$

$$F_h = \frac{1}{2} k \bar{\phi} \rho_P g h^2 \ell \cos \theta$$

$$F_{aw} = \phi_0 \rho_P V_0 g (\sin \theta - \mu_{dz} \cos \theta)$$

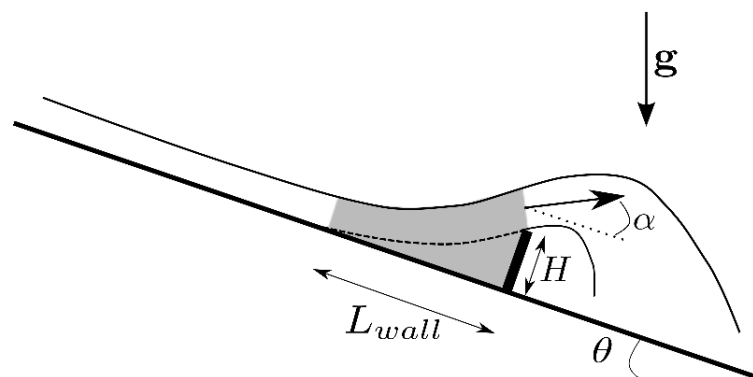
$$F_{mv} = \frac{1}{2} \frac{d}{dt} [\mathcal{G}_W(\kappa, \alpha) \bar{\rho} \bar{u}] \ell$$

Steady flow conditions: validation on DEM simulations [Faug, Beguin, Chanut, *Phys Rev E* 2009]

Unsteady flow conditions (avalanche): validation on DEM simulations [Chanut, Faug, Naaim, *Phys Rev E* 2010] and lab experiments [Faug, Chanut, Caccamo, *Phys Rev E* 2011]

Granular flow-obstacle problems

I. A granular flow overtopping a wall

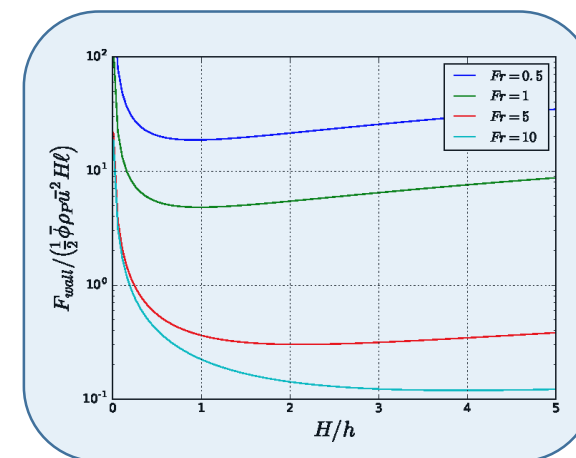
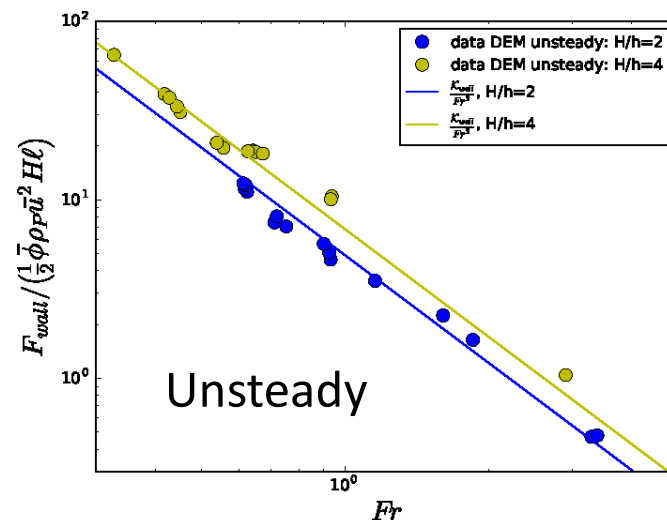
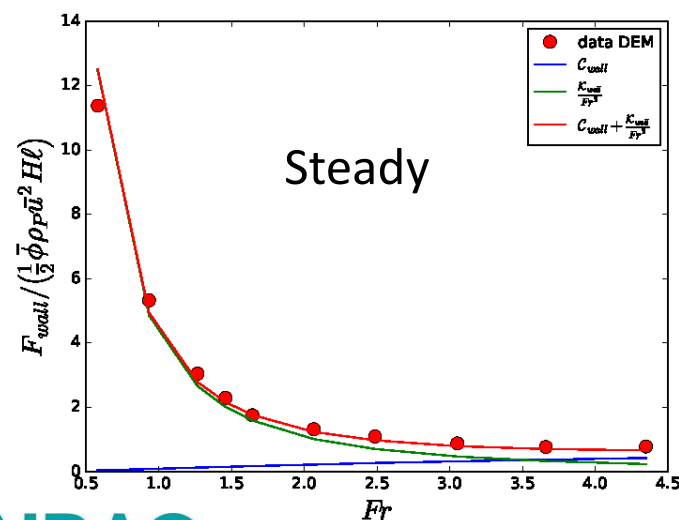


$$L_{wall} = \frac{H}{\tan(\theta - \theta_{min})}$$

$$\frac{F_{wall}}{\frac{1}{2} \bar{\phi} \rho_P \bar{u}^2 H \ell} = C_{wall} + \frac{K_{wall}}{Fr^2}$$

$$C_{wall} = \frac{2\beta}{H/h} \left(1 - \frac{[1 - \kappa(\theta - \theta_{min})] \cos \theta}{\cos \theta_{min}} \right)$$

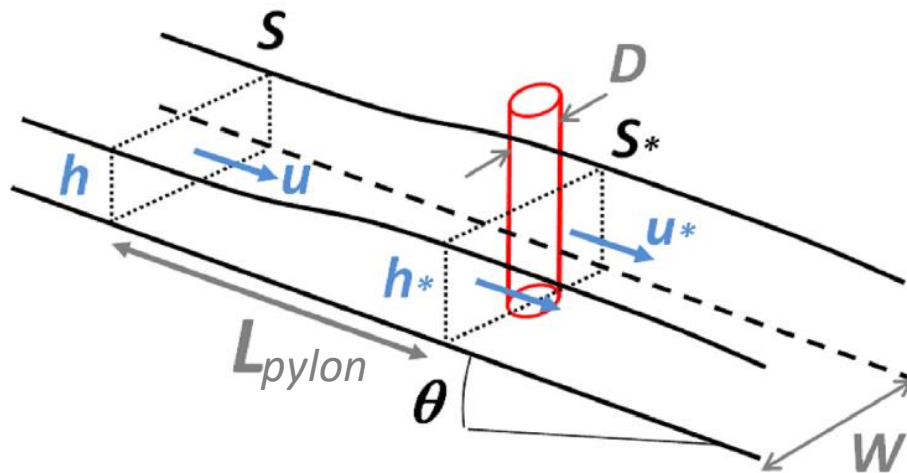
$$K_{wall} = \frac{k}{H/h} + \left(2 + \frac{H}{h} \right) (1 + \tan \theta \tan \theta_{min})$$



Granular flow-obstacle problems

II. A slender obstacle immersed in a granular flow

Momentum conservation applied to the control-volume of length L_{pylon}



$$F_{pylon} = F_u + F_h + F_{aw}$$

$$F_u = \frac{1}{2} C_{pylon} \bar{\phi} \rho_P \bar{u}^2 h D$$

$$F_h = \frac{1}{2} k \mathfrak{I} \bar{\phi} \rho_P g h^2 \ell \cos \theta$$

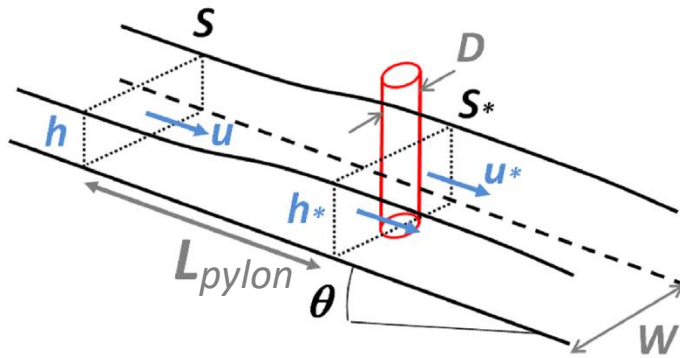
$$F_{aw} = k \mathcal{G} \frac{L_{pylon}}{h} \phi_0 \rho_P g h^2 \ell (\sin \theta - \mu_e \cos \theta)$$

$\mathfrak{I}$ and $\mathcal{G}$ are functions of $\frac{D}{\ell}$, ε and $r = \frac{\bar{\phi}}{\phi_0}$

[Faug, *Eur Phys J E* 2015]

Granular flow-obstacle problems

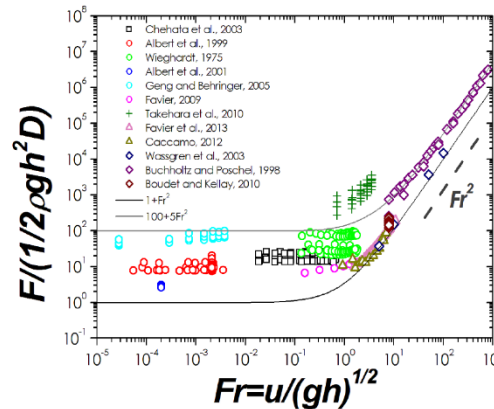
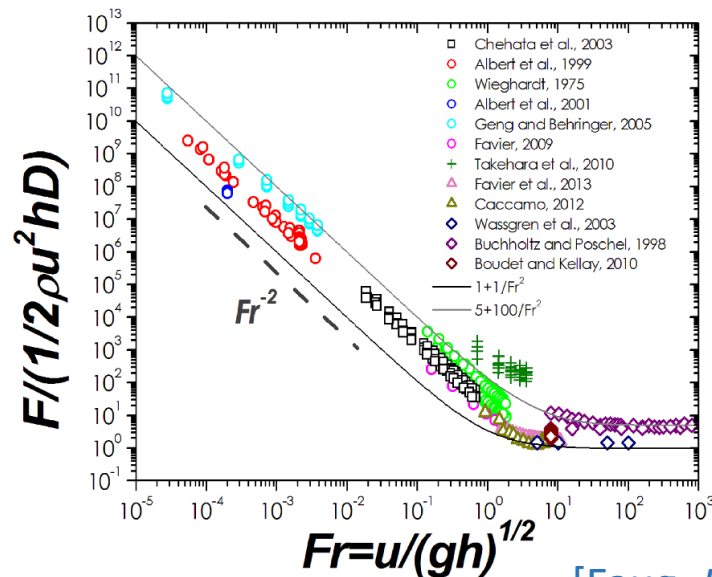
II. A slender obstacle immersed in a granular flow



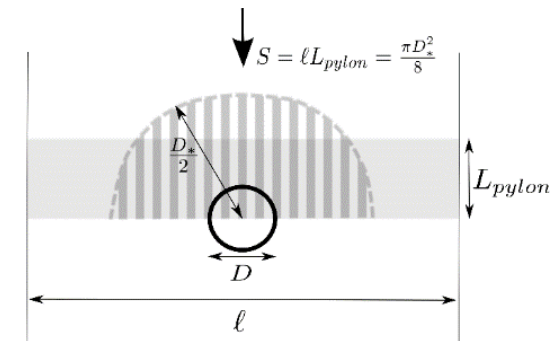
$$\frac{F_{pylon}}{\frac{1}{2} \bar{\phi} \rho_P \bar{u}^2 H D} = C_{pylon} + \frac{K_{pylon}}{Fr^2}$$

$$C_{pylon} = C_{pylon} \left(C_d, \beta, \frac{\ell}{D}, \epsilon \right) \approx C_d$$

$$K_{pylon} = \frac{\ell}{D} \left[k \mathfrak{T} + 2g \frac{L_{pylon}}{h} \frac{\phi_0}{\phi} (\tan \theta - \mu_e) \right]$$

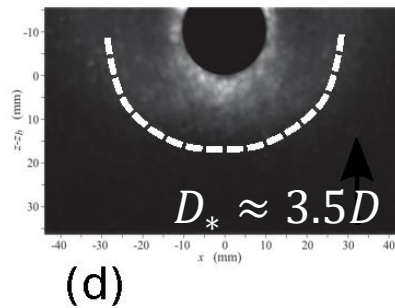
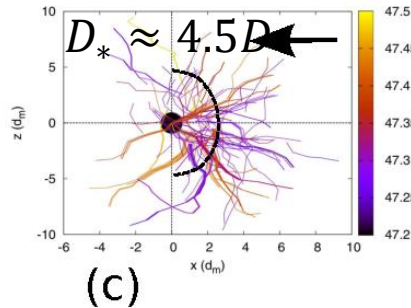
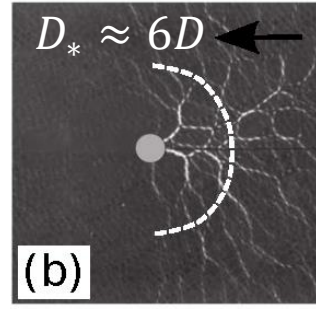
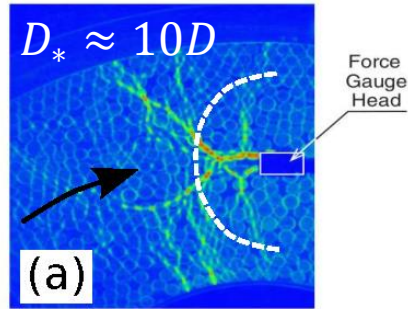


[Faug, Eur Phys J E 2015]



Granular flow-obstacle problems

II. A slender obstacle immersed in a granular flow



(a) [Geng & Behringer, *Phys Rev E* 2005]

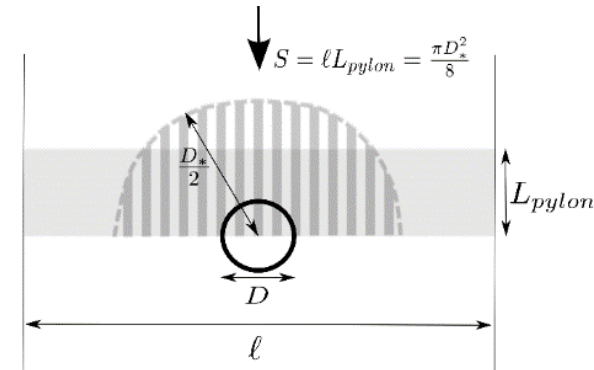
(b) [Seguin et al., *Phys Rev E* 2016]

(c) [Tordesillas et al, *Phys Rev E* 2014]

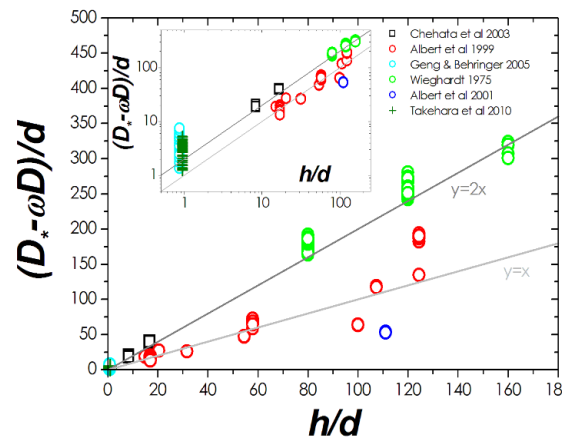
(d) [Seguin et al., *Phys Rev E* 2013]

+ snow avalanches: [Sovilla et al., *CRST* 2016]

$$\frac{F_{pylon}}{\frac{1}{2} \bar{\phi} \rho_P \bar{u}^2 H D} = C_{wall} + \frac{K_{pylon}}{Fr^2}$$

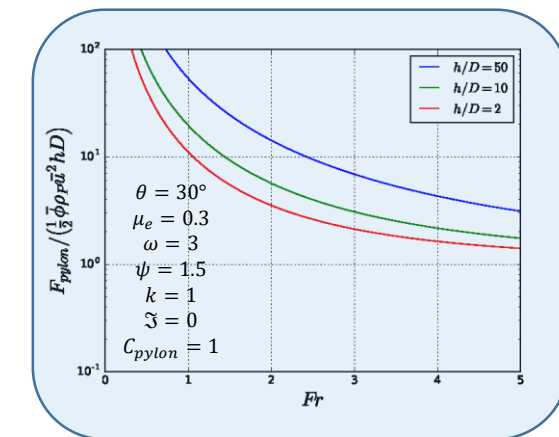


$$K_{pylon} = \underbrace{k \frac{\ell}{D} \mathfrak{I}}_{\sim 0} + \underbrace{\frac{\pi}{2} \left(2\omega\psi + \psi^2 \frac{h}{D} \right)}_{\sim a + b \frac{h}{D}} + \underbrace{\omega^2 \frac{D}{h}}_{\sim 0} \frac{\phi_0}{\phi} (\tan \theta - \mu_e)$$



$$L_{pylon} h = \frac{\pi D_*^2}{8}$$

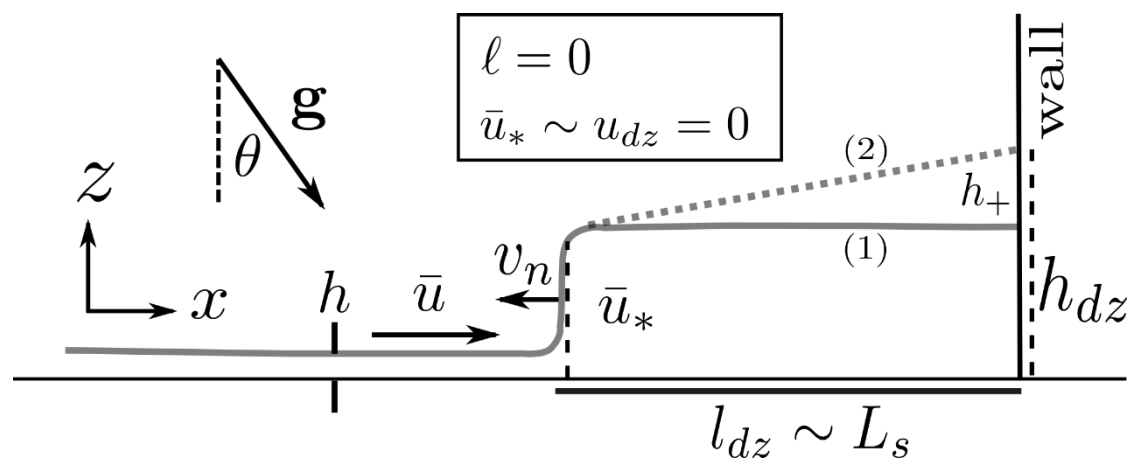
$$D_* = \omega D + \psi h$$



[Faug, *Eur Phys J E* 2015]

Granular flow-obstacle problems

III. Granular avalanche impact on a wall (no overflow)



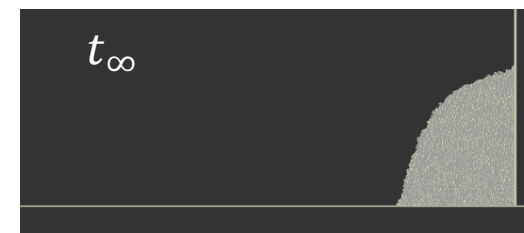
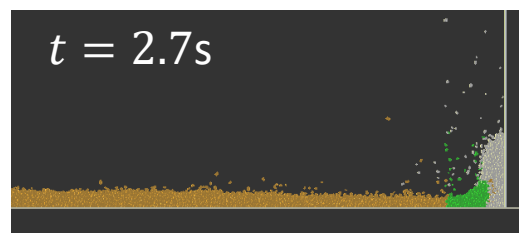
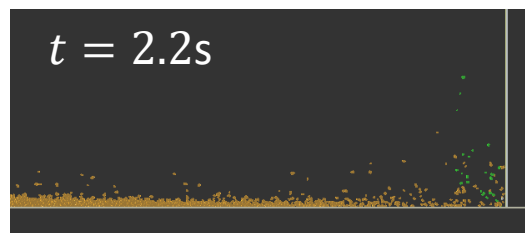
$$F_{\text{wall-jump}} = F_s + F_{dz}$$

$$F_s = \left(1 + \frac{1}{\frac{\rho_* h_*}{\rho h} - 1} + \frac{2}{Fr^2}\right) \bar{\phi} \rho_P \bar{u}^2 h w$$

$$F_{dz} = \frac{1}{2} c_{dz} (\tan \theta - \mu_{dz}) \rho_* g \ell_{dz} h_{dz} w \cos \theta$$

$$h_{dz} \geq h_*$$

[Albaba et al, *Phys Rev E* 2018]

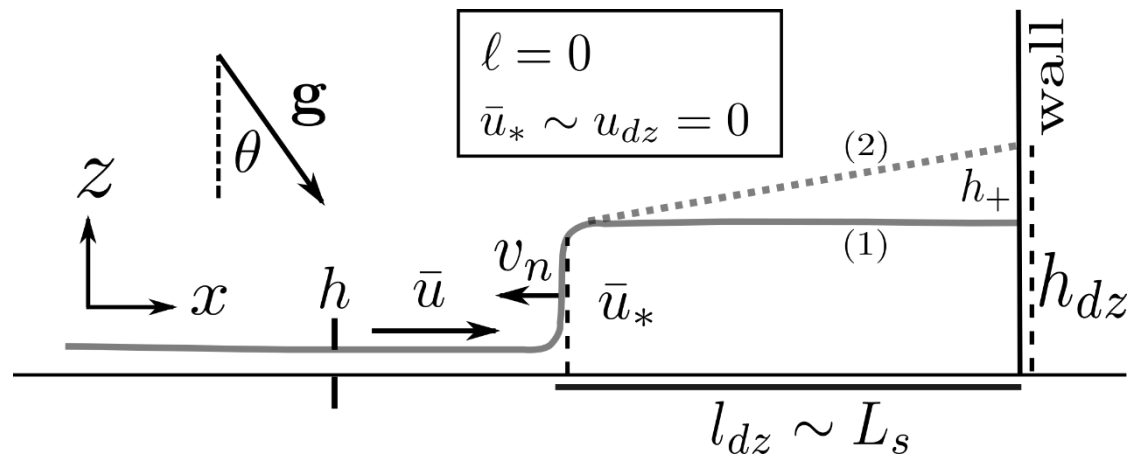


$\theta = 40^\circ$

Case $h_{dz} > h_*$

Granular flow-obstacle problems

III. Granular avalanche impact on a wall (no overflow)



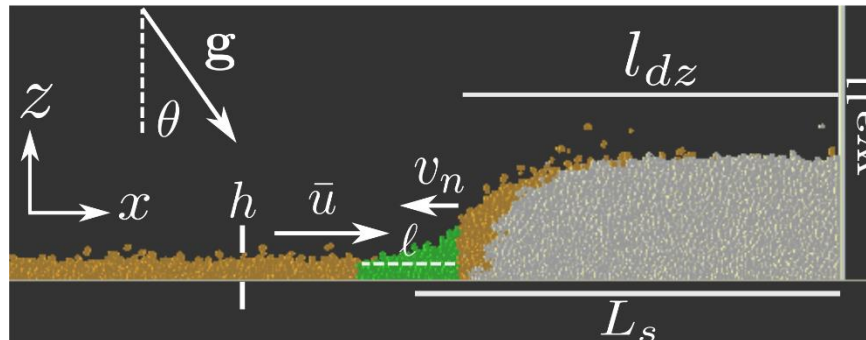
$$\frac{F}{\frac{1}{2} \rho \bar{u}^2 h_{dz} w} = C_{\text{wall-jump}} + \frac{K_{\text{wall-jump}}}{Fr^2}$$

$$C_{\text{wall-jump}} = 2 \left(1 + \frac{1}{\frac{\rho_* h_*}{\rho h} - 1} \right) \frac{h}{h_{dz}}$$

$$K_{\text{wall-jump}} = 2 \frac{h}{h_{dz}} + c_{dz} (\tan \theta - \mu_{dz}) \frac{\rho_* \ell_{dz}}{\rho h}$$

$$h_{dz} \geq h_*$$

$\theta = 30^\circ$
Case $h_{dz} = h_*$



[Albaba et al, Phys Rev E 2018]

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Generic law for avalanche impact force ?

$$F = F_u + F_h + F_{aw}$$

$$\frac{F}{D} = \mathfrak{T}_1 \bar{\rho} \bar{u}^2 h + \left[\mathfrak{T}_2 k + \mathfrak{T}_3 \frac{L}{h} (\tan \theta - \mu_0) \right] \bar{\rho} g h^2 \cos \theta$$

$$\frac{F}{\frac{1}{2} \bar{\rho} \bar{u}^2 S_o} = \mathbf{C} + \frac{\mathbf{K}}{Fr^2}$$

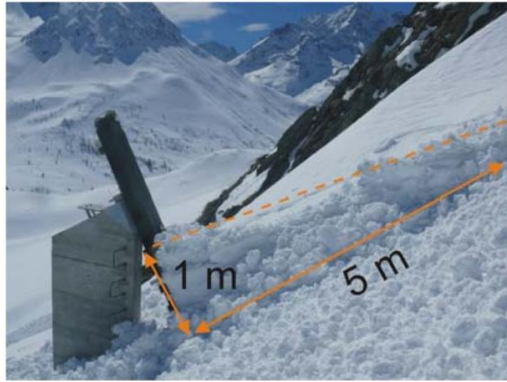
$$\mathbf{C} = 2 \mathfrak{T}_1 \frac{hD}{S_o}$$

$$\mathbf{K} = 2 \frac{hD}{S_o} \left[\mathfrak{T}_2 k + \mathfrak{T}_3 \frac{L}{h} (\tan \theta - \mu_0) \right]$$

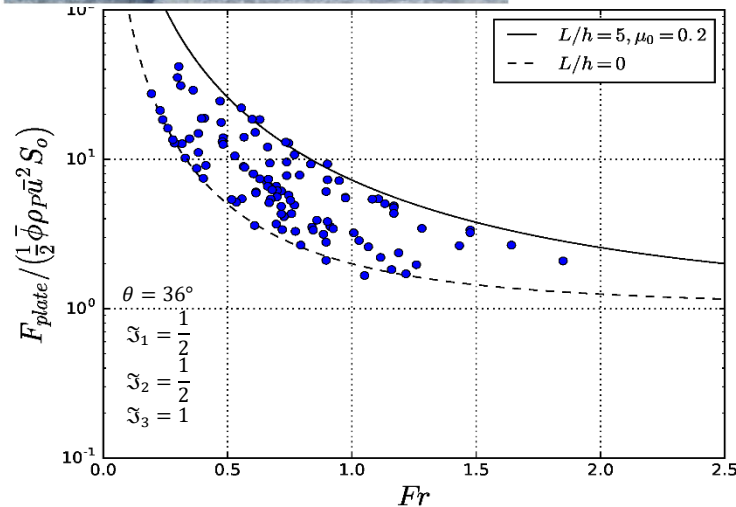
If $S_o = hD$ then $\frac{hD}{S_o} = 1$

- I. Flow overtopping a wall of height H
 $S_o = H\ell = HD$; $L_{wall} = H / \tan(\theta - \theta_{min})$
 $\mathfrak{T}_1 = \beta \mathfrak{T}_w(\alpha, \kappa, \mu_{dz})$; $\mathfrak{T}_2 = 1/2$; $\mathfrak{T}_3 = \frac{\phi_0}{\phi} \frac{V_0}{hL\ell}$
- II. Slender obstacle of width D immersed in a flow
 $S_o = hD$; $L_{pylon} = \pi D_*^2 / 8h$
 $\mathfrak{T}_1 = \frac{1}{2} \mathbf{C}_{pylon}(C_d, \beta, \frac{\ell}{D}, \epsilon)$; $\mathfrak{T}_2 = \frac{1}{2} \mathfrak{T}$; $\mathfrak{T}_3 = \mathcal{G} \frac{\phi_0}{\phi}$
- III. Avalanche impact on a wall (overflow prevented)
 $S_o = h_{dz} w = h_{dz} D$; $L = \ell_{dz}$
 $\mathfrak{T}_1 = \left(1 + \frac{1}{\frac{\rho_* h_*}{\rho h} - 1} \right)$; $\mathfrak{T}_2 = \frac{1}{k}$; $\mathfrak{T}_3 = \frac{1}{2} c_{dz} \frac{\rho_*}{\rho} \frac{h_{dz}}{h}$

Generic law for avalanche impact force ?

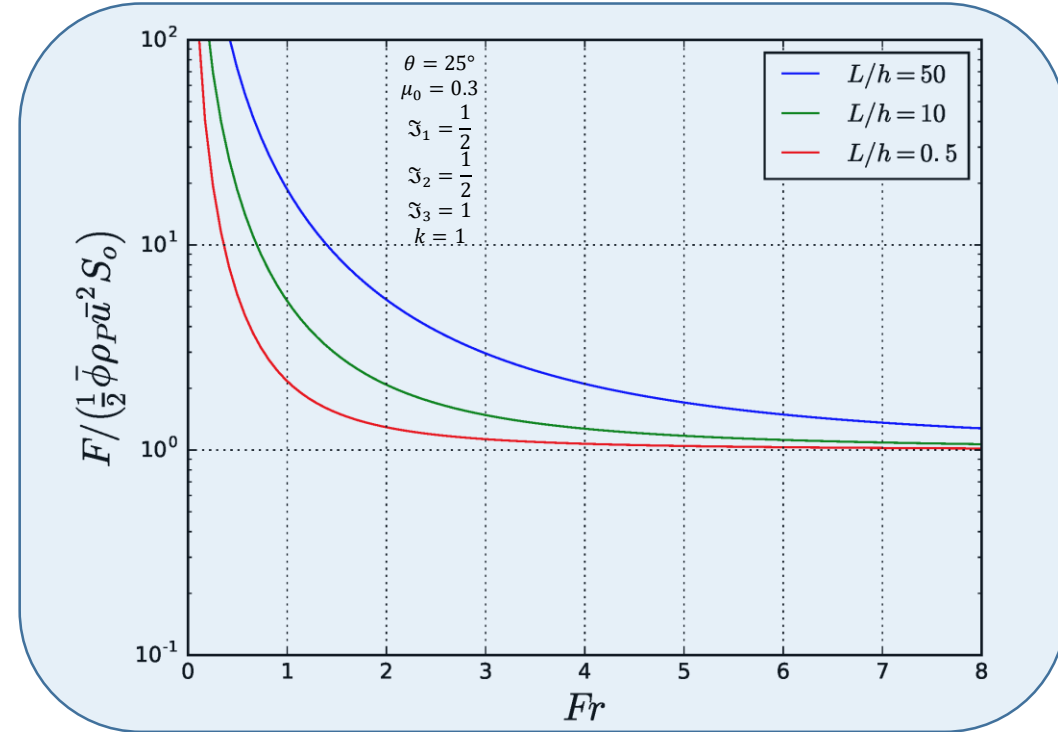


Snow avalanche impact on a plate-like obstacle (1m²) at Lautaret pass



Avalanche 18 March 2011

See data in [Thibert et al., *ISSW* 2013]



$$\frac{F}{\frac{1}{2} \bar{\rho} \bar{u}^2 S_o} = \mathbf{C}(\dots) + \frac{\mathbf{K} \left(\frac{L}{h}, \dots \right)}{Fr^2}$$

(for frictional granular flows, laws in the form $\propto Fr^{-n}$ remain pulled out of the hat)

Depth-dependent vs velocity-squared forces ?

$$\frac{F}{\frac{1}{2}\bar{\rho}\bar{u}^2S_o} = \mathbf{C} + \frac{\mathbf{K}}{Fr^2}$$

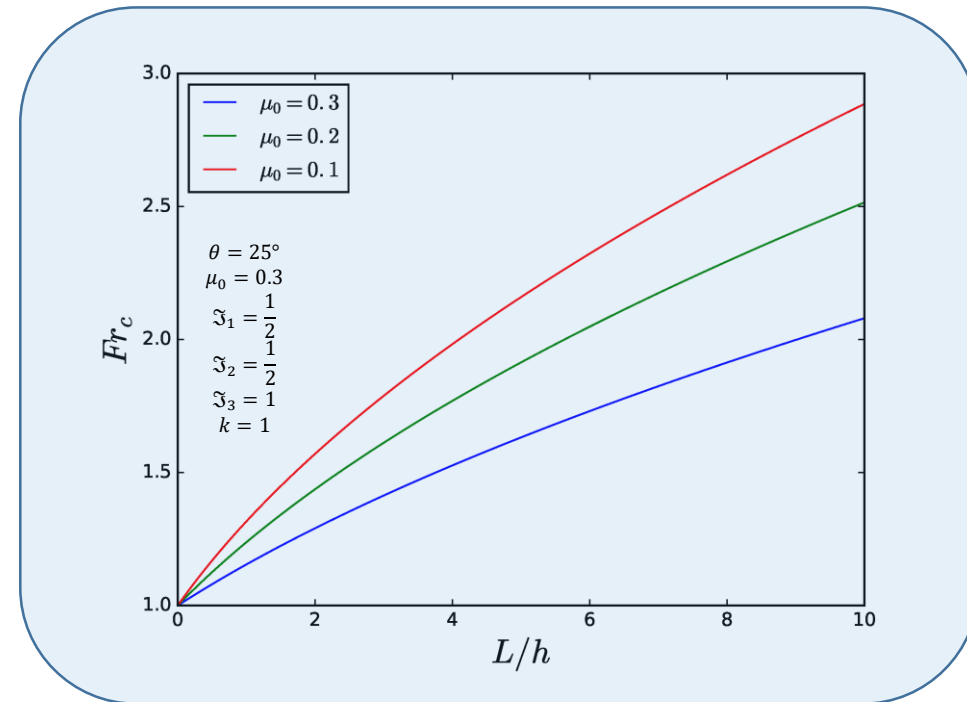
$$\mathcal{M}_o = \frac{\mathbf{C}}{\mathbf{K}/Fr^2} = \frac{\mathfrak{I}_1}{\mathfrak{I}_2 k + \mathfrak{I}_3 \frac{L}{h} (\tan \theta - \mu_0)} Fr^2$$

$$F_{\mathcal{M}_o \gg 1} \propto \rho u^2 h D$$

$$F_{\mathcal{M}_o \ll 1} \propto \rho g h^2 D$$

Transitional regime defined as $\mathcal{M}_o = 1$

$$Fr_c = \sqrt{\frac{\mathfrak{I}_2 k + \mathfrak{I}_3 \frac{L}{h} (\tan \theta - \mu_0)}{\mathfrak{I}_1}}$$



Conclusion & Outlook

- Key messages for (dry granular) snow avalanches impacting obstacles:
 - ✓ a generic law for the avalanche impact force has been discussed, based on a simple frictional model (dry granular snow).
 - ✓ ingredients: Froude number of the undisturbed flow and geometry of the zone of influence (obstacle to flow size; shape of the obstacle) + rheology.
 - ✓ choosing between a velocity-squared force and a depth-dependent force is therefore not an easy task. BTW: in many situations both contributions are needed.
 - ✓ in the depth-dependent regime and for slender obstacles: pressure amplification can be huge (increases with h/D).
- Other challenges:
 - ✓ cohesive snow: stress concentration in the influence zone, with or without a significant modification of the geometry of the latter ? Additional (cohesive) force contribution ?
 - ✓ humid snow: viscous contribution?

THANK YOU FOR YOUR ATTENTION !