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

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Motivation: destructive power of avalanches
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

Momentum conservation applied to the grey-colored volume

\[ F_{\text{wall}} = F_u + F_h + F_{aw} + F_{mv} \]

\[ F_u = \beta S_W(\alpha, \kappa, \mu_{dz}) \bar{\phi} \rho \bar{u}^2 h \ell \]

\[ F_h = \frac{1}{2} k \bar{\phi} \rho \rho g h^2 \ell \cos \theta \]

\[ F_{aw} = \phi_0 \rho V_0 g (\sin \theta - \mu_{dz} \cos \theta) \]

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

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

Granular flow-obstacle problems

I. A granular flow overtopping a wall

\[ \frac{F_{\text{wall}}}{\frac{1}{2} \phi \rho_p \bar{u}^2 H \ell} = C_{\text{wall}} + \frac{K_{\text{wall}}}{Fr^2} \]

\[ L_{\text{wall}} = \frac{H}{\tan(\theta - \theta_{\text{min}})} \]

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

\[ K_{\text{wall}} = \frac{k}{H/h} + \left( 2 + \frac{H}{h} \right) (1 + \tan \theta \tan \theta_{\text{min}}) \]
Granular flow-obstacle problems

II. A slender obstacle immersed in a granular flow

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

\[ F_{pylon} = F_u + F_h + F_{aw} \]

\[ F_u = \frac{1}{2} C_{pylon} \bar{\phi} \rho_p \bar{u}^2 h D \]

\[ F_h = \frac{1}{2} k \zeta \bar{\phi} \rho_p g h^2 \ell \cos \theta \]

\[ F_{aw} = k \zeta \frac{L_{pylon}}{h} \phi_0 \rho_p g h^2 \ell (\sin \theta - \mu_e \cos \theta) \]

$\zeta$ and $\zeta$ are functions of $\frac{D}{\ell}$, $\zeta$ 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

\[ \frac{F_{\text{pylon}}}{\frac{1}{2} \Phi \rho_p u^2 H D} = C_{\text{pylon}} + \frac{K_{\text{pylon}}}{F_r^2} \]

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

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

[Faug, Eur Phys J E 2015]
Granular flow-obstacle problems

II. A slender obstacle immersed in a granular flow

\[ \frac{1}{2} \phi \rho_p \bar{u}^2 H D + \frac{K_{pylon}}{Fr^2} = C_{wall} \]

\[ K_{pylon} = k \frac{\rho}{D} \frac{3}{8} + \frac{\pi}{2} \left( 2 \omega \psi + \psi^2 \frac{h}{D} \right) + \omega^2 \frac{D}{h} \phi_0 \frac{\phi}{\phi} (\tan \theta - \mu_e) \]

[Seguin et al., Phys Rev E 2016]

\[ L_{pylon} h = \frac{\pi D^2}{8} \]

\[ D_* = \omega D + \psi h \]

\[ D_* \approx 10D \]

\[ D_* \approx 6D \]

\[ D_* \approx 4.5D \]

\[ D_* \approx 3.5D \]

(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]

[Seguin et al., Phys Rev E 2016]

[Seguin et al., Phys Rev E 2013]

[Seguin et al., Phys Rev E 2016]

[Seguin et al., Phys Rev E 2013]

[Seguin et al., Phys Rev E 2016]
Granular flow-obstacle problems

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

\[ F_{\text{wall-jump}} = F_S + F_{dz} \]
\[ F_S = \left(1 + \frac{1}{\frac{1}{\rho h_s} - 1} + \frac{2}{Fr^2}\right) \bar{w} \rho \bar{u}^2 \bar{h} w \]
\[ F_{dz} = \frac{1}{2} c_{dz} (\tan \theta - \mu_{dz}) \rho \ell_{dz} h_{dz} w \cos \theta \]

\[ h_{dz} \geq h_* \]

[Albaba et al, Phys Rev E 2018]
Granular flow-obstacle problems

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

\[
\frac{F}{1/2 \rho \bar{u}^2 h dz W} = C_{\text{wall-jump}} + \frac{K_{\text{wall-jump}}}{Fr^2}
\]

\[C_{\text{wall-jump}} = 2 \left( 1 + \frac{1}{\frac{\rho}{\rho^*} h + 1} \right) \frac{h}{h dz}
\]

\[K_{\text{wall-jump}} = 2 \frac{h}{h dz} + c_{dz} (\tan \theta - \mu dz) \frac{\rho^* l dz}{\rho h}
\]

\[h dz \geq h^*_\]

[Albaba et al, Phys Rev E 2018]
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Generic law for avalanche impact force?

\[ F = F_u + F_h + F_{aw} \]

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

\[ \frac{F}{2 \bar{\rho} \bar{u}^2 S_o} = C + \frac{K}{Fr^2} \]

\[ C = 2 \mathfrak{S}_1 \frac{hD}{S_o} \]

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

If \( S_o = hD \) then \( \frac{hD}{S_o} = 1 \)

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I. Flow overtopping a wall of height \( H \)

\[ S_o = H \ell = HD; \quad L_{wall} = H / (\theta - \theta_{min}) \]

\[ \mathfrak{S}_1 = \beta \mathfrak{S}_w(\alpha, \kappa, \mu_{dz}); \quad \mathfrak{S}_2 = 1/2; \quad \mathfrak{S}_3 = \frac{\phi_0}{\phi} \frac{V_0}{h L \ell} \]

II. Slender obstacle of width \( D \) immersed in a flow

\[ S_o = h D; \quad L_{pylon} = \pi D^2 / 8 h \]

\[ \mathfrak{S}_1 = \frac{1}{2} C_{pylon}(C_d, \beta, \frac{\ell}{D}, \epsilon); \quad \mathfrak{S}_2 = 1/2 \mathfrak{S}; \quad \mathfrak{S}_3 = g \frac{\phi_0}{\phi} \]

III. Avalanche impact on a wall (overflow prevented)

\[ S_o = h_{dz} w = h_{dz} D; \quad L = \ell_{dz} \]

\[ \mathfrak{S}_1 = \left( 1 + \frac{\rho_s h_{dz}}{\rho h_{dz}} \right); \quad \mathfrak{S}_2 = \frac{1}{k}; \quad \mathfrak{S}_3 = \frac{1}{2} c_{dz} \frac{\rho_s h_{dz}}{\rho h} \]
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]

\[
\frac{F}{\frac{1}{2} \tilde{\rho} \bar{u}^2 S_o} = C(\ldots) + \frac{K}{L/h, \ldots} \frac{L}{Fr^2}
\]

(for frictional granular flows, laws in the form \( \propto Fr^{-n} \) remain pulled out of the hat)
Depth-dependent vs velocity-squared forces?

\[ \frac{F}{\frac{1}{2} \rho \ddot{u}^2 S_o} = C + \frac{K}{Fr^2} \]

\[ M_o = \frac{C}{K/Fr^2} = \frac{\mathcal{S}_1}{\mathcal{S}_2 k + \mathcal{S}_3 \frac{L}{h} (\tan \theta - \mu_0)} Fr^2 \]

\[ F_{M_o \gg 1} \propto \rho u^2 hD \]

\[ F_{M_o \ll 1} \propto \rho gh^2 D \]

Transitional regime defined as \( M_o = 1 \)

\[ Fr_c = \sqrt{\frac{\mathcal{S}_2 k + \mathcal{S}_3 \frac{L}{h} (\tan \theta - \mu_0)}{\mathcal{S}_1}} \]

\[ \theta = 25^\circ \]
\[ \mu_0 = 0.3 \]
\[ 3_1 = 1 \]
\[ 3_2 = \frac{1}{3} \]
\[ 3_3 = 1 \]
\[ k = 1 \]
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!