Assessing the performance of flexible barrier subjected to impacts of typical geophysical flows: a unified computational approach based on coupled CFD/DEM

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3rd May 2020

Outline

Introduction

Motivations, challenges, gaps and objectives

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Coupling outline, contacts, model set-up and test program

Major results

Typical snapshots showing three impact stages;

Run-up and pile-up impact mechanisms;

Debris-flexible barrier interactions, key angles and regimes;

Impact mechanism transition, impact load reduction & velocity loss ratio;

Summary

Introduction, *motivations*

Rockfall or rock avalanches

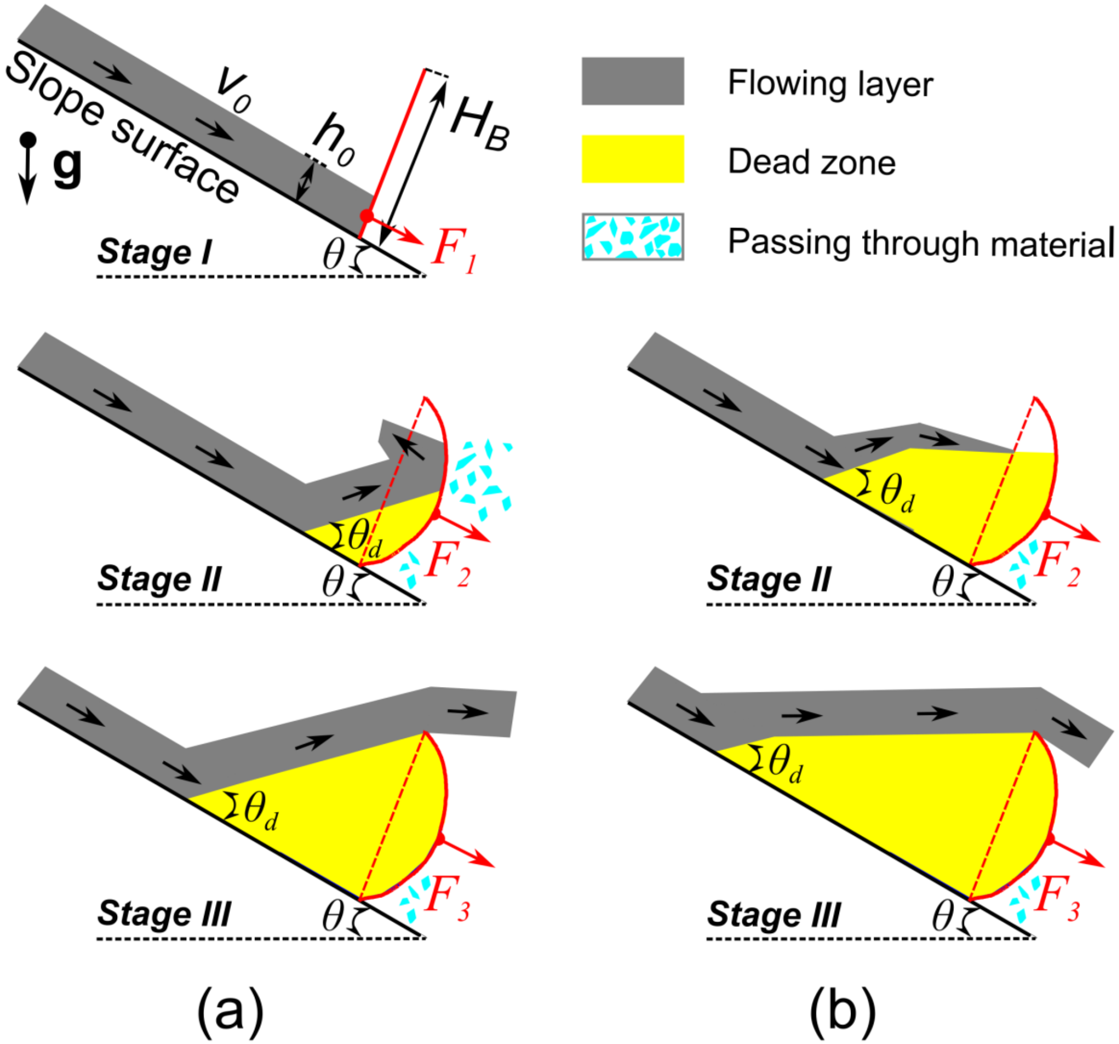
Muddy flow

Debris flow

Snow avalanches

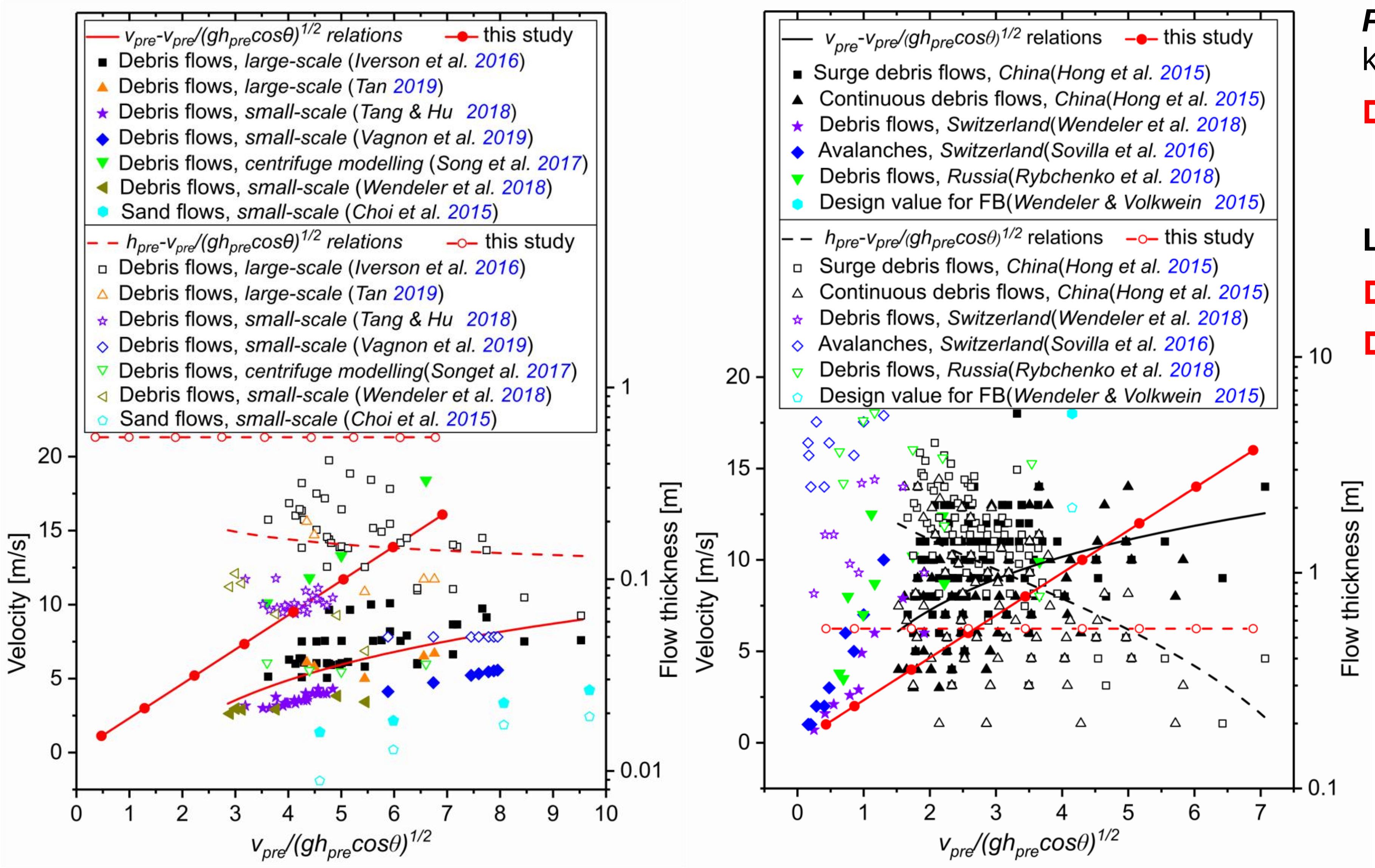
- Flexible barriers have been widely used in the mitigation of a wide spectrum of geophysical flows, ranging from debris avalanches and rock avalanches to muddy debris flows, debris flood and muddy flows.

Introduction, *motivations, impact mechanisms transitions*



Ng et al. (2020). Design recommendations for rigid and flexible debris flow-resisting barriers. Conference Keynote paper;
Wendeler (2007). Field measurements and numerical modelling of flexible debris flow barriers.

Introduction, *gaps*



A compilation of flow velocities and thickness for various types of geophysical flows over a broad Froude-number range: (a) large- and small- scale experimental tests (b) field data.

Fr: the square root of the ratio between kinetic and gravity force of the flow.

- a scale-independent relationship;

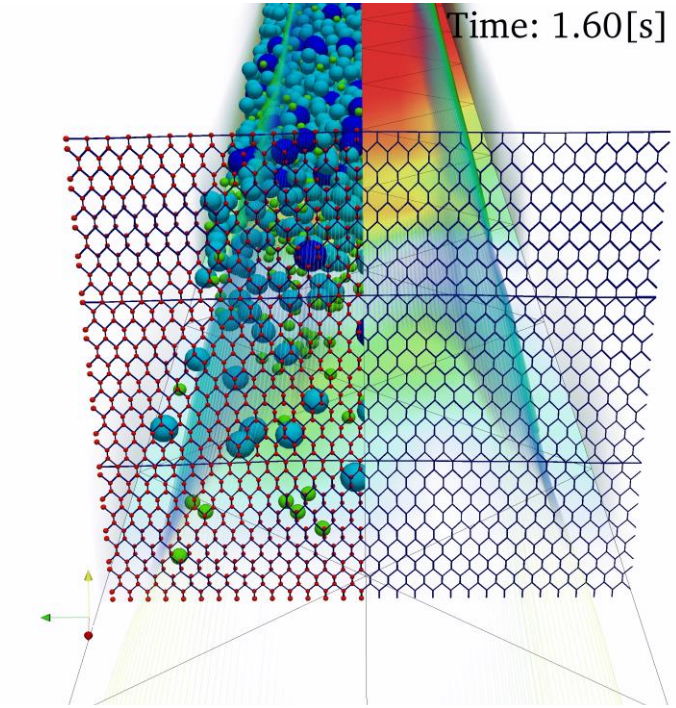
Limitations of physical tests:

- Narrow Froude-number range;
- Lack of large-scale, high-speed and low Froude number impact tests with flexible barrier.

Introduction, *gaps and objectives*

Research gaps:

- No rigorous analytical tools are available for the design of flexible barriers to resist different geophysical flows of different natures and over a broad range of Froude number.
- No clear criteria built upon sounded theoretical basis are available for the estimation of mechanism transition from pile-up impact to run-up impact.



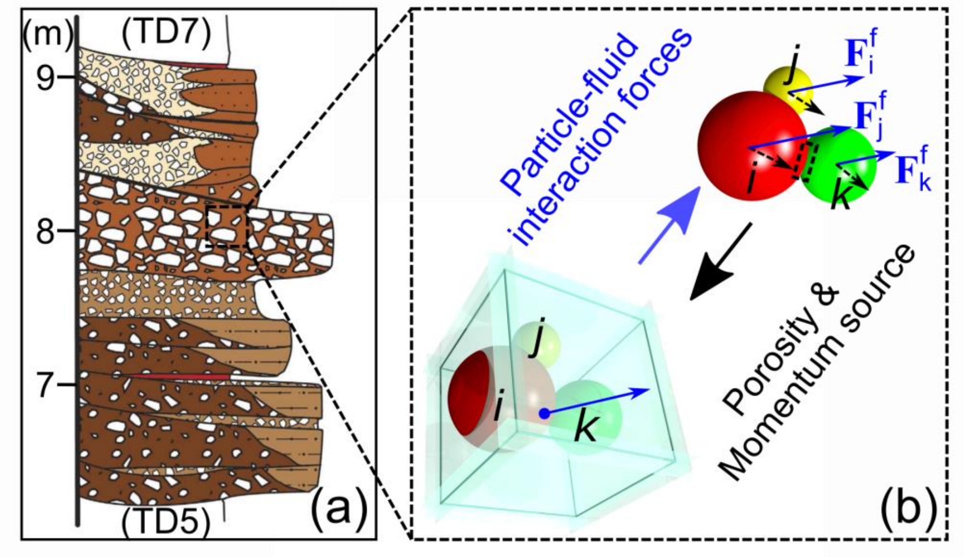
Modelling challenges:

- *various type of geophysical flows over a broad Froude-number range;*
- *various type and complex system of flexible barriers;*

Objectives:

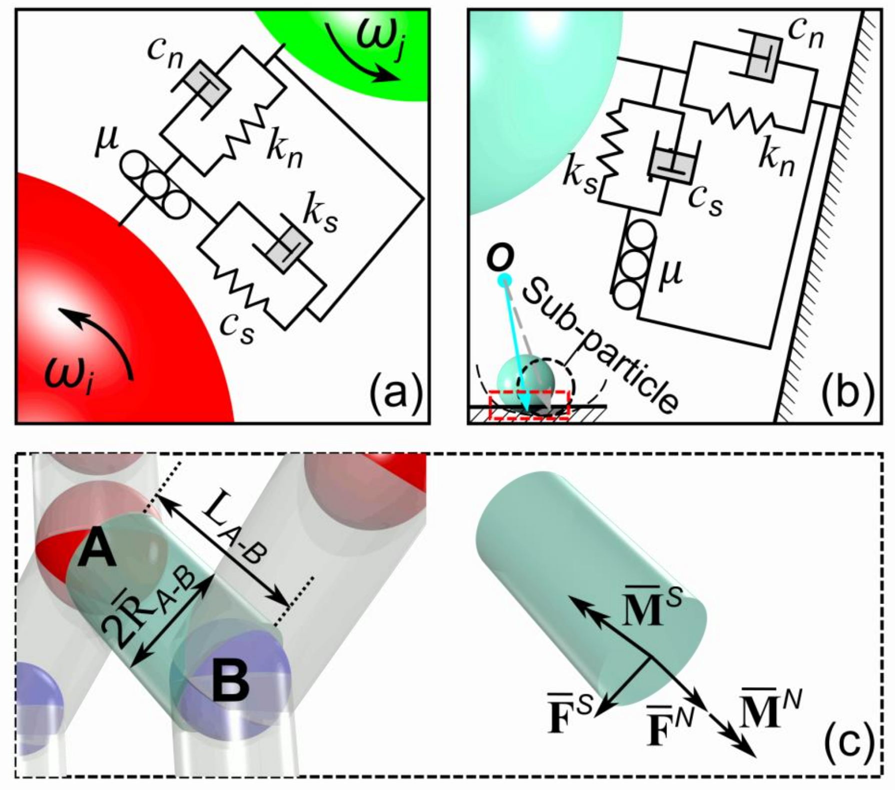
1. *Modelling of high-speed and large-scale (with quasi continuous overflow) approaching flows;*
2. *Modelling of permeable flexible barrier considering different components.*
3. *How to quantitatively characterize the pile-up impact and run-up impact mechanisms for different geophysical flows of different natures ?*

Methodology, *coupling outline, contacts and remote bond*



$$\begin{cases} \dfrac{\partial(\alpha_f \rho_f)}{\partial t} + \nabla\cdot(\alpha_f \rho_f \mathbf{U}^f) = 0 \\ \dfrac{\partial(\alpha_f \rho_f \mathbf{U}^f)}{\partial t} + \nabla\cdot(\alpha_f \rho_f \mathbf{U}^f \mathbf{U}^f) \\ = -\nabla p - \mathbf{f}^p + \alpha_f \nabla\cdot\tau + \alpha_f \rho_f \mathbf{g} + \mathbf{f}^s \end{cases}$$

$$\begin{cases} m_i \dfrac{d\mathbf{U}_i^p}{dt} = \sum_{j=1}^{n_i^c} \mathbf{F}_{ij}^c + \mathbf{F}_i^f + \mathbf{F}_i^g \\ I_i \dfrac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{n_i^c} (\mathbf{M}_{t,ij} + \mathbf{M}_{r,ij}) \end{cases}$$



$$\bar{\sigma}^{max} = \frac{-\bar{F}^n}{A} + \frac{|\bar{M}^s|\bar{R}}{I} \qquad \bar{\tau}^{max} = \frac{|\bar{F}^s|}{A} + \frac{|\bar{M}^n|\bar{R}}{J}$$

- Exchanging fluid-particle interaction forces between the CFD and DEM solvers.
- The bond is assumed to break: $\bar{\sigma}^{max} \geqslant \bar{\sigma}_c$ or $\bar{\tau}^{max} \geqslant \bar{\tau}_c$

Methodology, *model set-up*

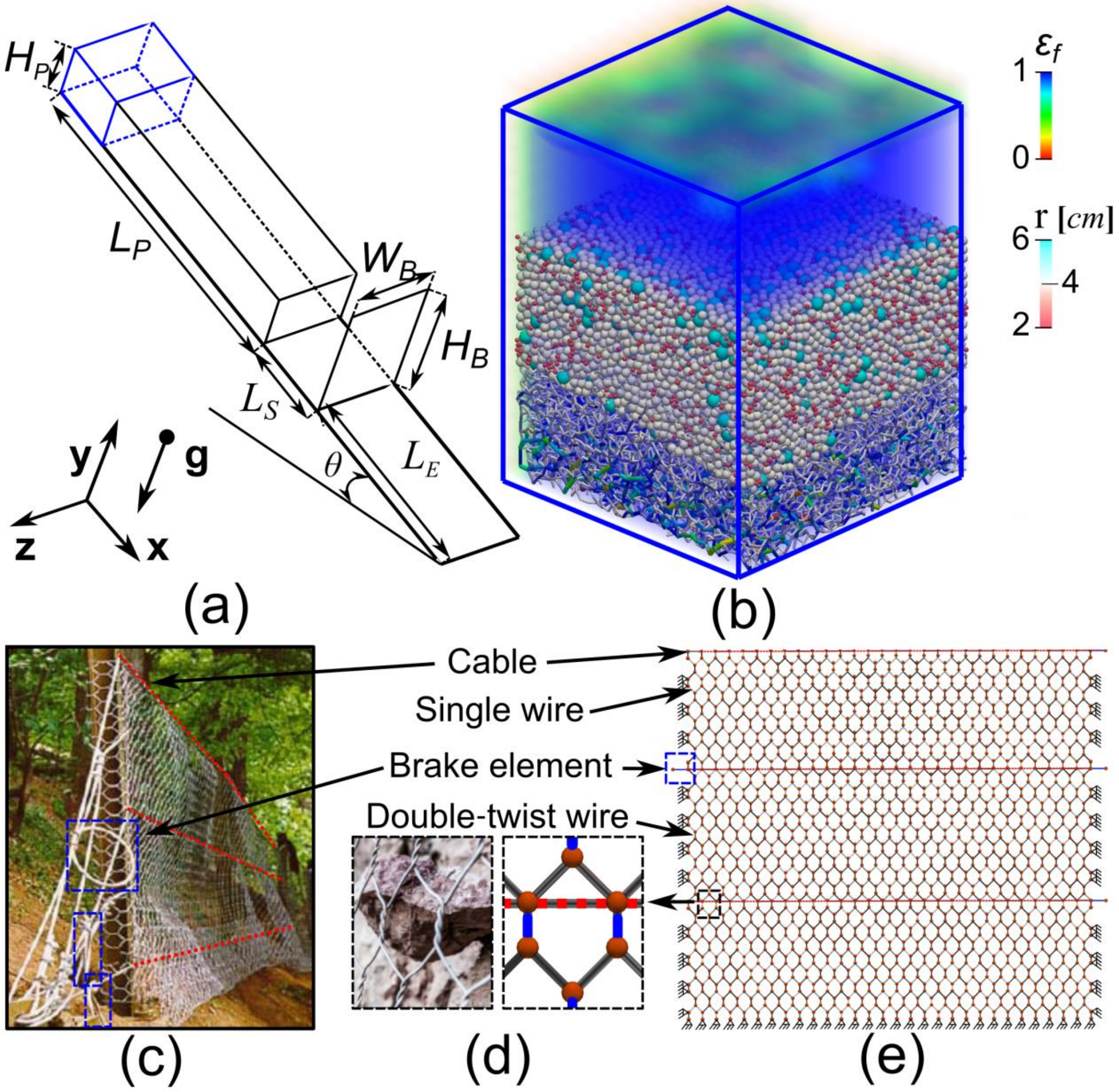


FIG. 3.

Key components:

- ✓ Cables (top, middle and bottom);
- ✓ Hexagonal wire meshes;
- ✓ Brake elements;

Debris-structure interactions:

- ✓ Solid debris and flexible structure;
- ✓ Viscous fluid and flexible structure;

Controlled values:

- h_{pre}/H_B = 0.5;
- r = 0.06m, 0.04m and 0.02m;

Research variables:

- *Approaching velocities;*
- *Solid fraction;*
- *Fluid type (water or slurry);*

Methodology, *test program*

Table 2

Groups	ε_s [%]	Vpre [m/s]	Fluid model	Examples for tests with Vpre = 1 m/s
MDF	20	1, 2, 3, 4, 6, 8, 10, 12, 14, 16	Slurry	***MDFS20V1***
	35	1, 2, 3, 4, 6, 8, 10, 12, 14, 16	Slurry	***MDFS20V1***
	50	1, 2, 4, 5, 6, 8, 10, 12, 14, 16	Slurry	***MDFS20V1***
DF	20	1, 2, 3, 4, 6, 8, 10, 12, 14, 16	Water	***DFS20V1***
DA	50	1, 2, 4, 5, 6, 8, 10, 12, 14, 16	Slurry	***DAV1***
RA	100	1, 2, 4, 6, 7, 8, 10, 12, 14, 16	None	***RAV1***
MF	0	1, 1.5, 2, 4, 6, 8, 10, 12, 14, 16	Slurry	***MFV1***

- The test ID ***MDFS20V1*** denote the muddy debris flow with solid fraction equal to 20 and pre-impact velocity equal to 2 m/s. Similarly, the ***DF*, *DA*, *RA*** and ***MF*** represent the debris flood, debris avalanche, rock avalanche and muddy flow respectively.

Table 3

Herschel-Bulkley model $\boldsymbol{\tau} = \boldsymbol{\tau}_0 + \kappa\dot{\gamma}^n$

Fluid properties	Herschel-Bulkley fluid
Density ρ_f [kg/m^3]	1600
Consistency index κ [Pa$\cdot s^n$]	25.07
Flow index n	0.34
Yield stress τ_0 [Pa]	210

Hungr et al. (2001) A Review of the Classification of Landslides of the Flow Type.
Remaître et al. (2005) Flow behaviour and runout modelling of a complex debris flow in a clay-shale basin.

Results, *typical snapshots showing three impact stages*

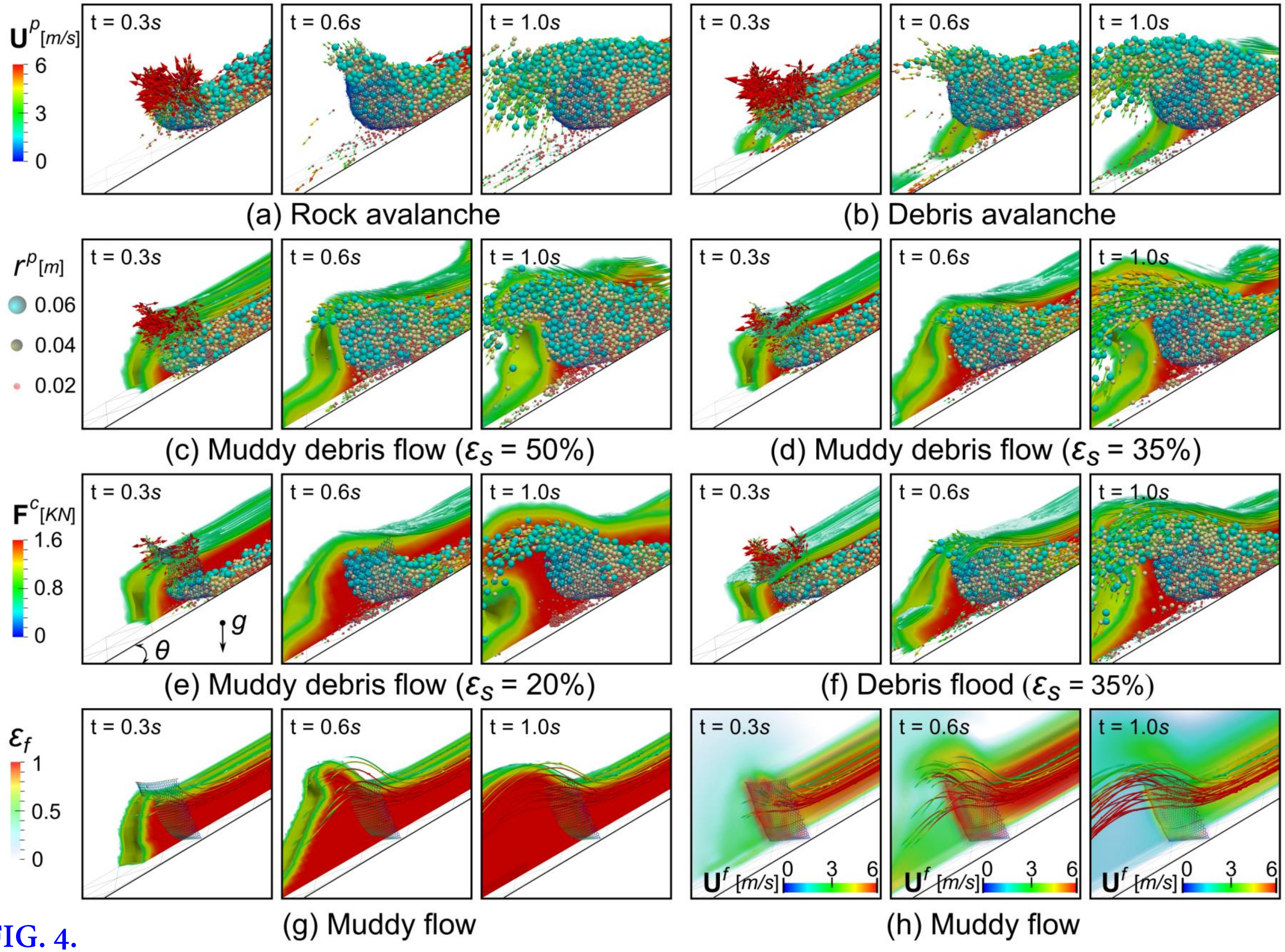


FIG. 4.

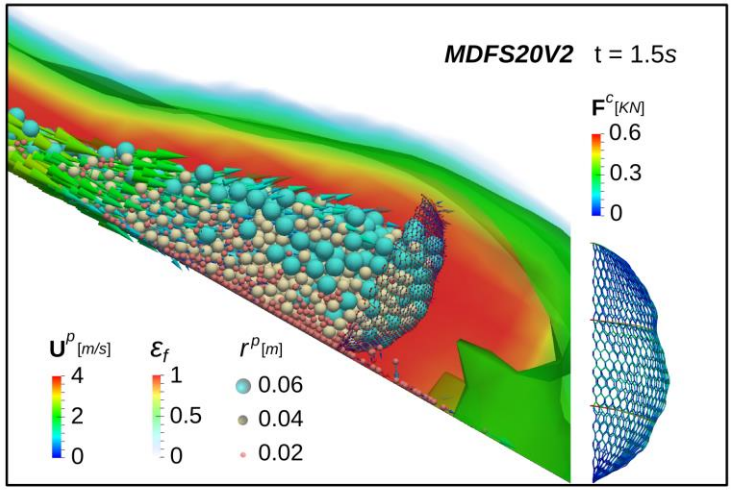
Geophysical flows impacting on a permeable flexible barrier with fixed pre-impact velocities equal to 6 m/s:

- ✓ *stage I (frontal impact, t = 0.3s);*
- ✓ *stage II (run-up and flow jet, t = 0.6s)*
- ✓ *stage III (overflow, t = 1s)*

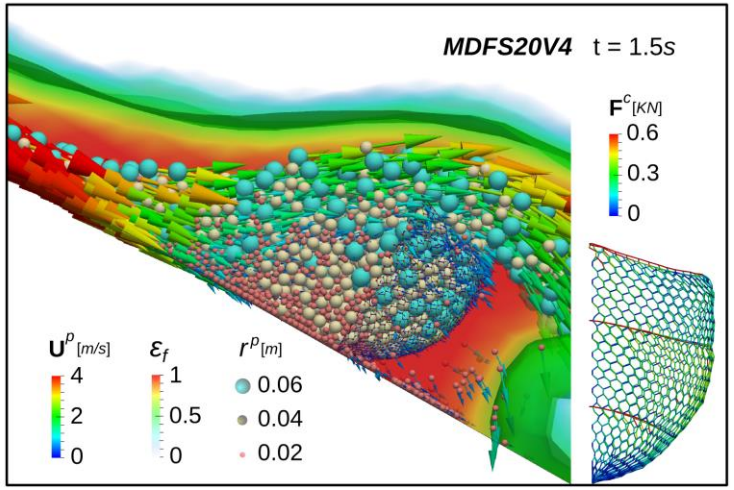
Key concerns:

- ✓ *Partial muddy debris flow passing through;*
- ✓ *Difference between **DF** and **MDF**;*
- ✓ *Velocity reduction in **MF**;*

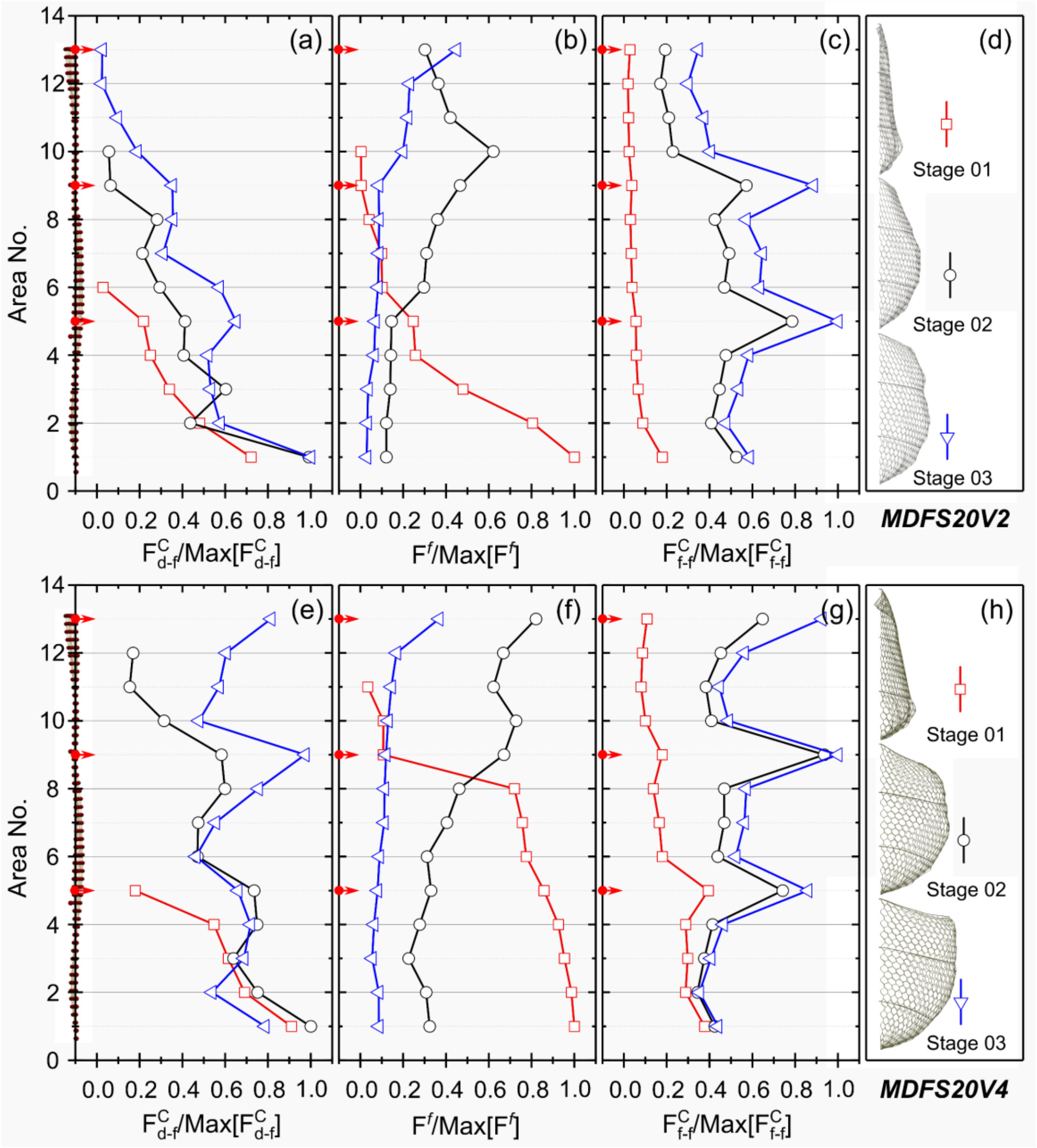
Results, *impact mechanism：Pile-up V.S. Run-up*



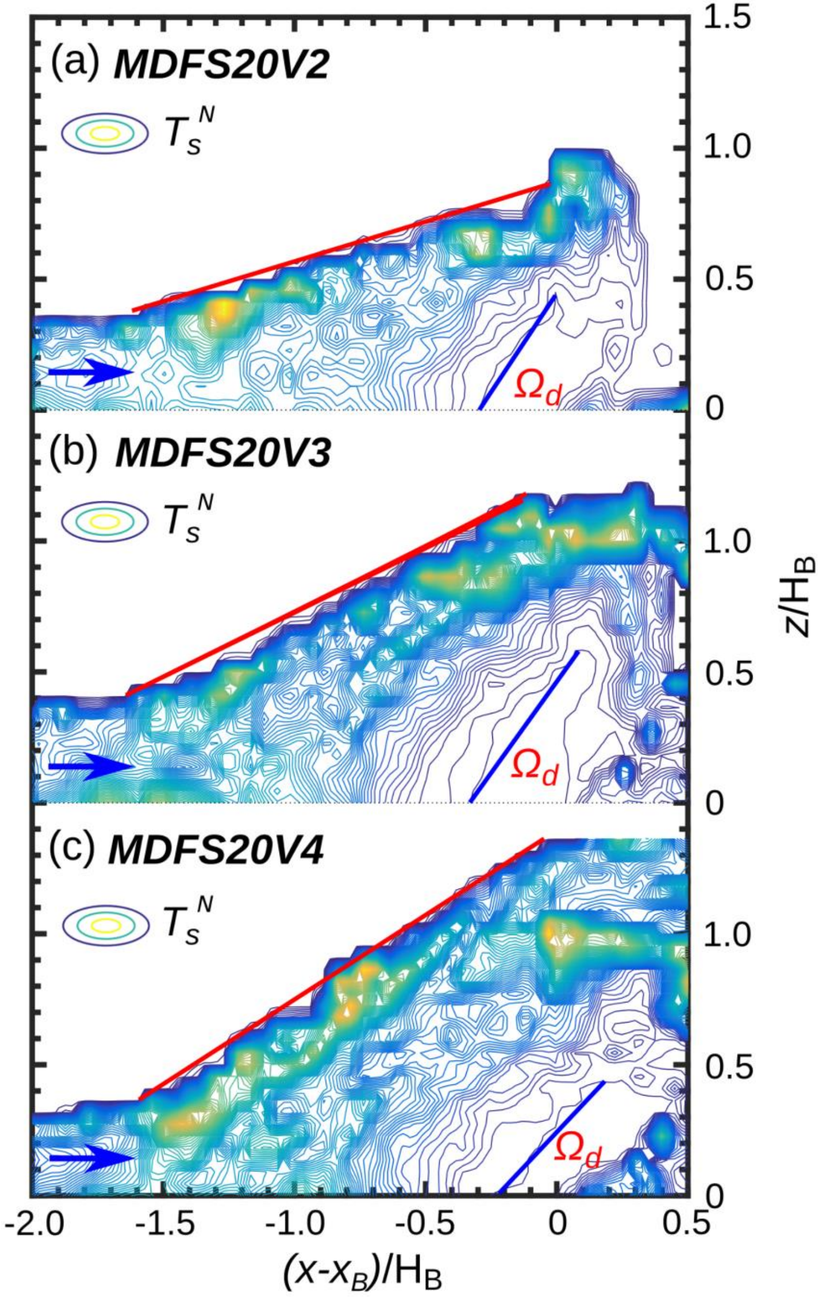
(a) Pile-up impact behaviour



(b) Run-up impact behaviour



Results, *debris-flexible barrier interactions, key angles and regimes*



A modified function of granular temperature considering material polydispersity and rotational motions of particles.

$$T_s(\mathbf{r}) = \sum_{i\in N_{\mathbf{r}}} (m_i u_i'^2 + I_i \omega_i'^2)/DN_{\mathbf{r}} \sum_{i\in N_{\mathbf{r}}} m_i$$

- $u'_s = \|\mathbf{u}_s\| - \|\bar{\mathbf{u}}_s\|$
- $\omega'_i = \|\boldsymbol{\omega}_i\| - \|\bar{\boldsymbol{\omega}}(\mathbf{r})\|$
- $I_i = 2m_i r_i^2/5$
- $D = 3$

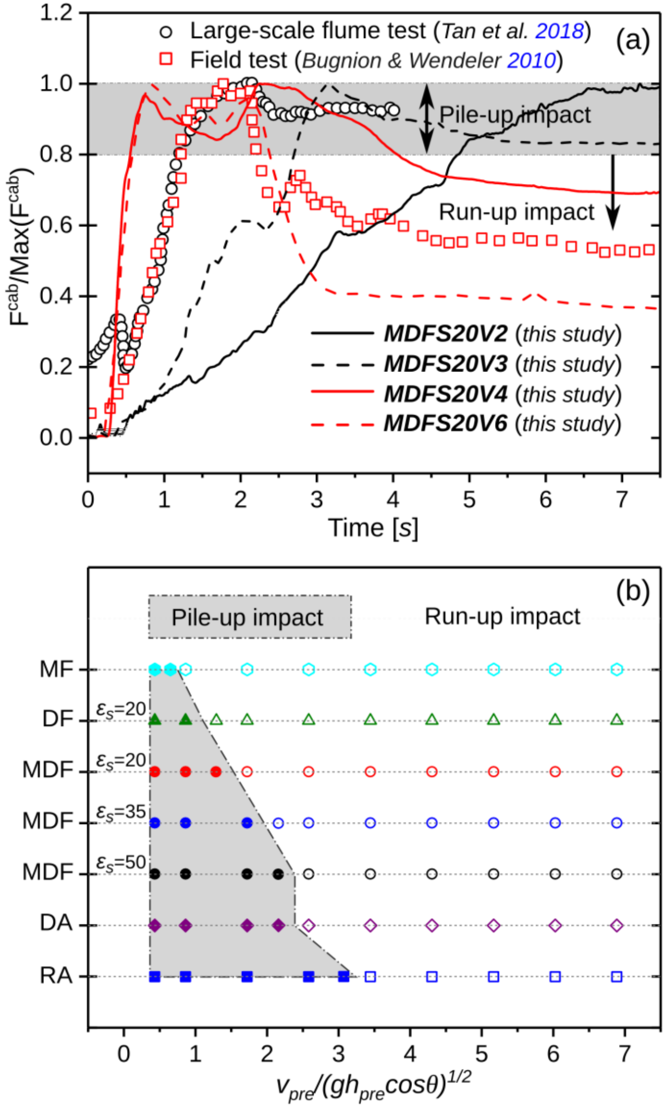
Key angles:

- ✓ Pile-up or run-up angle (increasing trend);
- ✓ Wedge angle of HDZ (decreasing trend);

Key regimes:

- ✓ Flowing layer (drag force and earth force);
- ✓ Hydrodynamic dead zone (gravity- and friction-induced force);

Results, ***impact mechanism transitions,*** *impact load and momentum reduction ratio*



impact load reduction ratio

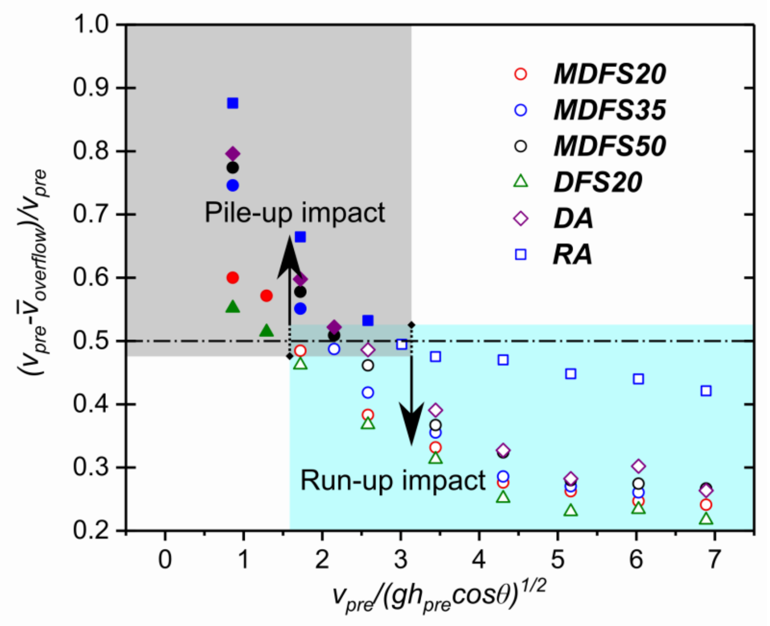
Two representative cases of scenarios identified for debris frontal impact on the flexible barrier:

(a) pile-up impact, indicating a static-force based design is advisable for flexible barrier.

(b) run-up impact (1 - $F^{cab}/max[F^{cab}] > 20\%$, widely adopted load model).

✓ The increasing trend of impact load reduction ratio (1 - $F^{cab}/max[F^{cab}]$).

✓ The transition from a pile-up mechanism to a run-up mechanism is mainly governed by the dynamics of the approaching flows and solid fraction.



momentum reduction ratio

Momentum-based load model by Koo et al. (2017) Velocity attenuation of debris flows and a new momentum-based load model for rigid barriers[J]. ***Landslides***

Load model considering partial muddy debris flow passing through by Tan et al. (2019). ***Journal of Geotechnical and Geoenvironmental Engineering.***

Summary

- ✓ We presented a unified hydro-mechanical computational framework based on coupled CFD/DEM to model how typical geophysical flows of different natures interact with a flexible barrier.
- ✓ The transition from pile-up impact to run-up impact was correlated quantitatively with the approaching flow dynamics and solid fraction. Two dimensionless numbers including the impact load ratio and the velocity loss ratio are calculated to characterize this transition for the first time.
- ✓ We identified the flowing layer, hydrodynamic dead zone and three typical impact stages, namely, frontal impact, run-up & flow-jet and overflow processes of typical geophysical flows interacting with a flexible barrier.

Thanks