POLITECNICO DI TORINO

EGU General Assembly 2020

Debris flow interaction with structures: challenges to traditional load models

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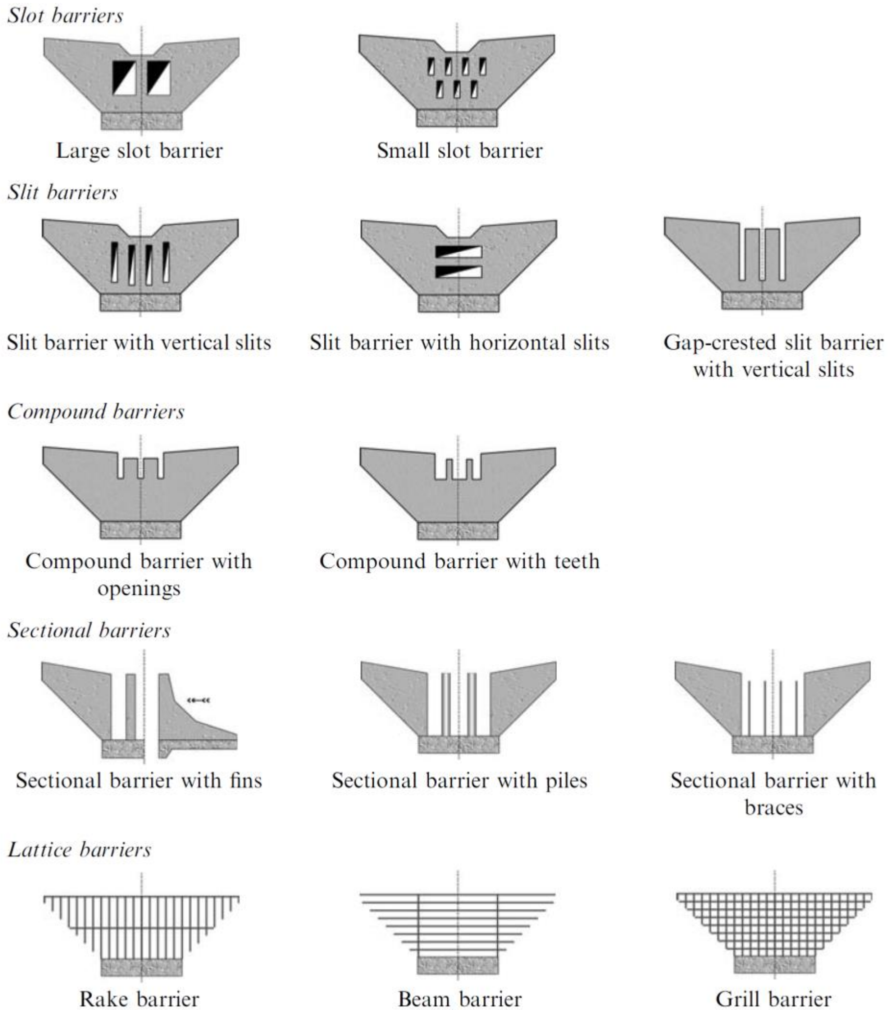
Footage by Swiss Federal Institute for Forest, Snow and Landscape Research WSL
Illgraben CH 28 July 2014

Debris flow are hazardous natural events. The presence of large boulders, transported at high speed on relatively gentle slopes, induces a destructive impact on exposed elements.

Brienz (CH) 2005

Structural countermeasures

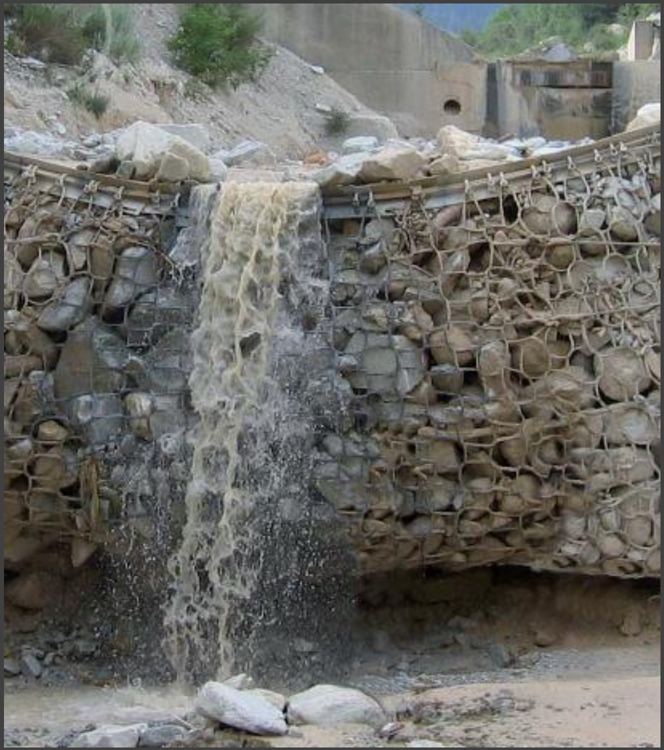
Barriers are designed for multiple purposes. Filtering large grains, laminating the flow, stabilizing the bed. However, design is still mostly based on trial-and-error approaches



Hübl J., Strauss A. Holub M. Suda J. (2005). "Structural Mitigation Measures". Proceedings of the 3rd Probabilistic Workshop: Technical Systems + Natural Hazards, 24.- 25. 2005, Vienna.in

Can a numerical framework aid in designing better barriers?

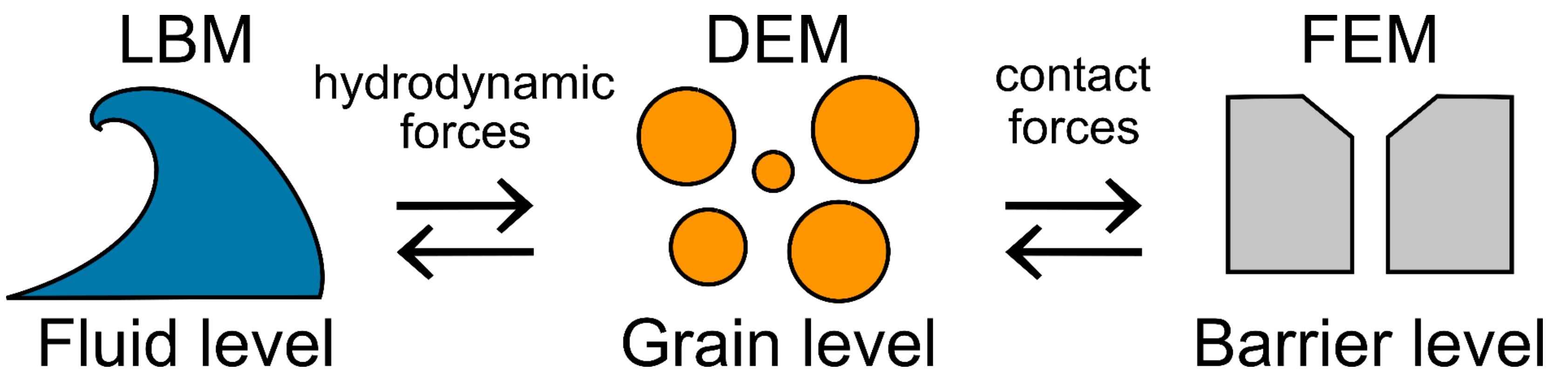
To do so, the framework should address these issues:



- **Filter:** the barrier interacts differently with different phases of the flow
- **Sediment trap:** The flow composition is different before and after the barrier
- **Forces:** Composition of discrete impacts and flow-like behaviour
- **Fluid-structure interaction:** non-linear effects due to barrier deformability

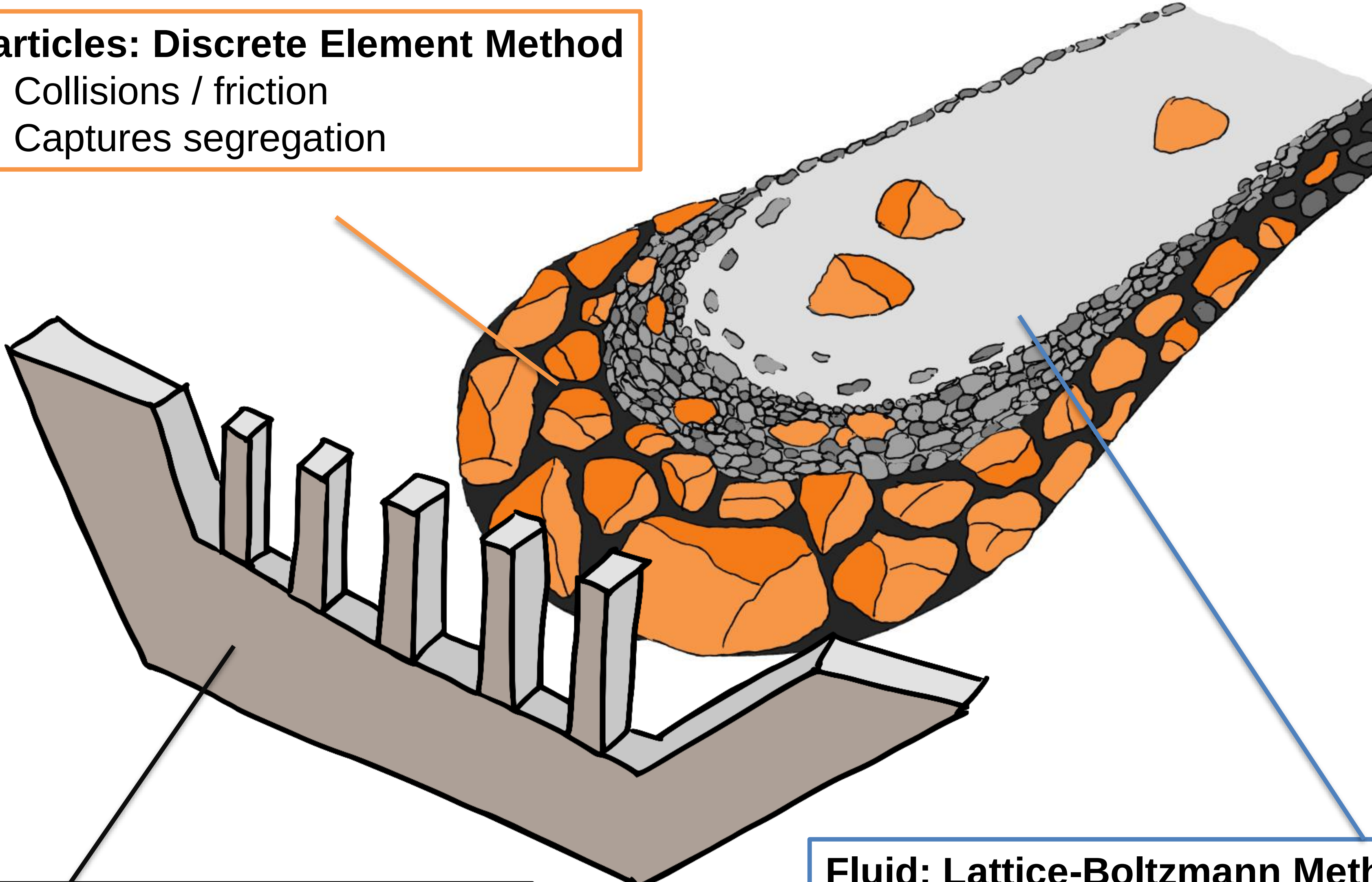
Numerical framework

We propose a hybrid approach, where different parts of the fluid-structure interaction problem are assigned to specific solvers:



Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333.

Particles: Discrete Element Method
- Collisions / friction
- Captures segregation



Barrier: Finite Element Method
- Large displacements
- Impact force patterns

Fluid: Lattice-Boltzmann Method
- Easy parallelization
- Can manage sophisticated boundary conditions

Presentation outline

The numerical framework is used to study three common barrier types

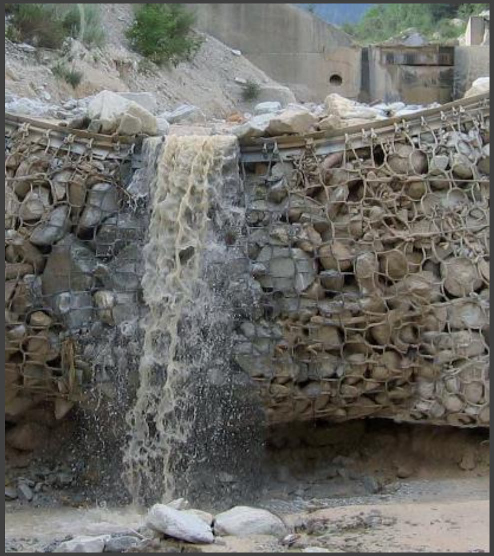
Case (A)
the slit dam

DEM
+ comparison with laboratory experiments

Case (B)
the rack dam

DEM-FEM
+ comparison with site measurements

Case (C)
the flexible barrier



LBM-DEM-FEM

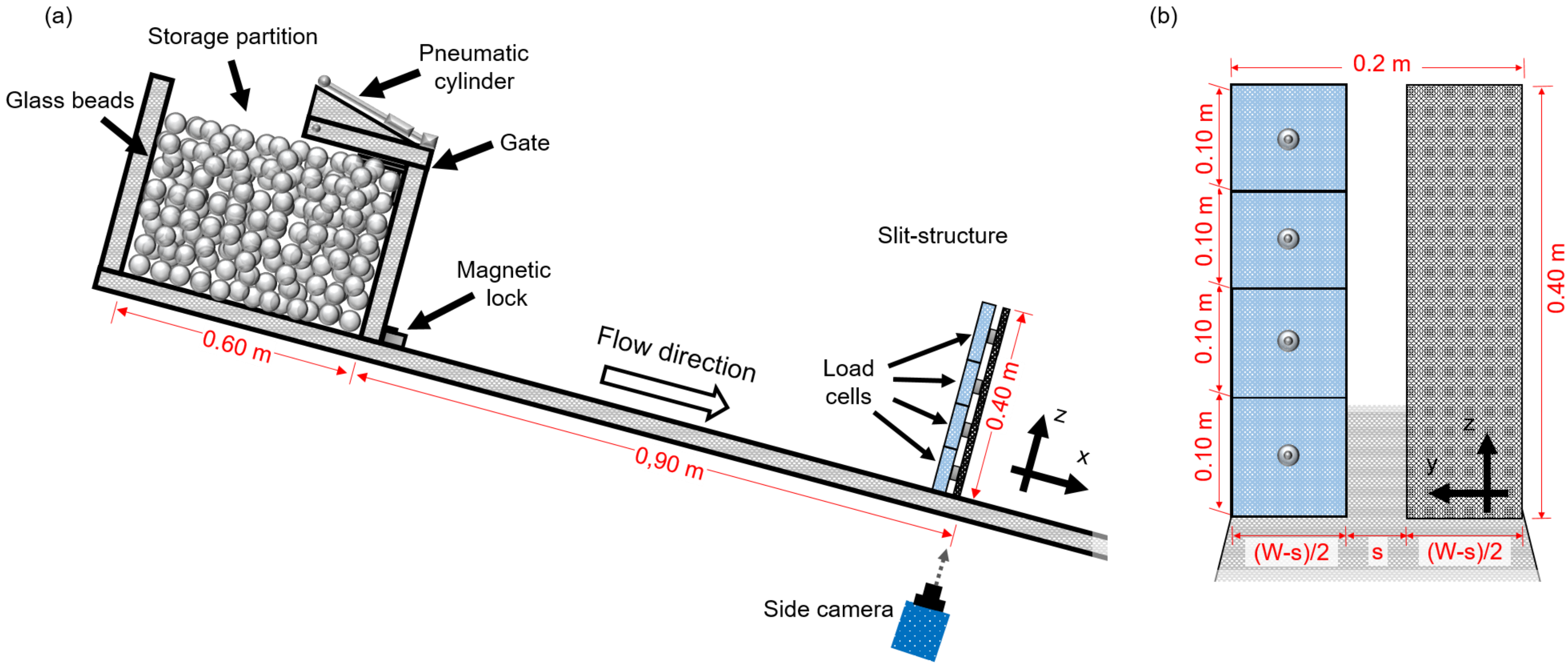
Case (A)
the slit dam

Method: DEM
Validation on laboratory experiments

A

Experimental setup

The study is based on the back-calculation of a series of small-scale flume experiments performed at the Hong Kong University of Science and Technology (HKUST)



Choi, C. E., Goodwin, G. R., Ng, C. W. W., Cheung, D. K. H., Kwan, J. S. H., & Pun, W. K. (2016). Coarse granular flow interaction with slit structures. *Géotechnique Letters*, *6*(4), 267–274.

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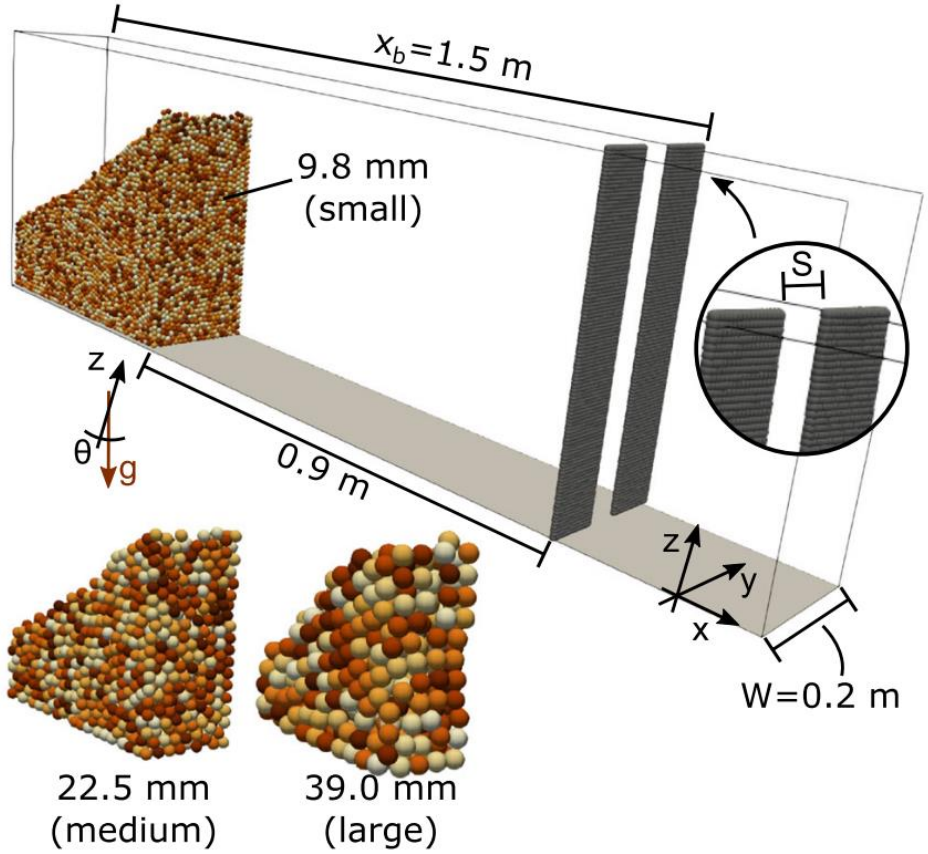
Numerical back-calculation

The experiments are simulated with a simple DEM model, using particles of different sizes d ("small", "medium", and "large"), different barriers S, and several flume inclinations θ. The actual particle stiffness is simulated exactly.



Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963.

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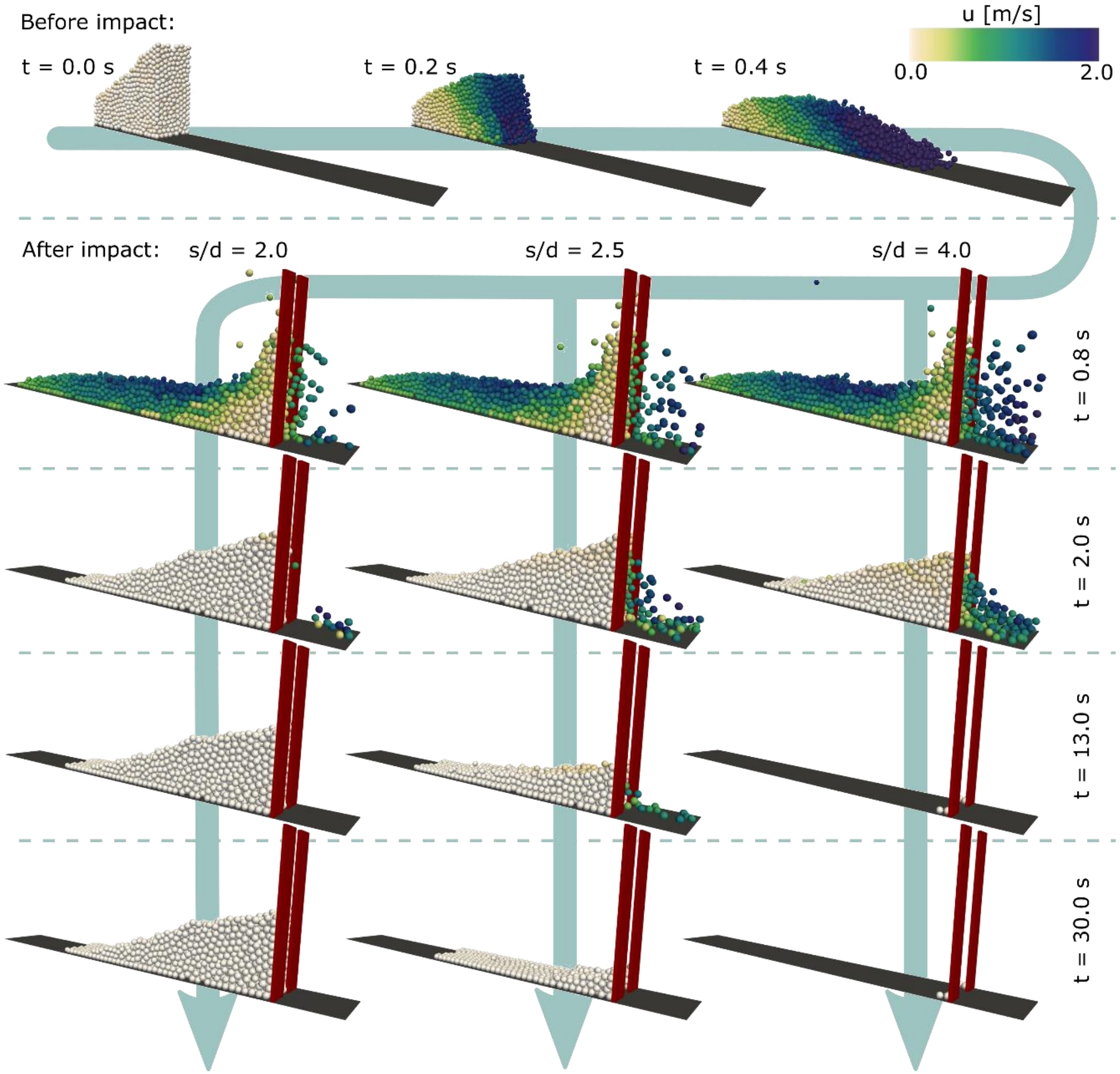
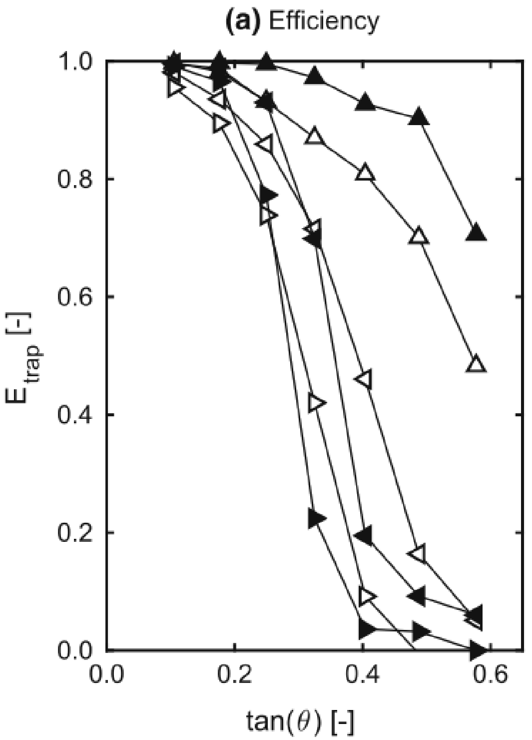
Numerical back-calculation



The simulated parametric matrix allows to observe the behaviour at different slit-to-particle-size ratio S/d.

The final trapping efficiency in experiments and simulations is very similar



Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963.

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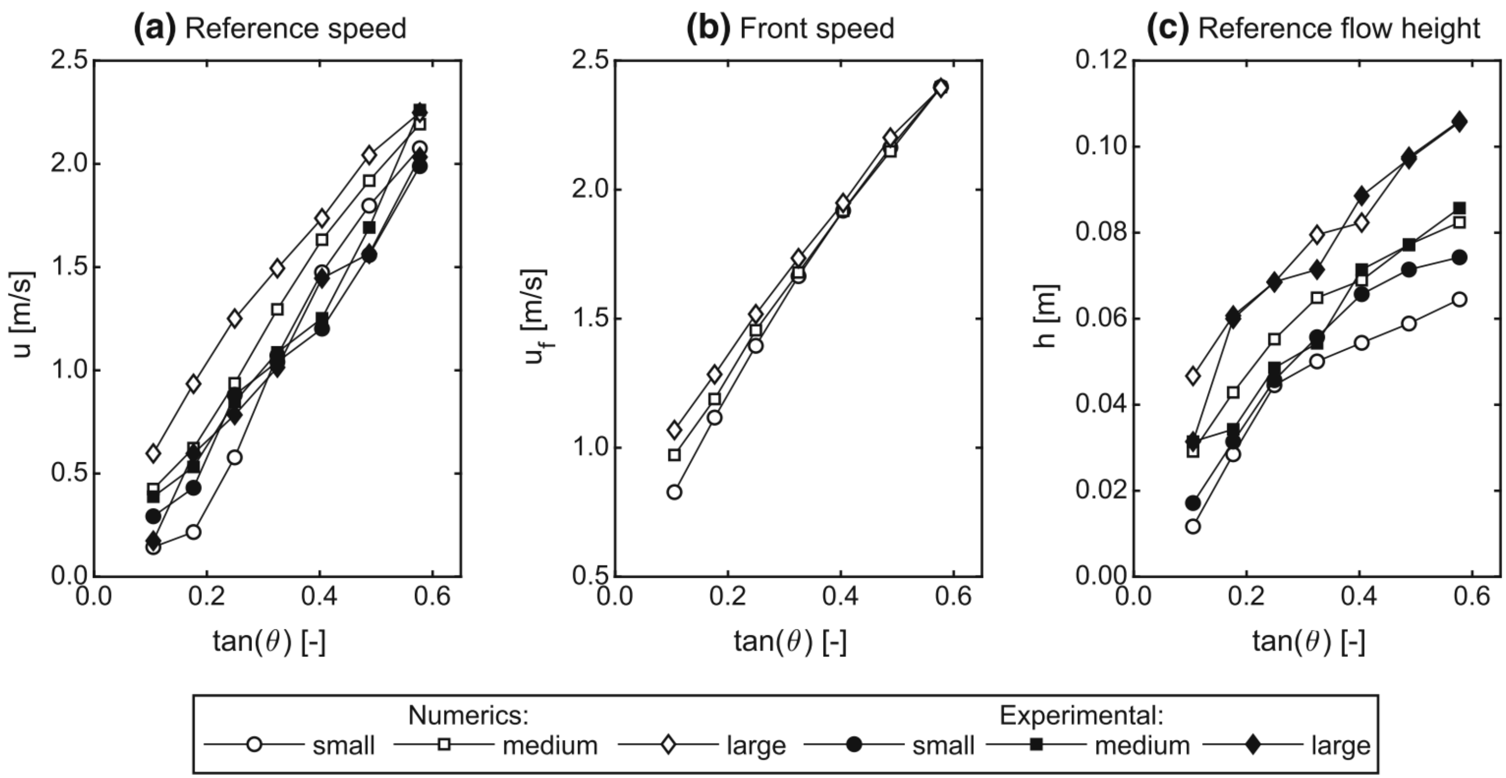
Numerical back-calculation

The kinematics obtained in experiments and simulation is quantitatively similar.



Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963.

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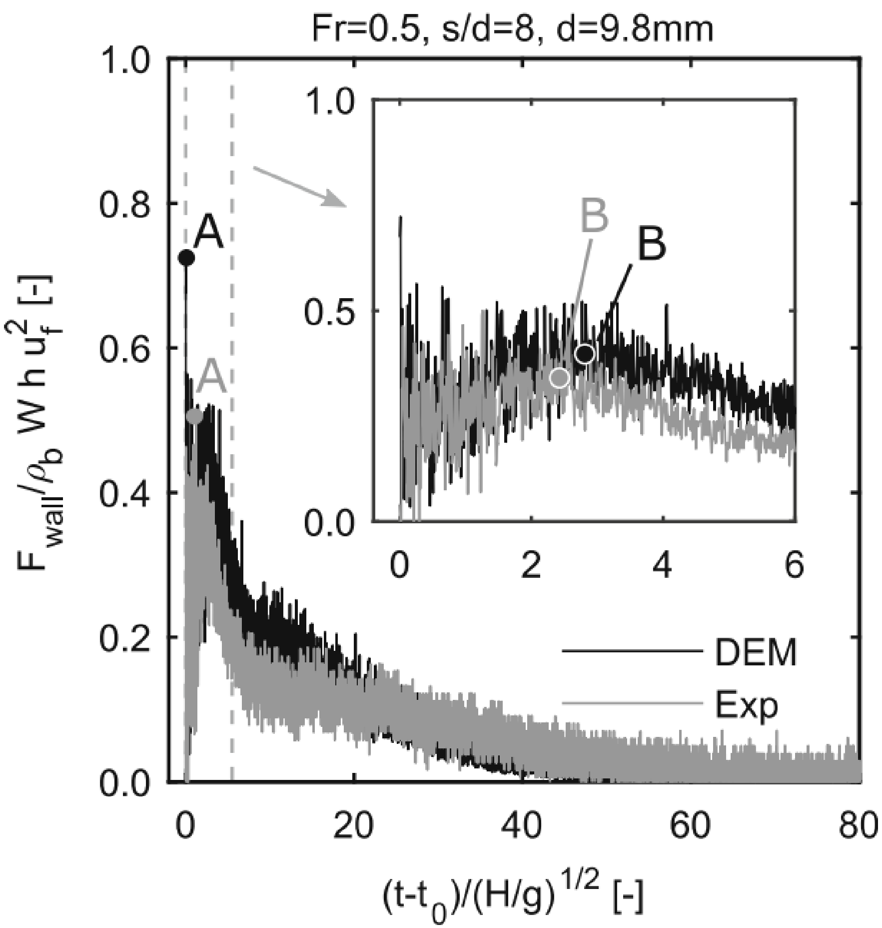
Numerical back-calculation

The forces recorded in experiments and DEM simulations follow very similar patterns.



Two characteristic force records are defined:

- The **single-impact peak**, corresponding to the **energetic collision of the front particles** (point A)
- The **continuum-like peak** observed after a short time from initial impact. Here **momentum exchange is maximum**, if single discrete contributions are smoothened out (point B)

Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963.

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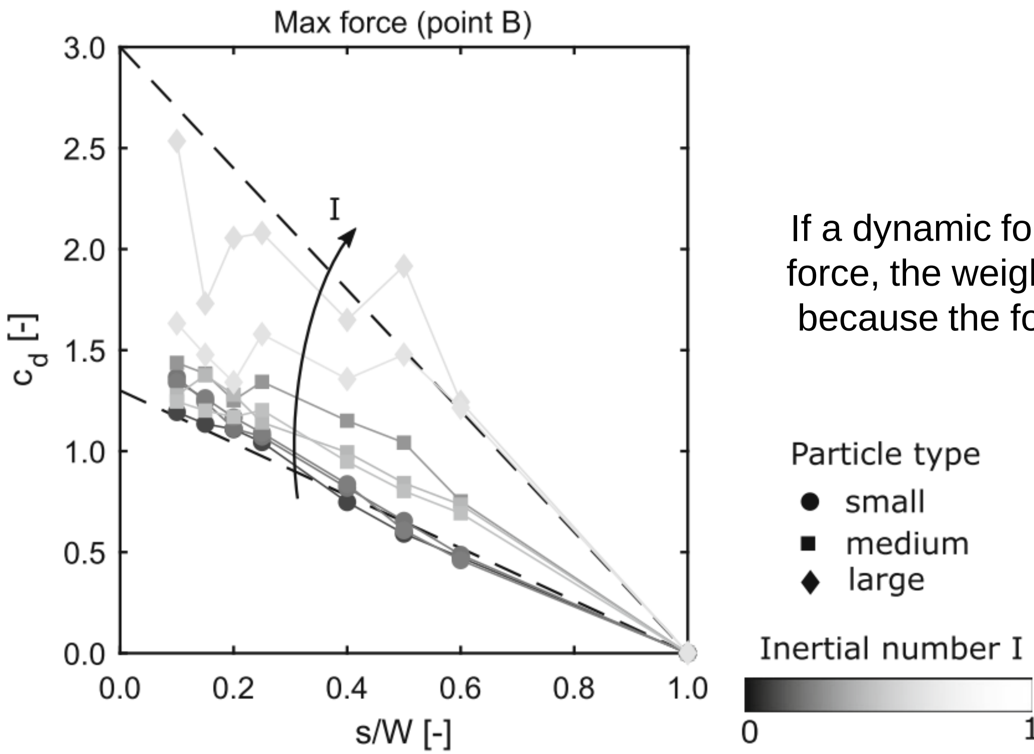
Force analysis

We find that the Inertial number can be an excellent tool for determining whether discrete- or continuum-like force signals will be prevalent



$$I = \frac{\dot{\gamma} d}{\sqrt{gh}}$$

If a dynamic formula is used to back-calculate the impact force, the weight coefficient must increase with growing I, because the formula does not consider single collisions.

$$c_d = \frac{F_B}{F_{dyn}}$$

$$c_d = c_d(\mathrm{I})$$

Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963.

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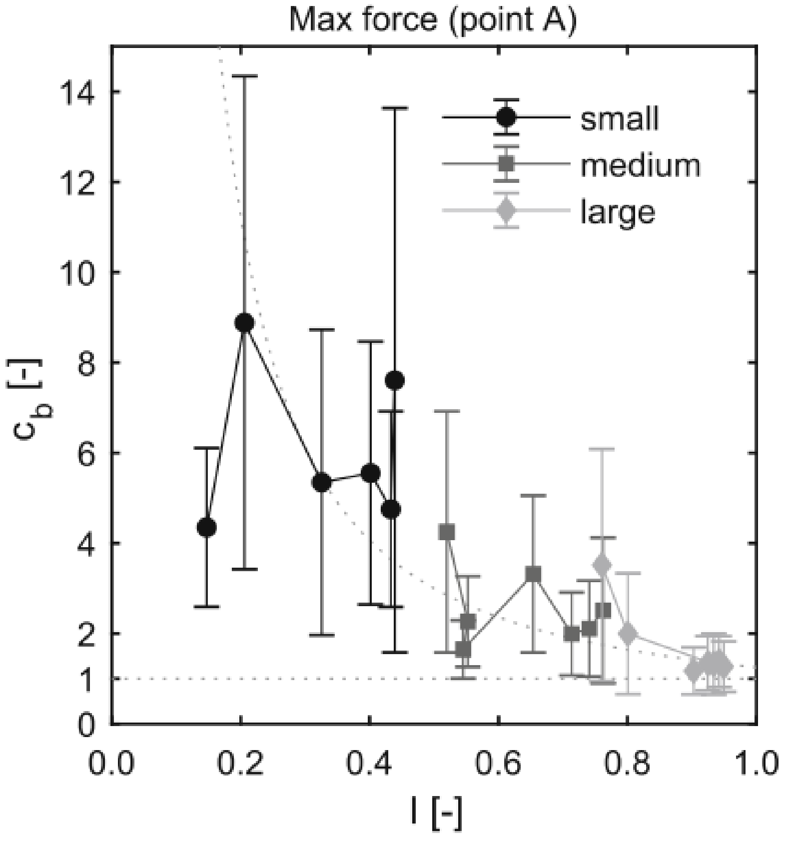
Force analysis

Likewise, discrete impacts become more dominant if the inertial number is large. Thus, if a single-particle collision formula is used (e.g. using Hertz theory) the weight coefficient reduces if I is large



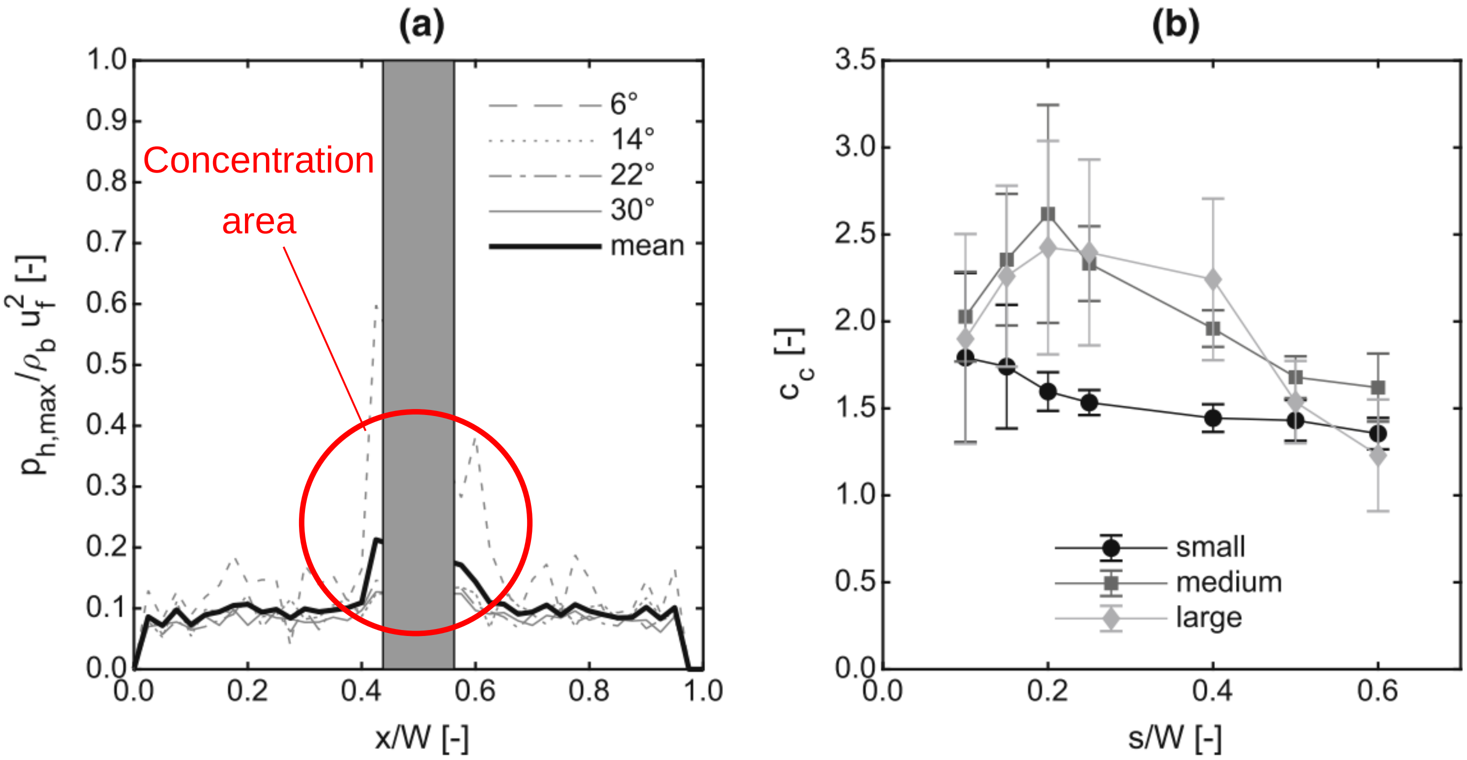
$$I = \frac{\dot{\gamma} d}{\sqrt{gh}}$$

$$c_b = \frac{F_A}{F_{Hertz}}$$

Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963.

Force analysis

Finally, forces concentrate at the bottom of the dam (as for an impervious barrier). Additionally, they also concentrate on the area around the slit. This effect is due to augmented discrete impacts on that are, and is more pronounced for larger particles



c_c is the concentration factor (pre-multiplier to determine the augmented impact pressure on the slit area)

Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963.

Case (B)
the rack dam

Method: DEM-FEM
Comparison with site measurements

B

Numerical back-calculation

The study is based on the monitoring campaign of barrier located in Italy

Courtesy of Regione Autonoma Valle d'Aosta

Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

B

Estimation of impact forces

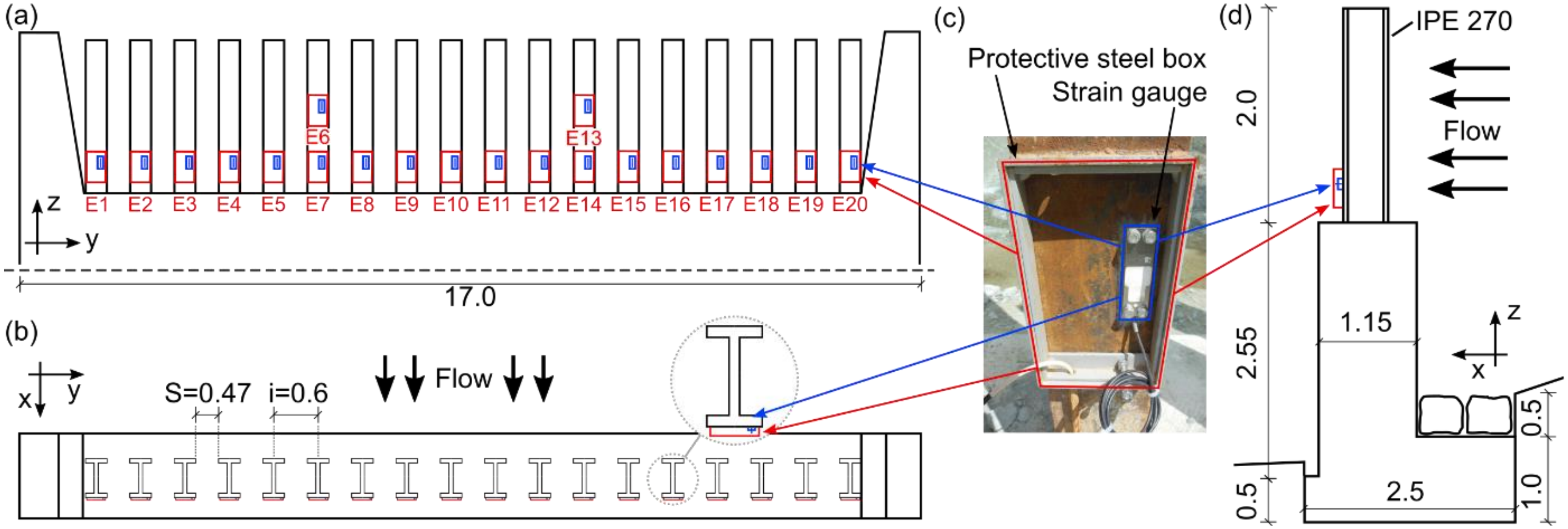
The barrier had previously collapsed during an event, leading to efforts toward a better understanding of its structural response to impact

Barrier in St. Vincent, Aosta Valley

Leonardi, A., Pirulli, M., Barpi, F., Borri-Brunetto, M., Pallara, O., Scavia, C., & Segor, V. (2020). Impact of debris flows on filter barriers: analysis based on site monitoring data. *Under Review for Environmental and Engineering Geosciences*.

B

Monitoring system

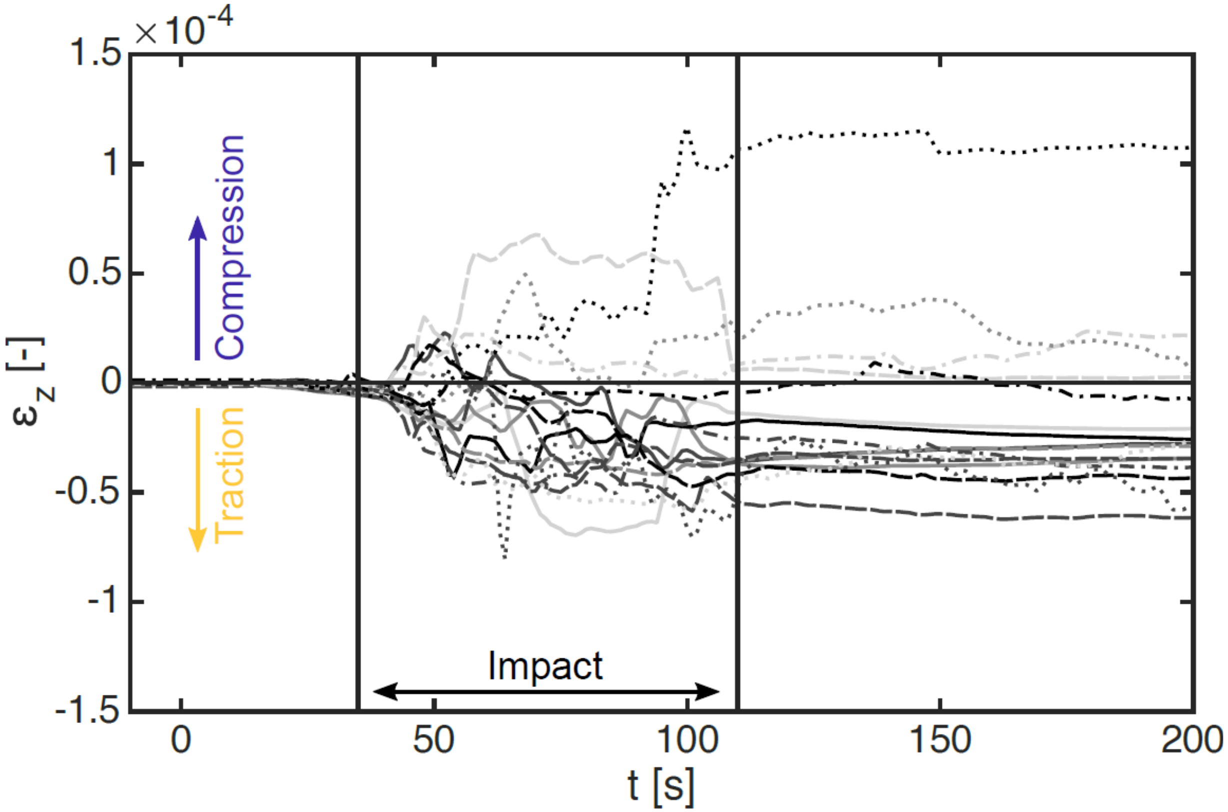


The monitoring system consists of a series of strain gauges installed on the rack elements. Strain recordings are available any time the barrier is hit.

Leonardi, A., Pirulli, M., Barpi, F., Borri-Brunetto, M., Pallara, O., Scavia, C., & Segor, V. (2020). Impact of debris flows on filter barriers: analysis based on site monitoring data. *Under Review for Environmental and Engineering Geosciences*.

B

Recordings



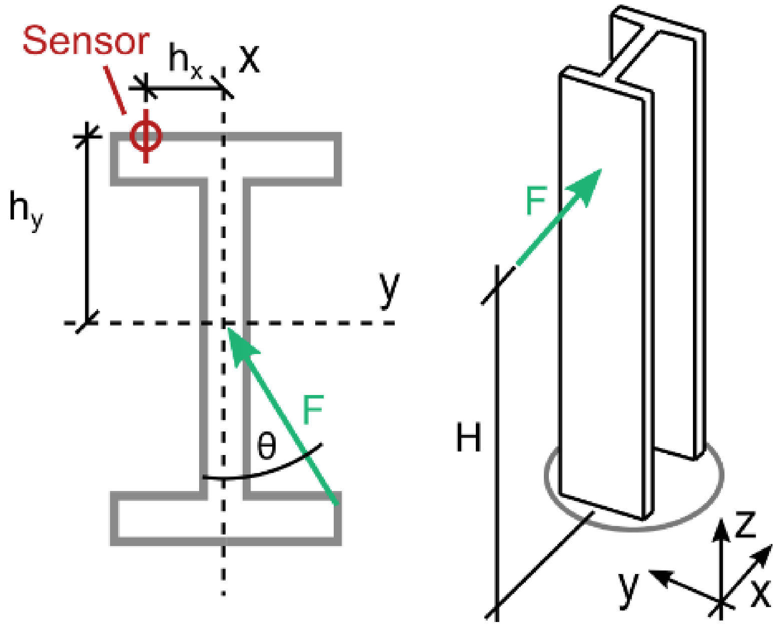
The recordings however always show a counter-intuitive pattern. Recorded strains are both positive and negative, as if the barrier were hit from both directions.

Leonardi, A., Pirulli, M., Barpi, F., Borri-Brunetto, M., Pallara, O., Scavia, C., & Segor, V. (2020). Impact of debris flows on filter barriers: analysis based on site monitoring data. *Under Review for Environmental and Engineering Geosciences*.

B

Signal interpretation

The recorded strains can be explained if the impact force is assumed to be inclined with respect to the main direction of the channel. This causes biaxial bending



Orthogonal load:

$$\varepsilon_z = \frac{M_y}{EI_{yy}} h_y \qquad M_y = \frac{\varepsilon_z}{h_y} EI_{yy}$$

Inclined load:

$$\varepsilon_z = \frac{M_y}{EI_{yy}} h_y + \frac{M_x}{EI_{xx}} h_x \qquad M = \frac{\varepsilon_z}{E}\left(\frac{\cos(\theta)}{h_y} I_{yy} + \frac{\sin(\theta)}{h_x} I_{xx}\right)$$

Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

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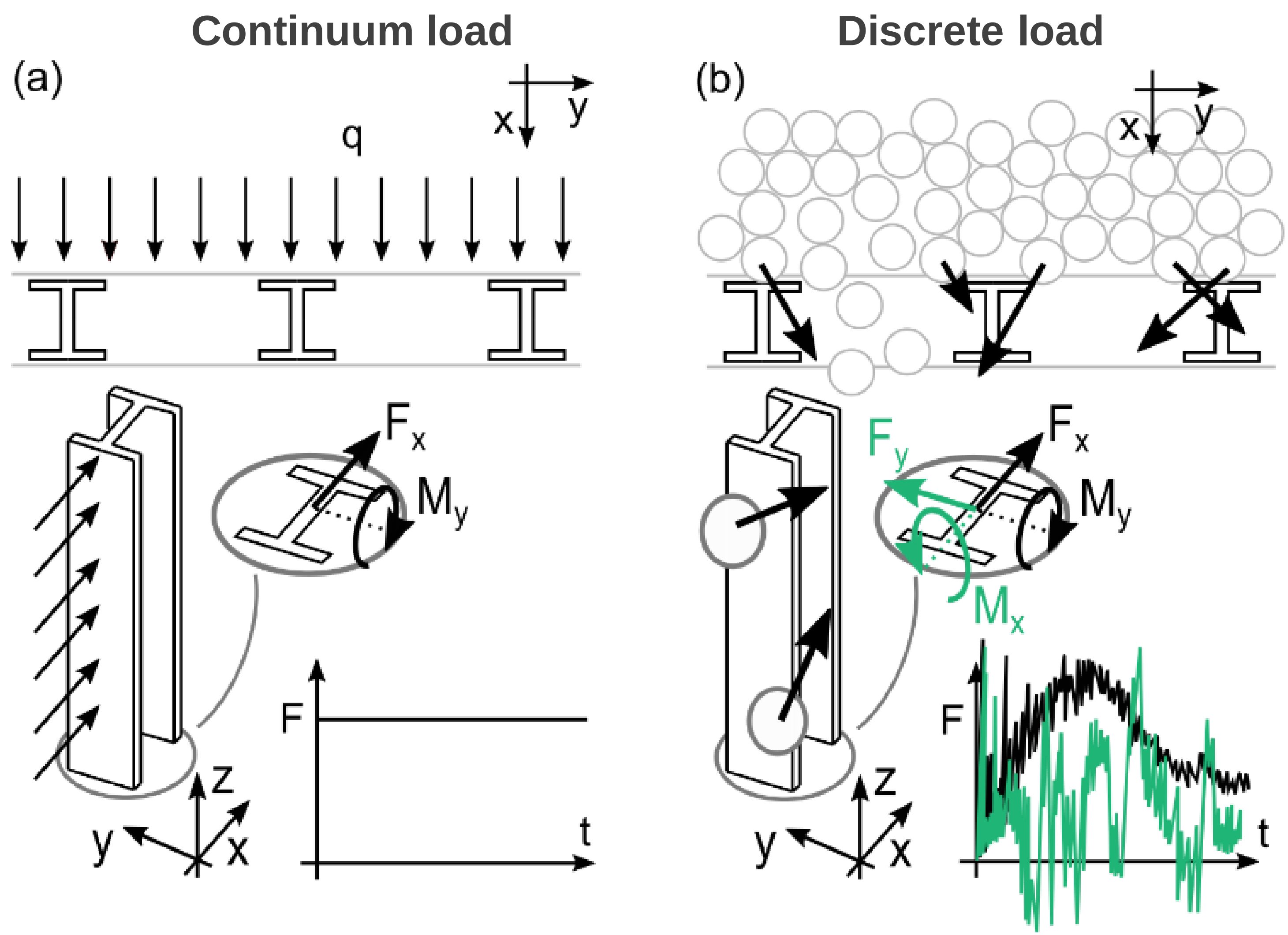
Signal interpretation



Inclined load could be due to discrete impacts, and by the formation of granular arches

Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

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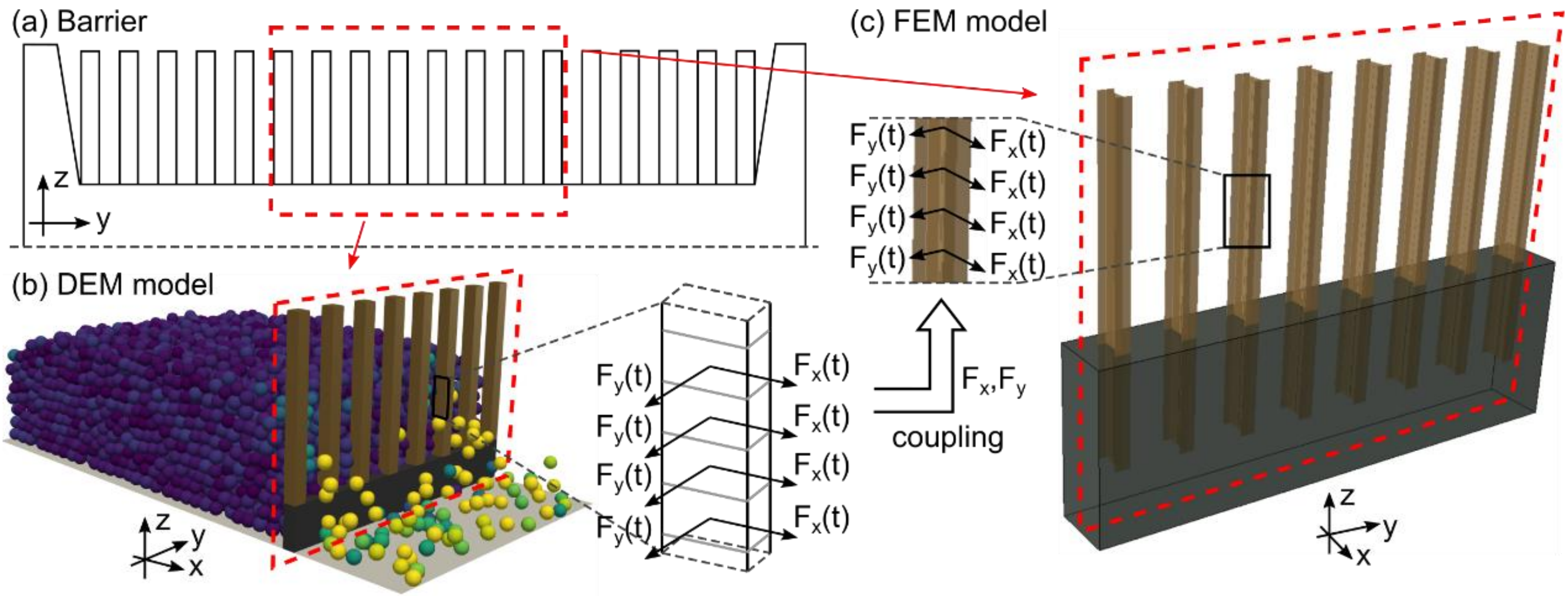
Numerical back-calculation

We reconstruct the impact on the barrier using a combined DEM-FEM approach



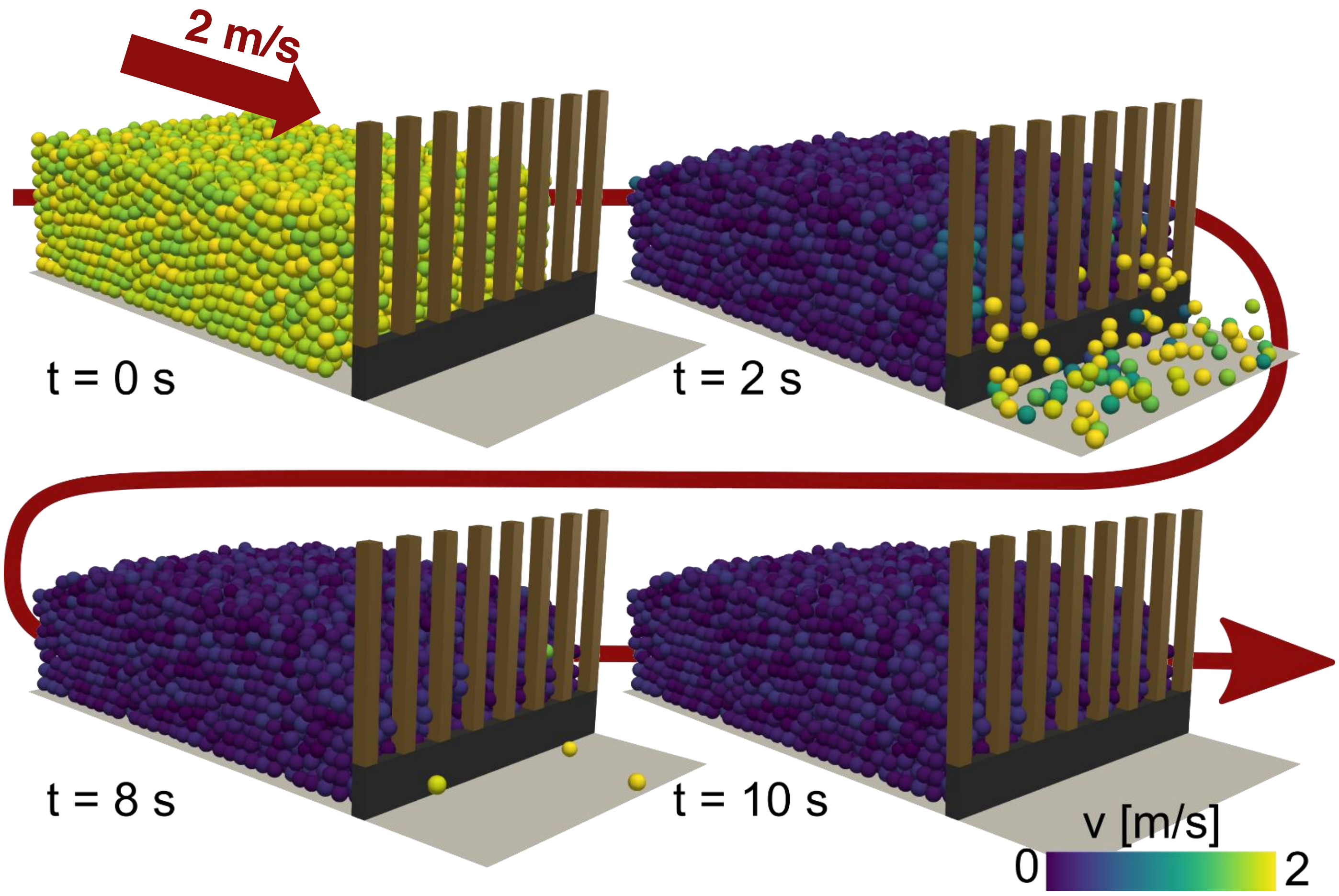
Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

B

Numerical back-calculation

The debris flow is reproduced as a dry granular flow, impacting at a given speed onto the barrier.

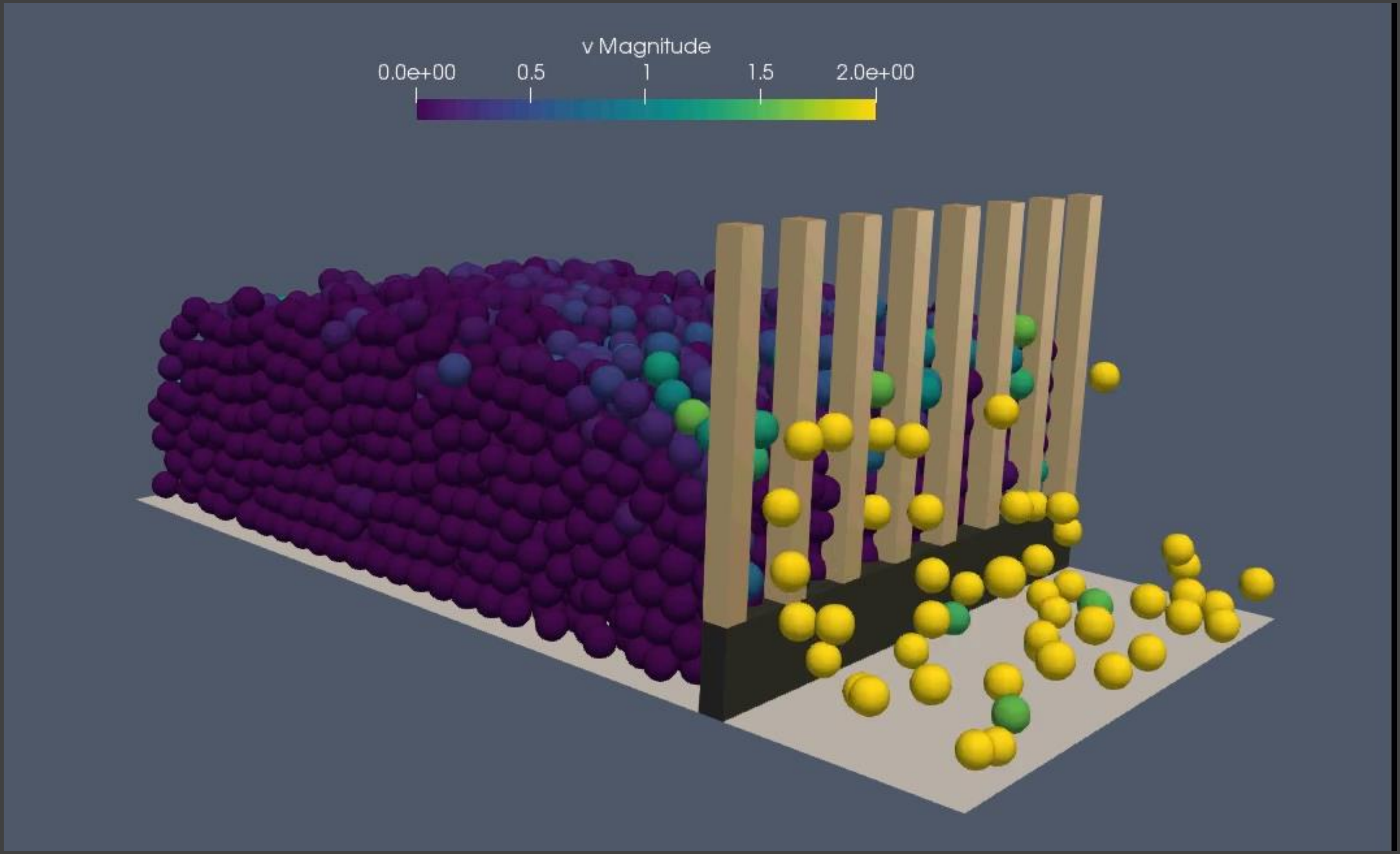
After some time, granular arches clog the barrier.



Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

B

DEM animation

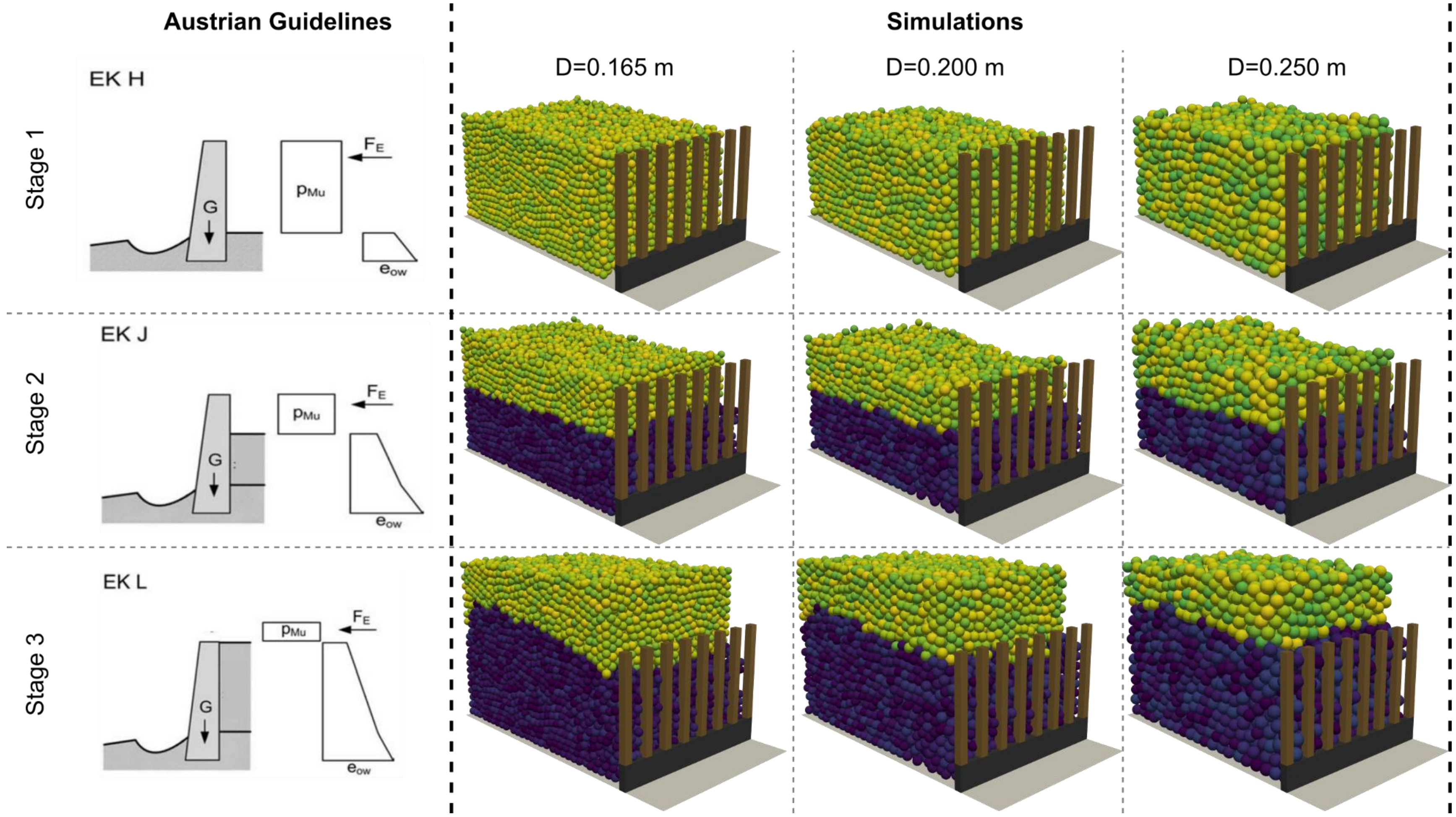


Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

B

Numerical back-calculation

Multiple combinations of surges and static deposit are tested

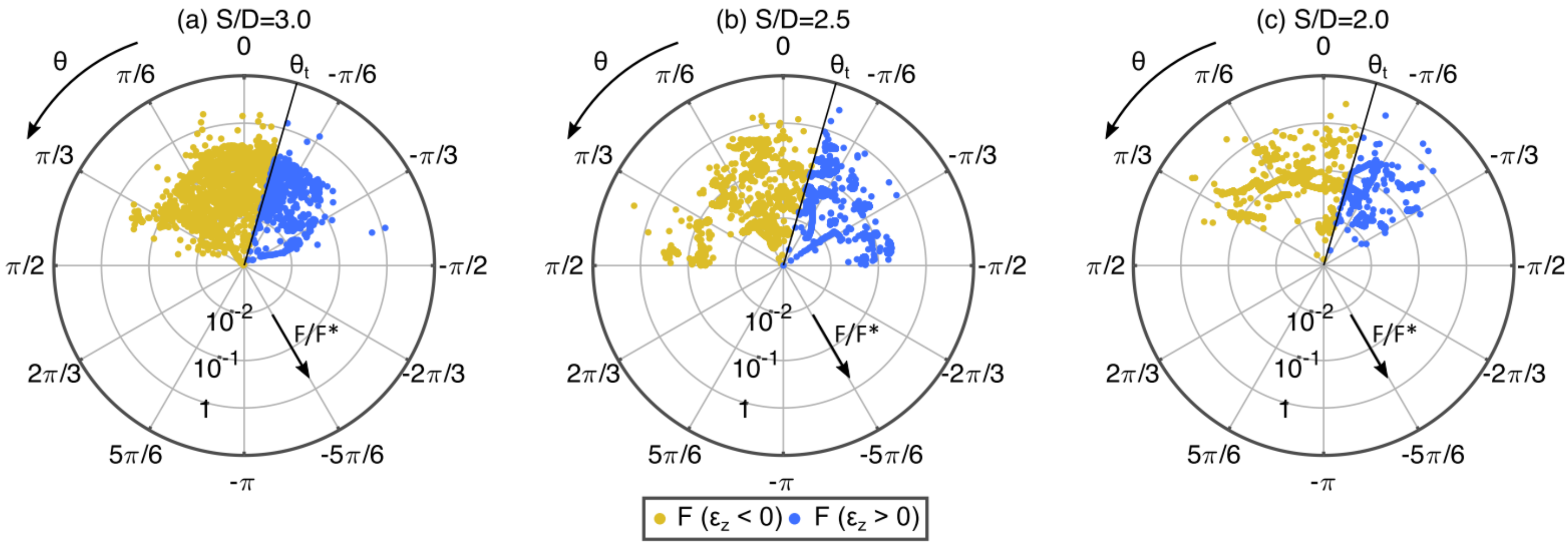


Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

B

Signal reconstruction

Single-impact time histories F



Small particles
D=0.165 (S/D=3)

Medium particles
D=0.200 (S/D=2.5)

Large particles
D=0.250 (S/D=2)

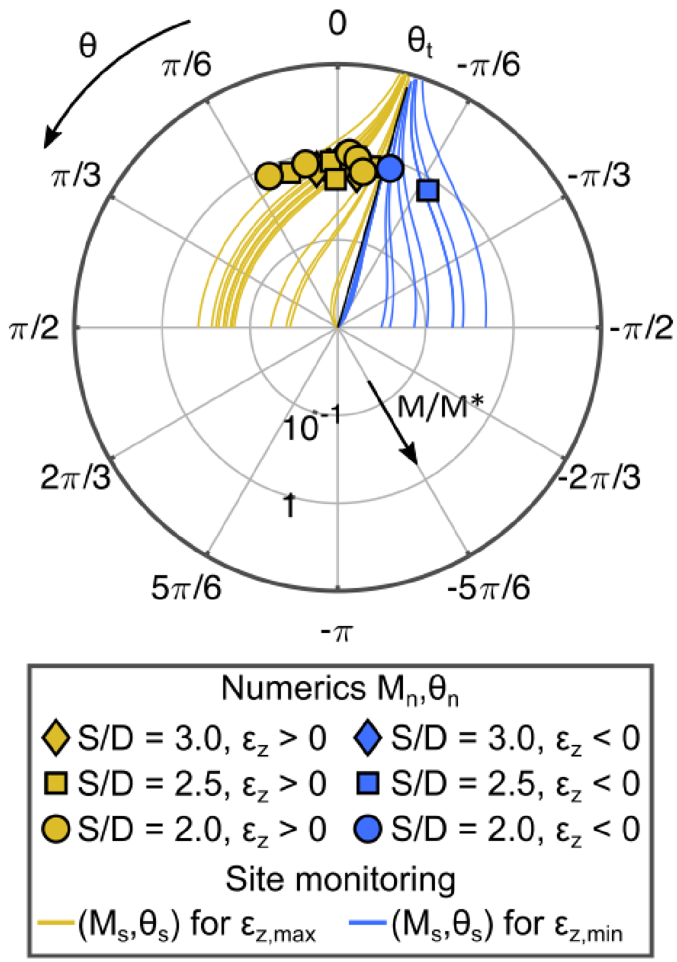
For each combination, impacts come at a wide range of directions. The colour in the figure divides the impact that compress the gauges from those that dilate them. Both behaviours are observed, as in the site monitoring.

Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

B

Signal reconstruction

Resultant moments M



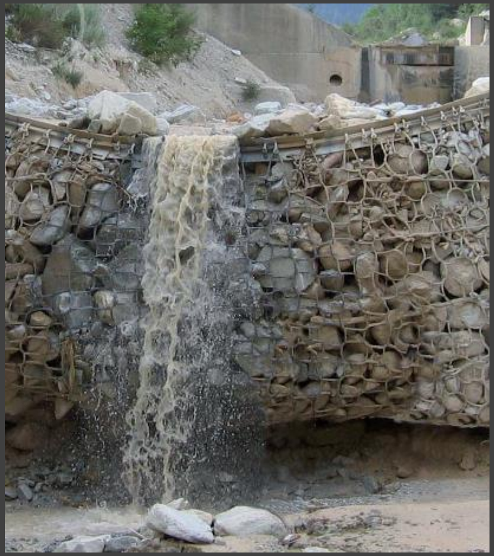
The numerical simulations yield results that are fully compatible with the site measurements, especially with respect to the application direction of the maximum forces.

Inclined forces lead to failure on the rack elements, which not designed to withstand them.

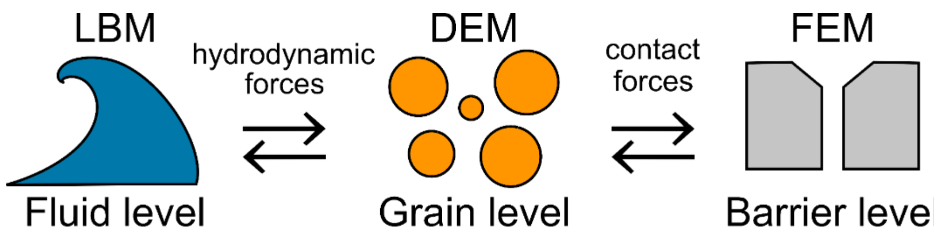
Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311.

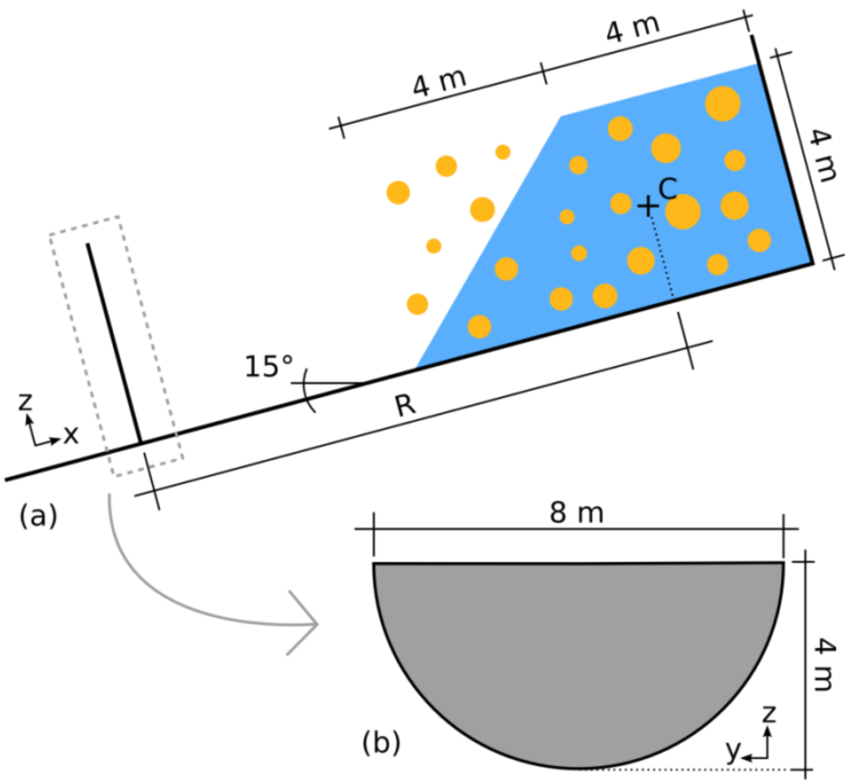
Case (C) the flexible barrier

Method: LBM-DEM-FEM



Simulation setup

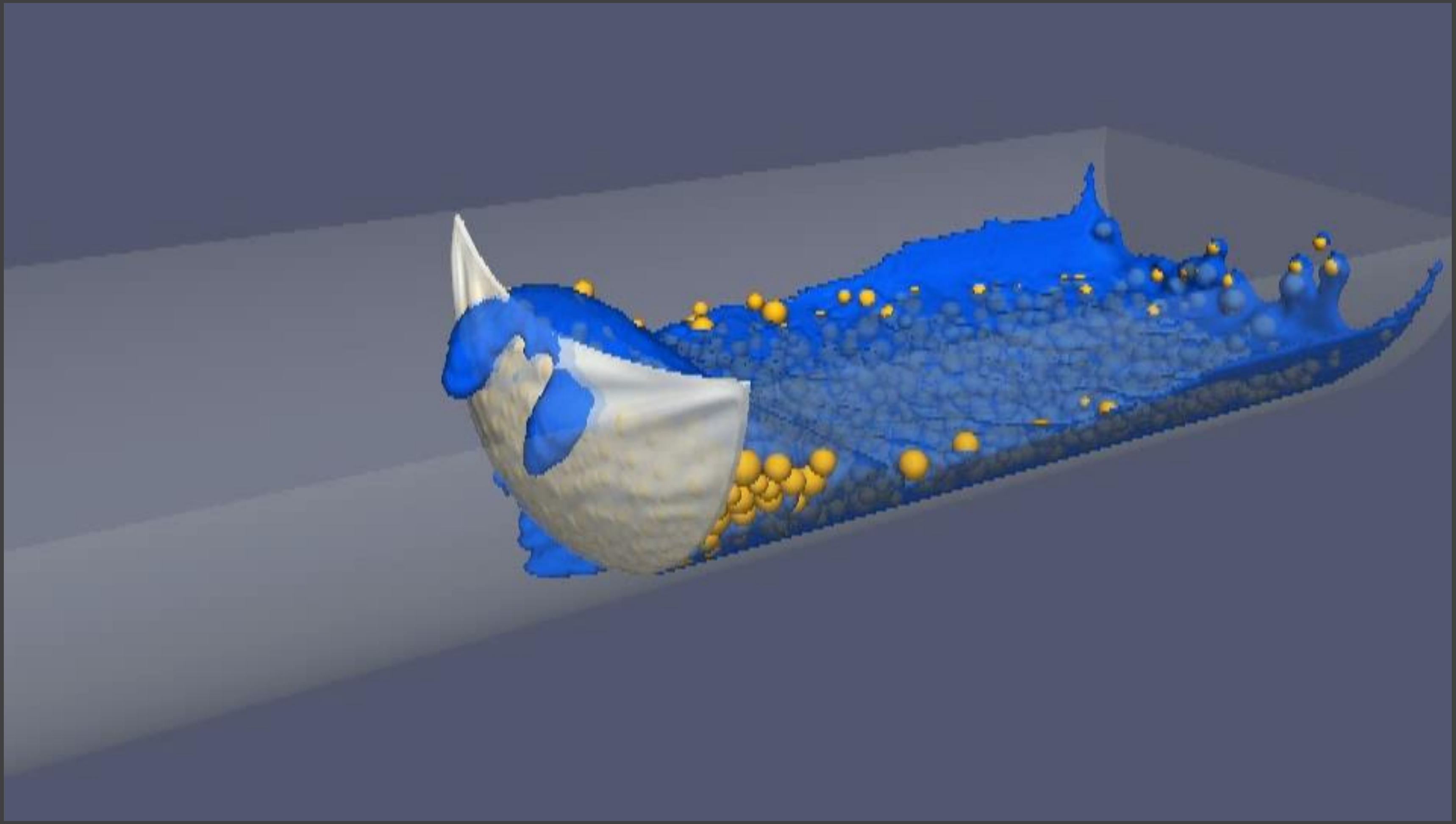




Full algorithm

- The debris flow is simulated as a multiphase medium. A Bingham fluid where coarse particles are immersed.
- The barrier is modelled as a membrane, impervious to the particles but permeable to the fluid.

Simulation setup



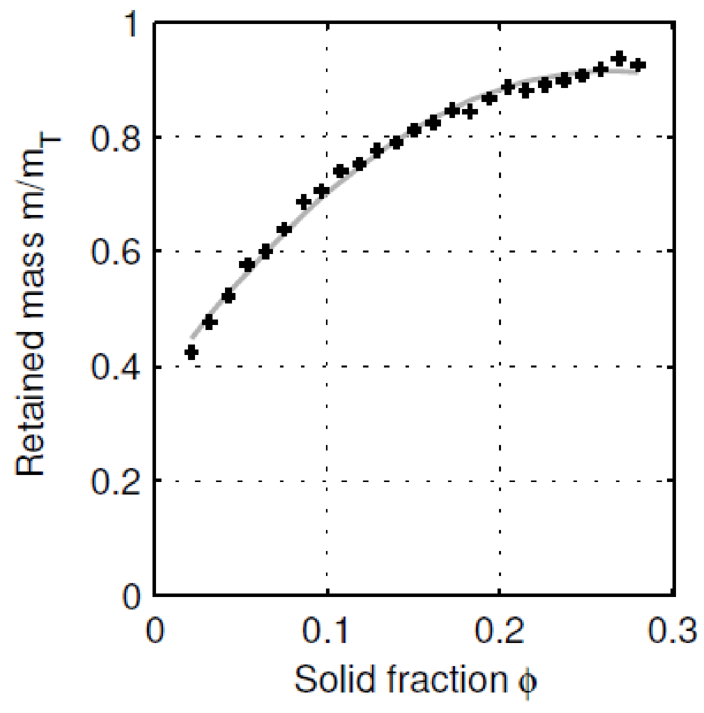
Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333.

C

Retained mass vs. grain content

Solid fraction ϕ:

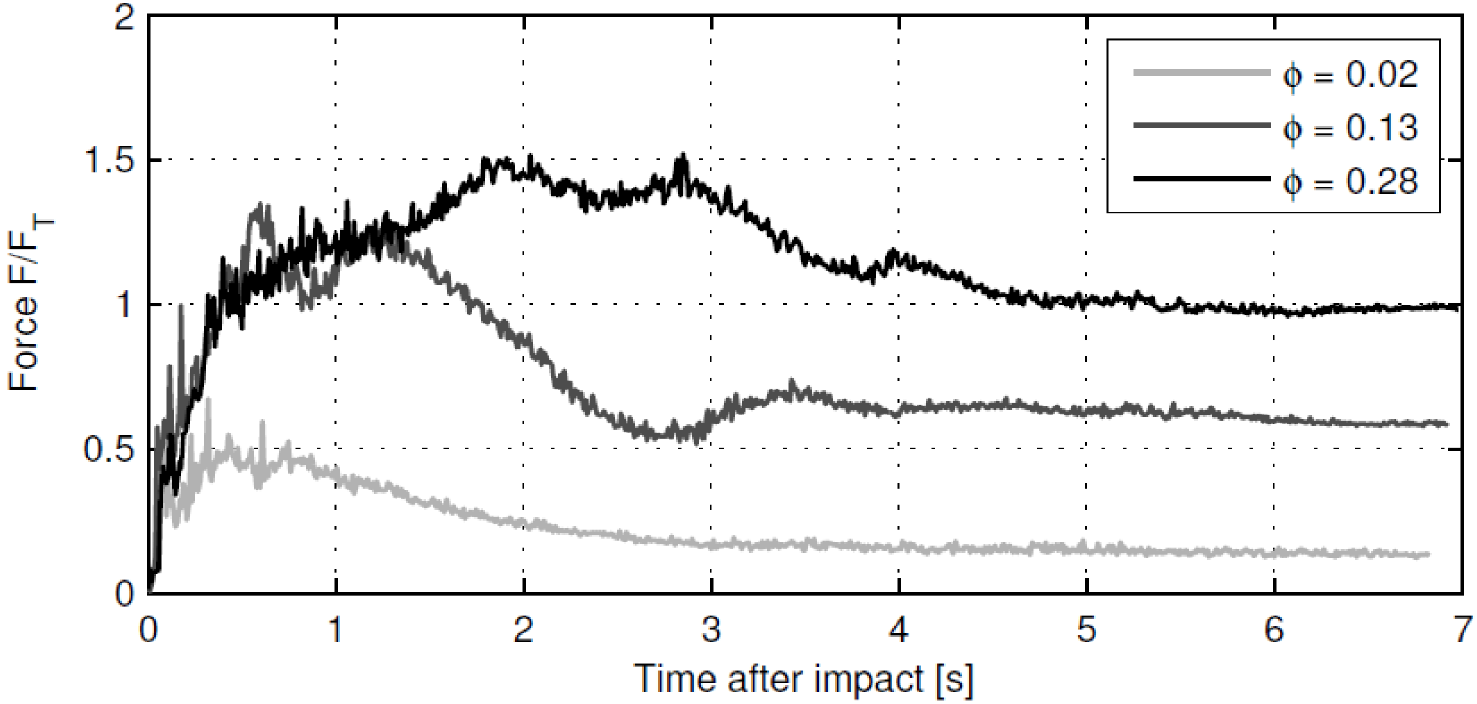
$$\phi = \frac{V_{grains}}{V_{total}}$$



The coarse-grain volume fraction is the main variable controlling the trapping efficiency of the barrier.

Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333.

Impact force evolution vs. grain content



«Static» force $F_T = \mathrm{m}_{tot} g \sin\theta$

The force is more intense if the grain content is higher

Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333.

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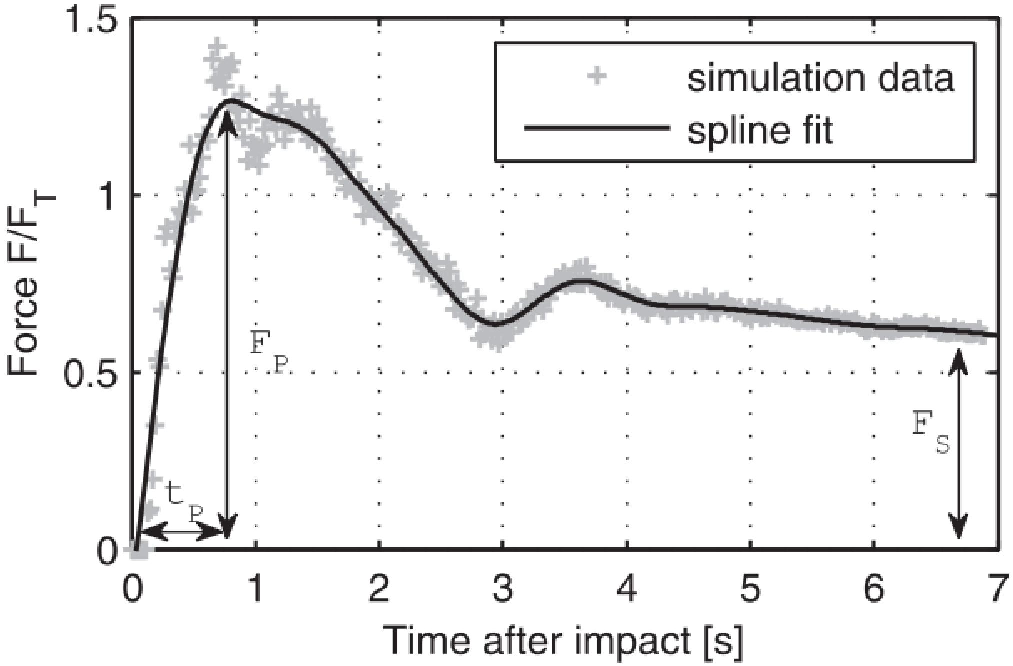

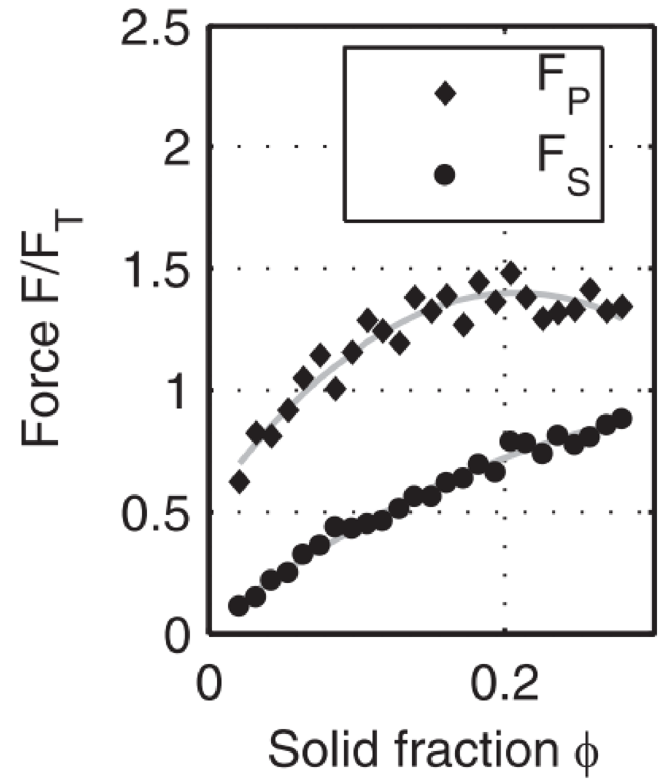

F_P = Peak force
F_S = Stationaryforce
t_P = Peak delay

Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333.

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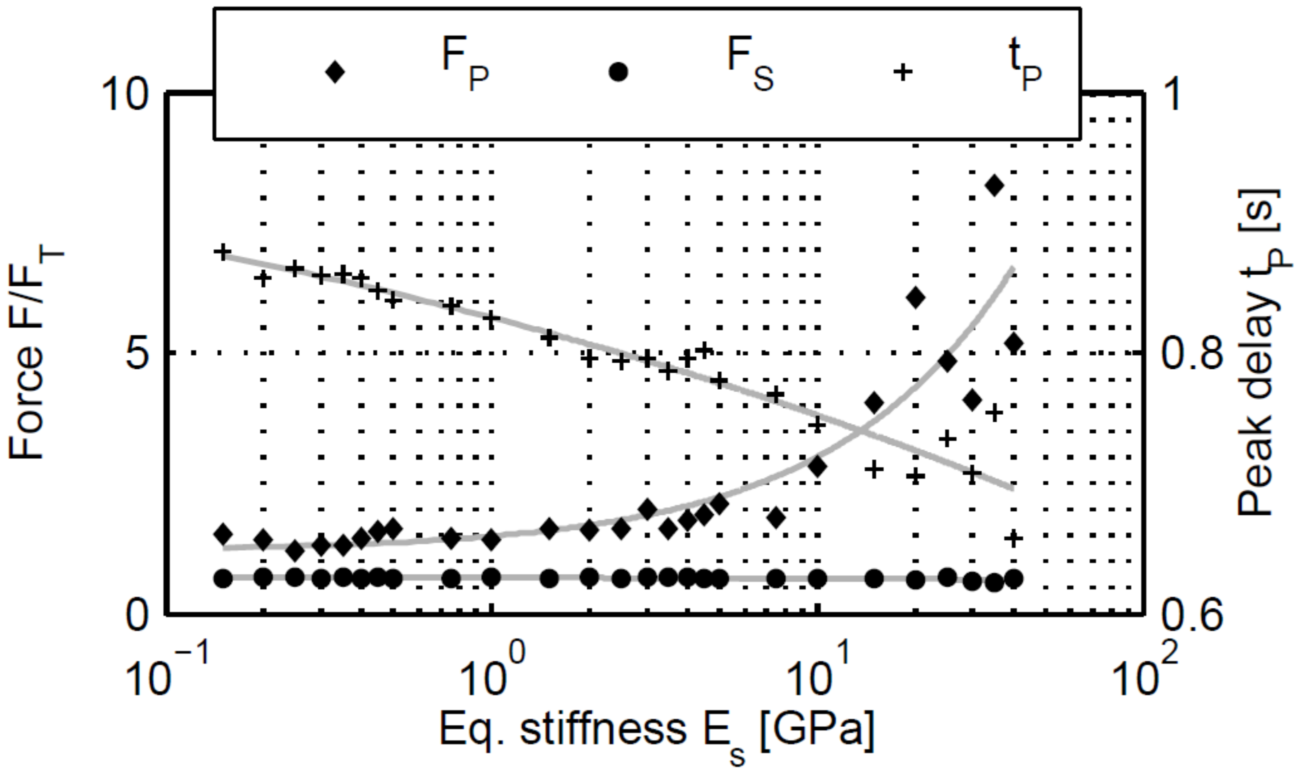
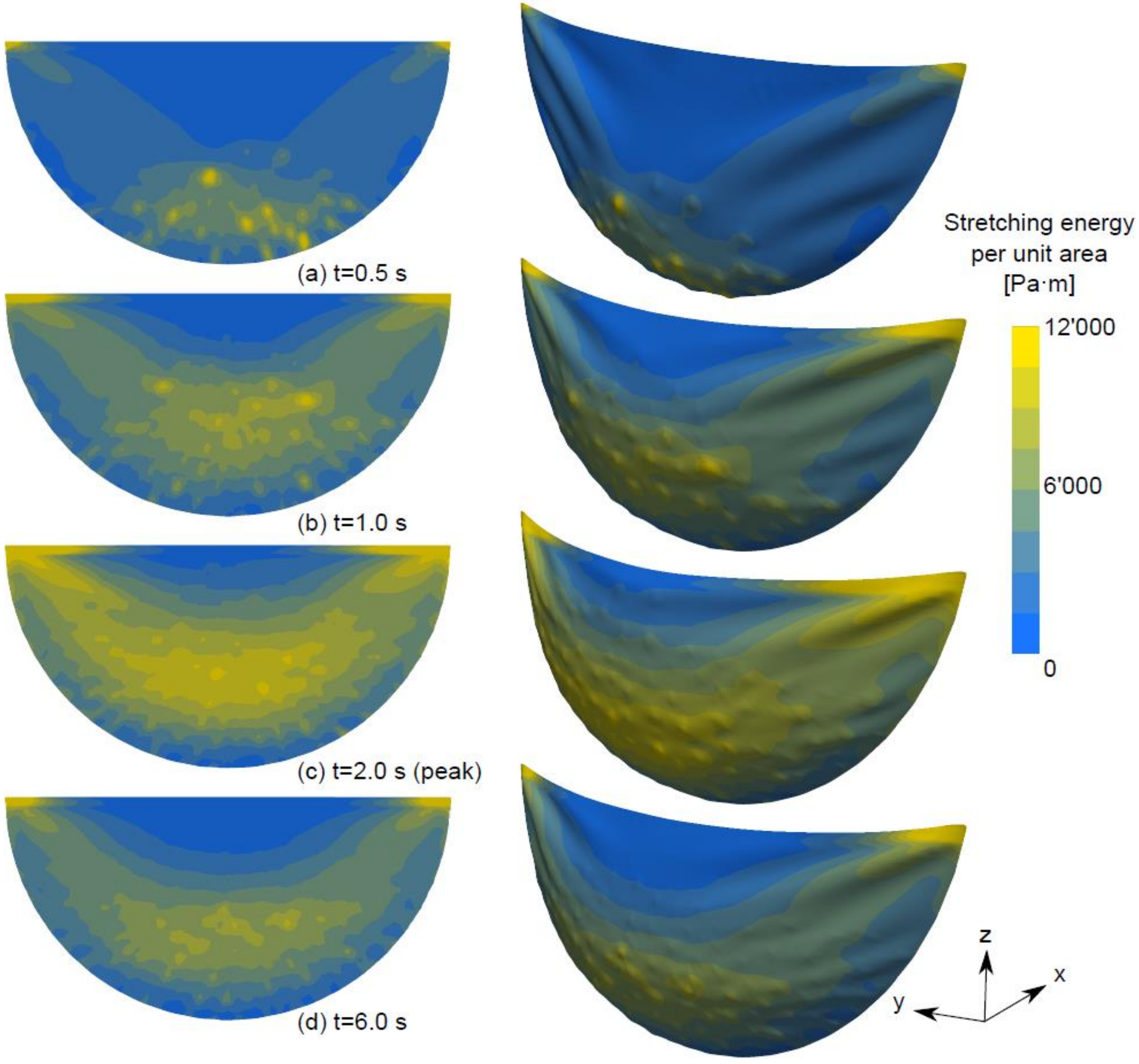
Impact force vs. barrier stiffness



A stiffer barrier is less efficient at laminating the momentum exchange, leading to higher peak forces

Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333.

Pressure distribution



A tensile stress transfer mechanism develops.

Forces concentrate on the upper anchors.

Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333.

Conclusions

The numerical framework highlights many aspects of impact that are not considered by current guidelines

1. **Direction:** Often the formation of granular arches induces forces that act in directions that are not orthogonal to the barrier surface. This might lead to early failure

2. **Concentration:** Pressure is not homogeneous. Apertures induce a concentration of impacts, leading to more intense wearing.

3. **Nonlinearity:** deformable barriers need a fully coupled interaction simulations. The force is also a function of the barrier deformability.

References

- Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2016). Particle-Fluid-Structure Interaction for Debris Flow Impact on Flexible Barriers. *Computer-Aided Civil and Infrastructure Engineering*, *31*(5), 323–333. LINK

- Leonardi, A., Goodwin, G. R., & Pirulli, M. (2019). The force exerted by granular flows on slit dams. *Acta Geotechnica*, *14*(6), 1949–1963. LINK

- Marchelli, M., Leonardi, A., Pirulli, M., & Scavia, C. (2020). On the efficiency of slit-check dams in retaining granular flows. *Geotechnique*, *70*(3), 226–237. LINK

- Leonardi, A., & Pirulli, M. (2020). Analysis of the load exerted by debris flows on filter barriers: Comparison between numerical results and field measurements. *Computer & Geotechnics*, *118*, 103311. LINK

- Leonardi, A., Pirulli, M., Barpi, F., Borri-Brunetto, M., Pallara, O., Scavia, C., & Segor, V. (2020). Impact of debris flows on filter barriers: analysis based on site monitoring data. *Under Review for Environmental and Engineering Geosciences*.