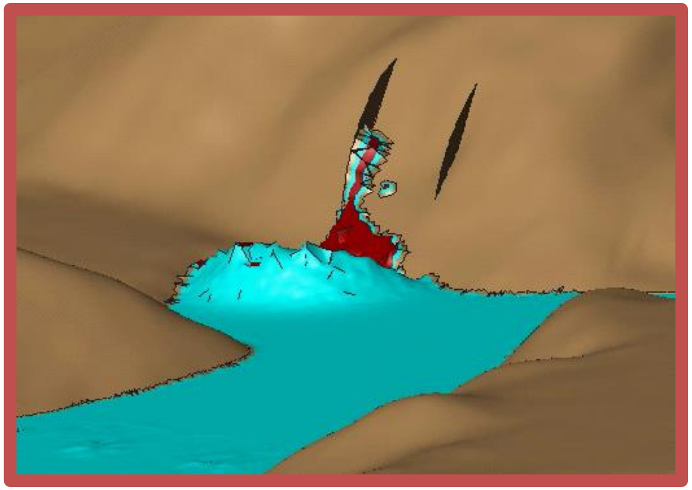
Numerical modelling of landslides in reservoirs using the Particle Finite Element Method and a non Newtonian Bingham model

J. Irazábal*, F. Salazar*, M.A. Celigueta*, A. Larese* and E. Oñate*

*Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE)

OUTLINE



- Landslides Overview
- PFEM Overview
- Constitutive Model
- 2D Validation
- 3D Lituya Bay Landslide Simulation
- Conclusions
- Further work

LANDSLIDES OVERVIEW

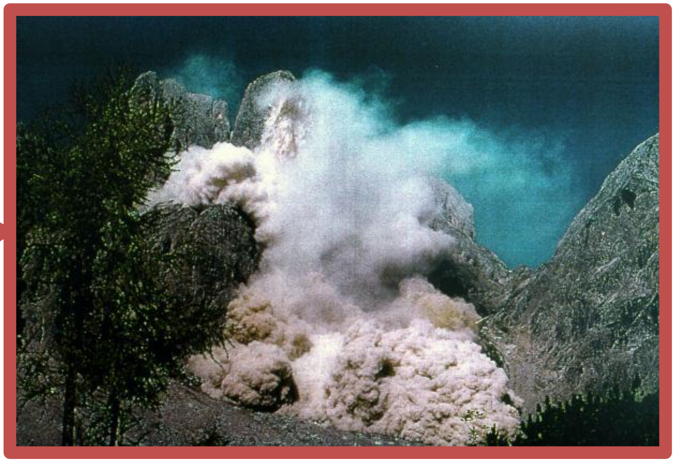
- **Why are landslides important?**
  - **Third most dangerous natural risk**
  - **Special interest of landslides in reservoirs**
- **To many classifications**
- **Rapid landslides**
  - **Debris flows and mudflows**
  - **Granular avalanches**
  - **Sliding flows**

LANDSLIDES OVERVIEW

Mudflow

Sliding flow

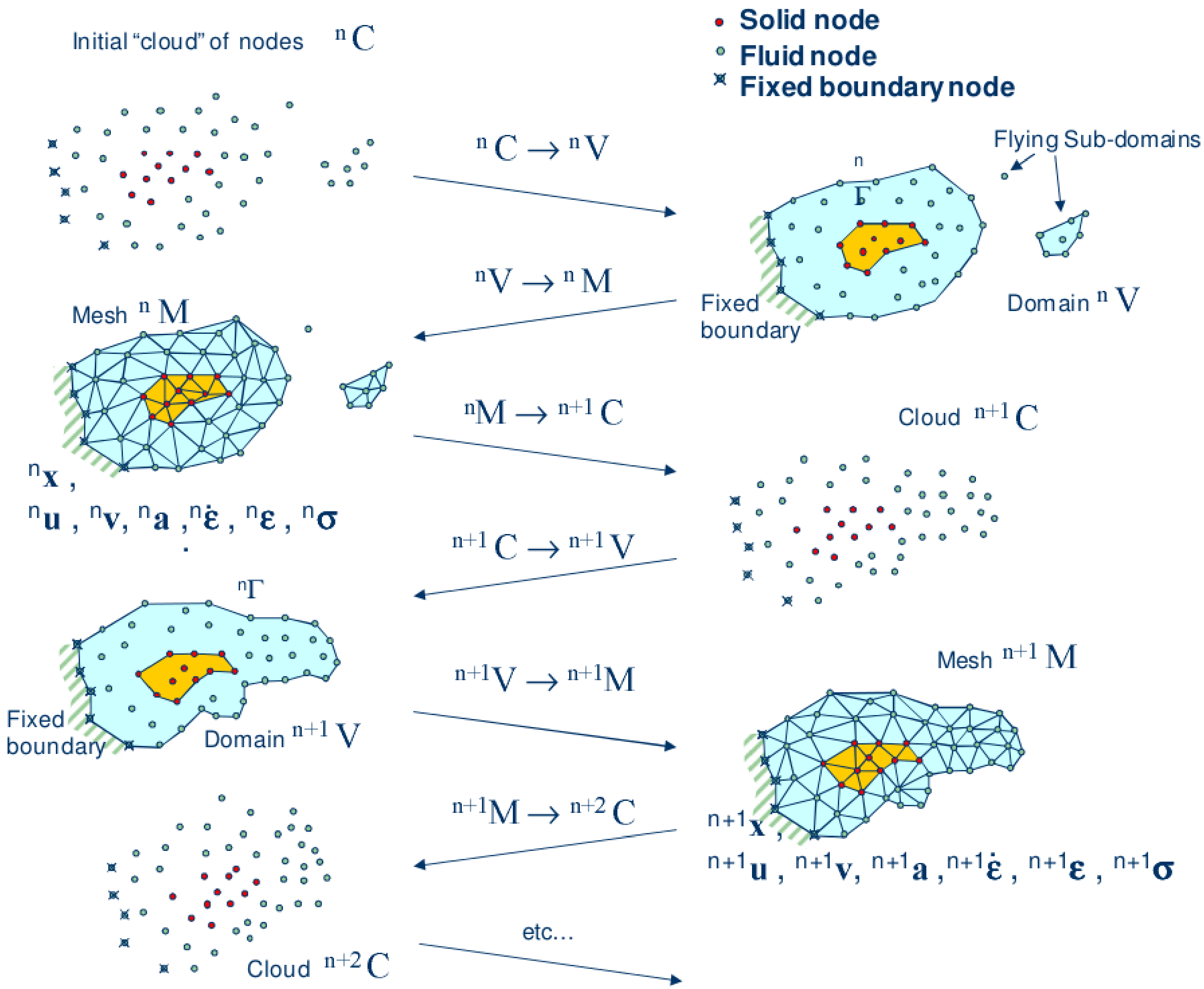
Avalanche



PFEM OVERVIEW

- **PFEM (Particle Finite Element Method): numerical technique for solving fluid-soil-structure interaction problems involving large motion**
- **PFEM uses an updated Lagrangian formulation to model the motion of particles (nodes)**
- **The mesh must be generated in each timestep to solve the governing equations in the standard FEM fashion**
- **The PFEM is particularly suited for modelling and simulation of landslides**

PFEM OVERVIEW



PFEM OVERVIEW

1. Loop over time steps, t=1, NTIME

Known values: ${}^t\bar{x}, {}^t\bar{v}, {}^t\bar{p}, {}^t\bar{\pi}, {}^t\bar{T}, {}^t\mu, {}^t f, {}^t q, {}^t C, {}^t V, {}^t M$

2. Loop over number of iterations, i =1, NITER

- Compute nodal velocities by solving $\left[\frac{1}{\Delta t}M + K\right]^{t+1} \bar{v}^{i+1} = {}^{t+1} f + G^{t+1}\bar{p}^i + \frac{1}{\Delta t}M^t\bar{v}$
- Compute nodal pressures from $\left[\frac{1}{\Delta t} - L\bar{M}\right]^{t+1} \bar{p}^{i+1} = G^{T\,t+1}\bar{v}^{i+1} + Q^{t+1}\bar{\pi}^i + \frac{1}{\Delta t}M^t\bar{p}$
- Compute nodal pressure gradient projections from ${}^{n+1}\bar{\pi}^{i+1} = -\hat{M}_D^{-1}\left[Q^T\right]^{t+1} \bar{p}^{i+1}$, $\hat{M}_D = diag\left[\hat{M}_D\right]$
- Update position of analysis domain nodes ${}^{t+\Delta t}\bar{x}^{i+1} = {}^t x^i + {}^{t+\Delta t} v^{i+1}\Delta t$

Define new cloud of nodes ${}^{t+1}C^{i+1}$

- Update strain rate and strain values
- Update stress values

Check convergence: NO $\rightarrow$ Next iteration $\rightarrow i = i + 1$

YES $\rightarrow$ Next time step $\rightarrow t = t + 1$

New time step

- Identify new analysis domain boundary: ${}^{t+1}V$
- Generate mesh: ${}^{t+1}M$

Go to 1

CONSTITUTIVE MODEL

Most rapid landslides ⟶ Viscous fluid

Stress tensor of a Newtonian fluid:

$$\boldsymbol{\sigma} = -p\mathbf{I} + 2\mu\nabla^S \bar{\mathbf{u}}$$

Symmetric part of the velocity gradient:

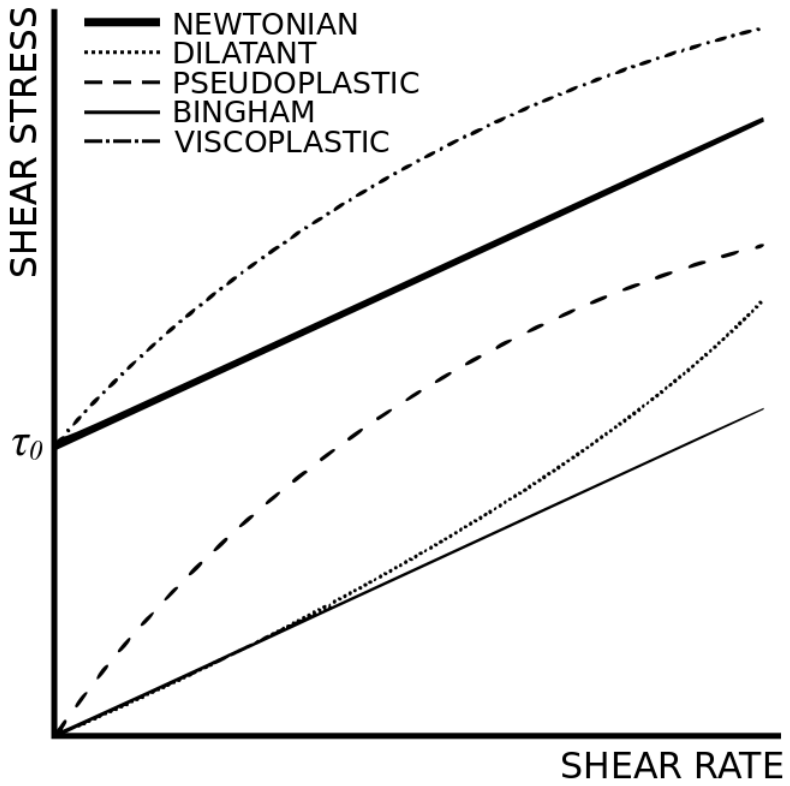
$$\left(\nabla^S \bar{\mathbf{u}}\right)_{kl} = \frac{1}{2}\frac{\partial \bar{u}_k}{\partial x_l} + \frac{\partial \bar{u}_l}{\partial x_k}$$

CONSTITUTIVE MODEL

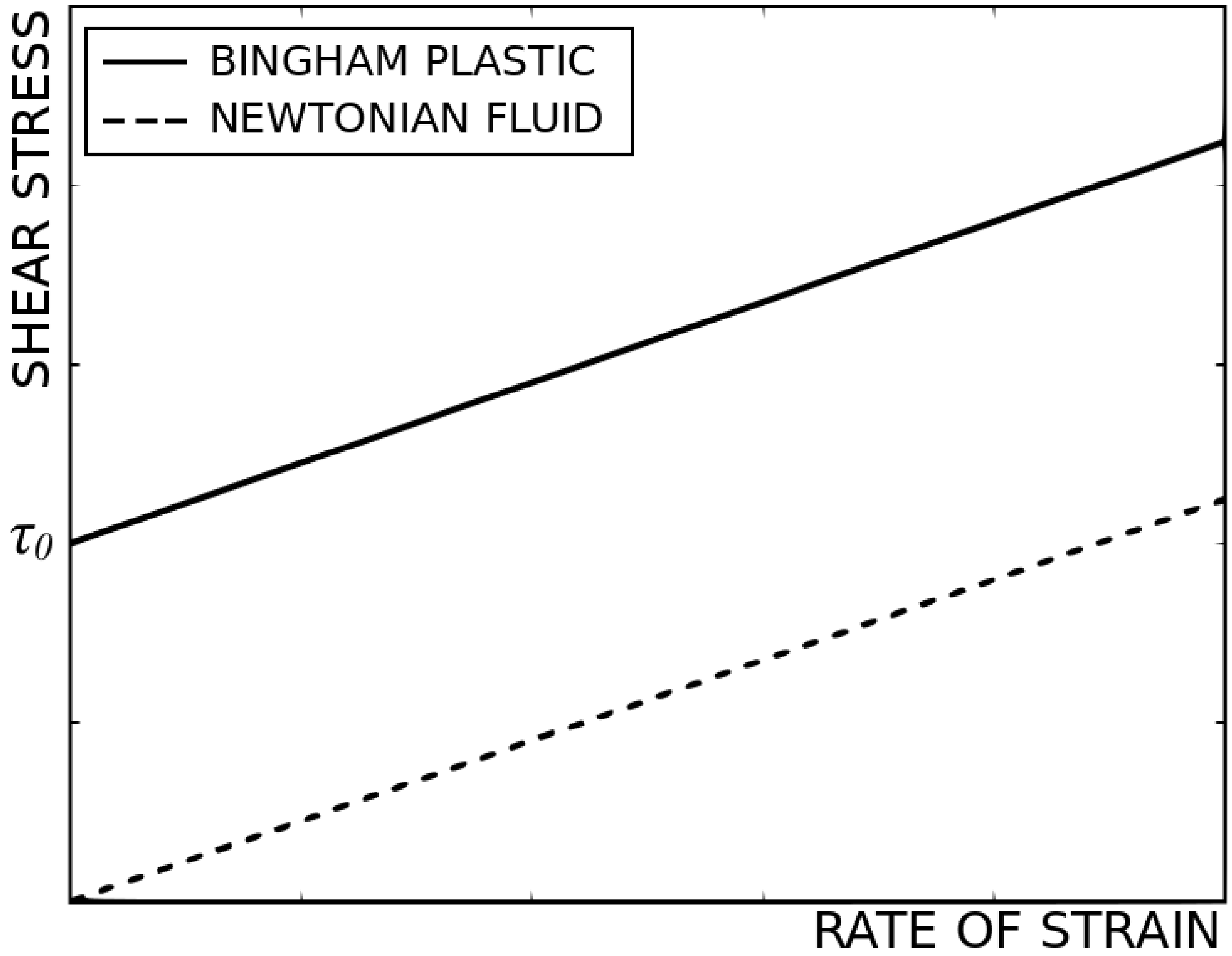
Mudflows → **Viscoplastic material**

One-dimensional apparent viscosity:

$$\tilde{\mu}(\dot{\gamma}) = \frac{\tau}{\dot{\gamma}}$$



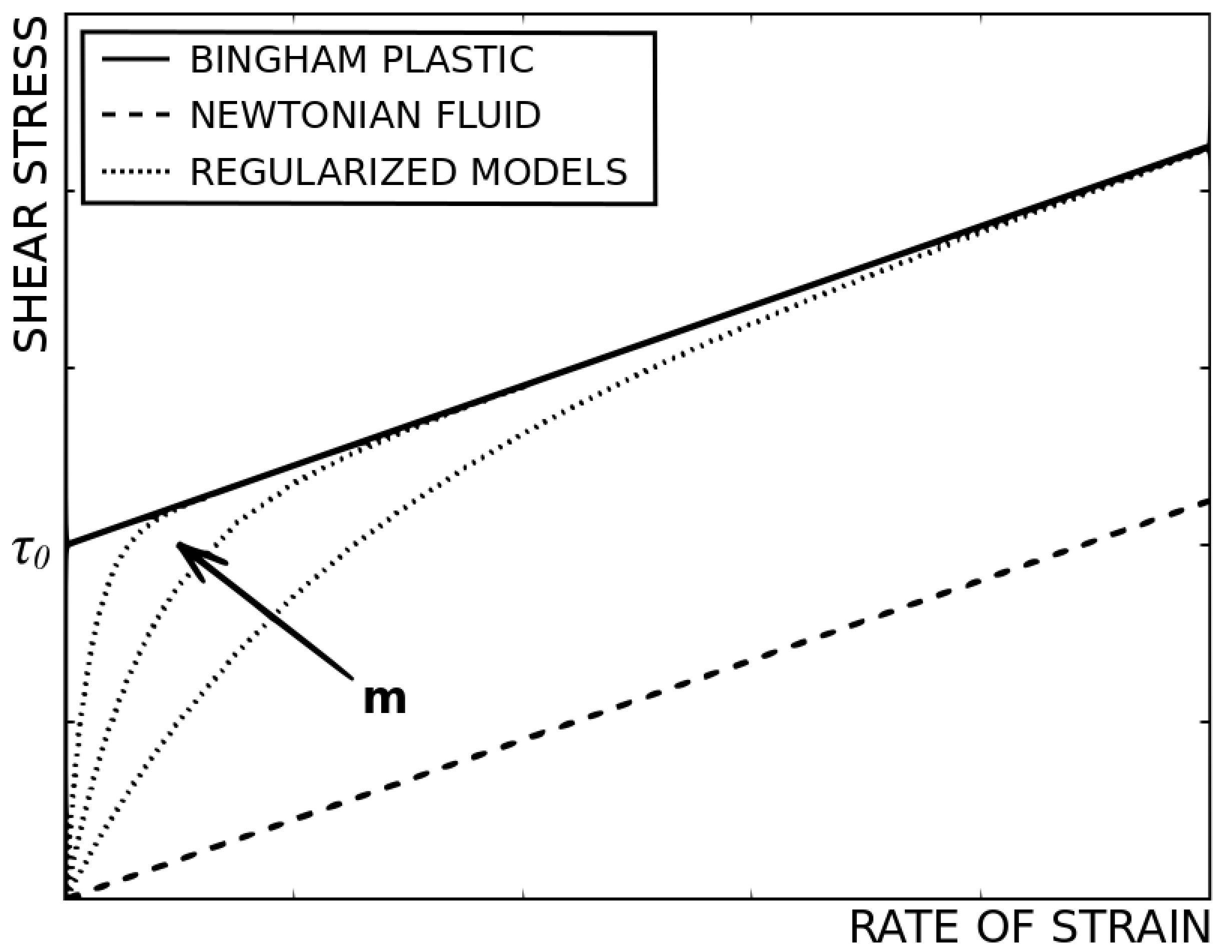
CONSTITUTIVE MODEL



CONSTITUTIVE MODEL

$$\tau = \left[\mu + \frac{\tau_0}{\dot{\gamma}}\left(1 - e^{-m\dot{\gamma}}\right)\right]\dot{\gamma}$$

$$\tilde{\mu}(\dot{\gamma}) = \mu + \frac{\tau_0}{\dot{\gamma}}\left(1 - e^{-m\dot{\gamma}}\right)$$

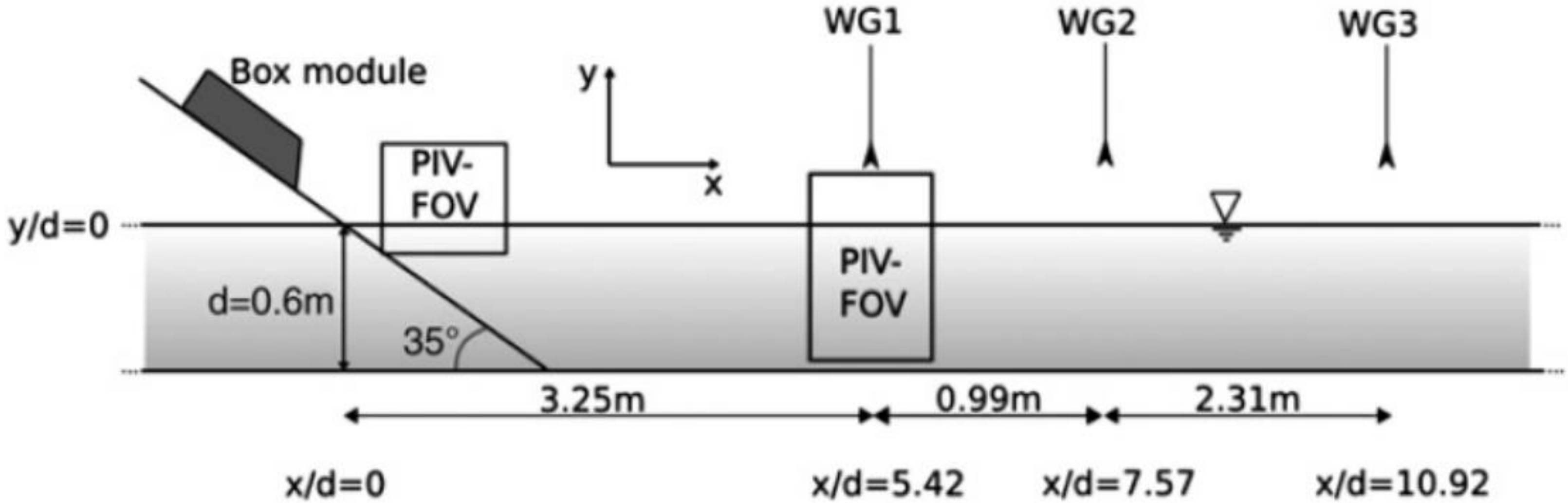


2D VALIDATION

- **Laboratory experiments**
  - Sælevick, G., Jensen, A., Pedersen, G., Experimental investigation of impact generated tsunami; related to a potential rock slide, Western Norway, Coastal Engineering 56 (9) (2009) 897–906.
- **Lituya 2D**
  - Fritz, H. M., Hager, W. H., Minor, H. E., Lituya Bay case: Rockslide impact and wave run-up. Science of Tsunami Hazards, 19(1): 3-22.
- **Vajont 2D**
  - Gómez, R., El desastre de Vajont. Jornadas técnicas de estabilidad de laderas en embalses. Zaragoza, 2007.

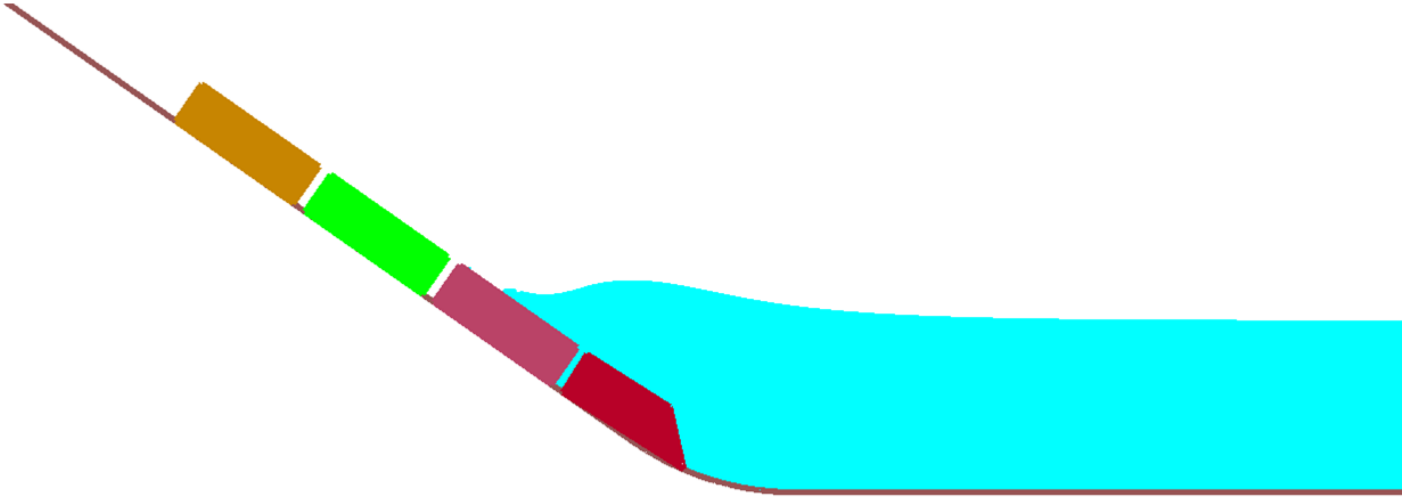
2D VALIDATION

Sælevick et al. laboratory experiments



Scenario	Height [m]	Total length [m]	Impact velocity [m/s]
1	0.16	2	2.45
2	0.16	1	3.38
3	0.12	1.6	3.56

2D VALIDATION

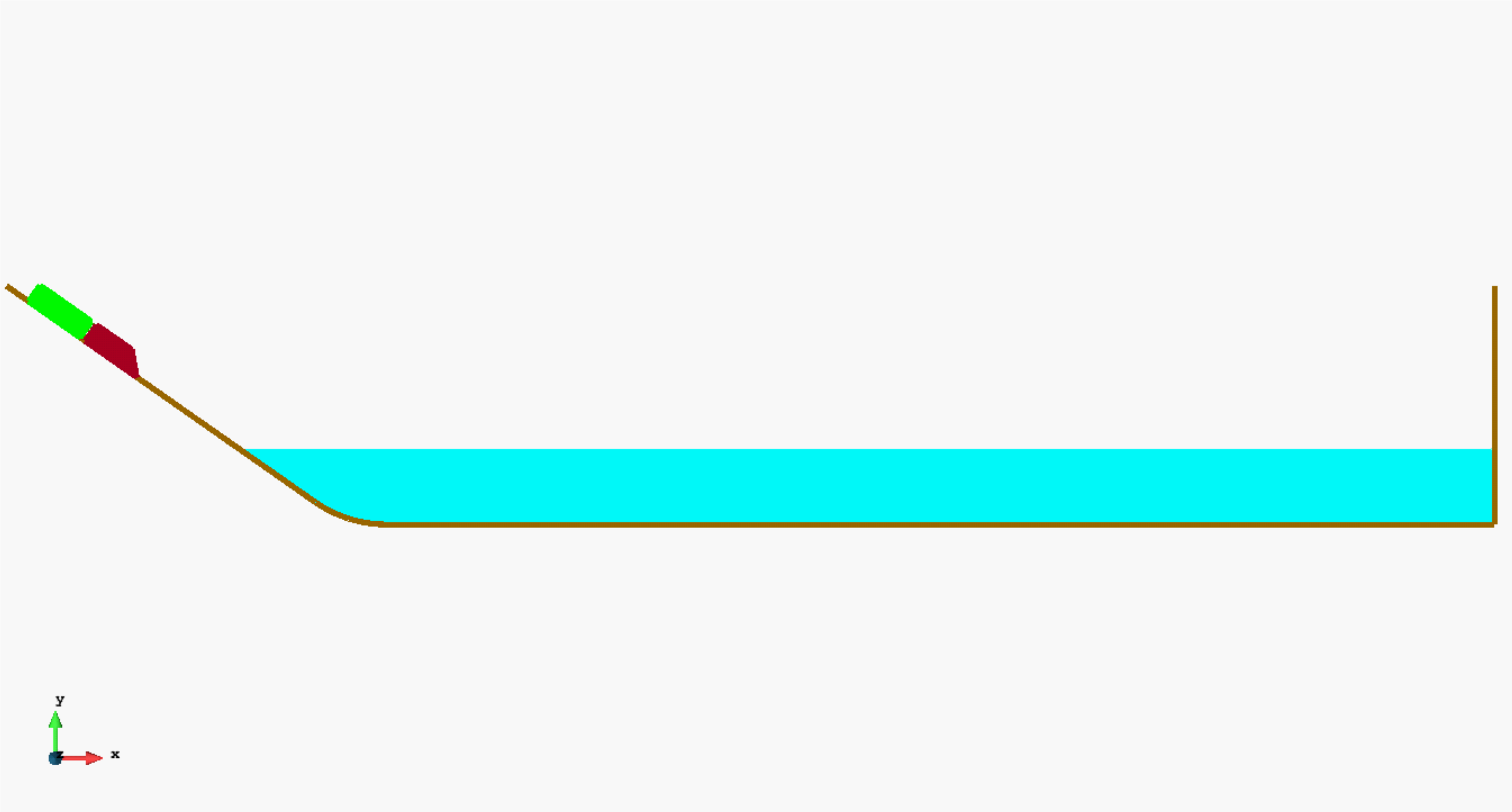


Scenario	Height [m]	Total length [m]	Impact velocity [m/s]
1	0.16	4 blocks of 0.5*	2.45
2	0.16	2 blocks of 0.5*	3.38
3	0.12	2 blocks of 0.5 and 1 of 0.6*	3.56

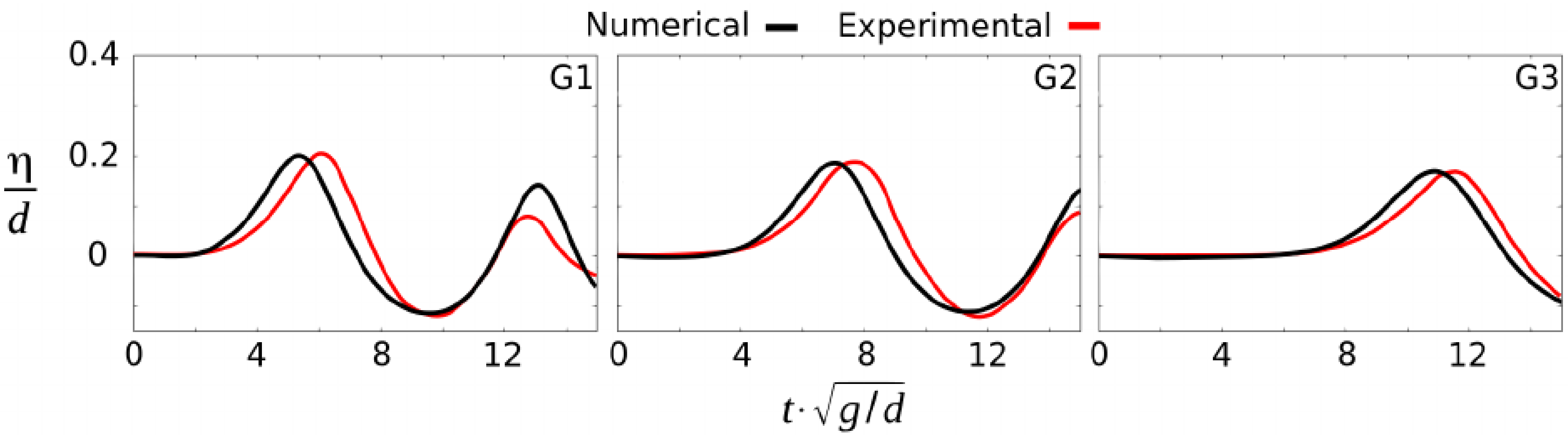
(*)The gap between blocks was considered of 0.05 m.

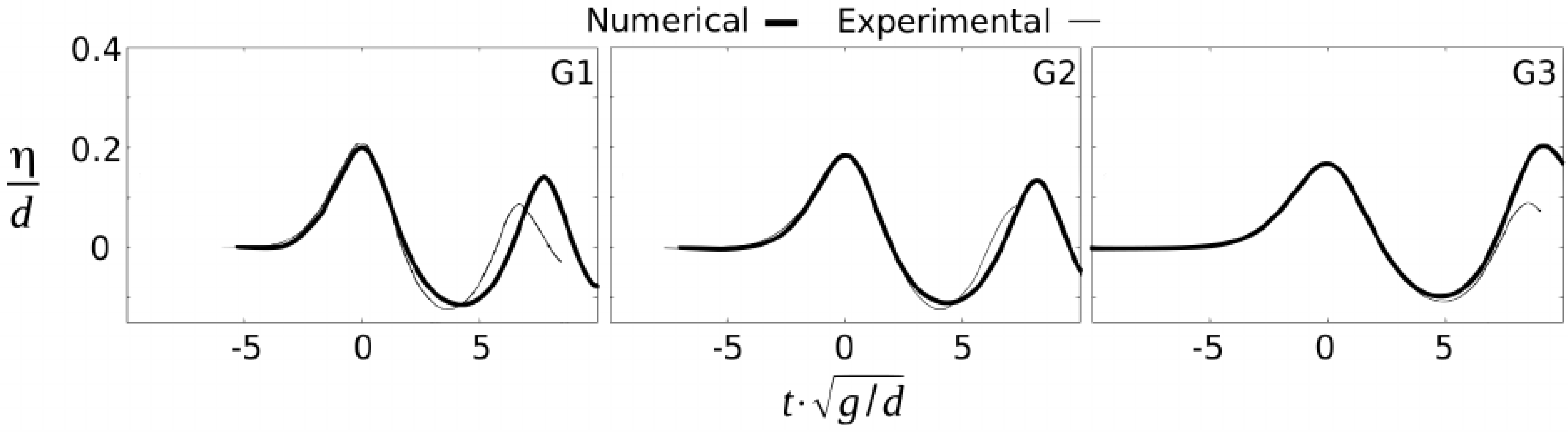
2D VALIDATION

Scenario 2



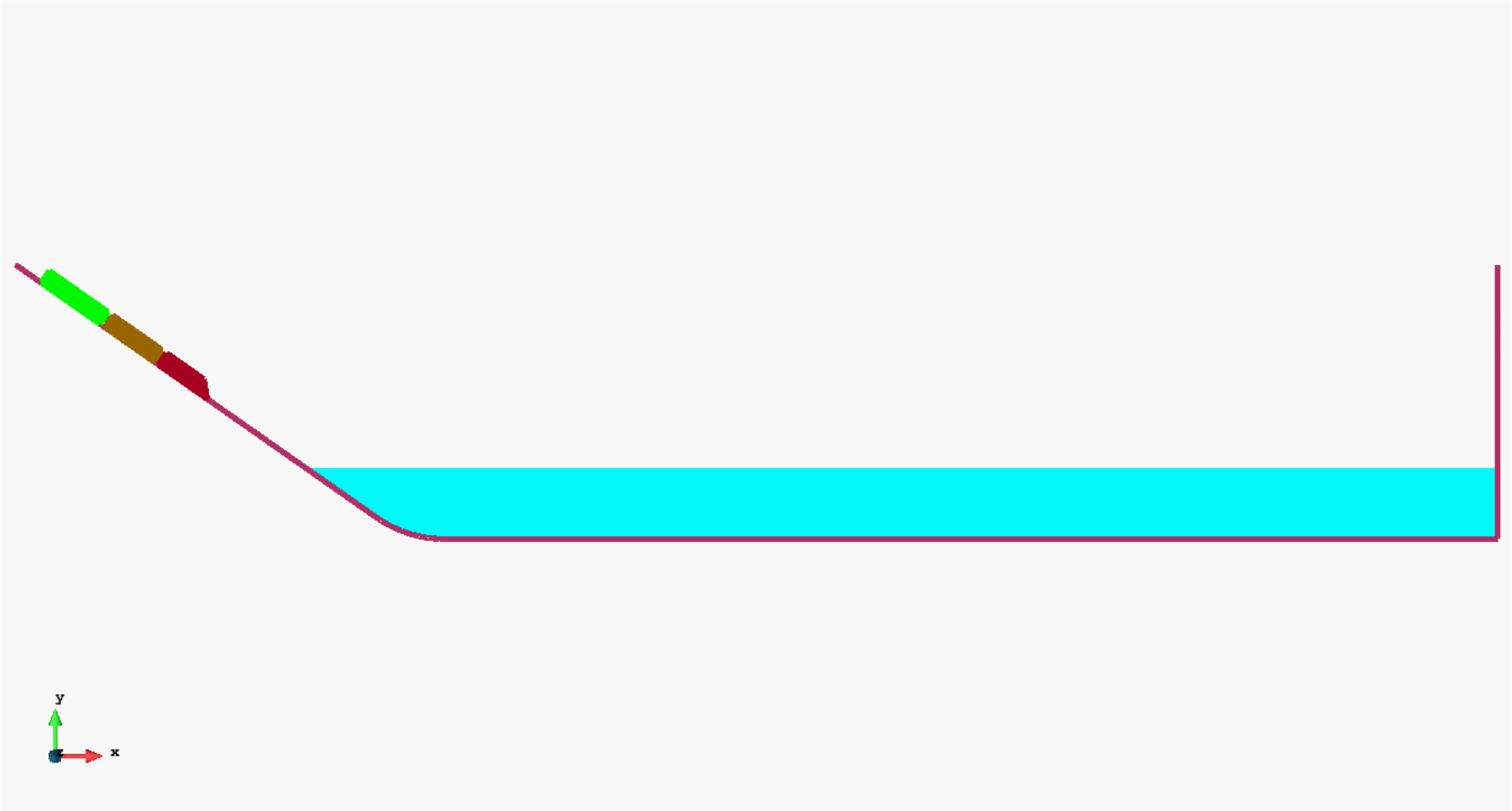
2D VALIDATION



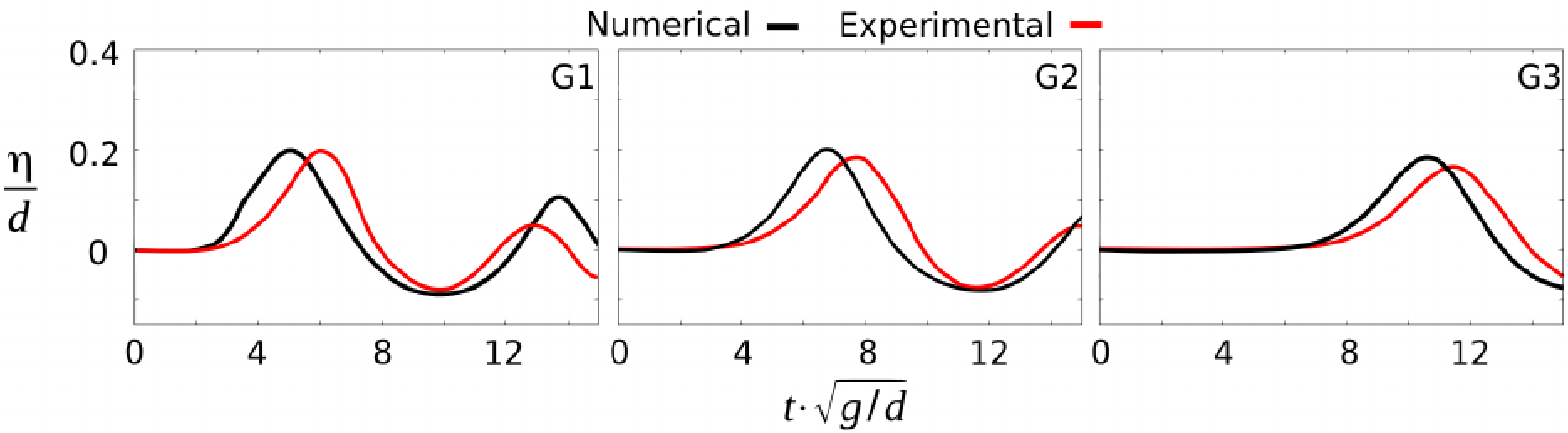


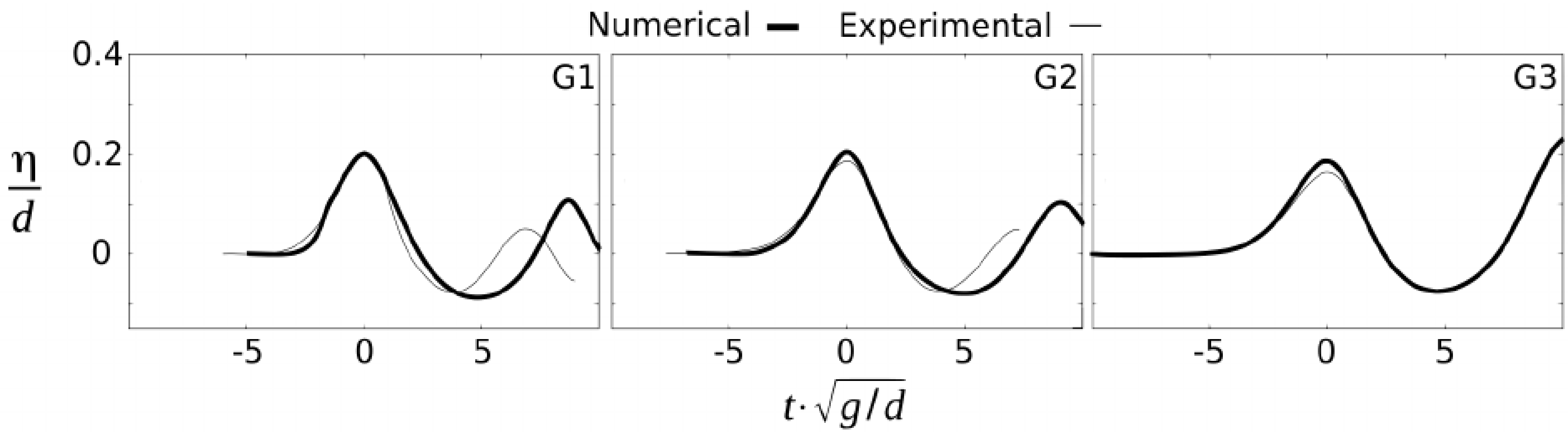
2D VALIDATION

Scenario 3



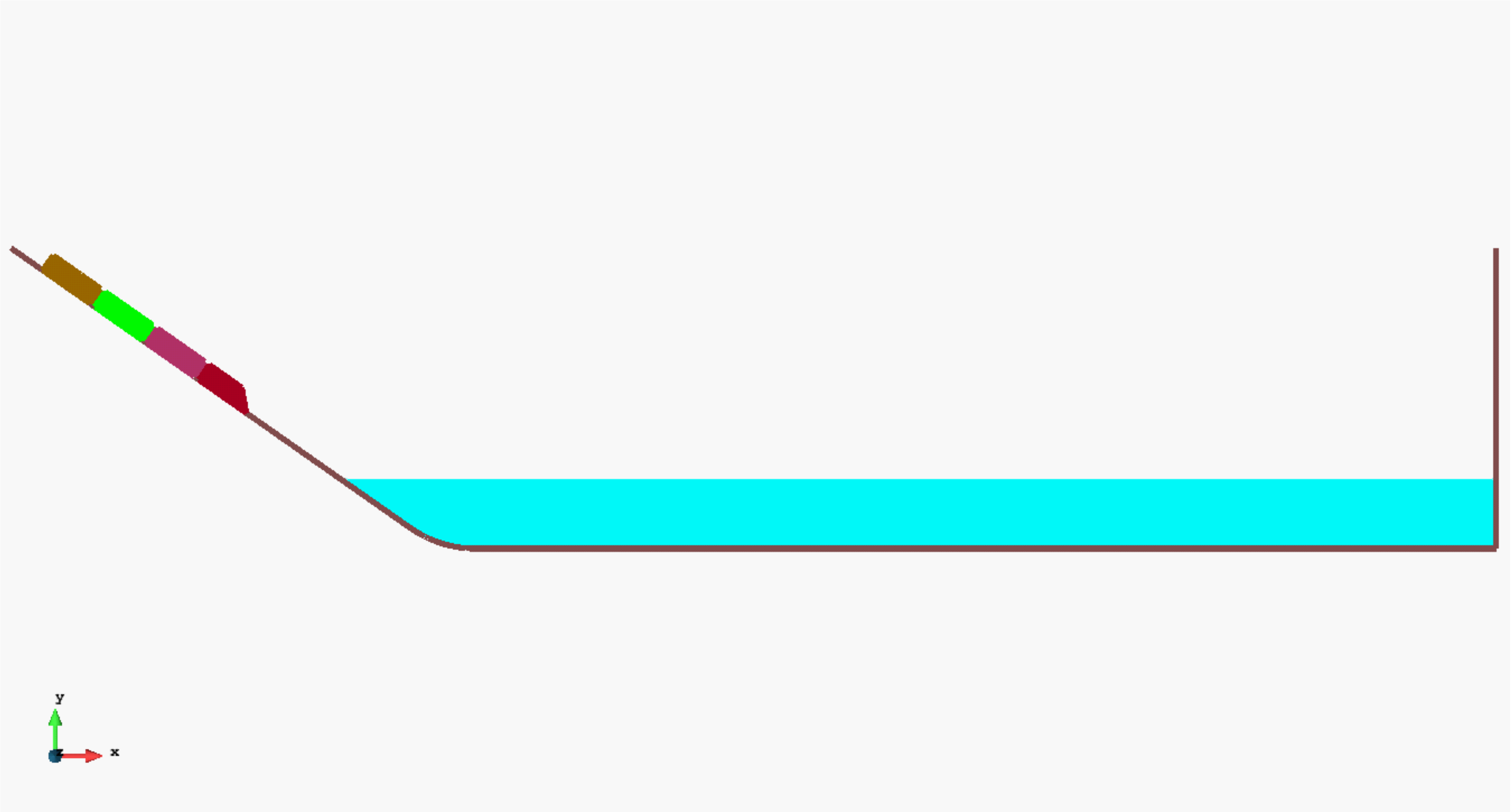
2D VALIDATION





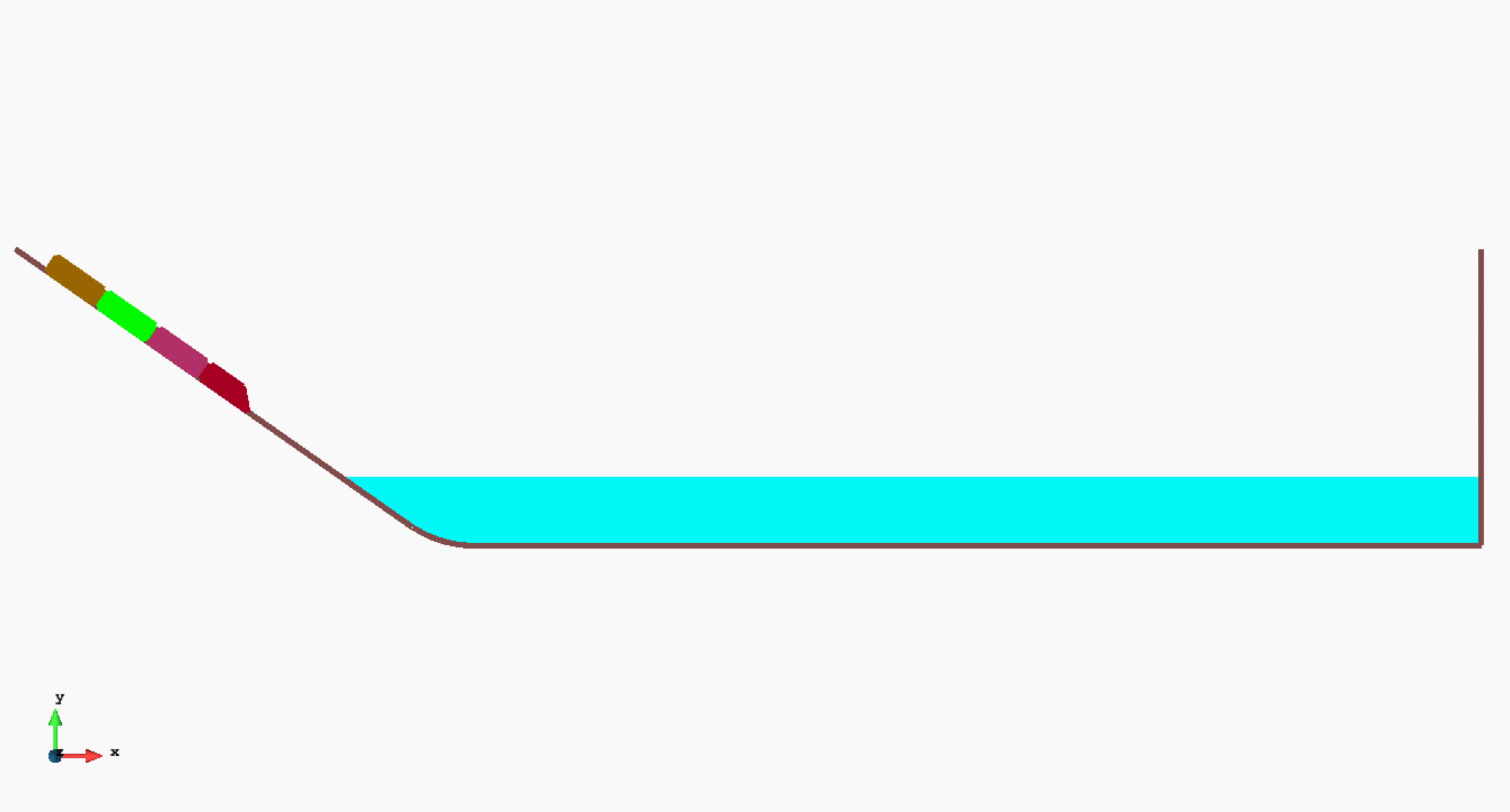
2D VALIDATION

Scenario 1

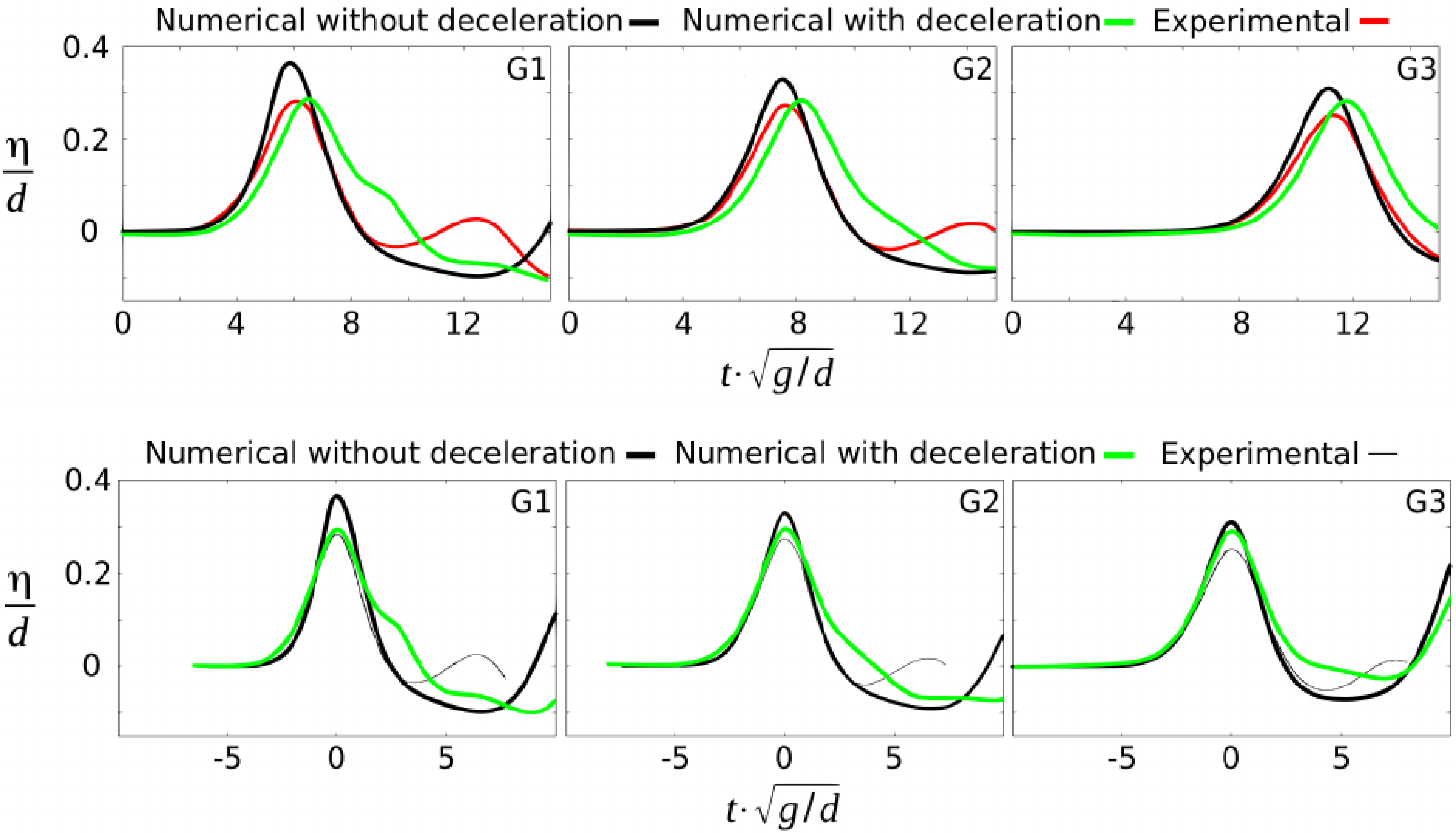


2D VALIDATION

Scenario 1 (deceleration)



2D VALIDATION

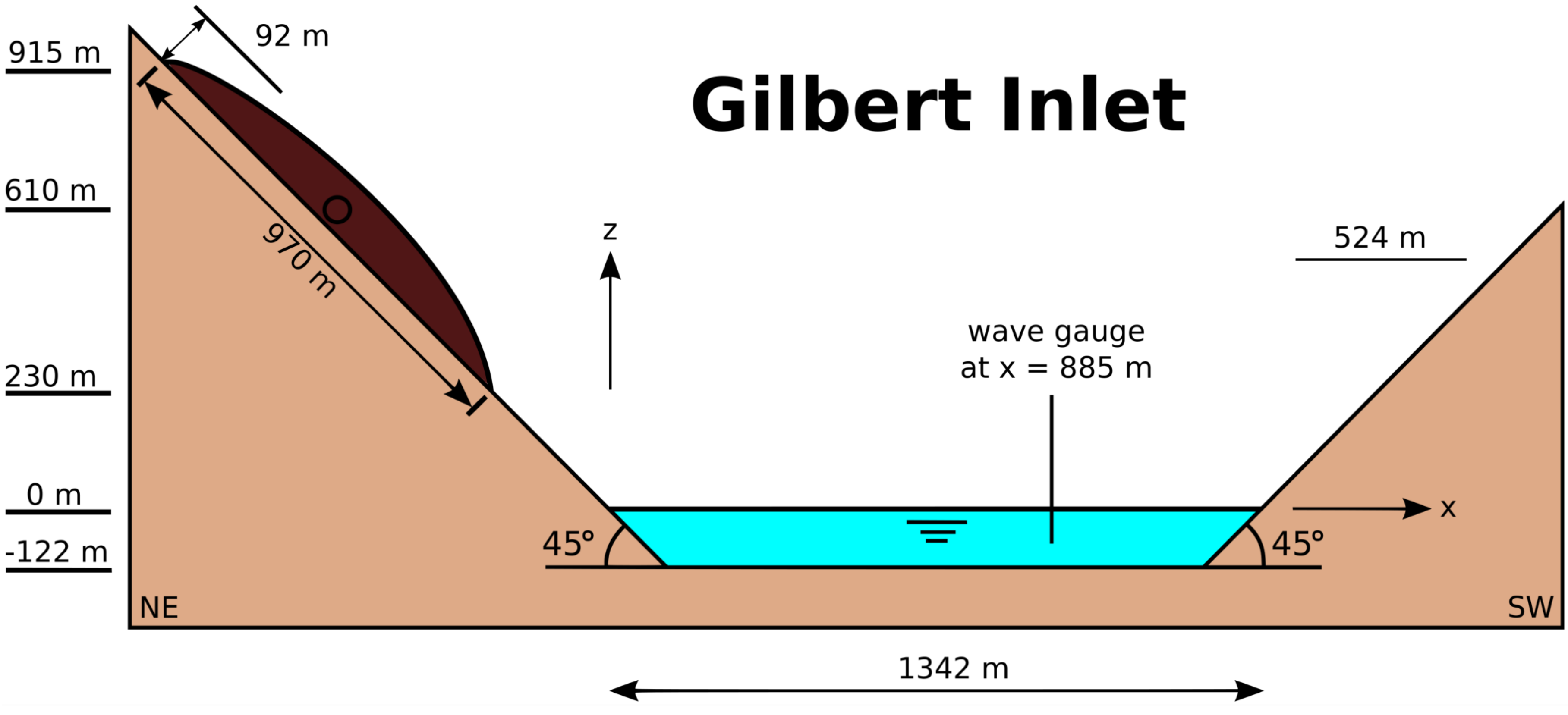


2D VALIDATION

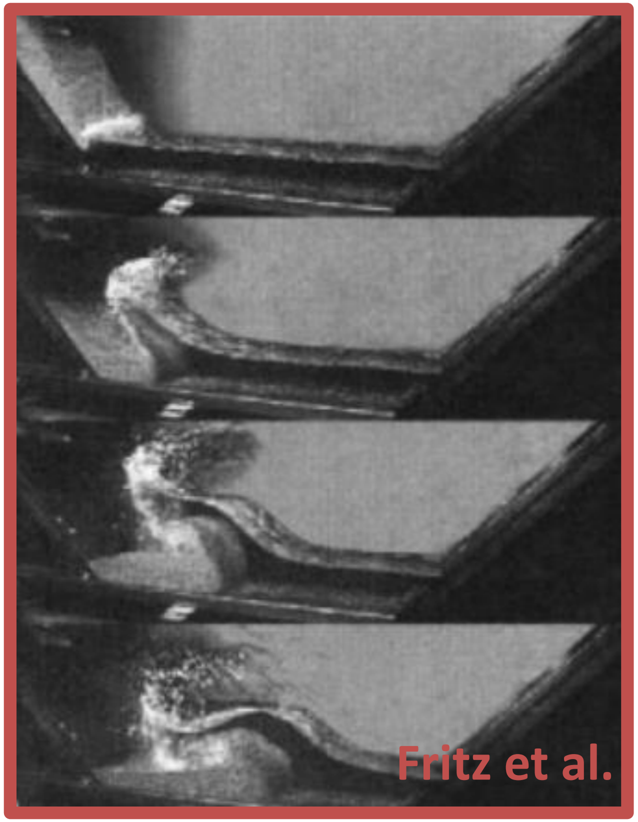
Scenario	Run	Difference in maximum wave height (%)		
		WG1	WG2	WG3
1	1	28.6	20.2	19.2
1	2	3.6	5.5	9.6
2	1	4.8	0.0	0.0
3	1	0.0	8.1	8.8

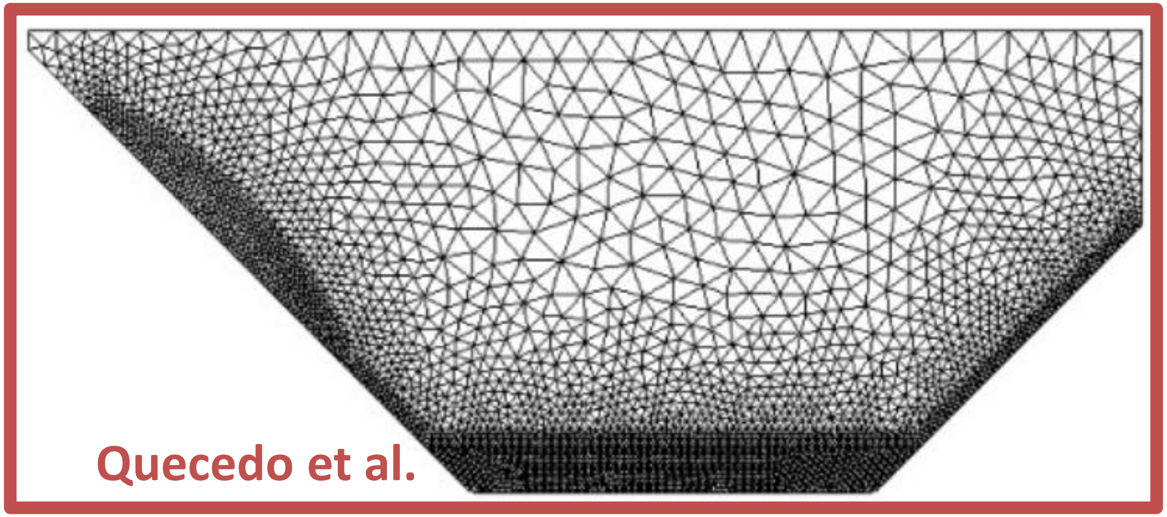
2D VALIDATION

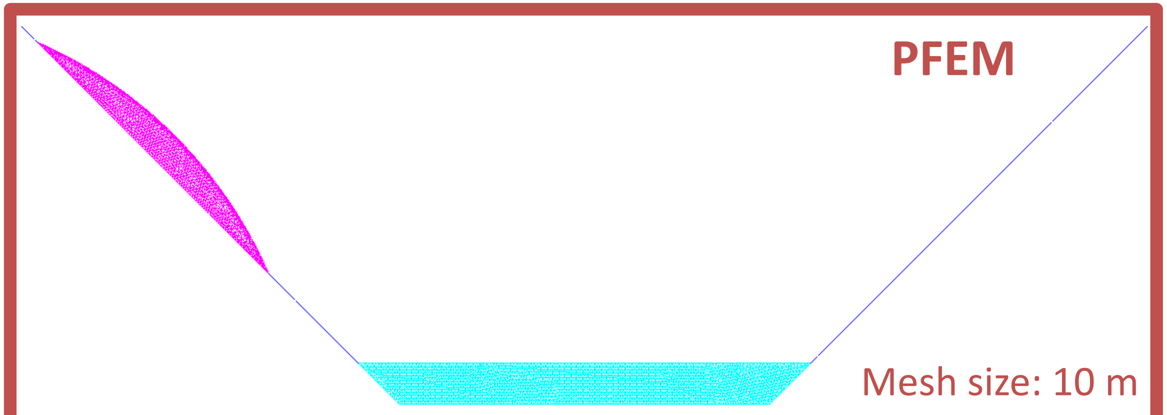
Lituya 2D



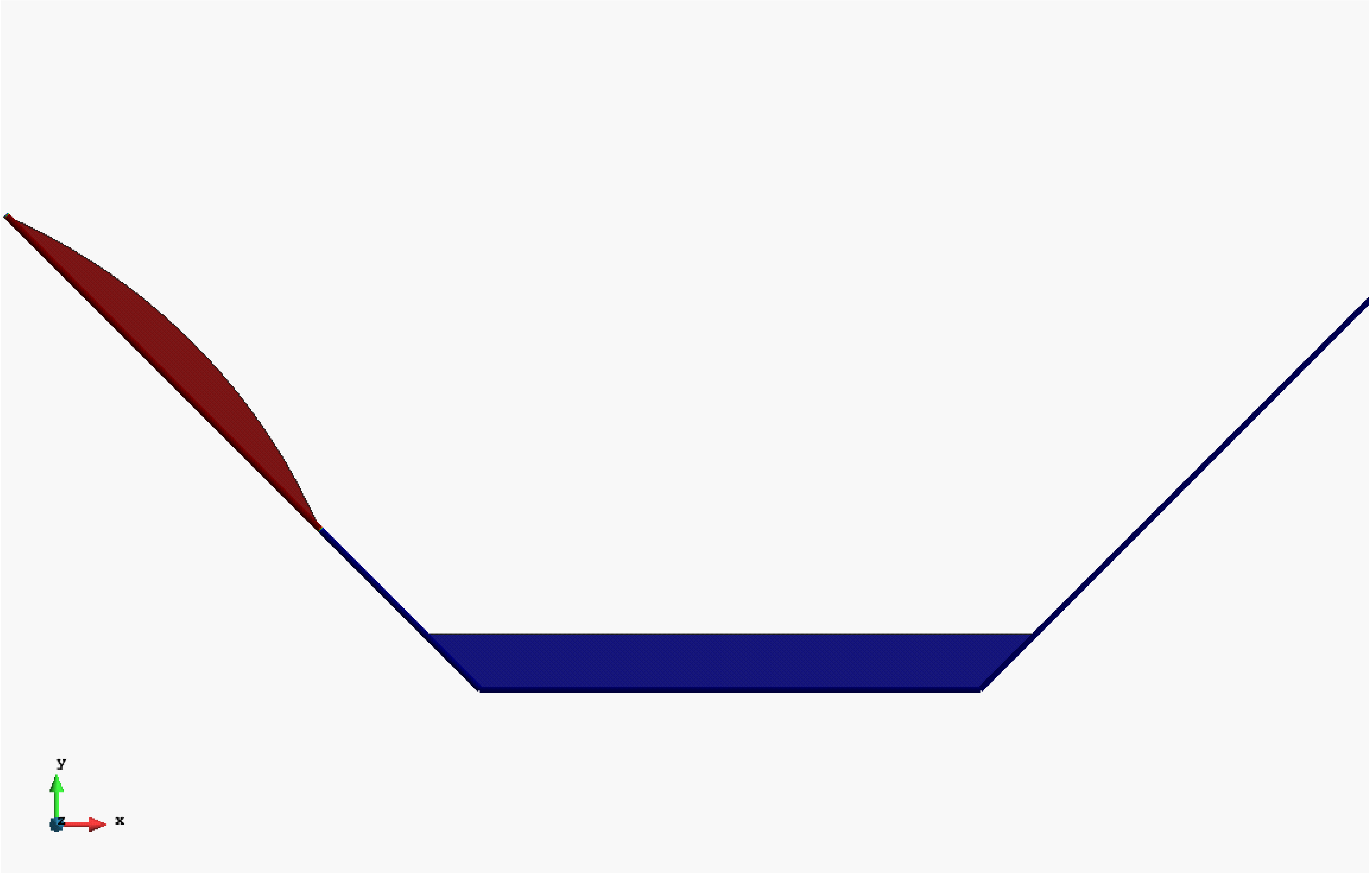
2D VALIDATION







2D VALIDATION

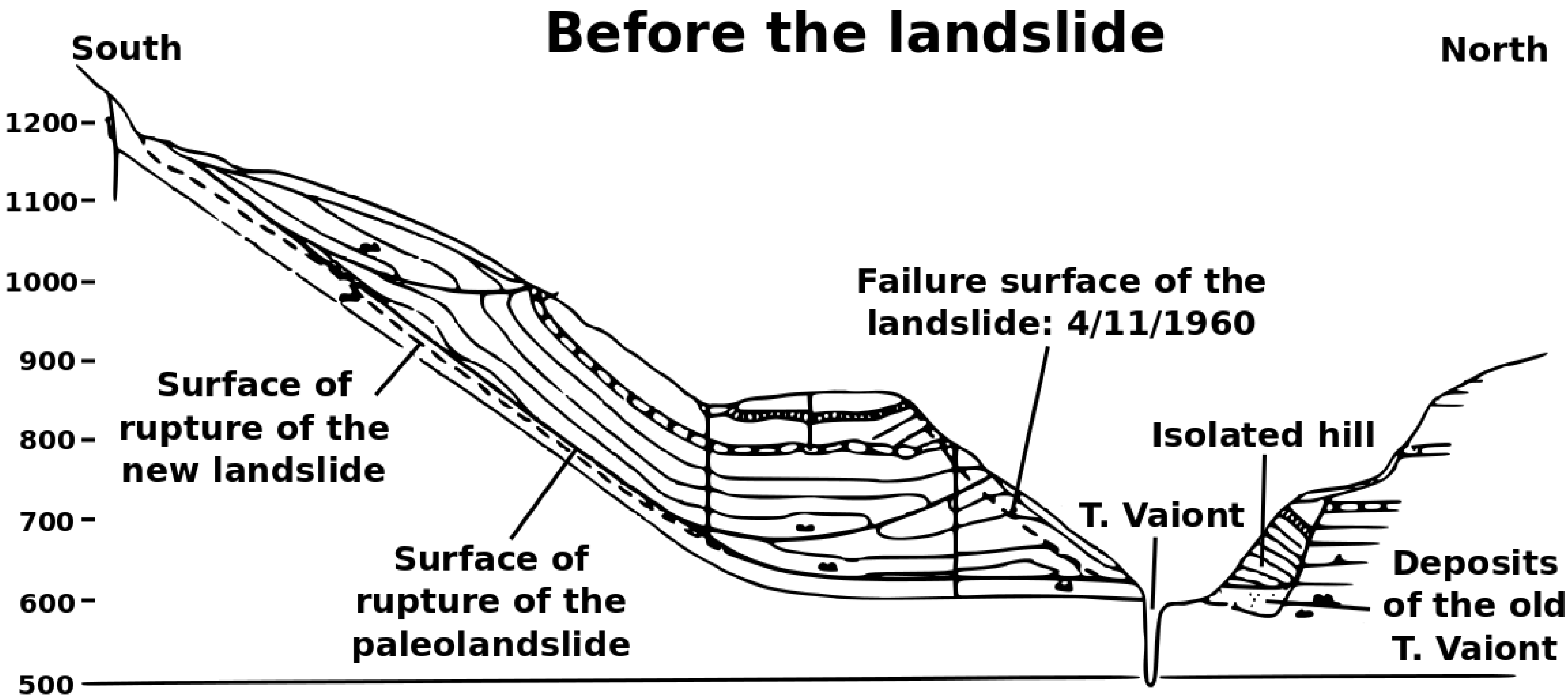


2D VALIDATION

	Measured (Fritz)	Quecedo et al.	PFEM
Slide duration (s)	7	9	9.5
Slide velocity at impact (m/s)	110	85	83
Slide length at impact (m)	748	1092	1052
Maximum wave height (m)	>200	226	234
Time for maximum wave (s)	11	21	26
Maximum wave position (m)	600	600	814
Maximum wave height at 885 m	152	266	232
Time for maximum wave at 885 m (s)	16	26.8	27.1

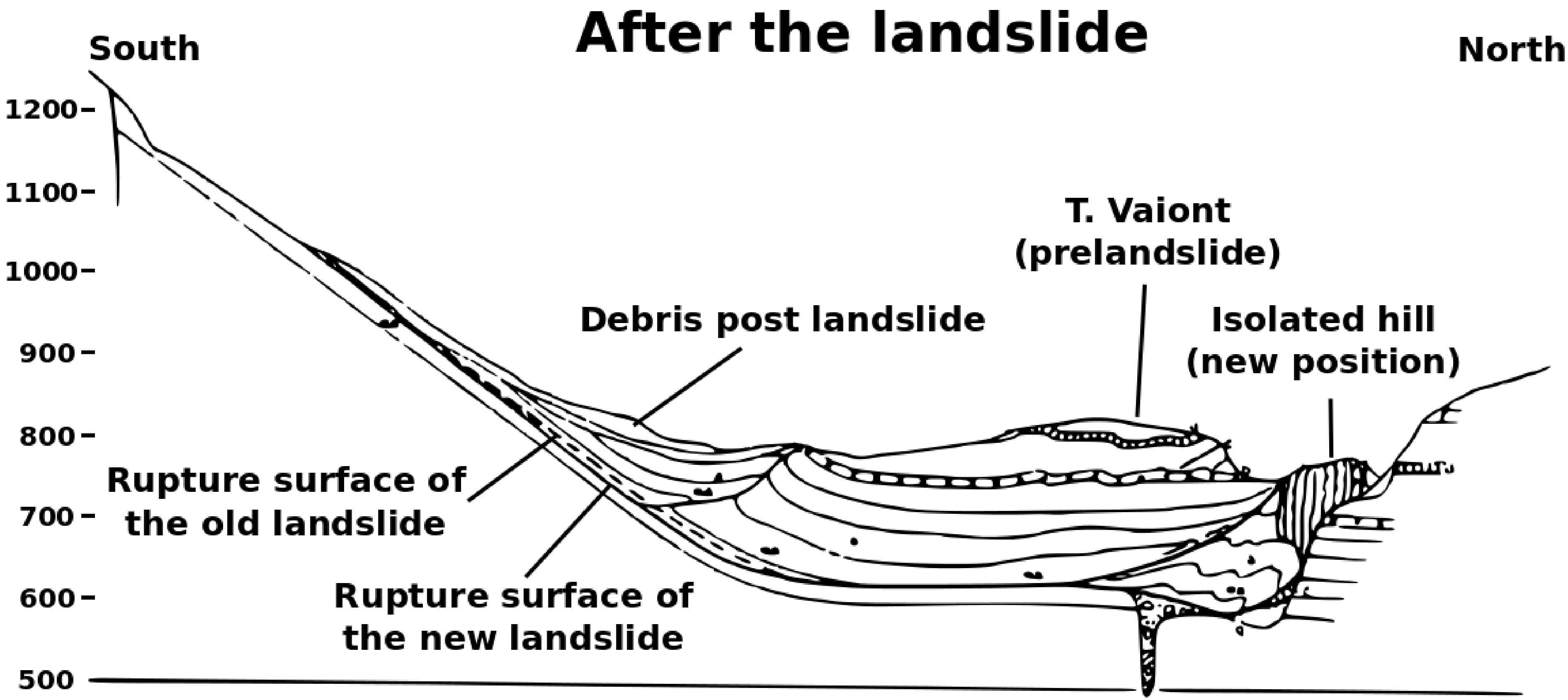
2D VALIDATION

Vajont 2D



2D VALIDATION

Vajont 2D

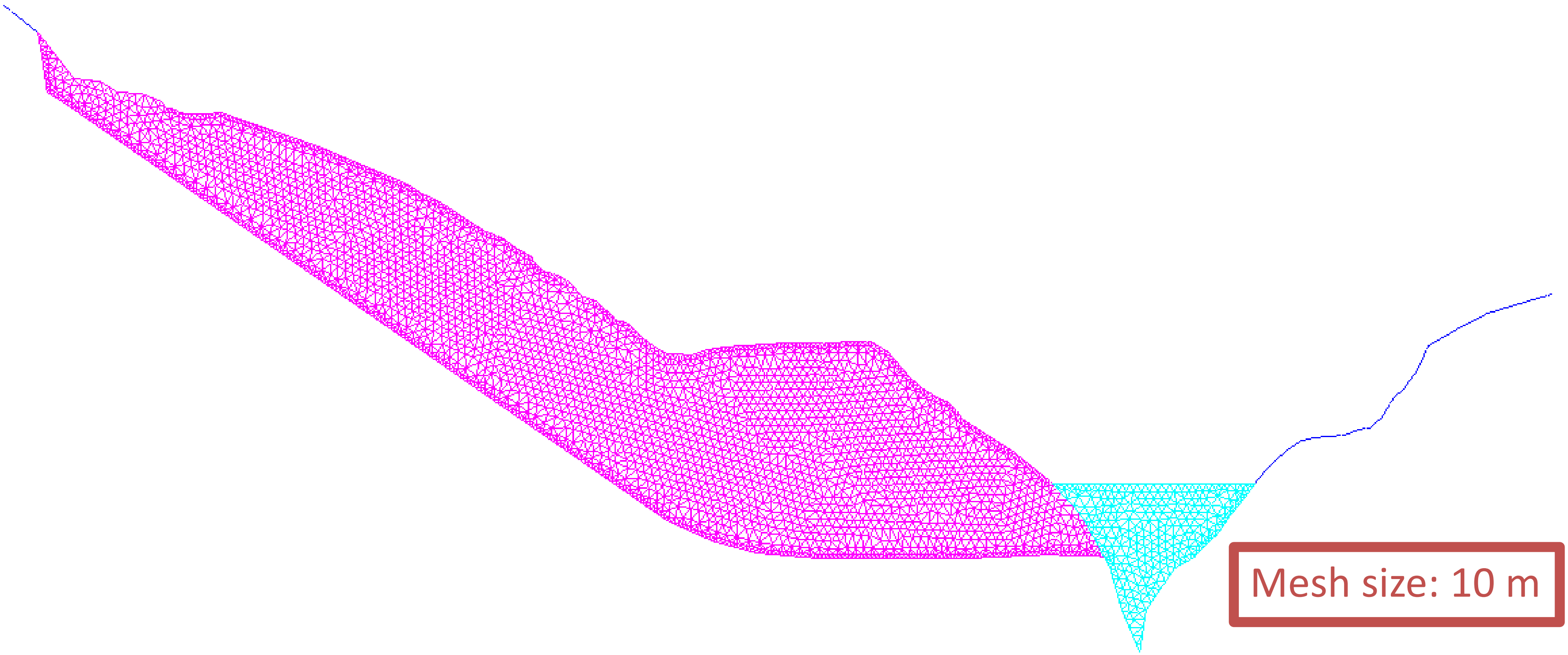


2D VALIDATION

Other data:

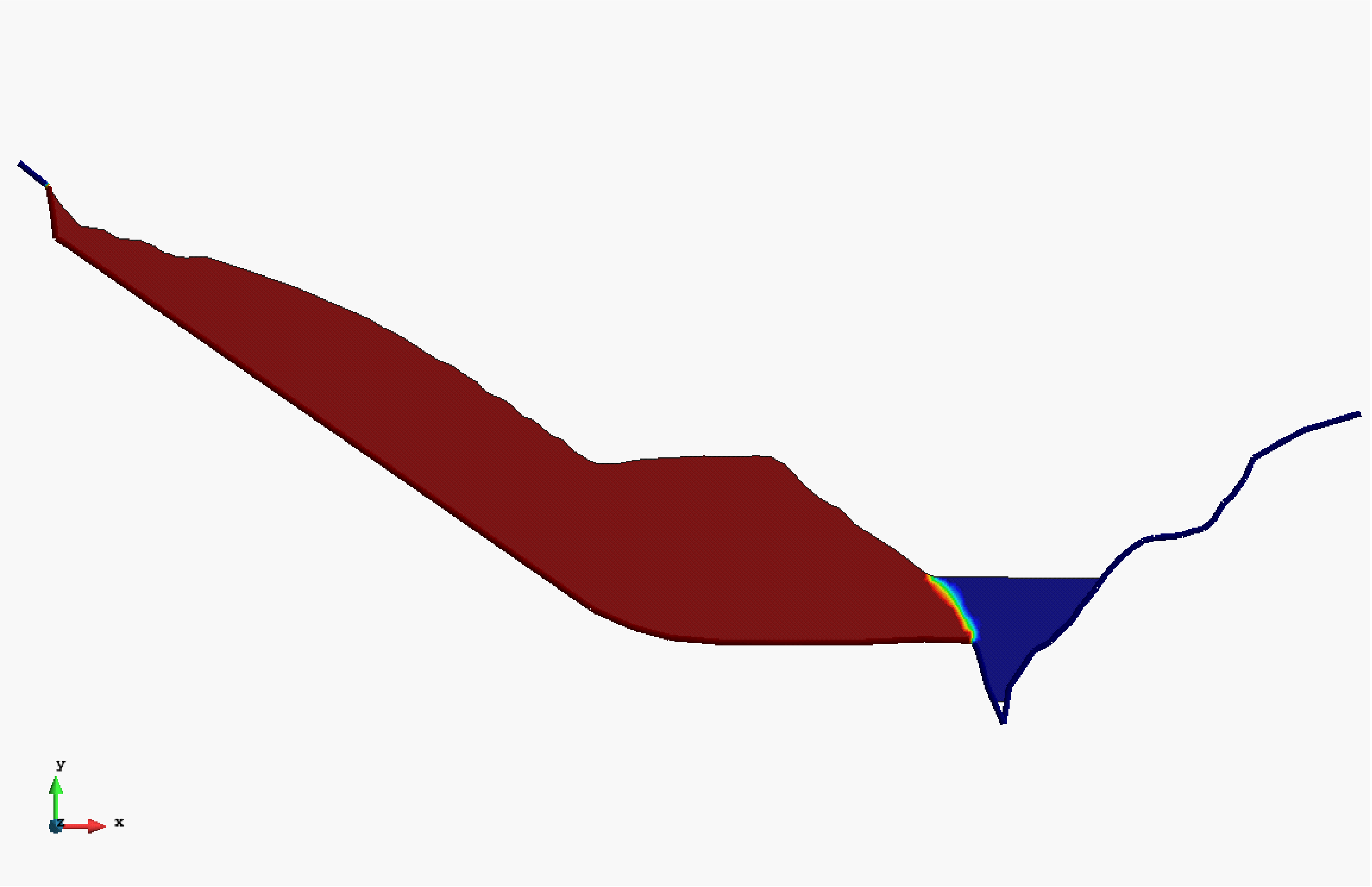
- Density: 1800 kg/m^3
- Maximum velocity: 28 m/s
- The landslide mass ceased after 30-40 s

2D VALIDATION



Mesh size: 10 m

2D VALIDATION



2D VALIDATION

Calibration campaign 1

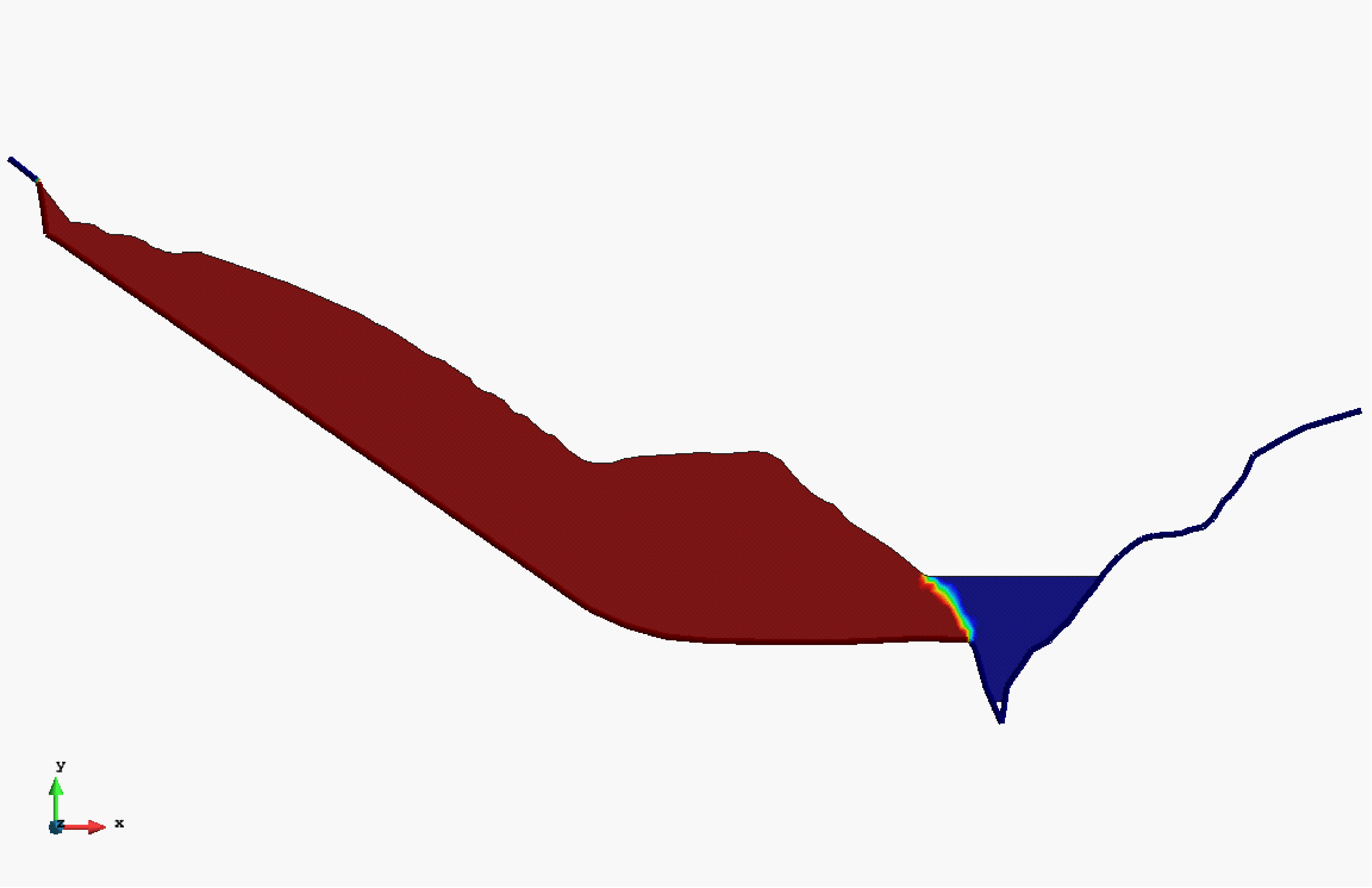
- Used data:
  - Yield stress (kPa): 15, 150, 300
  - Viscosity (Pa·s): 50, 500, 5000
  - m: 50, 500, 5000
- Results: no simulation provides adequate results
- Conclusion: yield stress is the most affecting parameter. It should be between 150 and 300 kPa

2D VALIDATION

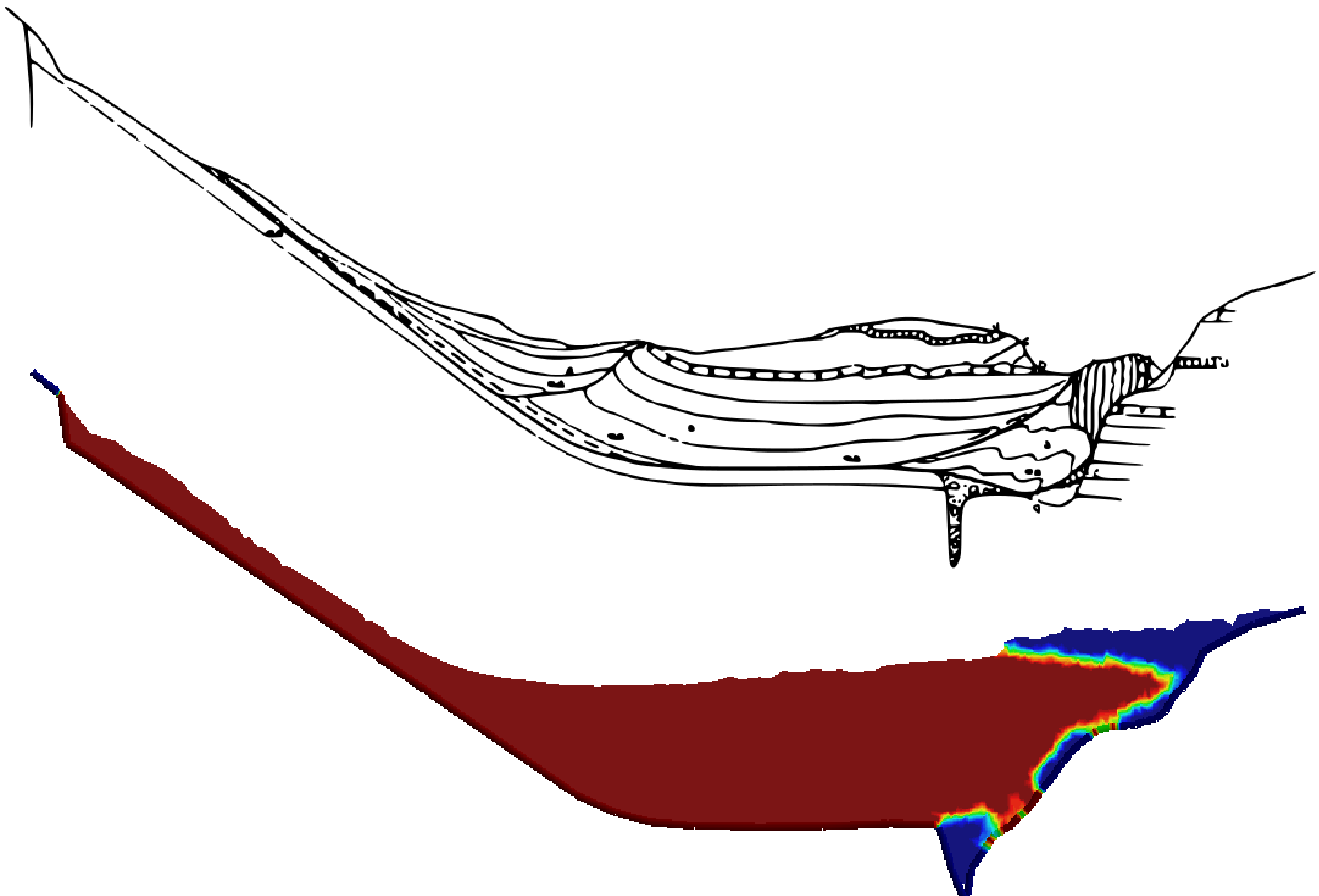
<u>Calibration campaign 2</u>

- **Used data:**
  - **Yield stress (kPa): 250**
  - **Viscosity (Pa·s): 500**
  - **m: 50, 500, 5000**
- **Results: all simulations provide good results**
- **Data chosen: Yield stress <u>250 kPa</u>, Viscosity <u>500 Pa·s</u> and m <u>500</u>**

2D VALIDATION

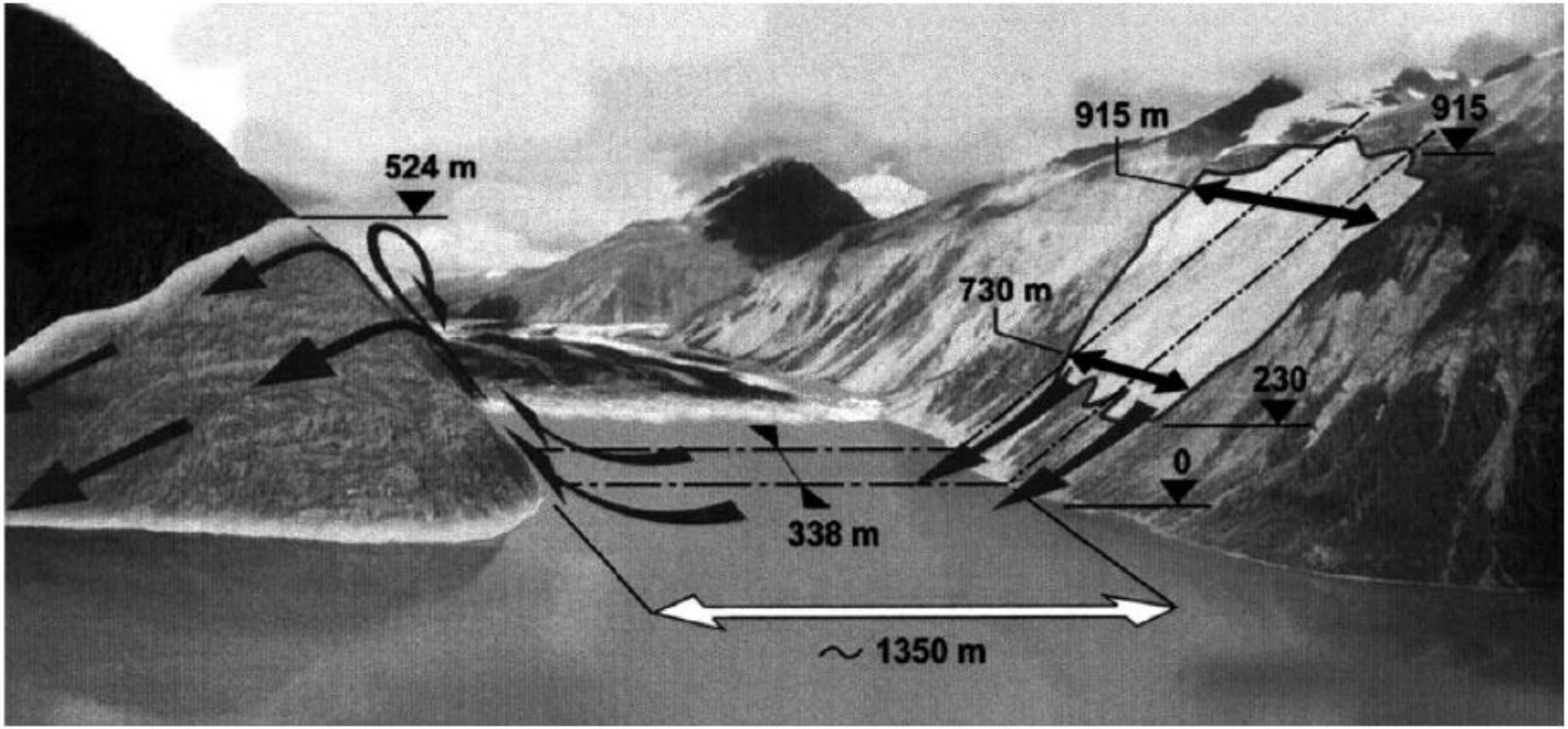


2D VALIDATION

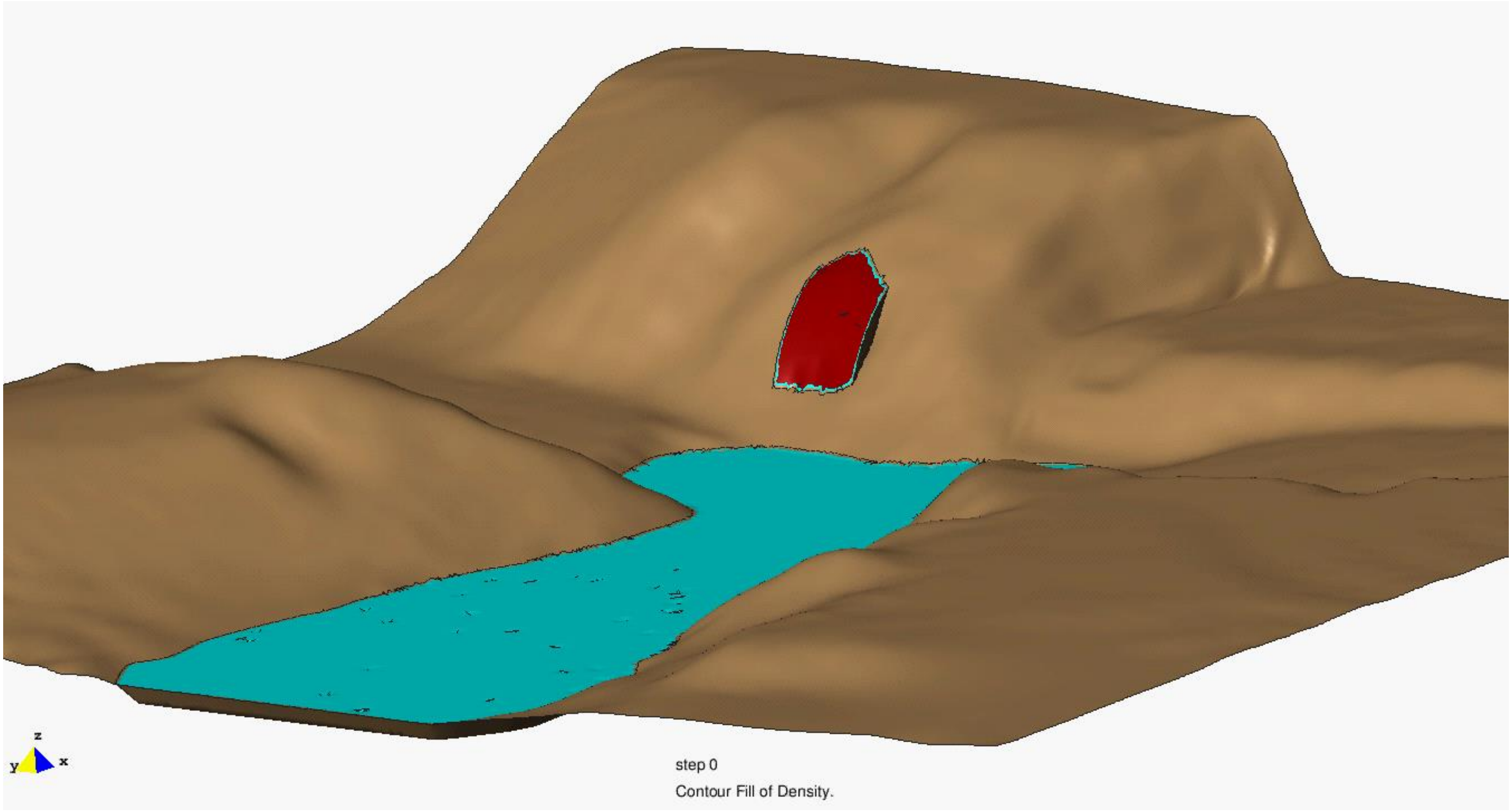


3D SIMULATION

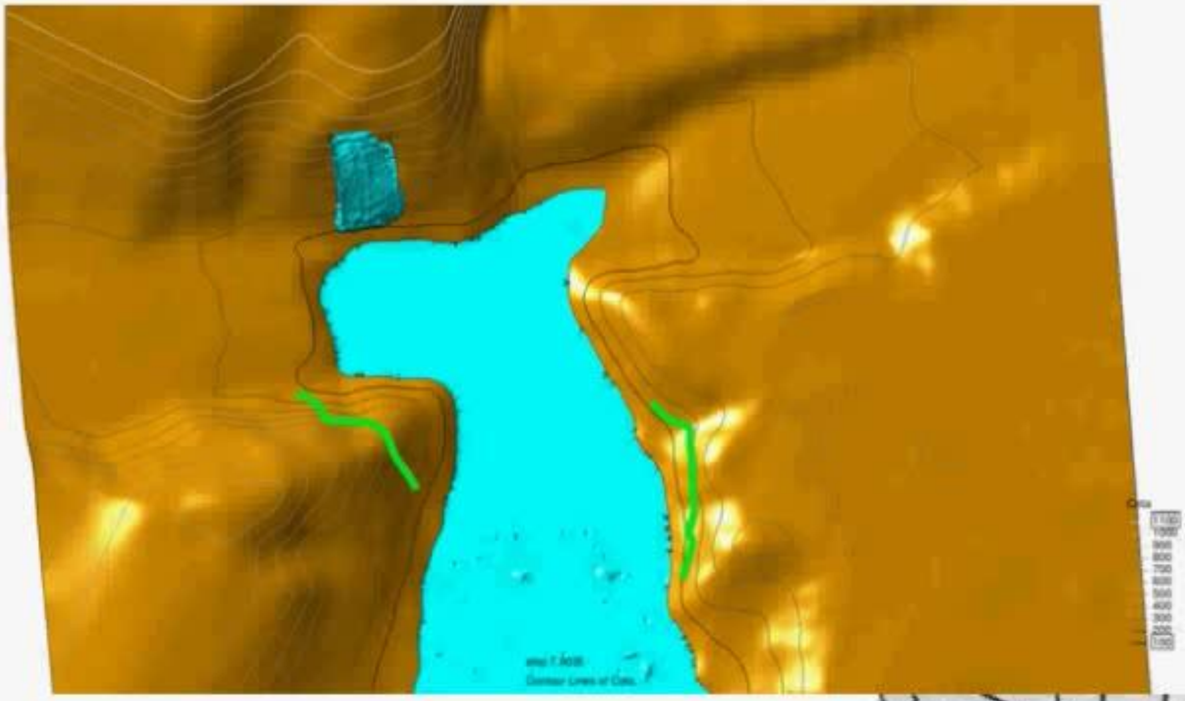
Lituya 3D

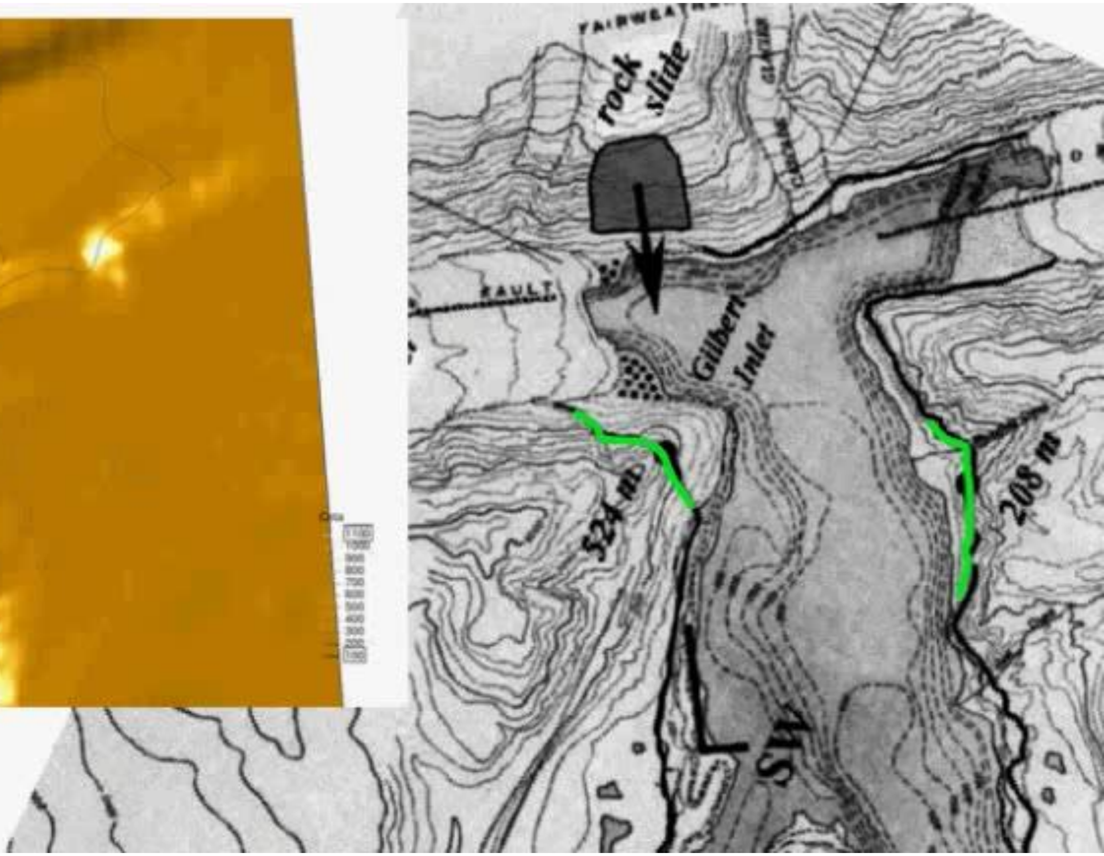


3D SIMULATION



3D SIMULATION





CONCLUSIONS

- **Landslides can behave as newtonian and non – newtonian fluids**
- **Complex phenomenon**
- **Numerical models must apply simplifications so results are approximations to reality**
- **PFEM can be useful in the estimation of possible affections caused by landslides in reservoirs**
- **PFEM is effective reproducing landslides as a Bingham fluid**

FURTHER WORK

- **Further two and three-dimensional calibrations and simulations will be developed (Vajont 3D)**
- **Non-homogeneuos landslide simulations**
- **Simulations of potencial landslides**
- **Code optimization**

THANK YOU FOR YOUR ATTENTION