Quantification of the vulnerability of buildings exposed to the risk of debris flows and flash floods through numerical modelling (Quorum Project CAP2025 Region)

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Itasca symposium

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INSTITUT PASCAL sciences de l'ingénierie et des systèmes

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Laboratoire Magmas et Volcans

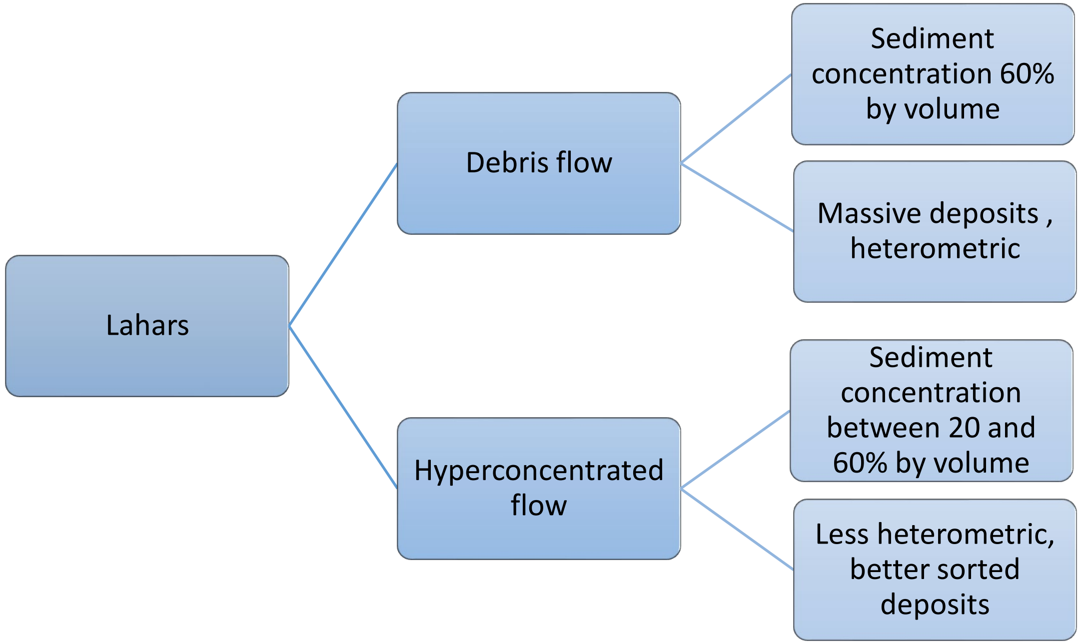
Plan

1. Background
2. Numerical approach
3. Coupling *PFC* with fluid?
4. Parametric study
5. Comparison with empirical methods
6. Conclusions and outlooks

1. Background

- As a result of global warming, mudslides and flash floods (lahars) are increasingly frequent in the latitudes and expose urbanized areas to a significant risk.

Lahar = mixture of sediments and water originating from volcanoes.



damage caused by a mudslide in Mocoa, Colombia, on 3 April 2017.

1. Background

- **Case study: Arequipa-Peru**

- **Location:** 17 km of the summit of the El Misti volcano
- **Hazard:** high precipitation + volcanic ash deposits
- **Consequences:** exposed residential areas, poor populations; infra. exposed

Very high risk for the safety of the population

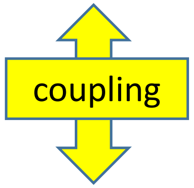
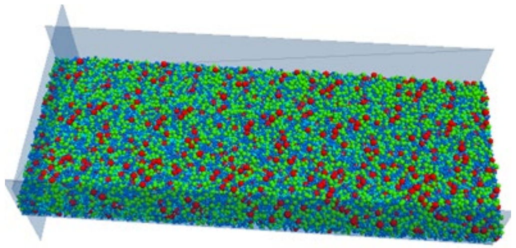
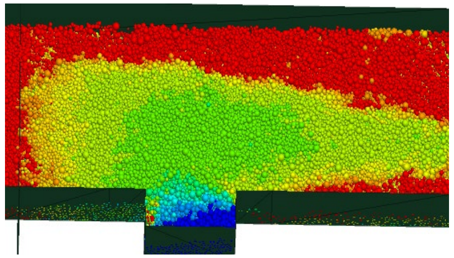
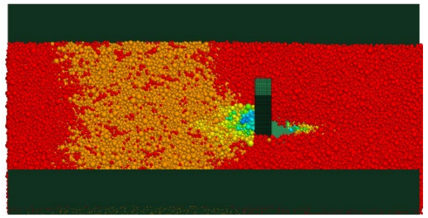
→ **It is necessary to assess and map the risk through vulnerability quantification**

Lahars in Arequipa

+

2. Numerical approach

- **General approach**

Step 1. Modeling the lahar	***Step 2. Modeling the interaction between lahars and structures***	***Step 3. Assessing the vulnerability of structures***
Blocks modeled with DEM (*PFC3D*)  Fluid modeling ⇩ 	Pressure induced by the flow on different types of obstacles  *Lahars in a canal with a recess*  *Lahars in a canal with an obstacle*	Flow vs. Structure ⇩ Stress levels calculated from the total flow pressure ⇩ Deformation/damage to quantify the vulnerability of the structure

2. Numerical approach

- **Modeling scales**

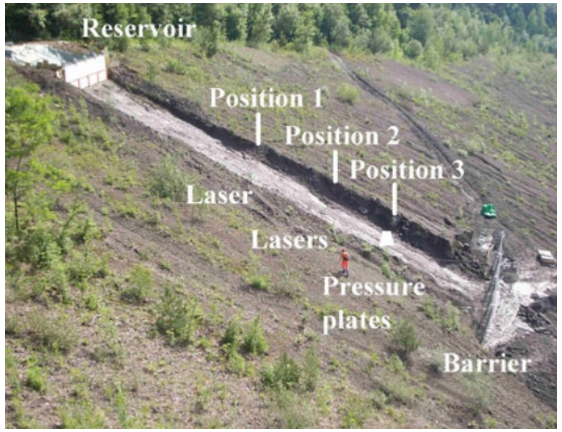
✓ **Models to obtain trajectory of the flow and global flow characteristics**

Existing models

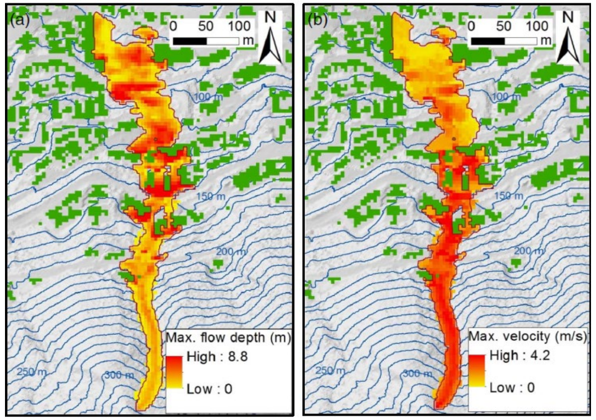
Experimental

Numerical

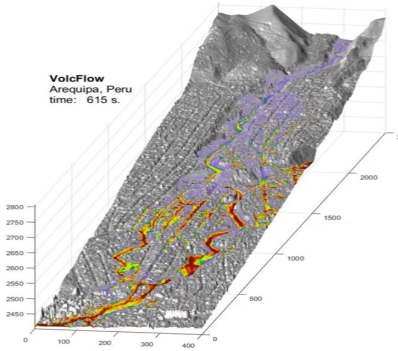
USGS debris-flow flume(Iverson 2010)



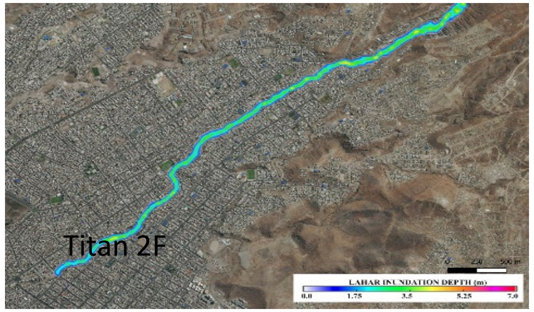
Bugnion et al .2012



Gao et al. 2018 (2D flow simulation)



Volc Flow simulation



✓ **Modeling at the scale of the structure**

Our numerical model

- Complement existing models at smaller scale
- Export suitable flow parameters to this area (h, v , $\boldsymbol{\rho}$)
- Calculate the impact of the blocks on the structures in this region

2. Numerical approach

Lahars modeling

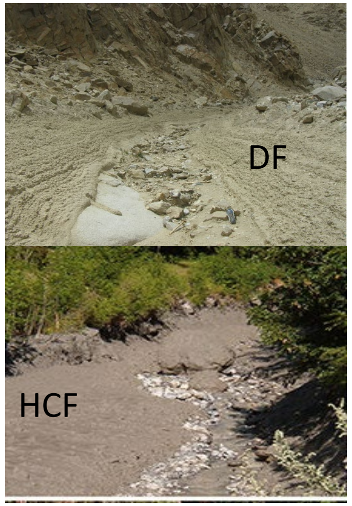
Type of flow:
- DF or HCF
- Macro

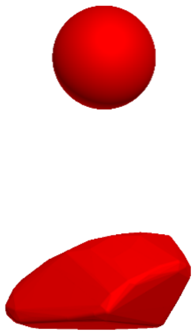
Parameters:
h, v, ρ

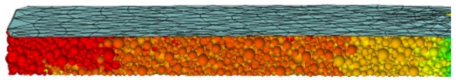
Blocks:
- Shape
- Granulo…

Fluid phase:
(water+fine)
- Coupling blocs-fluide

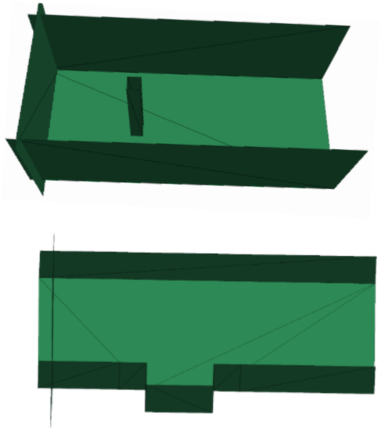
Geometry of the simulated channel:
- linear
- obstacle
- recess…







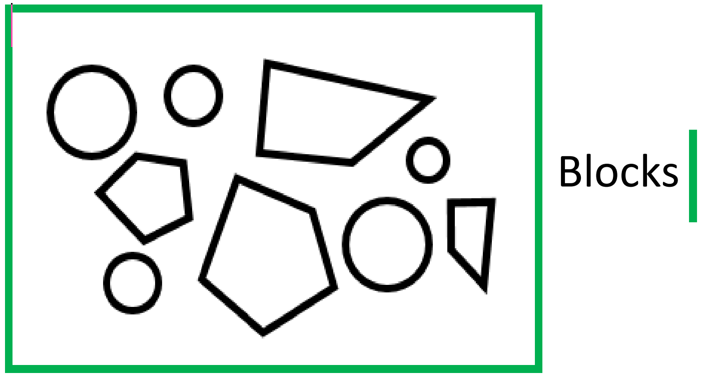
Fluid+blocks



2. Numerical approach

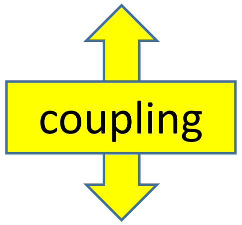
- **Problem modeling**

Solid fraction

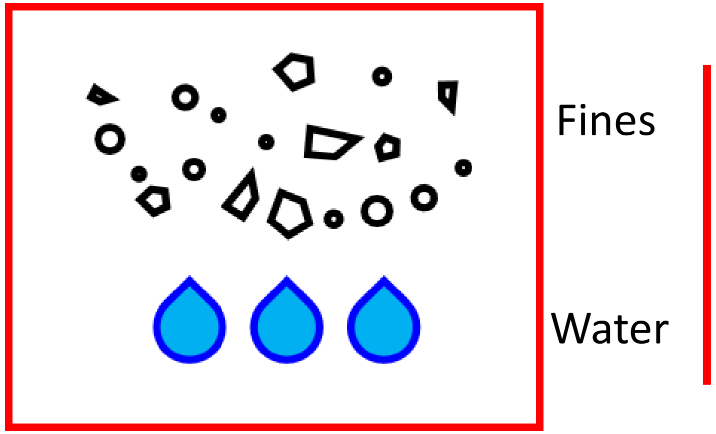


Modeled explicitly with DEM

✓ Blocks with a given size distribution



Fluid phase



Modeling of the fluid and its effects on blocks

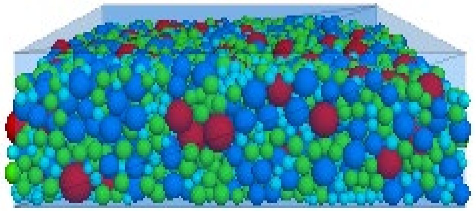
✓ Buoyancy effect

✓ Drag force

2. Numerical approach

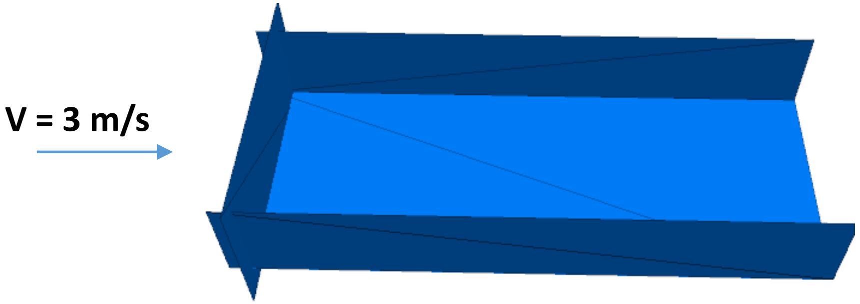
- **Model procedure**

1. Representative Elementary Volume (REV) (5 m × 10 m × 1.5 m)

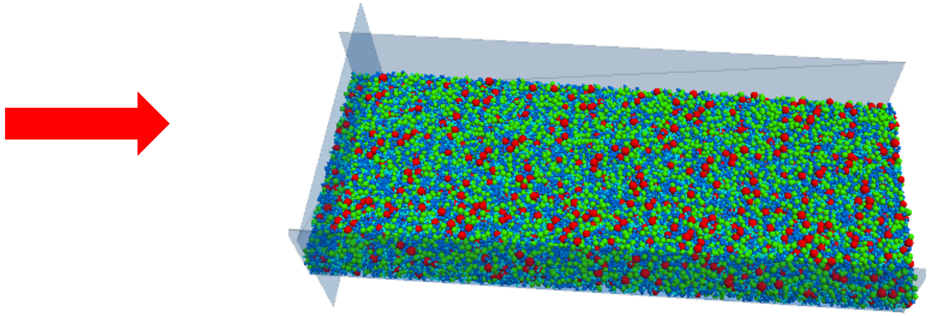


2. Generation of a rectangular channel (25 m × 10 m × 4 m)

Fluid velocity assumed to be constant and equal to 3 m/s
➔ fixed velocity for the blocks at the entrance of the channel then released



Channel flow generation



2. Numerical approach

- **Model calibration**

Blocks density (kg/m³)	Fluid density (kg/m³)	Dynamic viscosity (Pa.s)	Friction ball-ball	Friction Ball-wall	Rolling resistance
Between 2500 et 2700	Between 1000 et 2000	Between 0.03 et 0.075	Between 0.05 et 0.4	Between 0 et 1	Between 0 et 0.6

Iverson (1997)

Solid Grain Properties		
Mass density, kg/m³	ρ_s	2500–3000
Mean diameter, m	δ	10^{-5}–10
Friction angle, deg	ϕ_g	25–45
Restitution coefficient	e	0.1–0.5
Pore Fluid Properties		
Mass density, kg/m³	ρ_f	1000–1200
Viscosity, Pa s	μ	0.001–0.1
Mixture Properties		
Solid volume fraction	v_s	0.4–0.8
Fluid volume fraction	v_f	0.2–0.6
Hydraulic permeability, m²	k	10^{-13}–10^{-9}
Hydraulic conductivity, m/s	K	10^{-7}–10^{-2}
Compressive stiffness, Pa	E	10^{3}–10^{5}
Friction angle, deg	ϕ	25–45

DF characteristics searched

Solid concentration = 50 %
Apparent density = 1800 kg/m³
Flow rate = 35-40 m³/s

Property calibration

Blocks density = 2500 kg/m³
Fluid density = 1100 kg/m³
Dynamic viscosity = 0.048 Pa.s
Friction Ball-Ball = 0.4
Friction wall-ball = 0.5
Rolling resistance = 0.2

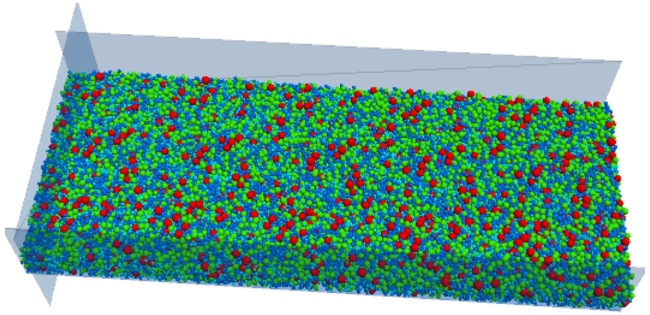
Result

Solid concentration 55 %
Apparent density 1867 kg/m³
Flow rate 38-40 m³/s

3. Coupling *PFC with fluid*?

- **Geometry of the simulated flow**

Straight rectangular channel



Constant velocity
Homogeneous and constant flow field

Complex channel

Choosing a code to model the fluid phase

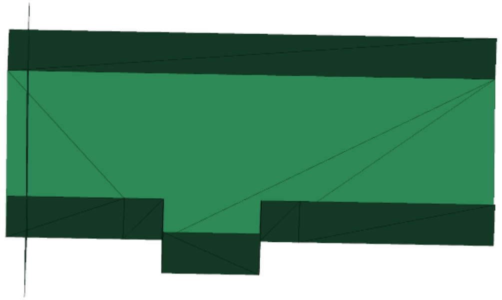
Solution 1: *Darcy (with FLAC3D)*

Solution 2: *Navier stokes FE (Telemac3D)*

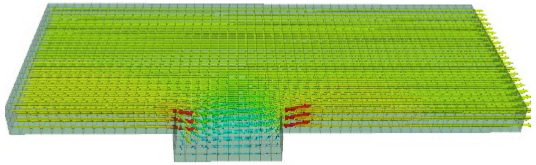
3. Coupling *PFC with fluid*?

- **Solution 1 : coupling with a *Darcy flow***

Channel geometry



***FLAC3D* velocity field**

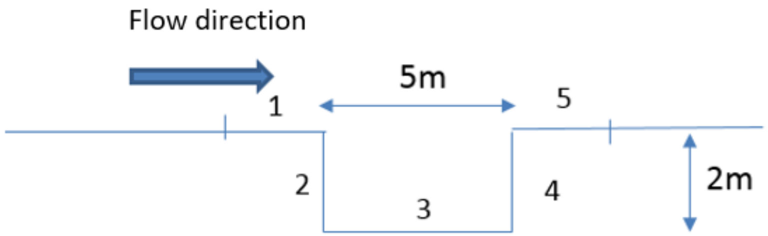


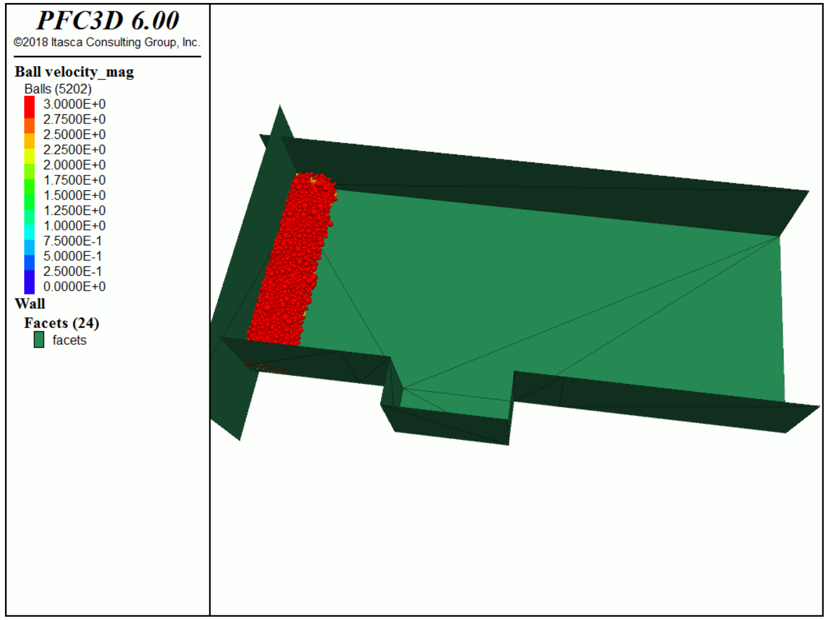
Using *FLAC3D* flow model (*incompressible flow in a porous media)*

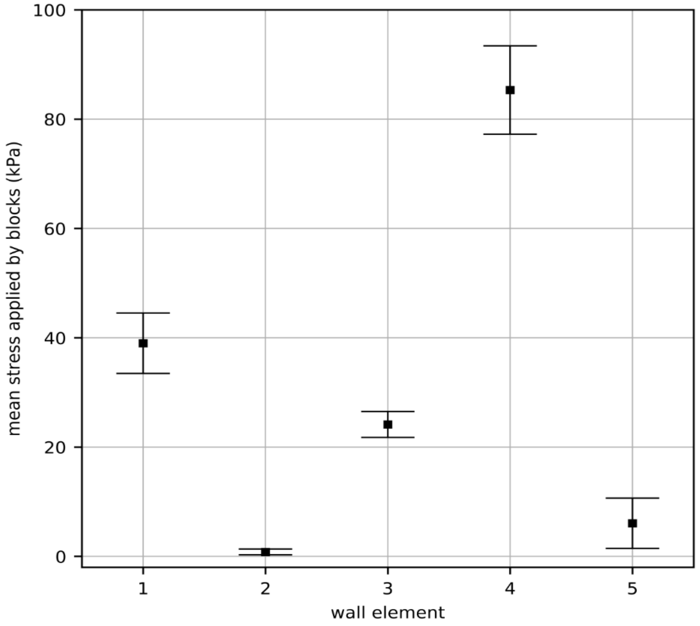
Obtaining the norm and orientation of the fluid velocity vectors in each cell of the *FLAC3D* mesh

Applying the velocity fields to the particles located in each cell (drag)

Force history







3. Coupling *PFC with fluid*?

- **Why *Darcy?***

✓ Easy to couple *FLAC3D* with *PFC3D*
✓ Two ways coupling
✓ Access to fluid velocity vectors in each cell of the channel

- ***Darcy* Limitations**

✓ Difficult to model the free surface
✓ No turbulences
✓ Difficulties to obtain realistic velocity vectors

Solution 2 : Simulate fluid calculation with Navier stokes FE (*Telemac3D*)

- **Objectif**

✓ Obtaining a velocity field of a free surface flow with defined boundary conditions
✓ Simple turbulence model
✓ Method for resolving velocity vectors and fluid depth

- **Limitations**

✓ Simulate newtonian fluid (water)
✓ One way coupling

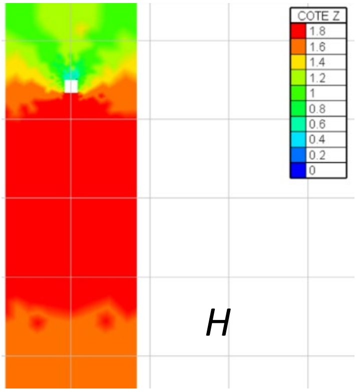
3. Coupling *PFC with fluid*?

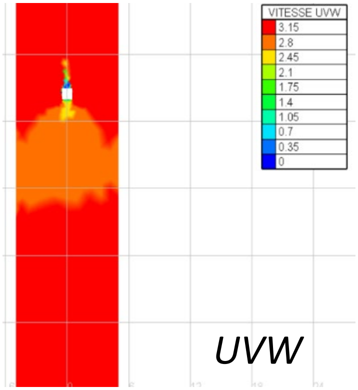
- **Solution 2 : *Telemac3D***

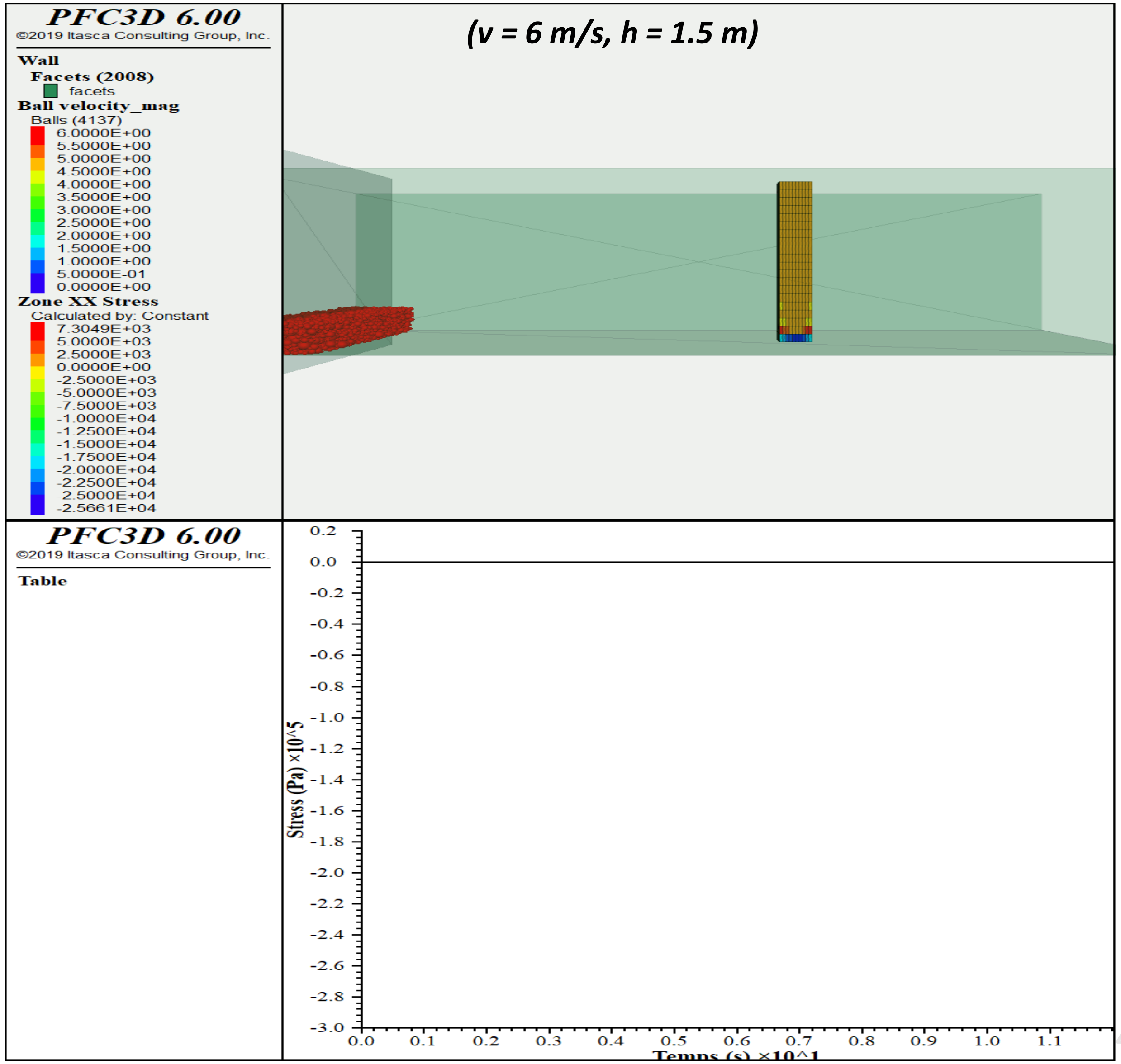
Fluid calculation *Telemac 3D:*

- Obtain a flow whose average velocity and fluid height is fixed at a certain distance from the obstacle .
- Calibration of the BC and the slope to obtain the desired characteristics of the flow.

Coupling steps:
1. Fluid calculation in Telemac3D to obtain the velocity vectors and the free surface height
2. Analysis and verification of results
3. Exporting the CFD file to *PFC3D*







The " CFD " file contains (X , Y, Z, Vx, Vy, Vz, Hfluid)

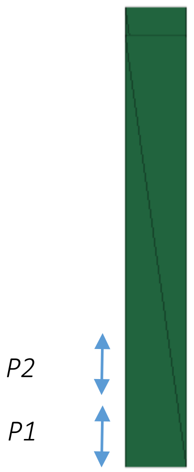
4. Parametric study

- **Code Telemac3D / influence of h , v and ρ s**

Case	Flow height h	Nb Froude
ref case	1.5 m	0,79
Case 2	3 m	0,55
Case 3	4 m	0,5

Case	Velocity v	Nd Froude
ref case	3 m/s	0,79
Case 2	4,5 m/s	1,18
Case 3	6 m/s	1,56

Case	Blocks density ρs
ref case	2500 kg/m^3
Case 2	2700 kg/m^3
Case 3	3000 kg/m^3



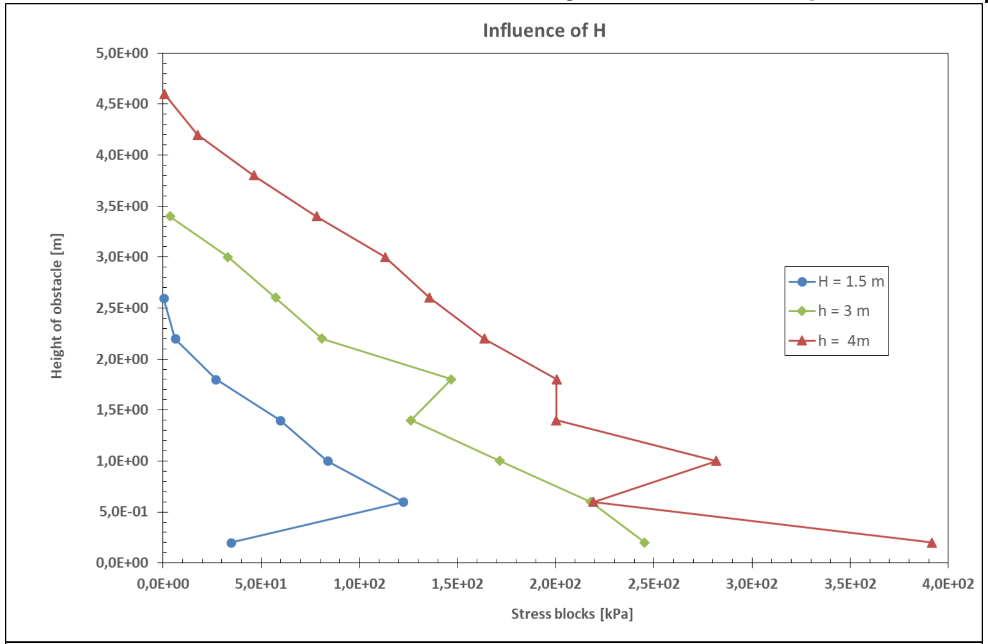
Obstacle 1x1x8

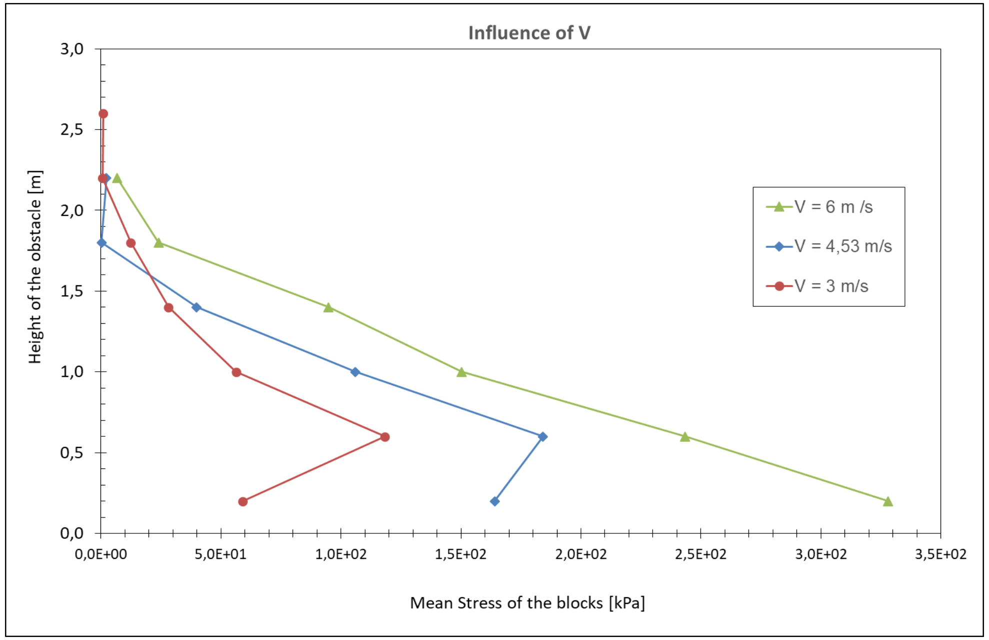
TABLE 3. Typical Values of Basic Physical Properties of Debris Flow Mixtures

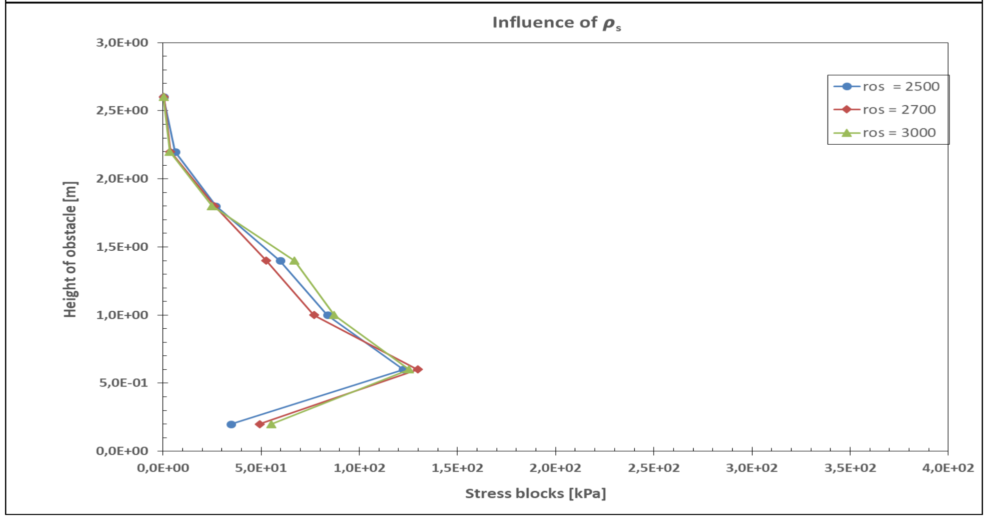
Property and Unit	Symbol	Typical Values
Solid Grain Properties		
Mass density, kg/m^3	ρ_s	2500–3000
Mean diameter, m	δ	10^{-5}–10
Friction angle, deg	ϕ_g	25–45
Restitution coefficient	e	0.1–0.5
Pore Fluid Properties		
Mass density, kg/m^3	ρ_f	1000–1200
Viscosity, Pa s	μ	0.001–0.1
Mixture Properties		
Solid volume fraction	v_s	0.4–0.8
Fluid volume fraction	v_f	0.2–0.6
Hydraulic permeability, m^2	k	10^{-13}–10^{-9}
Hydraulic conductivity, m/s	K	10^{-7}–10^{-2}
Compressive stiffness, Pa	E	10^3–10^5
Friction angle, deg	ϕ	25–45

4. Parametric study

- **Influence of the flow parameters (h, v and ρs) on the impact pressure of blocks on a structure**







- ✓ When the flow height is higher, it is noticed that the pressure of the blocks on the obstacle is higher
- ✓ The impact of the blocks on the obstacle is much greater with a higher flow velocity
- ✓ Density influences the result of the impact but not strong enough as the two other parameters h and v

5. Comparison with empirical models

- **References**

Zeng et al . 2015 : Models of impact force of large boulders mixed in debris flow

Models	Description	Author
$F=48{,}200\cdot v^{1.2}\cdot R^2\cdot g$	Derived from elastic collision theory modified by Mt. Yakedake's field investigation data. F impact force (N), v velocity (m/s), R diameter of particles (m), g the acceleration of gravity (m/s^2)	Mizuyama (1979)
$F=50{,}000\cdot v^{1.2}\cdot R^2\cdot g$	Derived from elastic collision theory modified by Myoukou field investigation data	Yamaguchi (1985)
$F=30{,}800\cdot v^{1.2}\cdot R^2\cdot g$	Derived from elastic collision theory modified by miniaturized test	Huang et al. (2007)
$F = c\left[\frac{Mv^2(n+1)}{2c}\right]^{n/n+1}$	Derived from modified Hertz contact theory considering elastic to plastic deformation of barriers. M boulder mass (kg); coefficients c and n describe the character of barrier material	He (2010)
$F = \sqrt{Mv^2k}$	Equating the kinetic energy of the boulder with work expanded in bending deflection of beam. K is a stiffness factor of structure	Hungr et al. (1984)
The cantilever beam: $F = \sqrt{\frac{3EJV^2G'}{gL^3}}$ The simply supported beam: $F = \sqrt{\frac{48EJV^2G'}{gL^3}}$	Derived from material mechanics. E Young's modulus (N/m^2), J inertia moment of transverse square to neutral axis (m^4), G' the weight of the boulder which is submerged in the debris flow (N), L the length of the member	Zhang (1993)

Hubl et al.2010 :

$$p_{\max} = 5 \cdot \rho_{Mu} \cdot v^{0.8} \cdot (g \cdot h_{Mu})^{0.6}$$

Table 1. Debris flow properties estimated on field events based on Costa [6] and computed impact forces, empirical factors k and a, and the Froude-number

Torrent	h_{MU} [m]	ρ_{Mu} [kg/m^3]	v [m/s]	p_{max} in MN/m^2	k**	a**	Fr**
Rio Reventado	8-12	1130-1980	2.9-10	0.7	4.67	18.67	0.50
Hunshui Gully	3-5	2000-2300	10-12	0.7	8.33	2.31	1.90
Bullock Greek	1.0	1950-2130	2.5-5.0	0.13	6.50	4.06	1.26
Pine Creek	0.1-1.5	1970-2030	10-31.1	0.3	21.43	0.38	7.56
Wrightwood Canyon (1969)	1.0	1620-2130	0.6-3.8	0.07	3.68	4.09	0.95
Wrightwood Canyon (1941)	1.2	2400	1.2-4.4	0.15	5.21	6.94	0.87
Lesser Almatinka	2.0-10.4	2000	4.3-11.1	0.6	4.29	6.12	0.84
Nojiri River	2.3-2.4	1810-1950	12.7-13.0	0.44	10.07	1.37	2.71

* Mean values and based on the Hübl & Holzinger Formula
** Mean values

Hong et al. 2014 :Statistics of the maximum impact pressure and total discharge from 1960 to 2000 in Jiangja Ravine, China

Parameter	Value			
	Maximum impact pressure P_{max} (kPa)		Total discharge Q_{Total} (m^3)	
	Surge flow	Continuous flow	Surge flow	Continuous flow
Mean	221	114	240,447	161,169
Standard deviation (SD)	102	96	248,490	281,331
Coefficient of variation	0.5	0.8	1.0	1.7
Maximum	744	434	1,260,549	1,751,537
Minimum	31	14	166	269
Mean, SD of Lognormal distribution	5.3, 0.4	4.5, 0.7	12.0, 0.9	11.3, 1.2
α, β for Weibull distribution*	2.3, 249.4	1.2, 120	1.0, 237,000	0.6, 107,918
α, β for Gamma distribution*	4.7, 46.8	1.4, 81.5	1.0, 256,803	0.3, 491,083

*α = shape parameter; β = scale parameter.

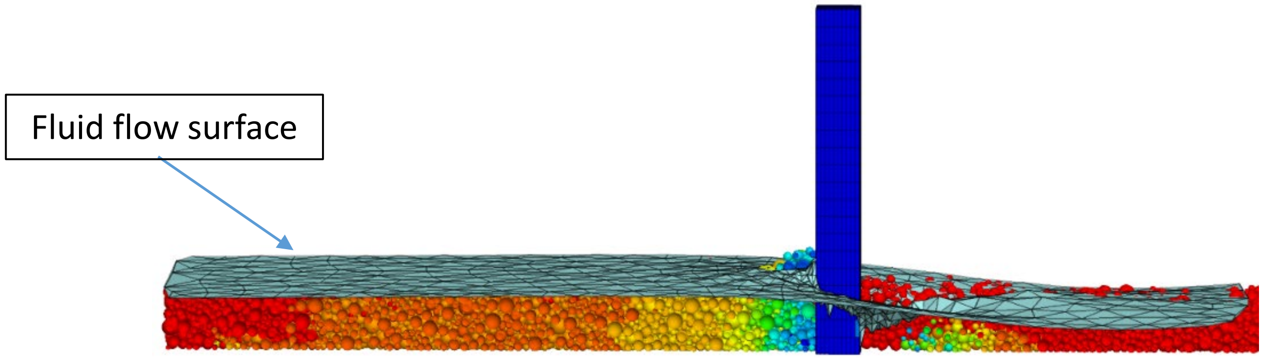
Hu et al.2011 : hydrodynamic models , p is the impact pressure

$$P=k\rho v \text{ or } P= k\rho v^2\cos^2\theta$$

$$p = c_m\,(0.5\rho g h + \rho V^2)$$

5. Comparison with empirical models

- **Model analysis - Reference case /Telemac3D**



✓ **Numerical model: h fluide ≈ h blocs**

Max blocks pressure P1 = 122,31 kPa
Fluid pressure P2 = 17,6 kPa → **P total = P1+P2 = 140 kPa**

✓ **Analytical model (Hubl et al. 2010)**

$$p_{max} = 5 \cdot \rho_{Mu} \cdot v^{0.8} \cdot (g \cdot h_{Mu})^{0.6}$$ → **P max = 155 kPa**

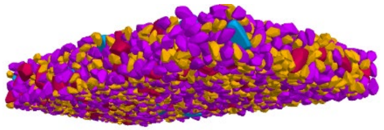
6. Conclusions and outlooks

Conclusions

- ✓ Make a flow model able to reproduce desired macro characteristics
- ✓ Use a simplified method to model the fluid with the aim of obtaining a fluid flow field around the obstacle
- ✓ Measuring the forces induced by the blocks on the structures
- ✓ Comparison of effort results with existing analytical models

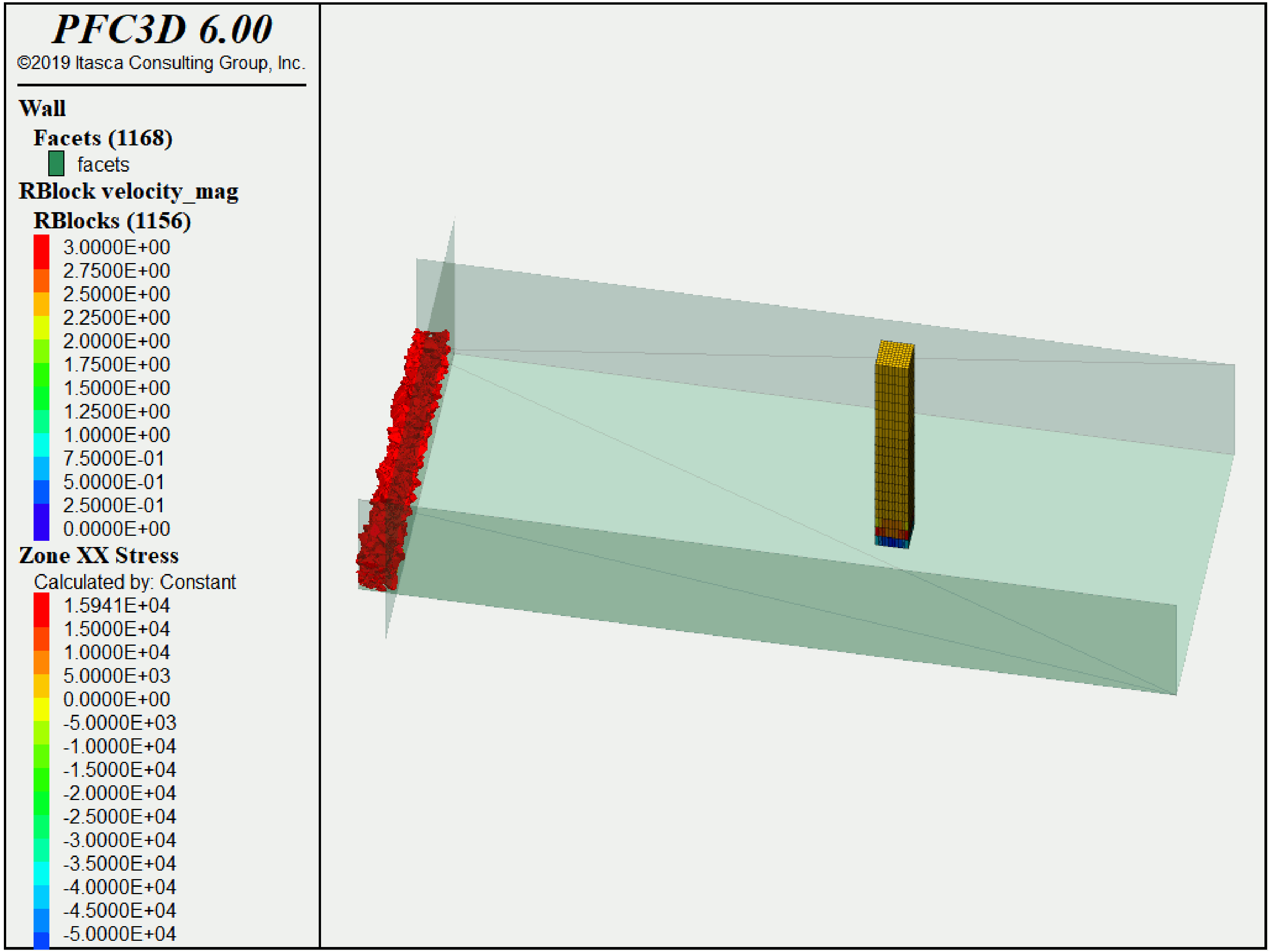
Outlooks

- ✓ Effect of other parameters remains to be identified e.g.: blocks size and shape, dynamic viscosity , orientation and position of obstacles..



- ✓ Use efforts generated by debris flows (blocks + fluid) to quantify the vulnerability of structures
- ✓ Analyze the damage from the flow intensity, the impact pressure on the structures by bibliography.

6. Conclusions and outlooks



Thank you for your attention

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Thouret, J. C., Ettinger, S., Guitton, M., Santoni, O., Magill, C., Martelli, K., &Arguedas, A. (2014). Assessing physical vulnerability in large cities exposed to flash floods and debris flows: the case of Arequipa (Peru). Natural Hazards, 73(3), 1771-1815.

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