Investigation of Smoothed Particle Hydrodynamics capabilities of running 2D multiphase flows:

From Benchmarks to sloshing in vessels Moon Pool

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Secondment: Esteco Engineering Service and Support Team

March 28-29, 2023

COMETE FINAL MEETING

Udine-Trieste, Italy

PhD Student at:

Institute of Fluid-Flow Machinery Polish Academy of Sciences

Gdansk, Poland

On secondment at:

ESTECO SpA, Design Optimization Software Company

Trieste,Italy

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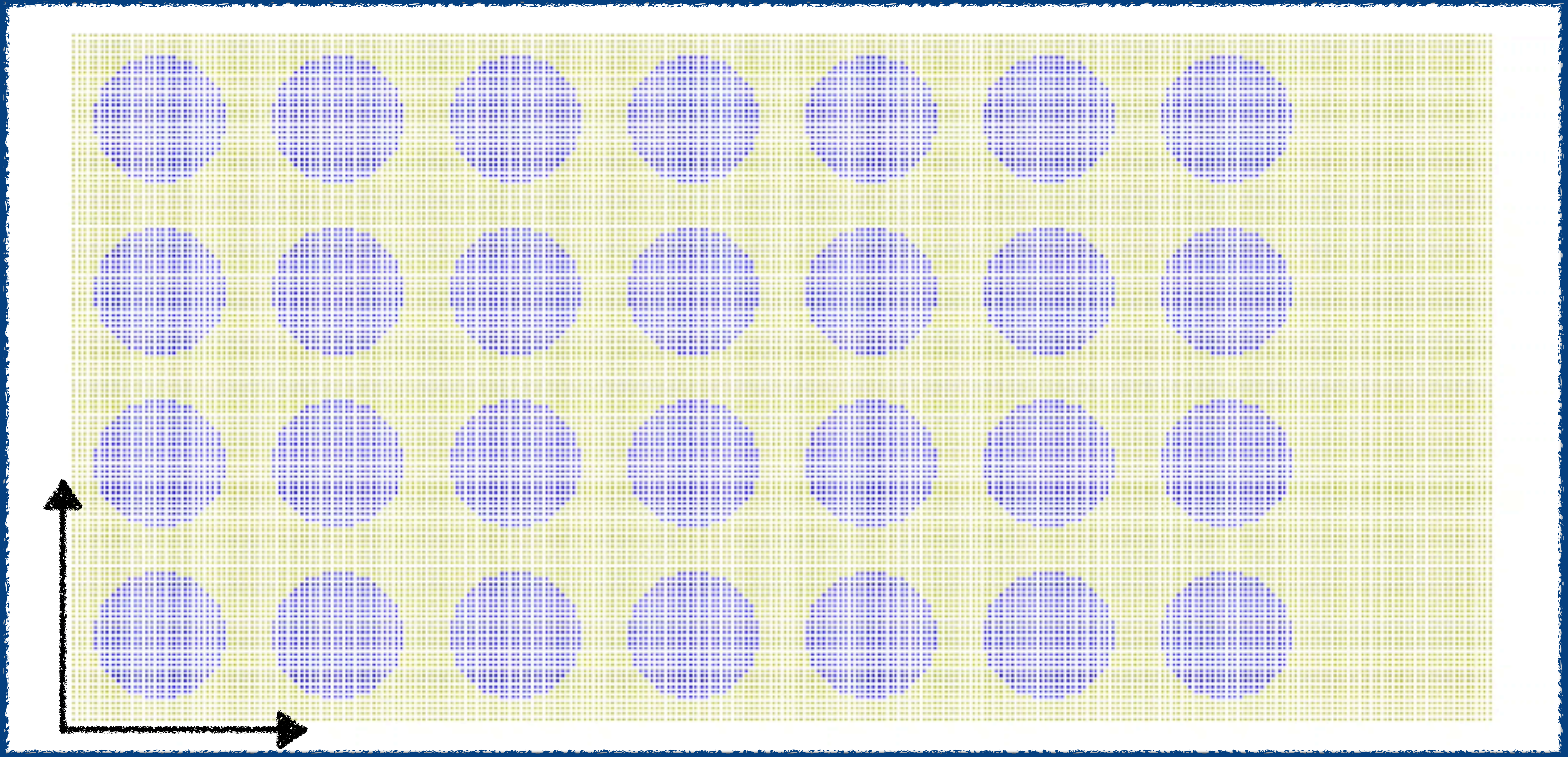
SPH - Smoothed Particle Hydrodynamics

- Proposed in 1977 by Monaghan & Gingold and Lucy
- Lagrangian approach
- Meshless method
- Discretization done using particles
- No need for special treatment of the interface

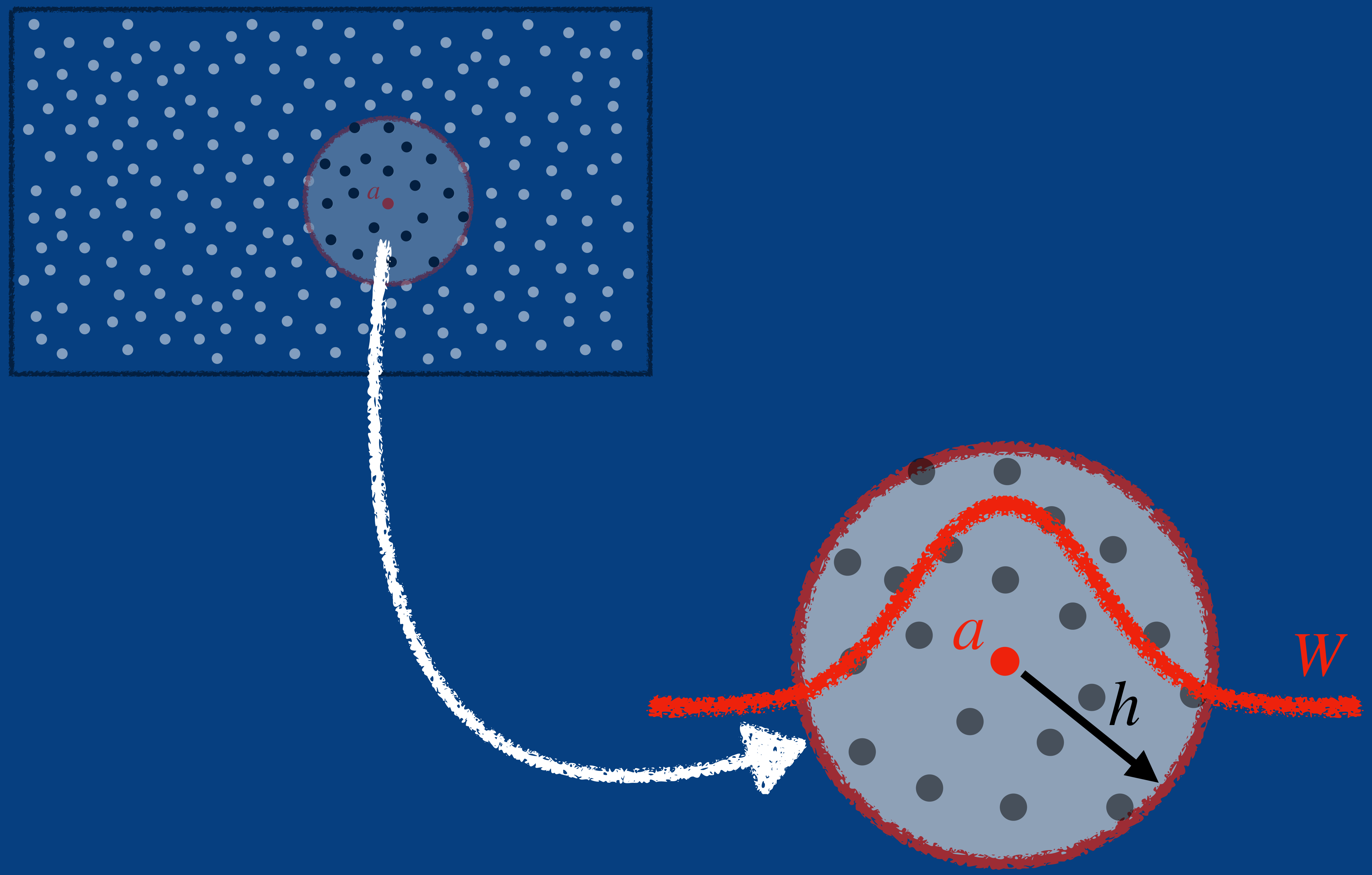


Animation of two-phase slug flow in a channel (taken from Olejnik et al. , 2016)

Gingold R.A, Monaghan J. J. (1977) *Smoothed particle hydrodynamics: theory and application to non-spherical starts,* RAS **181:**375-389
Lucy L. (1977) *A numerical approach to the testing of the fission hypothesis*, AAS **82:**1013-1024
Olejnik M, Szewc K., Pozorski J. (2016) *Modelling of the flow regime transition with the Smoothed Particle Hydrodynamics,* ICMF-2016

SPH - Smoothed Particle Hydrodynamics

Fluid Domain

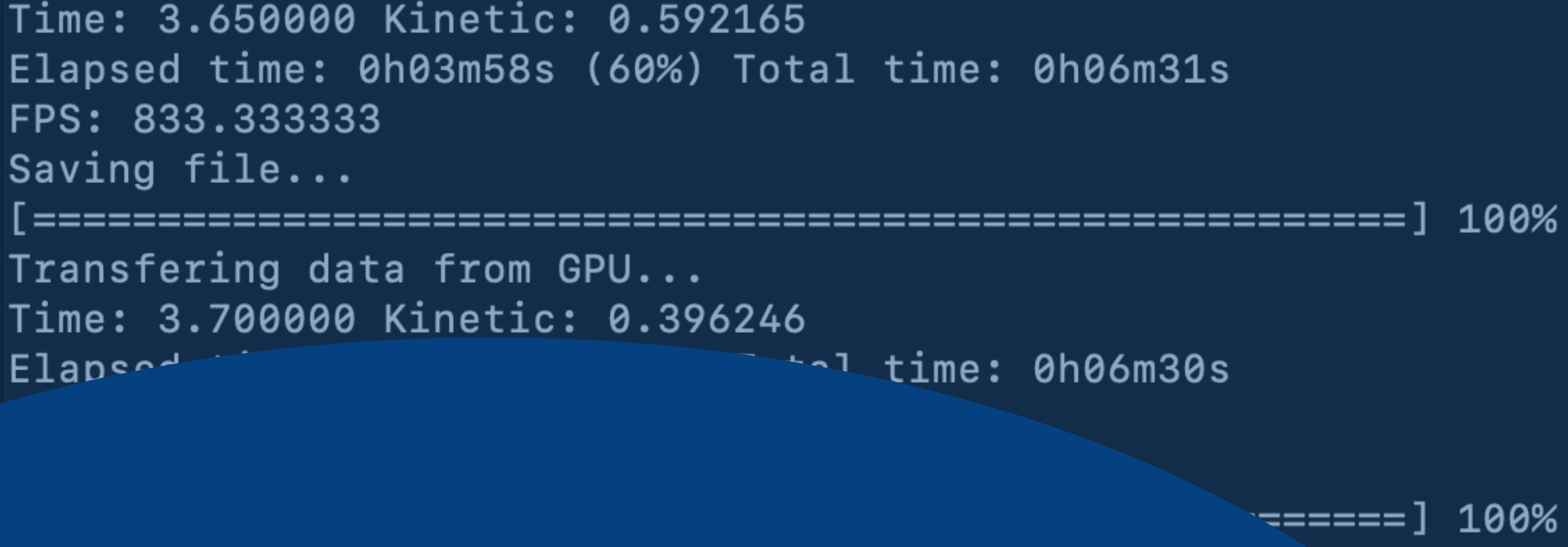


SPH approximation of a function:

$$\langle A(\mathbf{r})\rangle_a \simeq \sum_b A(\mathbf{r}_b)W(\mathbf{r}-\mathbf{r}_b,h)V_b$$

and its derivative:

$$\nabla A(\mathbf{r}_a) = \sum_b A(\mathbf{r}_b)\,\nabla W(\mathbf{r}_a-\mathbf{r}_b,h)V_b$$



```
Time: 3.650000 Kinetic: 0.592165
Elapsed time: 0h03m58s (60%) Total time: 0h06m31s
FPS: 833.333333
Saving file...
[==========================================================] 100%
Transfering data from GPU...
Time: 3.700000 Kinetic: 0.396246
Elaps                            tal time: 0h06m30s



                                                     ======] 100%
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Our in-house SPH code

Our in-house code was originally written by Dr. K.Szewc (2013-2016). It is written in C++, parallelized using GPU with CUDA .

The code has been further developed within our group since then.

Governing Equations

$$\left[\begin{aligned} &\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{u} \\ &\frac{d\mathbf{u}}{dt} = -\frac{1}{\varrho}\nabla p + \frac{1}{\varrho}\mathbf{f}_{st} + \mathbf{f}_b + \frac{1}{\varrho}\mathbf{f}_\nu \\ &\frac{d\mathbf{r}}{dt} = \mathbf{u} \\ &p = s^2(\rho - \rho_0) \end{aligned}\right.$$

$$\left[\begin{aligned} &\rho_a = m_a\sum_b W_{ab} = m_a\theta_a \\ &\left\langle\frac{d\mathbf{u}}{dt}\right\rangle_a = \frac{1}{m_a}\sum_b\left(\frac{p_a}{\theta_a} - \frac{p_b}{\theta_b}\right)\nabla_a W_{ab} + \left\langle\frac{\sigma\kappa}{\rho}\hat{\mathbf{n}}\right\rangle_a + \mathbf{f}_b + \left\langle\frac{1}{\varrho}\nabla\cdot\boldsymbol{\tau}\right\rangle_a \\ &\left\langle\frac{d\mathbf{r}}{dt}\right\rangle_a = \mathbf{u}_a \\ &p_a = s_a^2(\rho_a - \rho_{a,0}) \end{aligned}\right.$$

Weakly Compressible SPH

Hu X.Y. Adams N.A. (2006) *A multi-phase SPH method for macroscopic and mesoscopic flows*. J. Comp. Phys. **123:**844-861
Violeau D. (2012) *Fluid Mechanics and the SPH Method*. Oxford University Press
Morris J. (2000), *Simulating surface tension with smoothed particle hydrodynamics*, Int. J. Numer. Methods Fluids **33:**333-353
Olejnik M., Szewc K., Pozorski J. (2017), *SPH with dynamical smoothing length adjustment based on the local flow kinematics*, J. Comput. Phys. **348:**23-44

Modified Viscous Force

$$\nabla \cdot \boldsymbol{\tau} = \nabla \cdot (\mu \nabla \mathbf{u}) + \nabla \cdot [\mu(\nabla \mathbf{u})^T]$$

This formulation is based on the work by Violeau (2012), we account for a considerable variability of viscosity across the interface.

The difference is on the definition of the dynamic viscosity, instead of the arithmetic we are proposing the harmonic mean:

$$\bar{\mu}_{ab} = \frac{2\mu_a\mu_b}{\mu_a + \mu_b}$$

$$\left\langle \frac{1}{\varrho}\nabla \cdot \boldsymbol{\tau} \right\rangle_a = \frac{1}{\rho_a}\sum_b \left[V_b \frac{\bar{\mu}_{ab}}{r_{ab}}(n+2)(\mathbf{u}_{ab} \cdot \mathbf{e}_{ab})\mathbf{e}_{ab}\frac{\partial W}{\partial r_{ab}} + V_b \frac{\bar{\mu}_{ab}}{r_{ab}}\mathbf{u}_{ab}\frac{\partial W}{\partial r_{ab}} \right]$$

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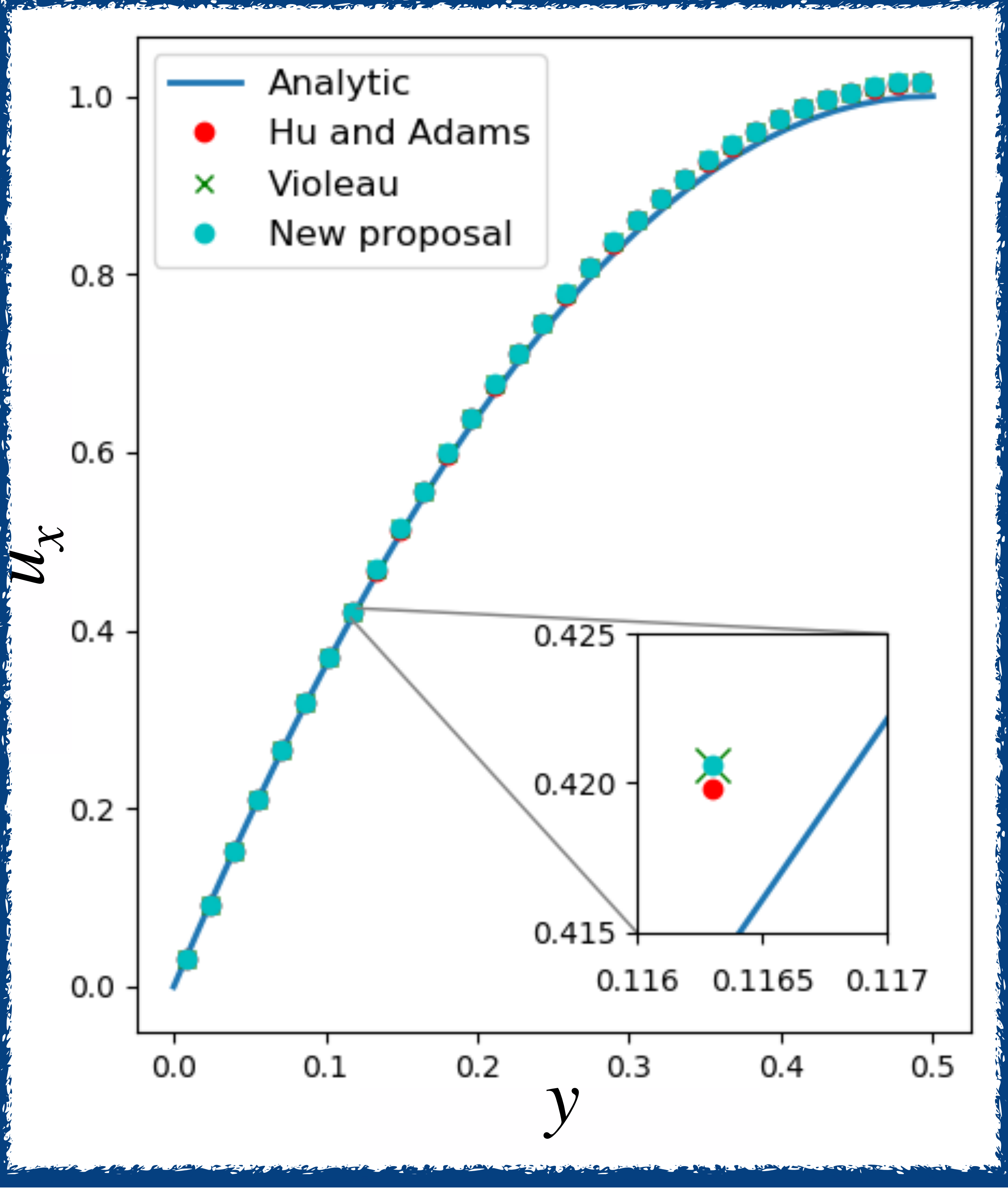
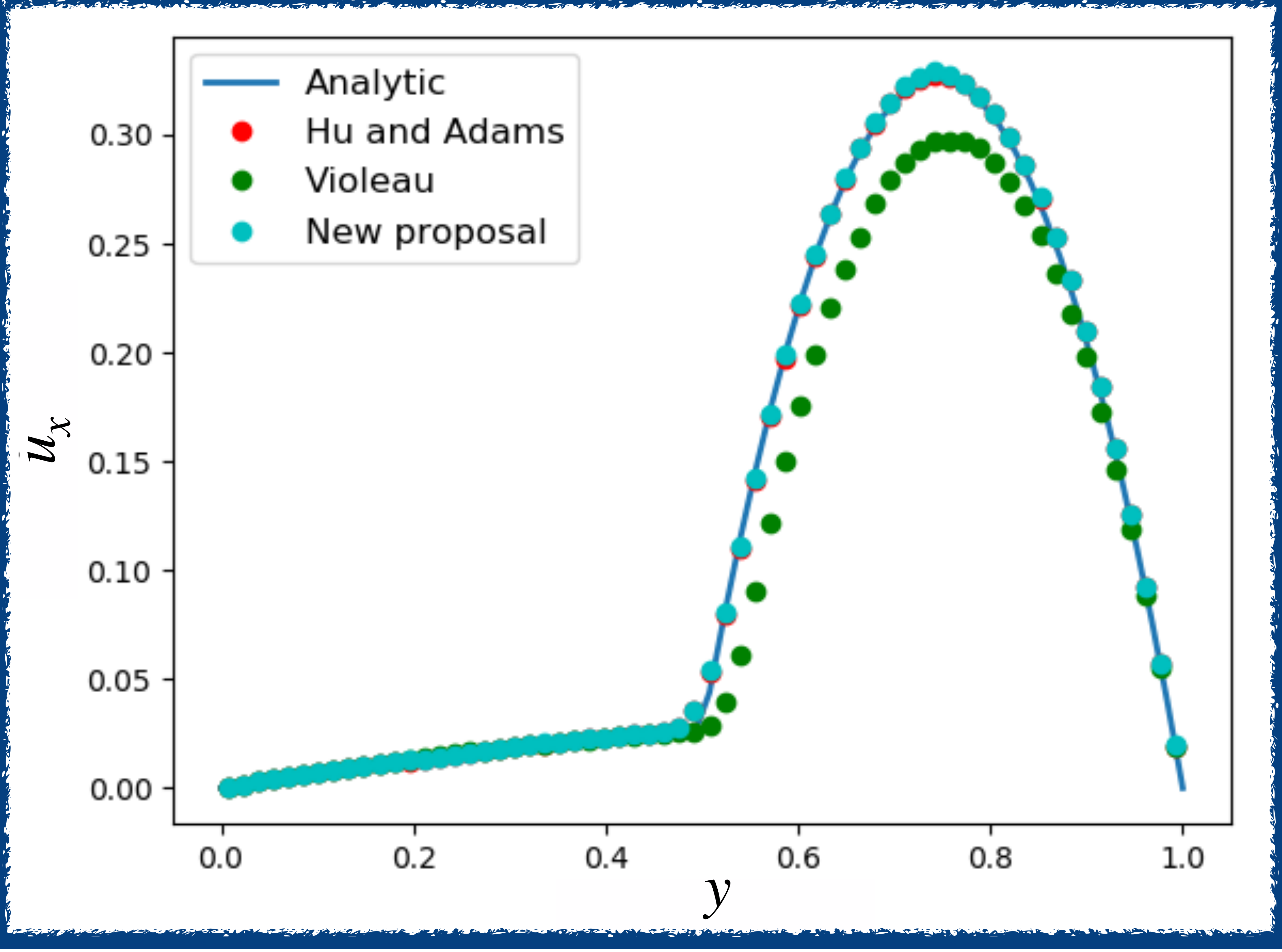
Modified Viscous Force

$$\left\langle \frac{1}{\varrho}\nabla\cdot\boldsymbol{\tau} \right\rangle_a = \frac{1}{\rho_a}\sum_b \left[V_b \frac{\bar{\mu}_{ab}}{r_{ab}}(n+2)(\mathbf{u}_{ab}\cdot\mathbf{e}_{ab})\mathbf{e}_{ab}\frac{\partial W}{\partial r_{ab}} + V_b \frac{\bar{\mu}_{ab}}{r_{ab}}\mathbf{u}_{ab}\frac{\partial W}{\partial r_{ab}} \right]$$

Single-phase Poiseuille flow



Two-phase Poiseuille flow



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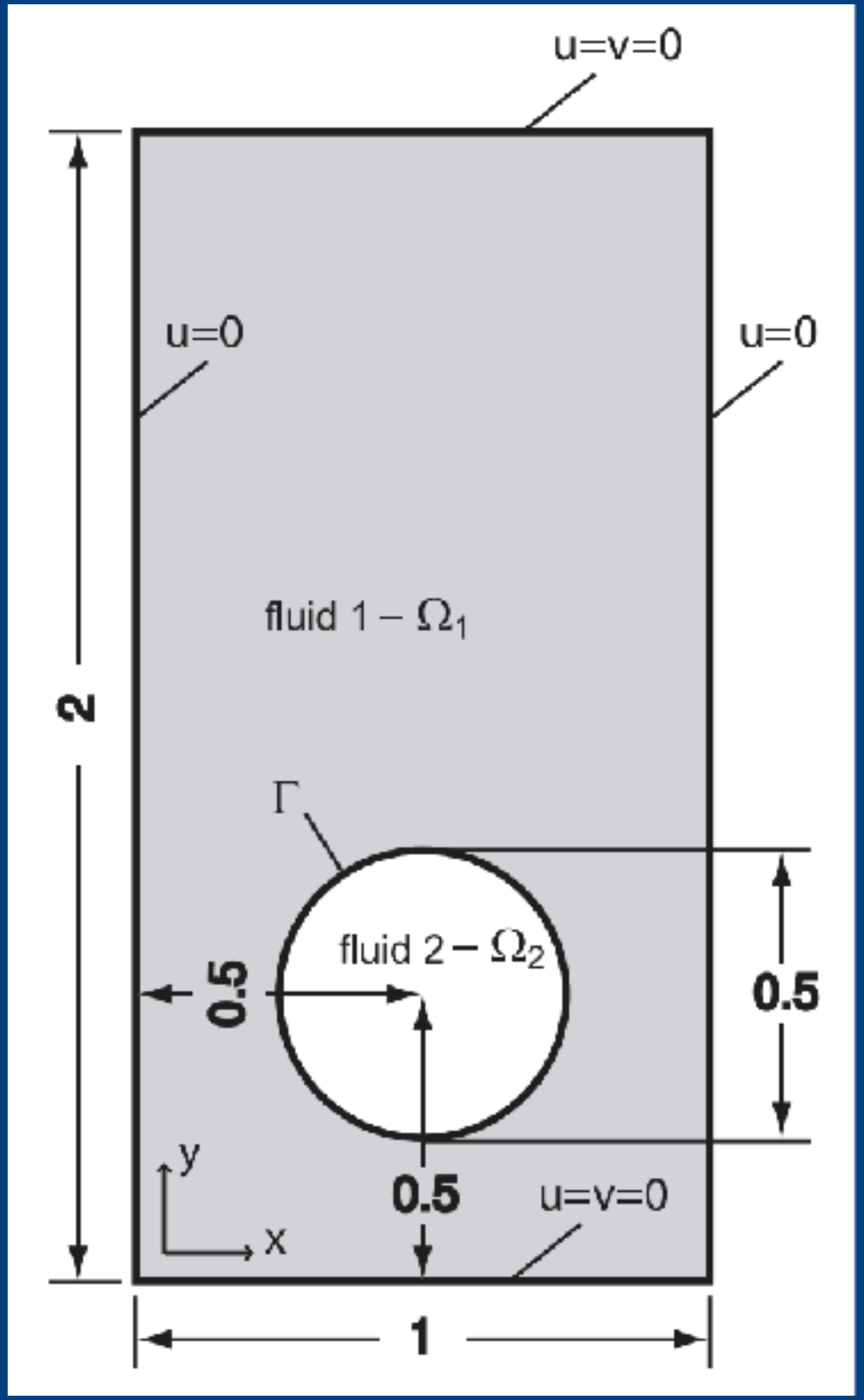
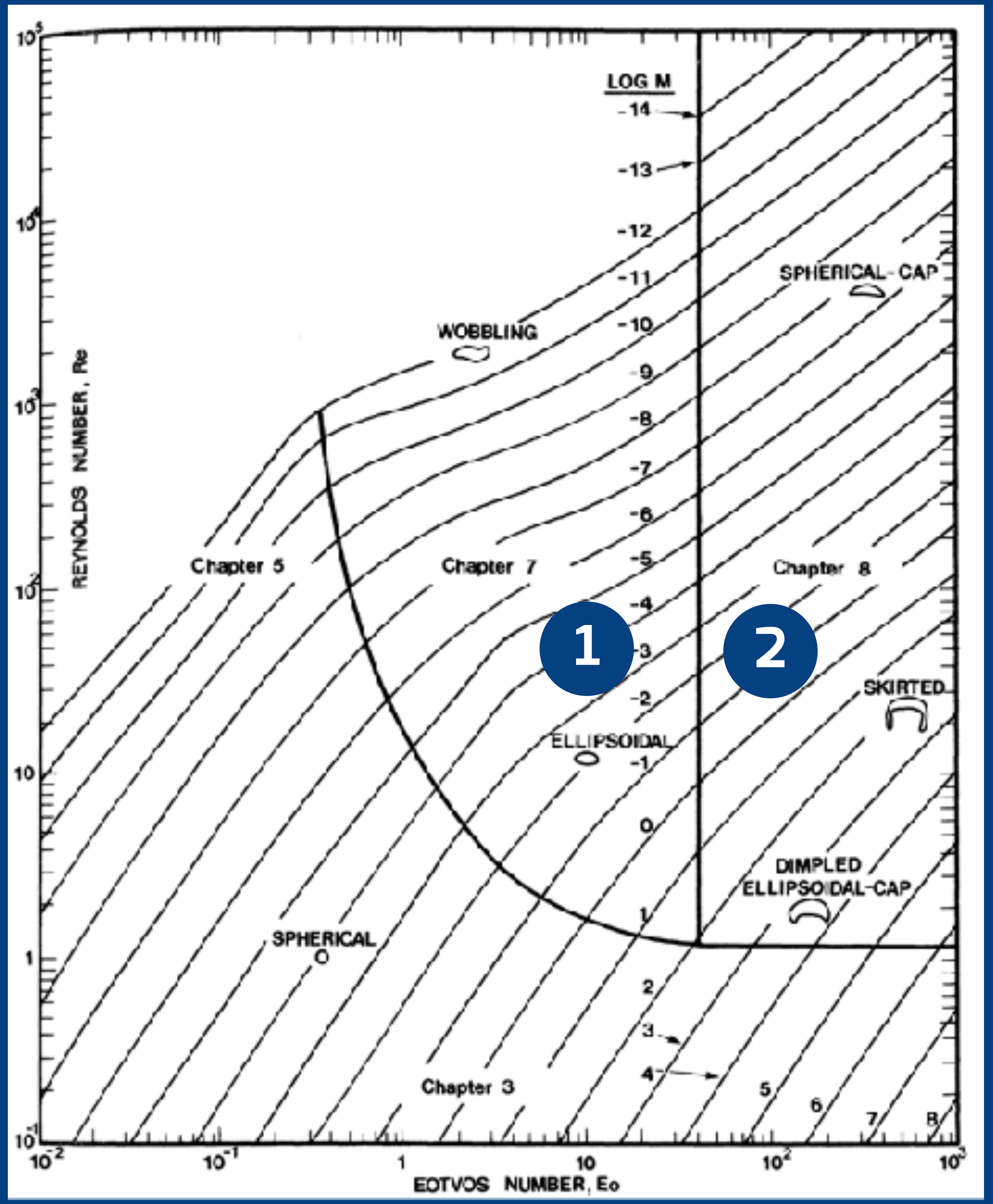
The rising bubble

The rising bubble case by Hysing et al.



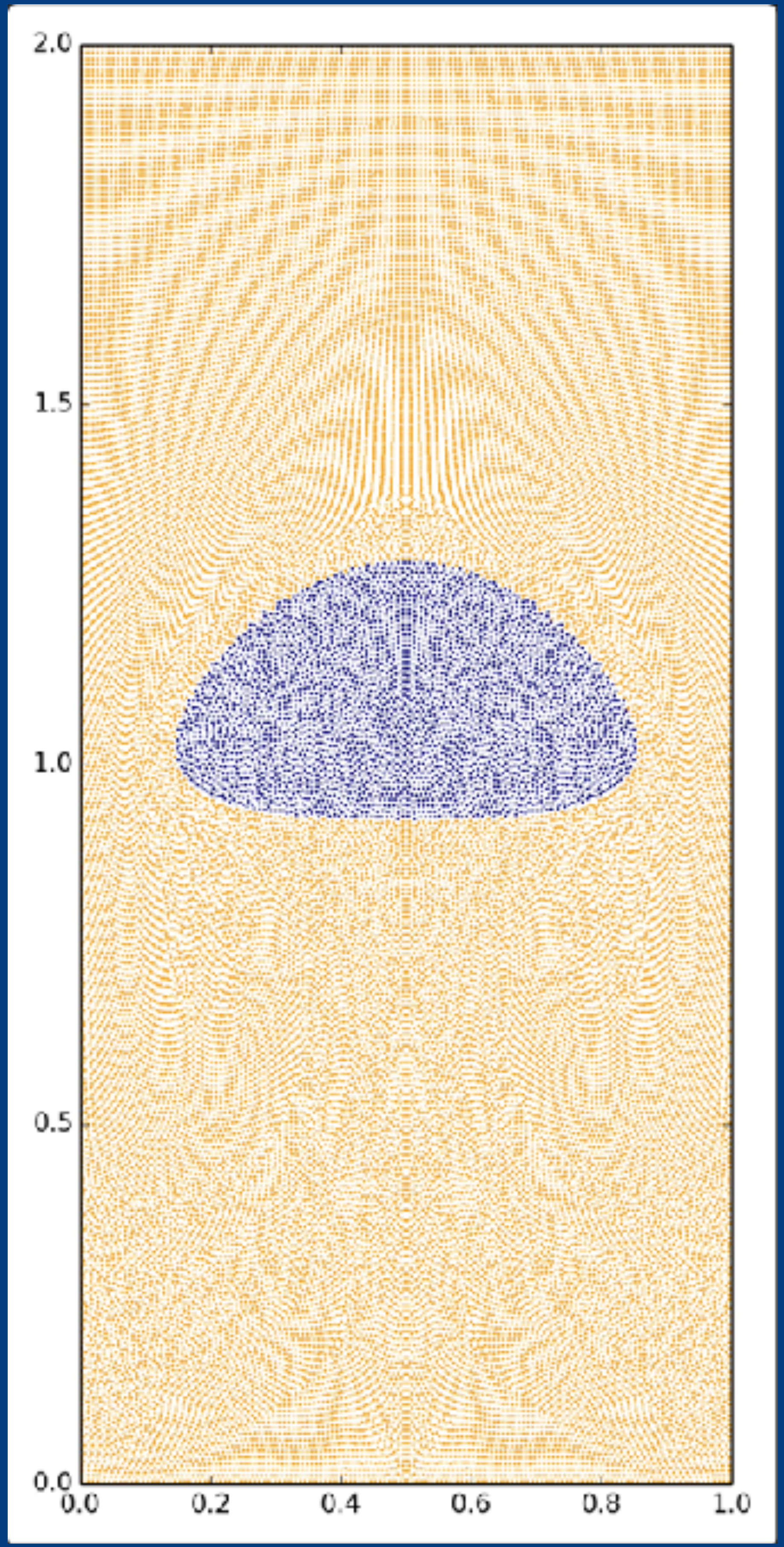


	ρ_1	ρ_2	μ_1	μ_2	g	σ	Re	Eo	ρ_1/ρ_2	μ_1/μ_2
1	1000	100	10	1	0.98	24.5	35	10	10	10
2	1000	1	10	0.1	0.98	1.96	35	125	1000	100

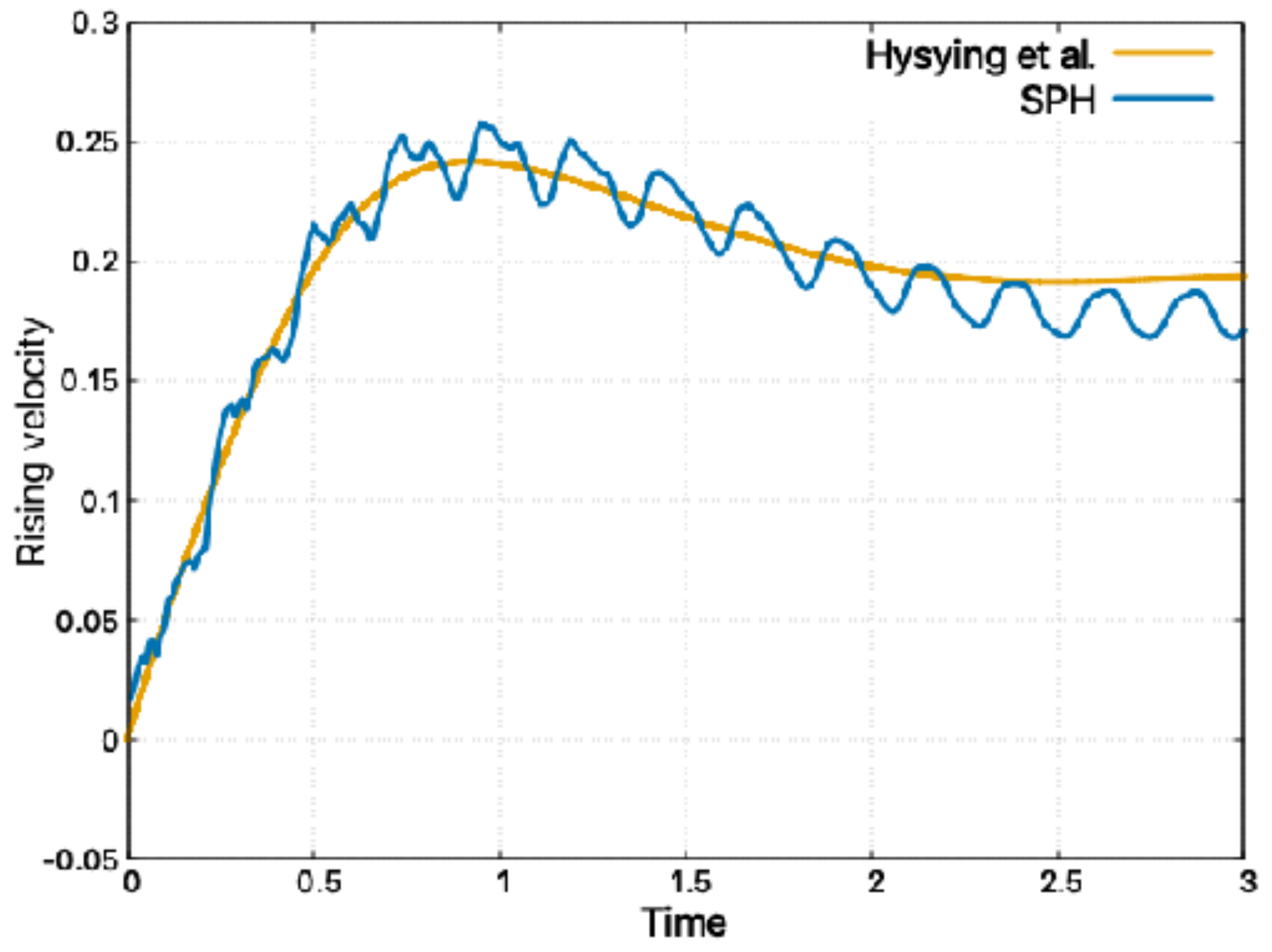
Hysing et al. (2008) *An immersed finite element method for permeability determination of a porous media*, Int. J. Numer. Meth. Fl. **60:**1259–1288
Clift, Grace, Weber, Bubbles, Drops, and Particles, Int. J. Numer. Meth. Fl. (1978)

The rising bubble

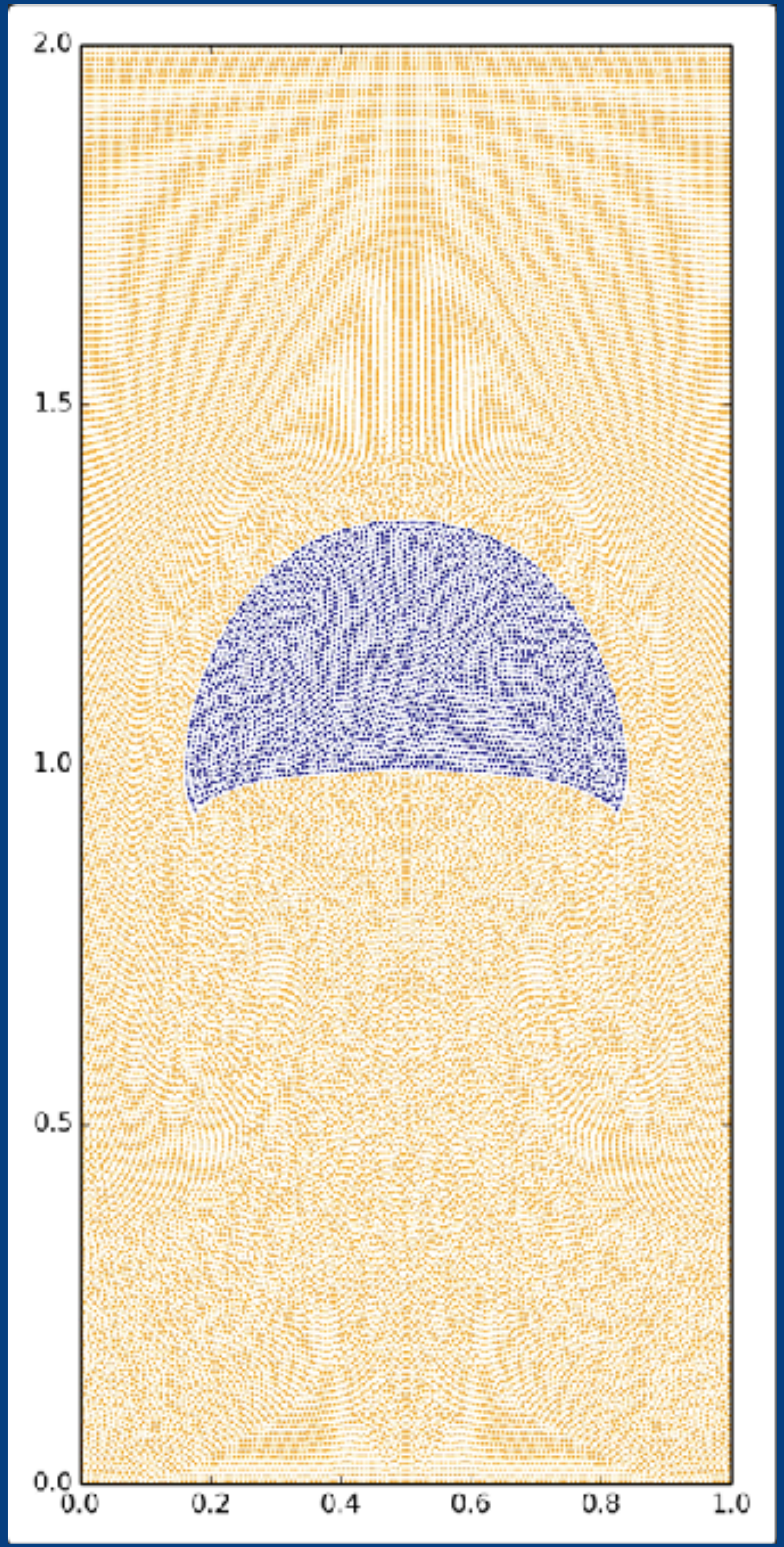
1st Regime



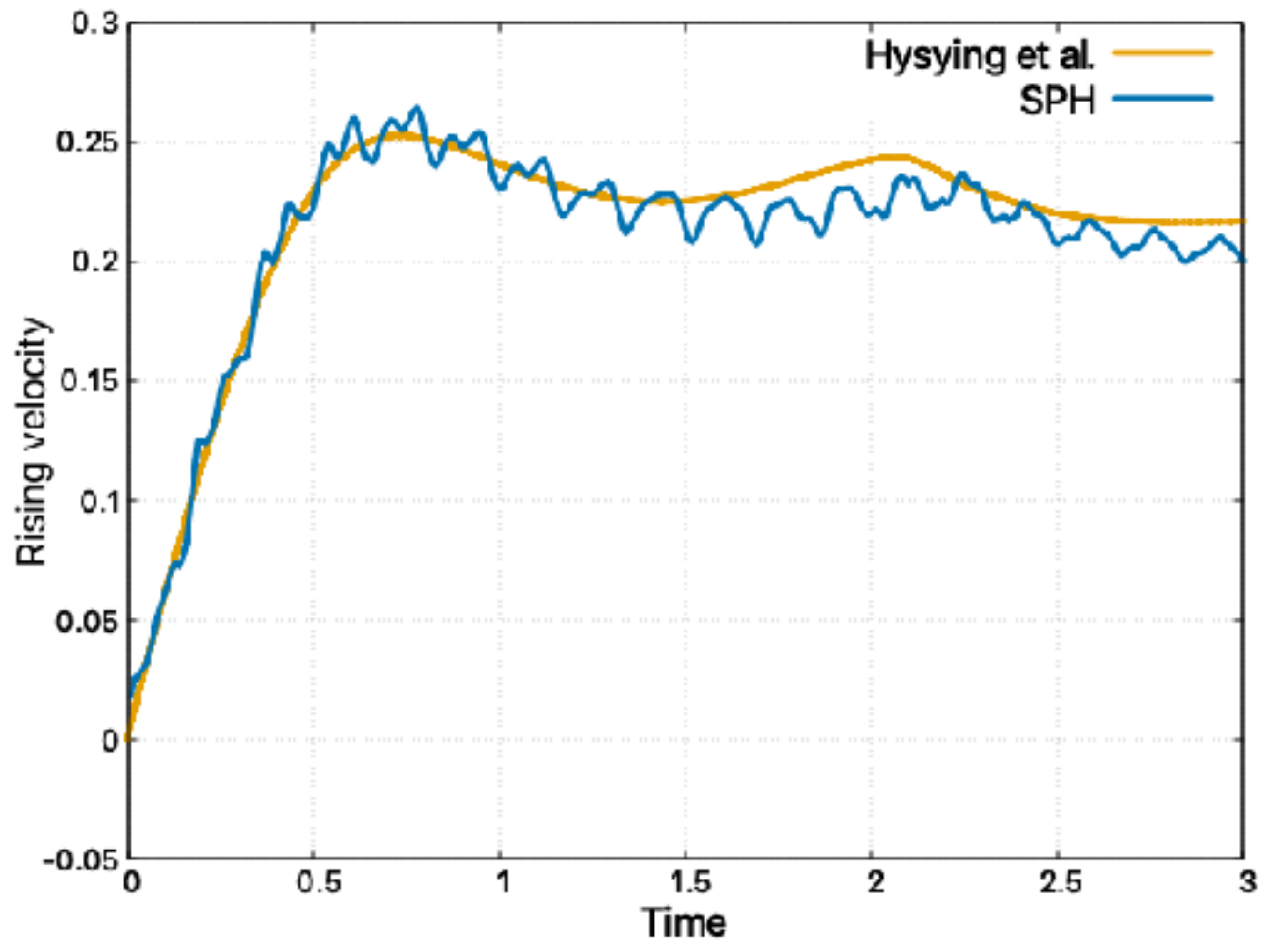
Rising velocity



2nd Regime



Rising velocity



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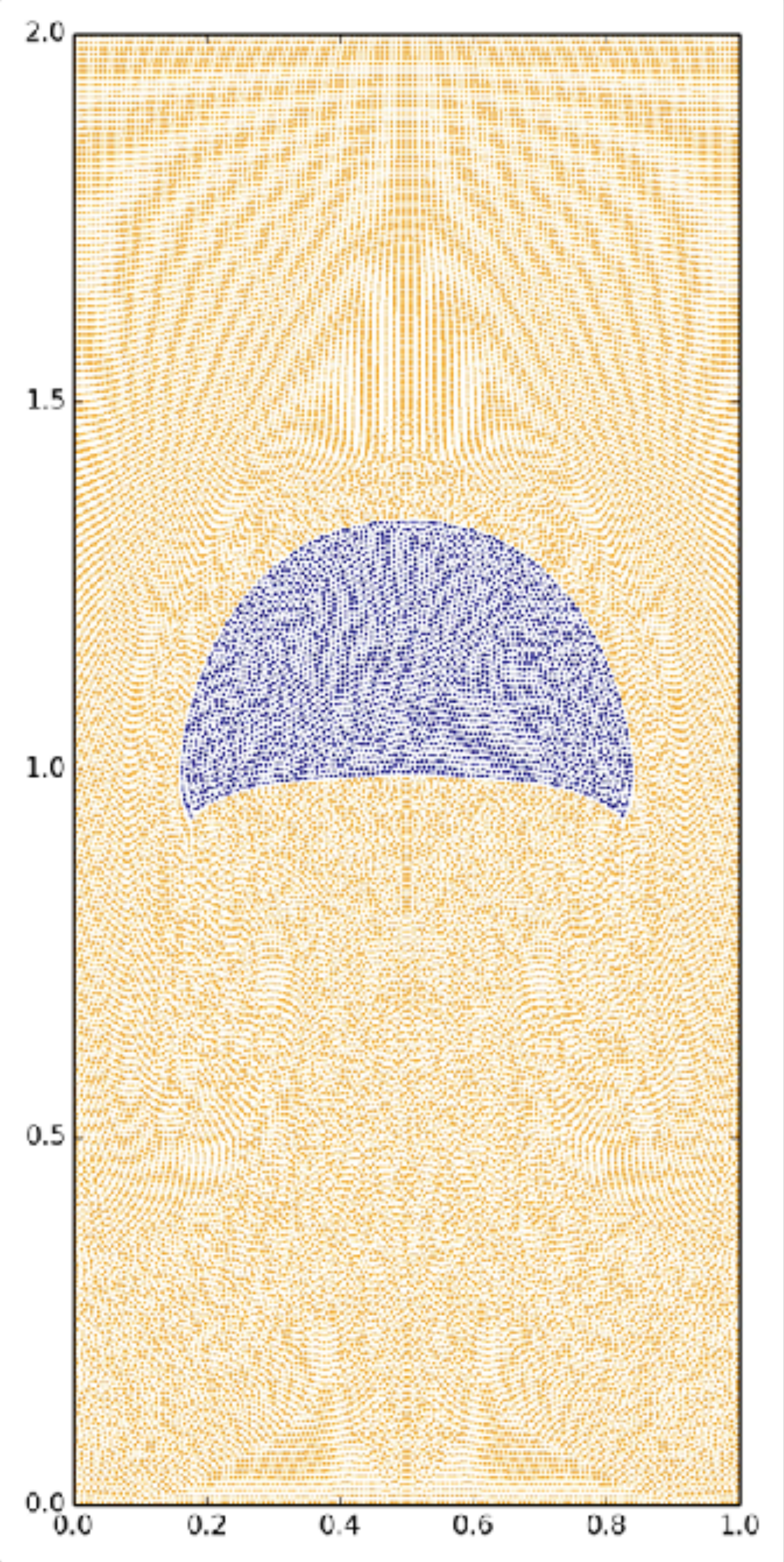
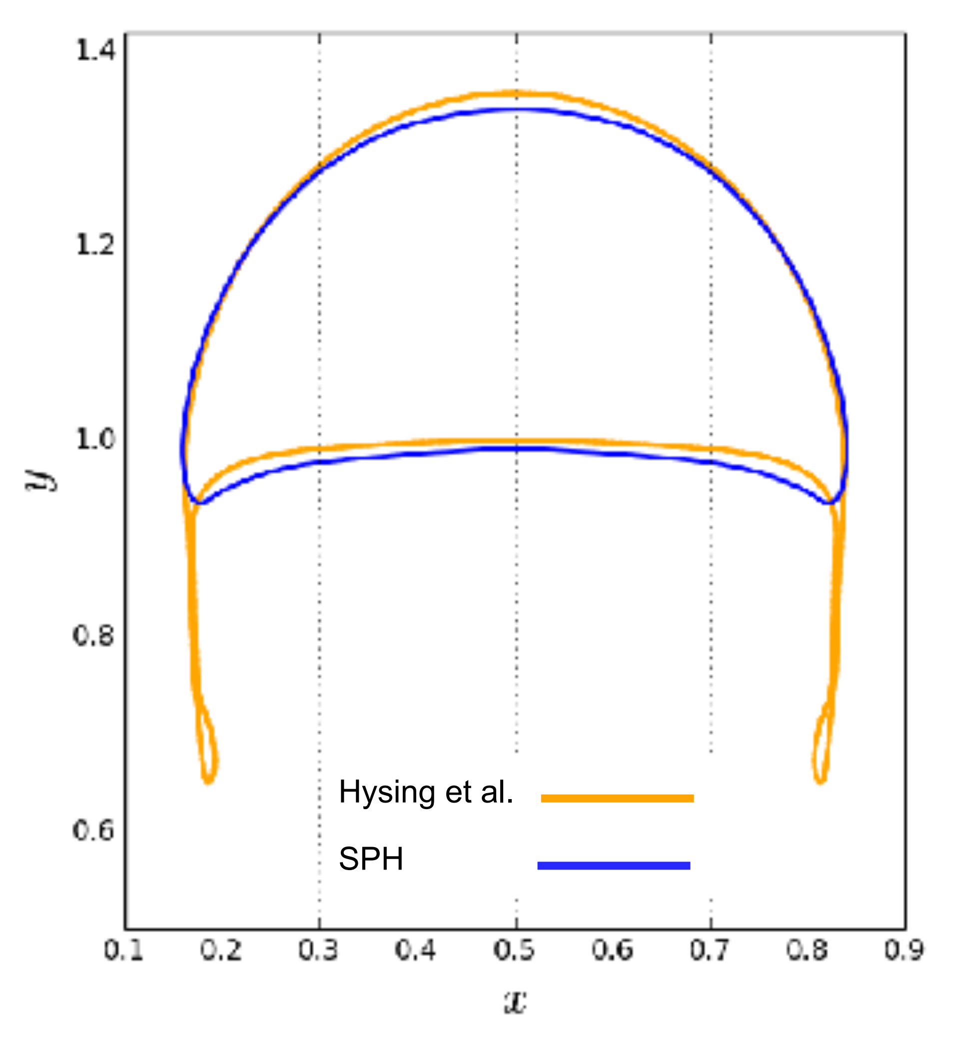
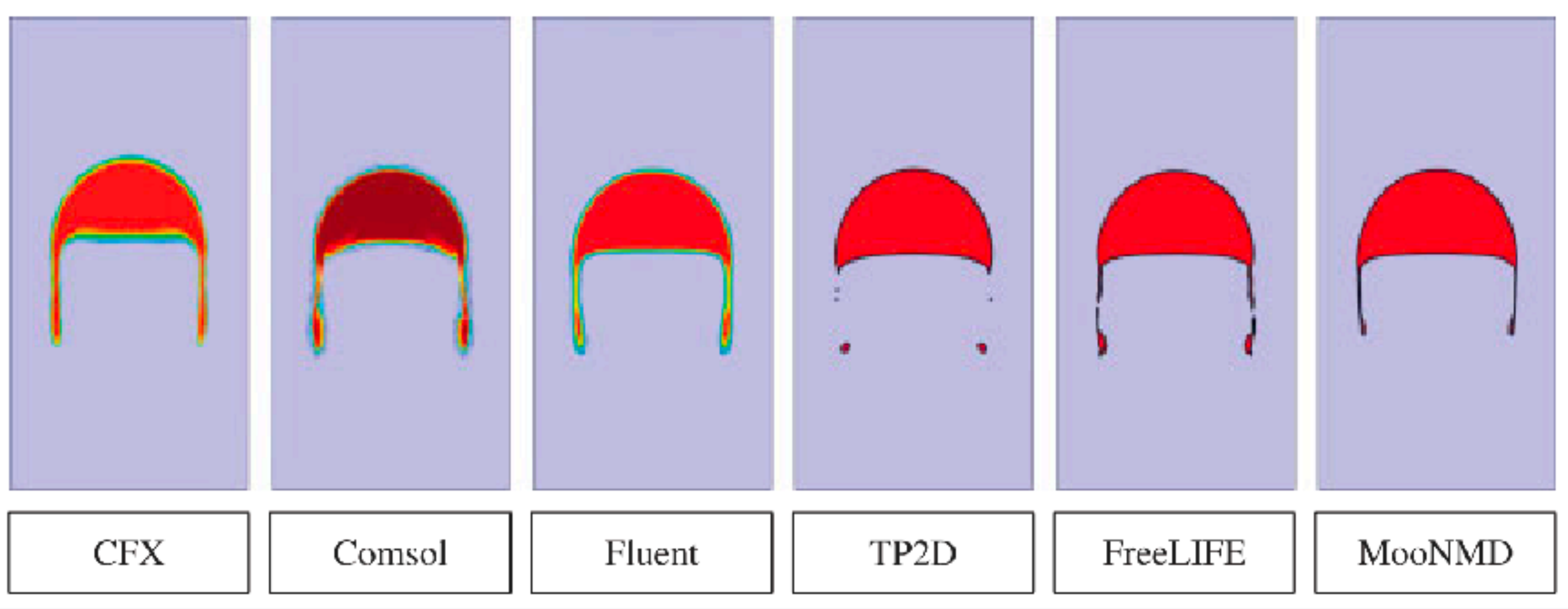
The rising bubble

2nd Regime







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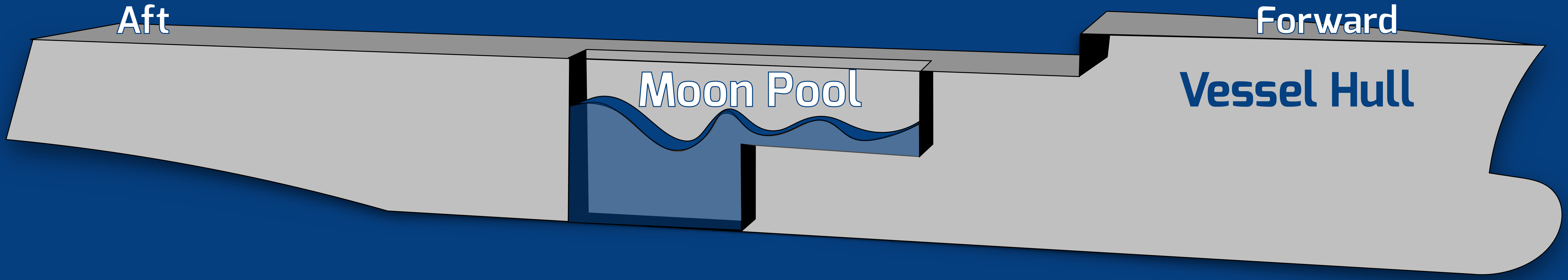
The Moon Pool



The moon pool is an opening through the hull of vessels from the deck to the bottom, typical of drill ships, offshore platforms, diving vessel and others.

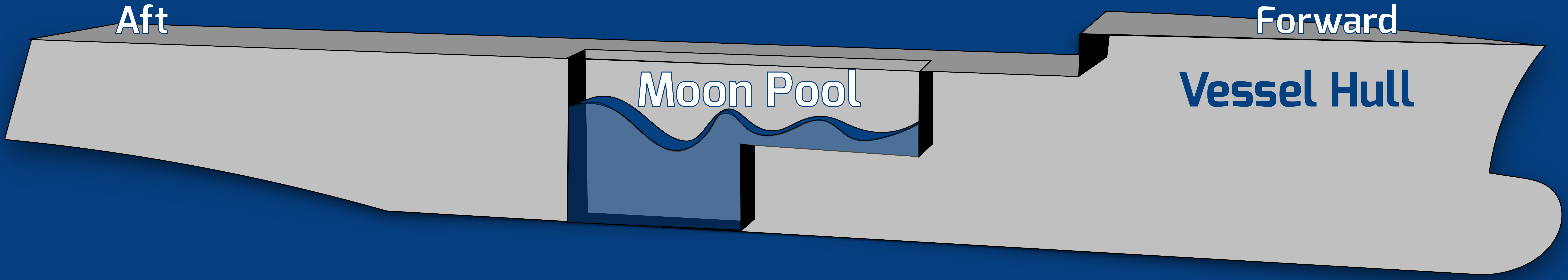
The moon pool is designed to provide a safe environment for underwater activities, preventing operation in open sea.

The recessing (L-shape) type of moon pool is preferred for drilling.

In general, the moon pool is subjected to violent water motion; some research has been done to improve it, but very little on the recessing moon pool.

Hammergren E. Törnblom, John (2012) *Effect of the Moonpool on the Total Resistance of a Drillship, MSc Thesis*
Guo X., Lu H., Yang J., Peng T., 2017, Resonant water motions within a recessing type moonpool in a drilling vessel, *Ocean Engineering* **129** 228
Machado L (2020) *Moonpool Dimensions and Position Optimization with Genetic Algorithm of a Drillship in Random Seas, PhD Thesis*

The Moon Pool



There are two types of water motion inside the moon pool:

1. *piston motion* - vertical rise;
2. *sloshing* - horizontal oscillations between walls.

The sloshing is affecting more the moon pool with elongated shape.

Furthermore, SPH easily handles interfaces and free-surface flows.

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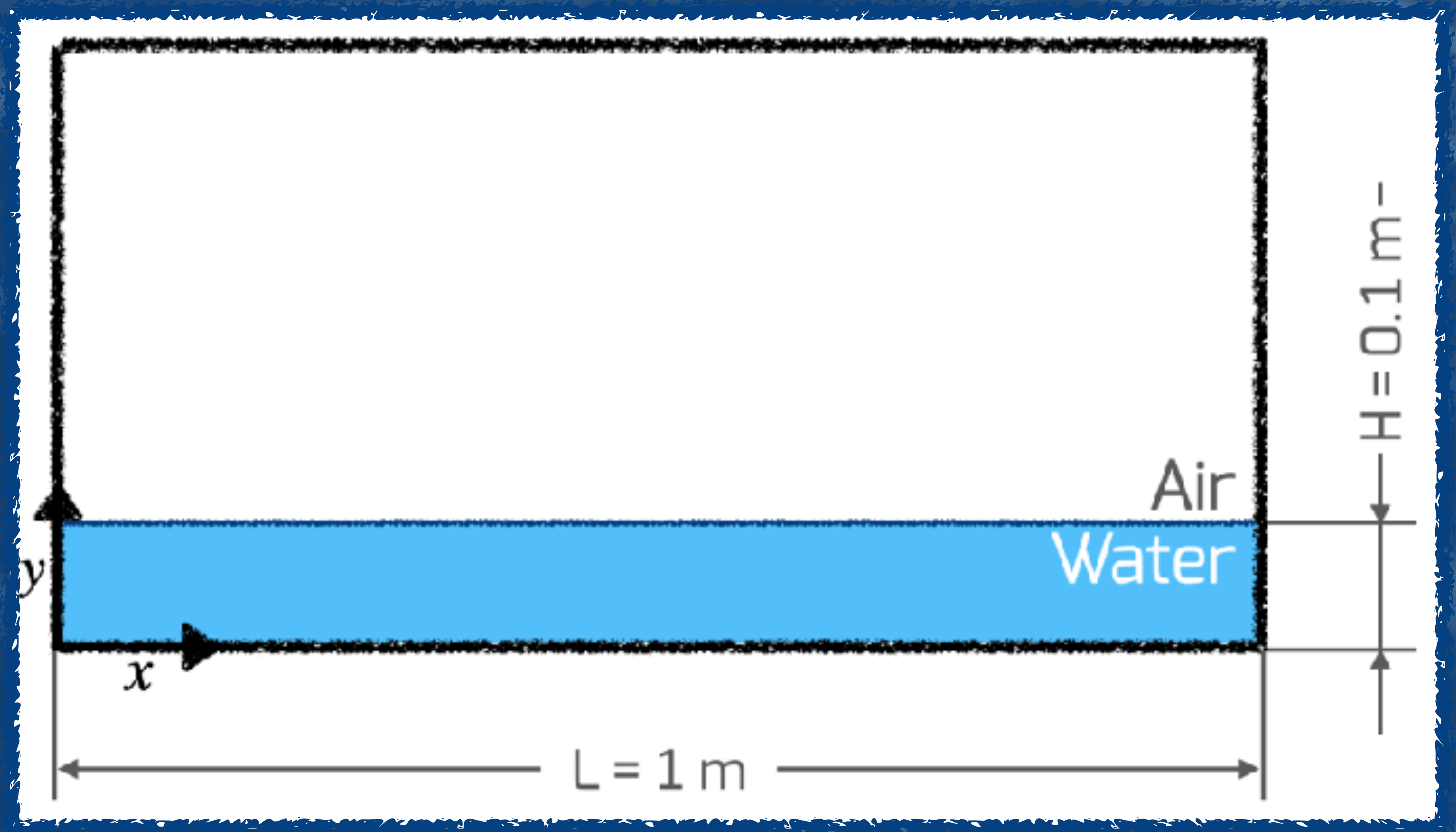
Sloshing validation



Horizontal sloshing force

$$\mathrm{f}_x(t) = A(2\pi f_w)^2 \cdot \sin(2\pi f_w t)$$

$$f_w = k f_0$$

$$f_{(m-1)} = \frac{\omega_m}{2\pi}$$ **with** $m = 0$

$$\omega_m = \sqrt{\|\mathbf{g}\| \frac{\pi m}{L} \tanh\left(\frac{\pi m}{L} H\right)}$$

Benchmark:

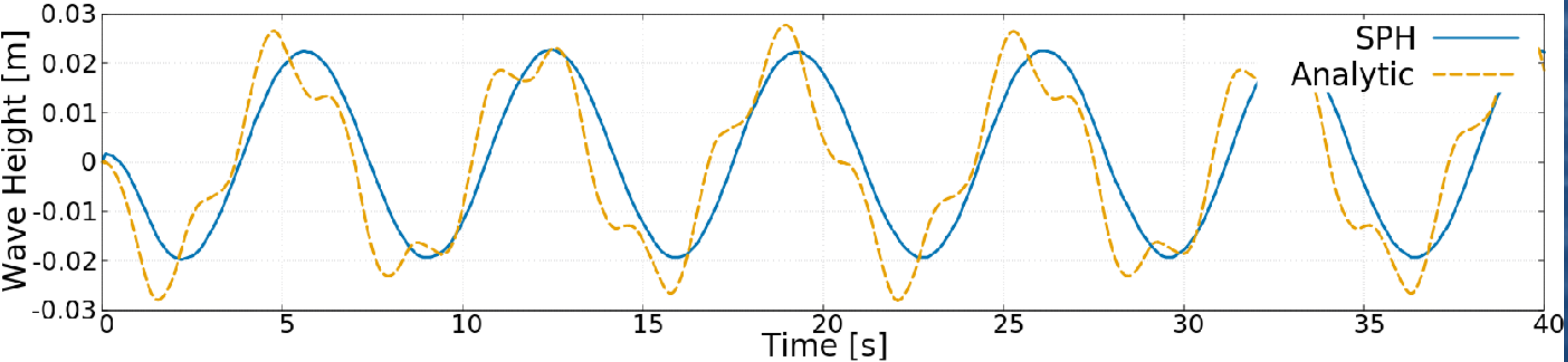
Sloshing tank by Green and Peiró (2018)

$N = 32768$ $\Delta r \simeq 0.0039\,\mathrm{m}$

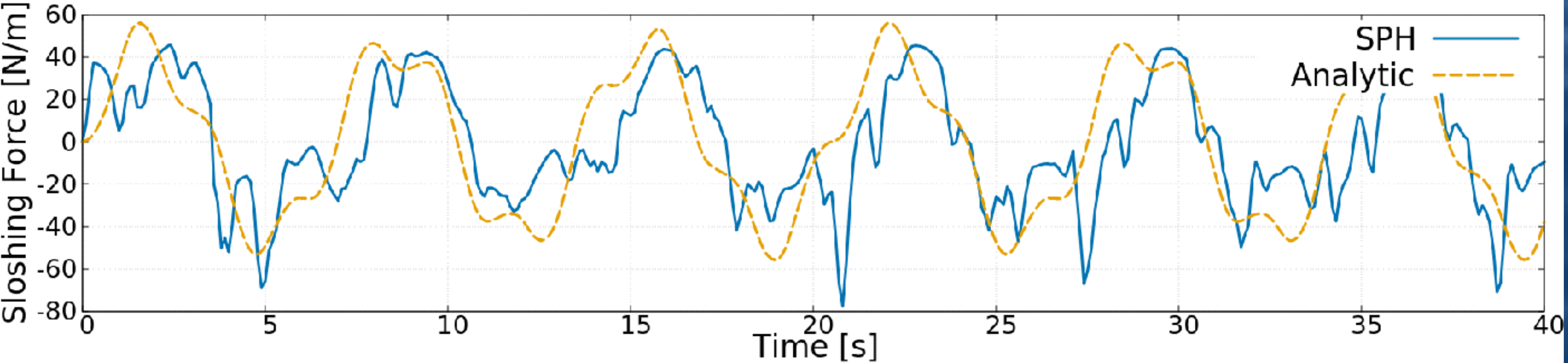
Colagrossi et al., A study of violent sloshing wave impacts using an improved SPH method, J. Hydraul. Res. (2010)
Faltinsen O.M. (2009) *Sloshing* Cambridge University Press
Gotoh et al., On enhancement of Incompressible SPH method for simulation of violent sloshing flows, Appl. Ocean Res. (2014)
Green and Peiró, Long duration SPH simulations of sloshing in tanks with a low fill ratio and high stretching, Comput. Fluids (2018)
Zheng et al., Multiphase smoothed particle hydrodynamics modeling of forced liquid sloshing, Int. J. Numer. Methods Fluids (2021)

Sloshing validation

Wave Elevation



Sloshing Force



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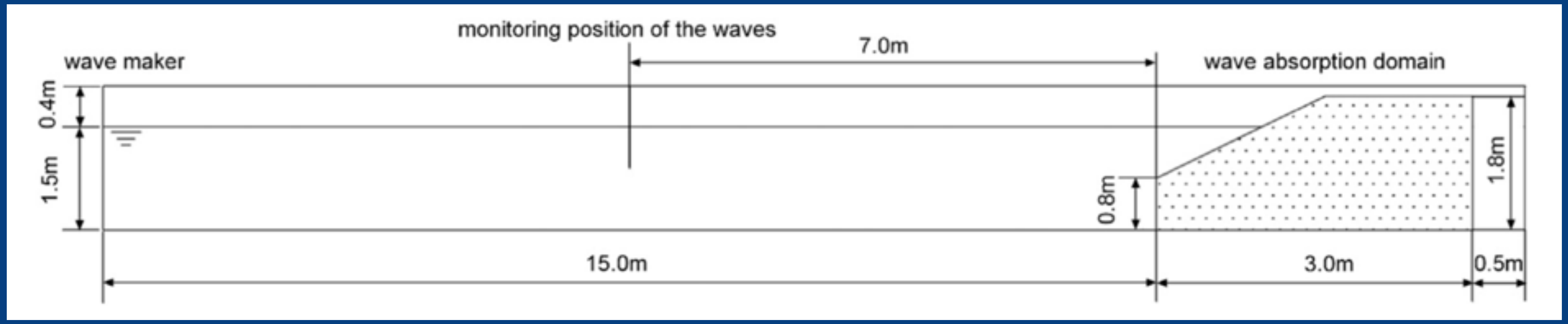
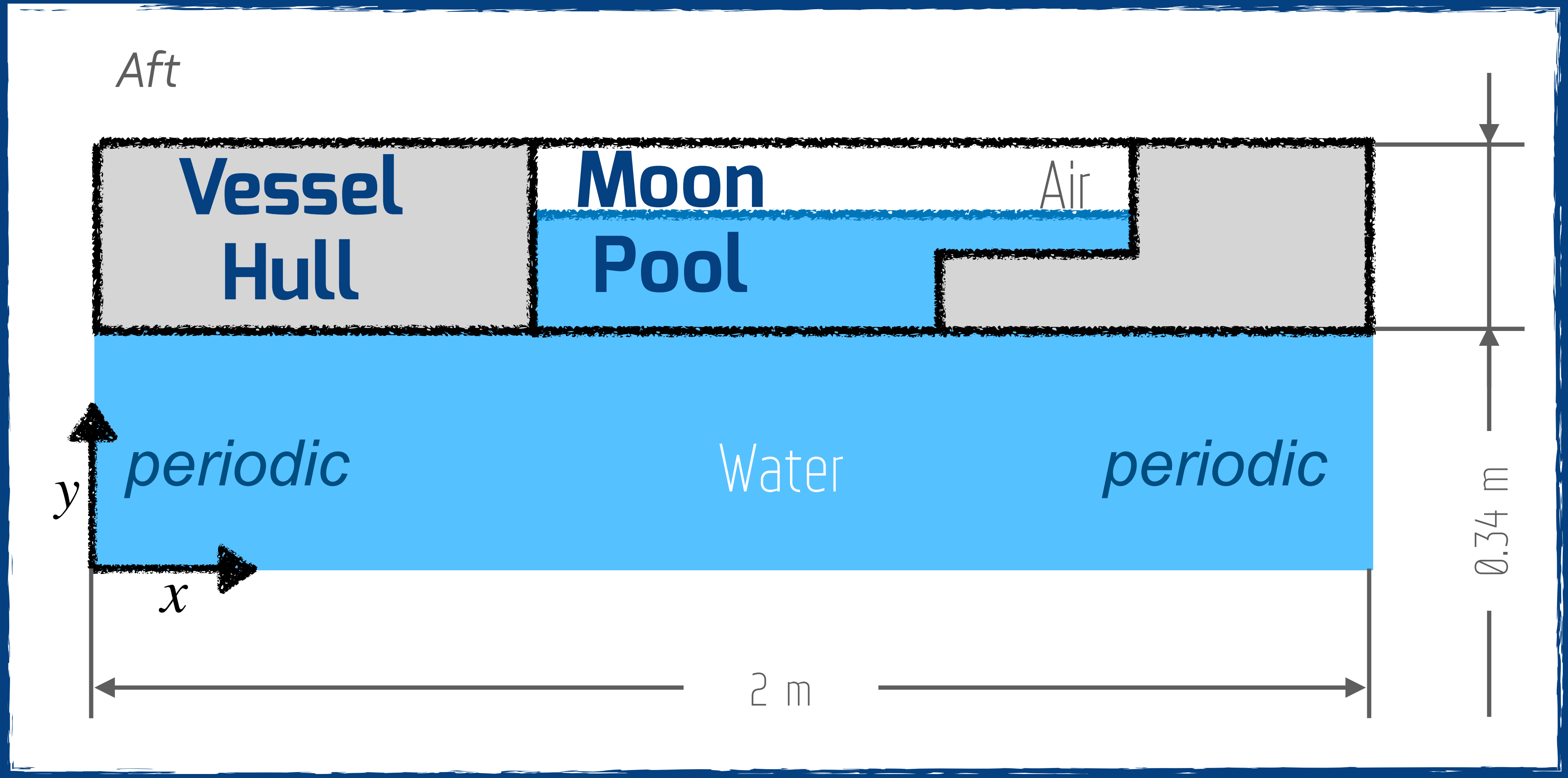
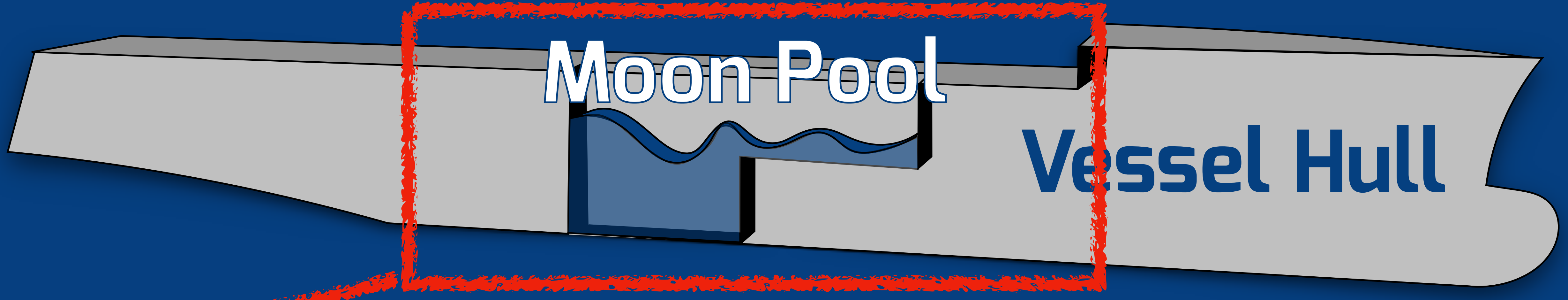
Our Moon Pool based on Guo et al. (2017)

Experimental

Numerical







Our ***2D multiphase SPH*** moon pool model for captive vessel, based on the model by Guo et al. (2017), scaled 1:50.

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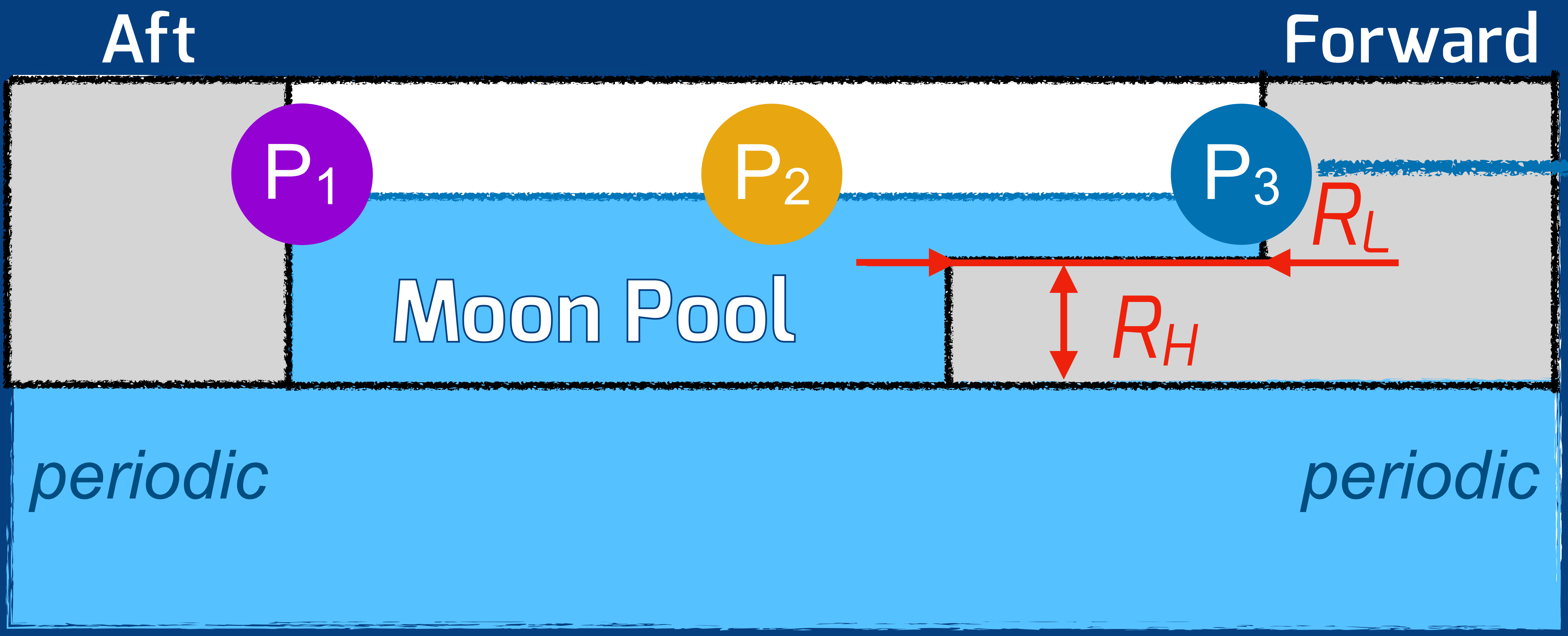

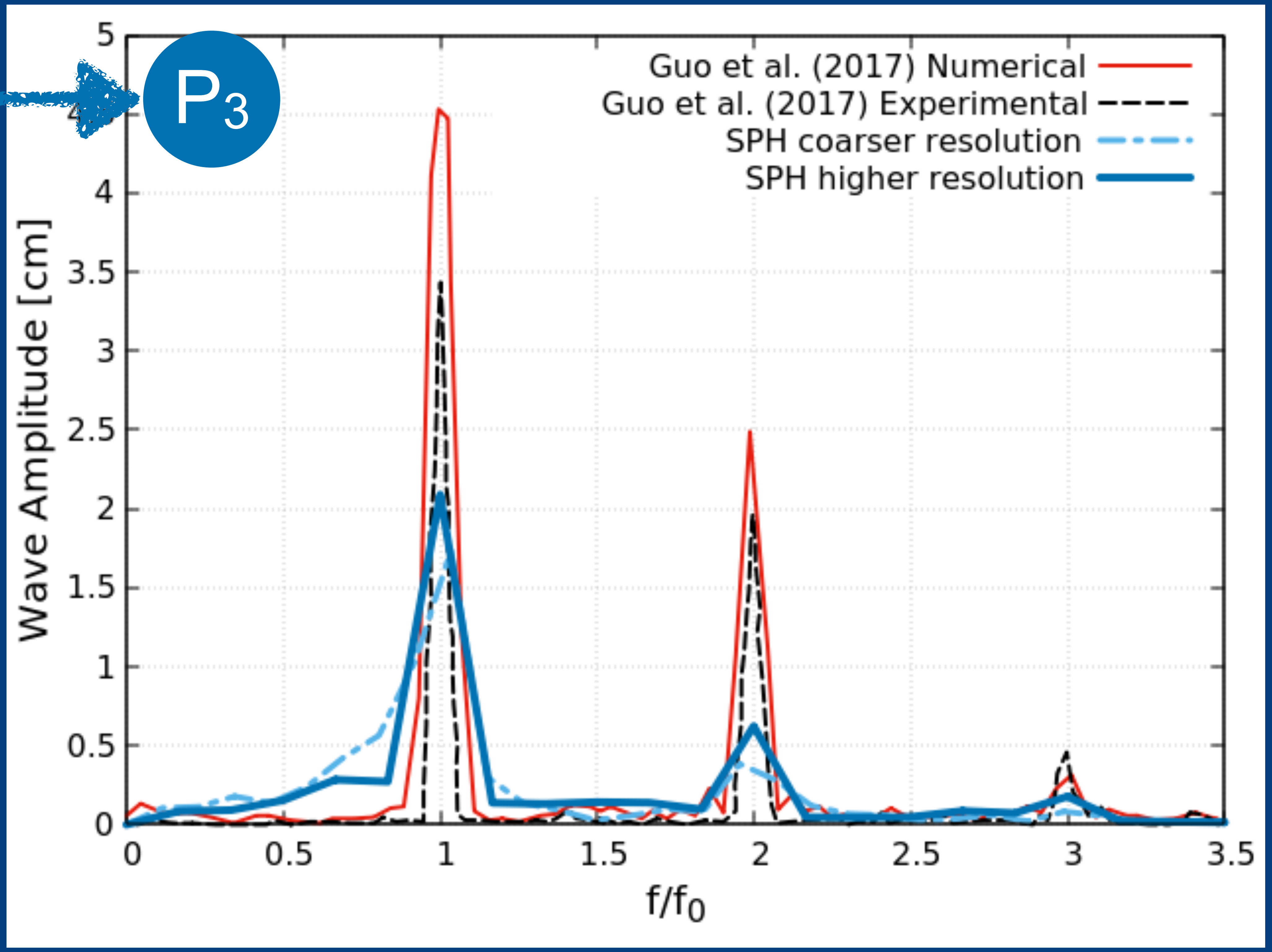

Sloshing horizontal force acting on the water phase

$N = 131072$ $\Delta r \simeq 0.0039\,\mathrm{m}$

Resonant frequency $f_0 = 0.87\,\mathrm{Hz}$

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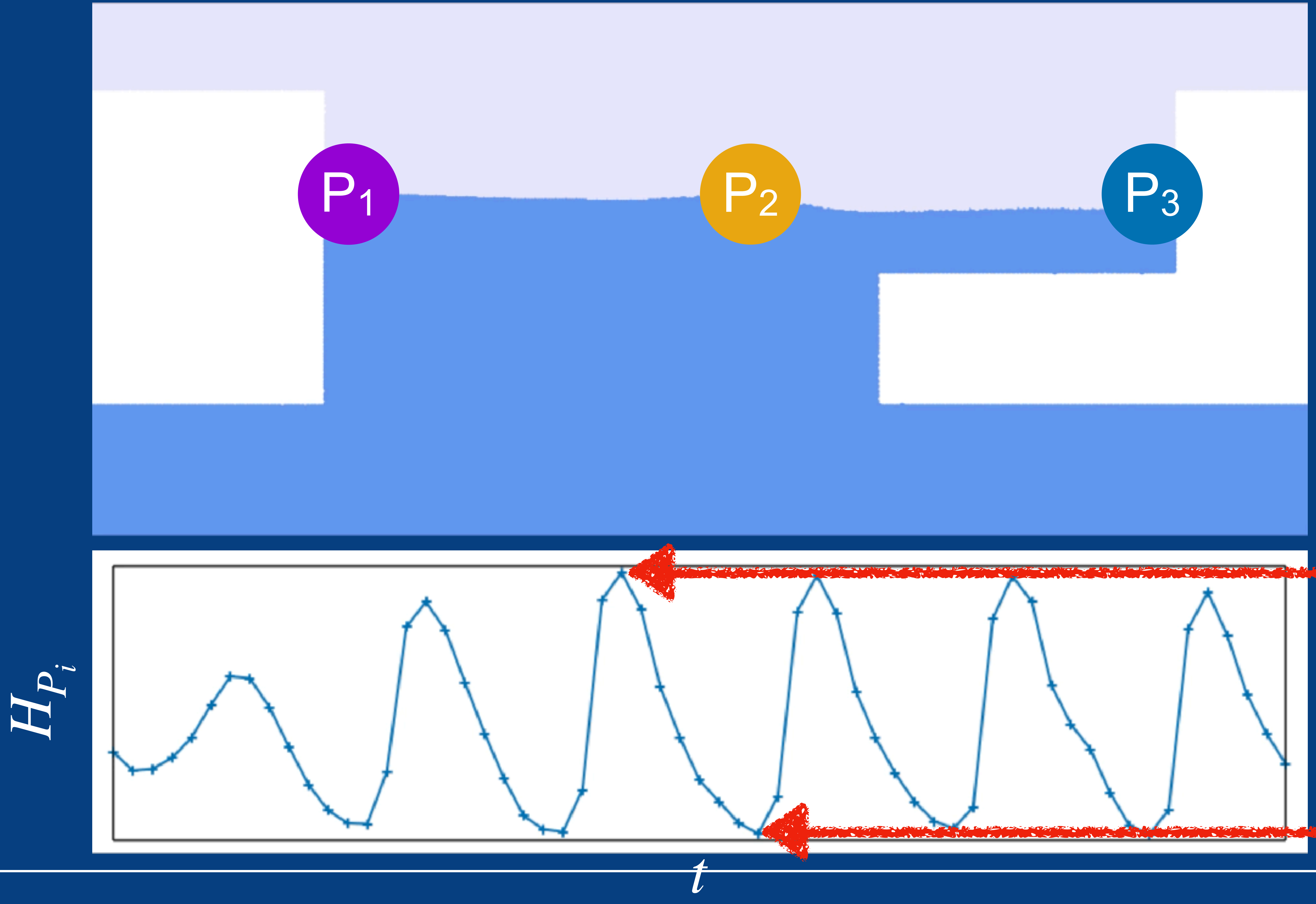
How can change the recess based on the flow rate?

Optimize the recess (R_H, R_L) for different sloshing force (fluid frequency F):



Input Parameters

F, R_H, R_L

Objective

Minimize the wave height variation at P_i locations

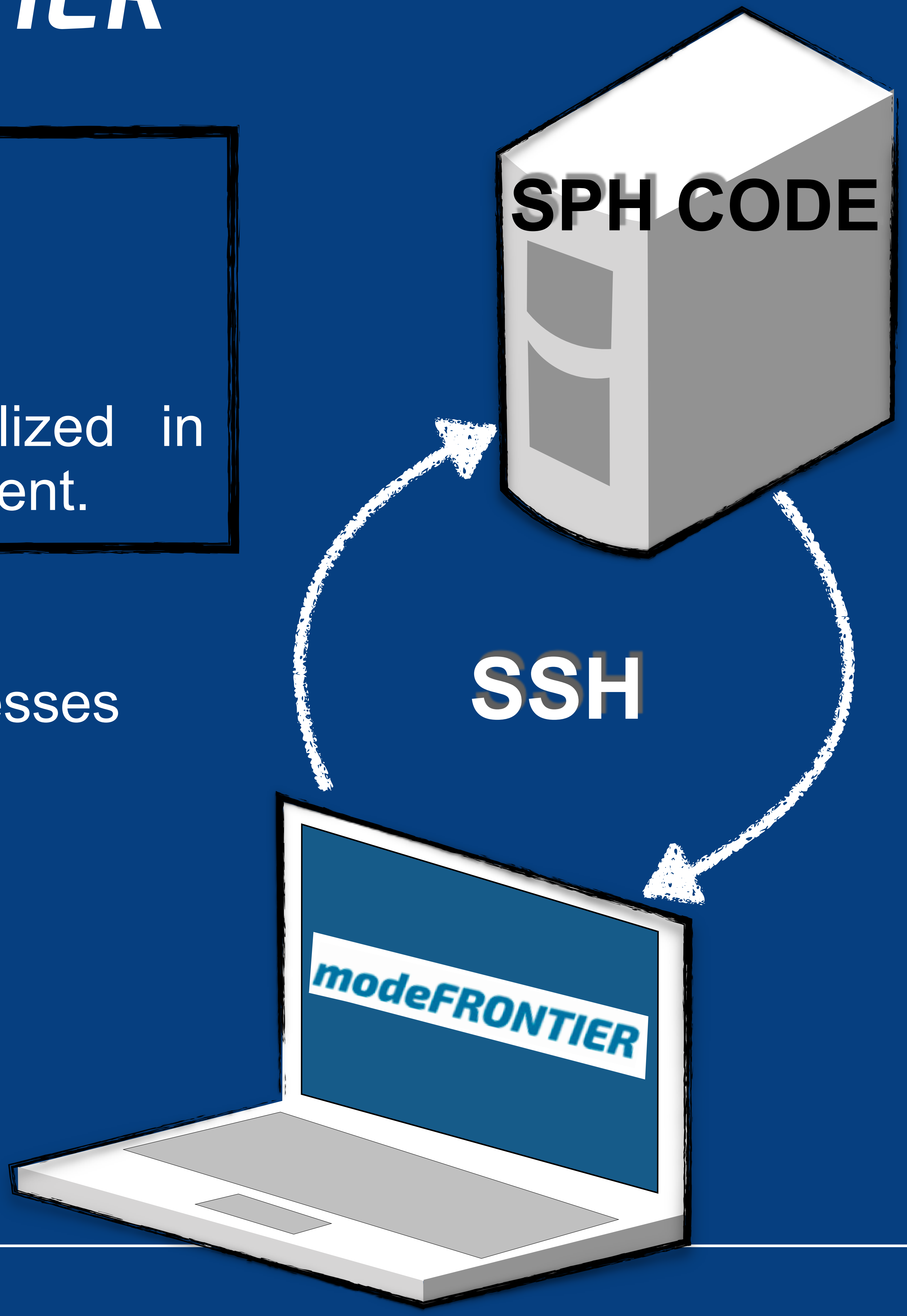
$$\Delta H_{P_i} = \max(H) - \min(H)$$

ESTECO’s software: *modeFRONTIER*

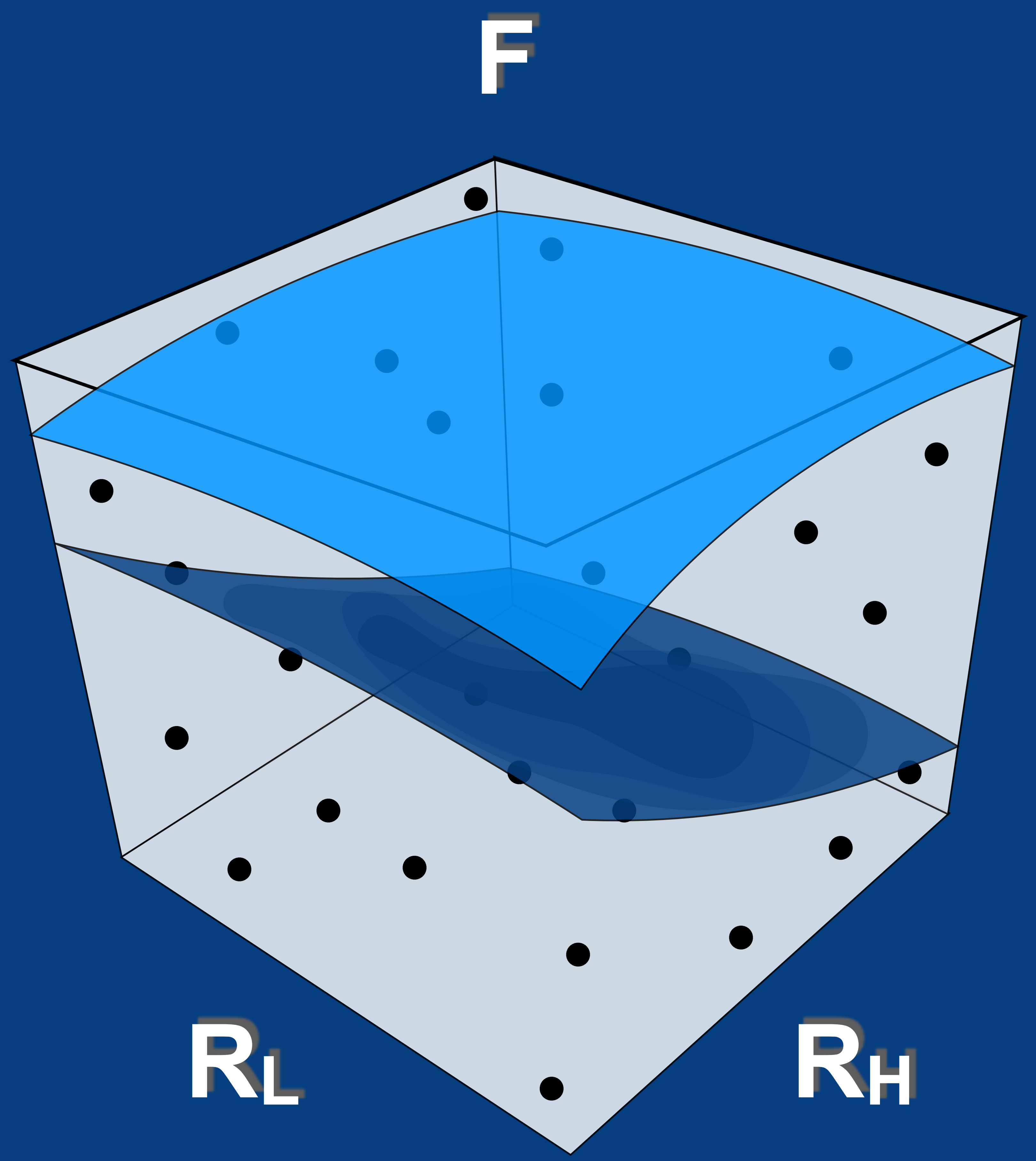
ESTECO is an independent software company, specialized in numerical optimization, simulation process and data management.

modeFRONTIER is the software solution for simulation processes automation and design optimization.

modeFRONTIER integrates third-party software assigned to run the simulations, stores the outputs, analyses and optimizes the result data.

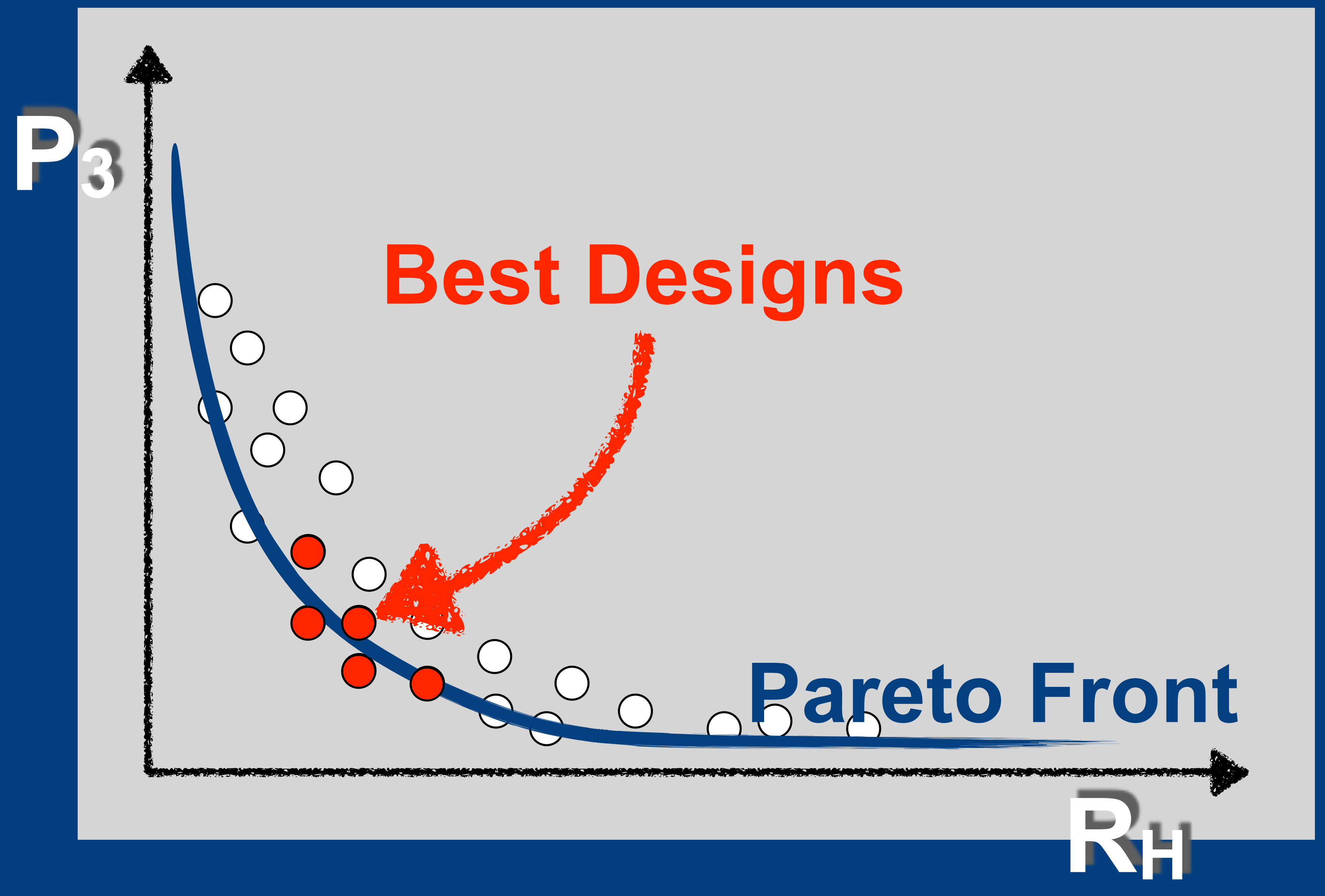


Optimization Process:



1. Run the SPH code for an initial set of simulations characterized by parameters (R_L, R_H, F) within a given range
2. Build a Response Surface Model (RSM), a statistical meta-model represented by a function obtained from the interpolation of the outputs. The RSM meta-model can give many more virtual designs (e.g., 5000 designs)

Optimization Process:



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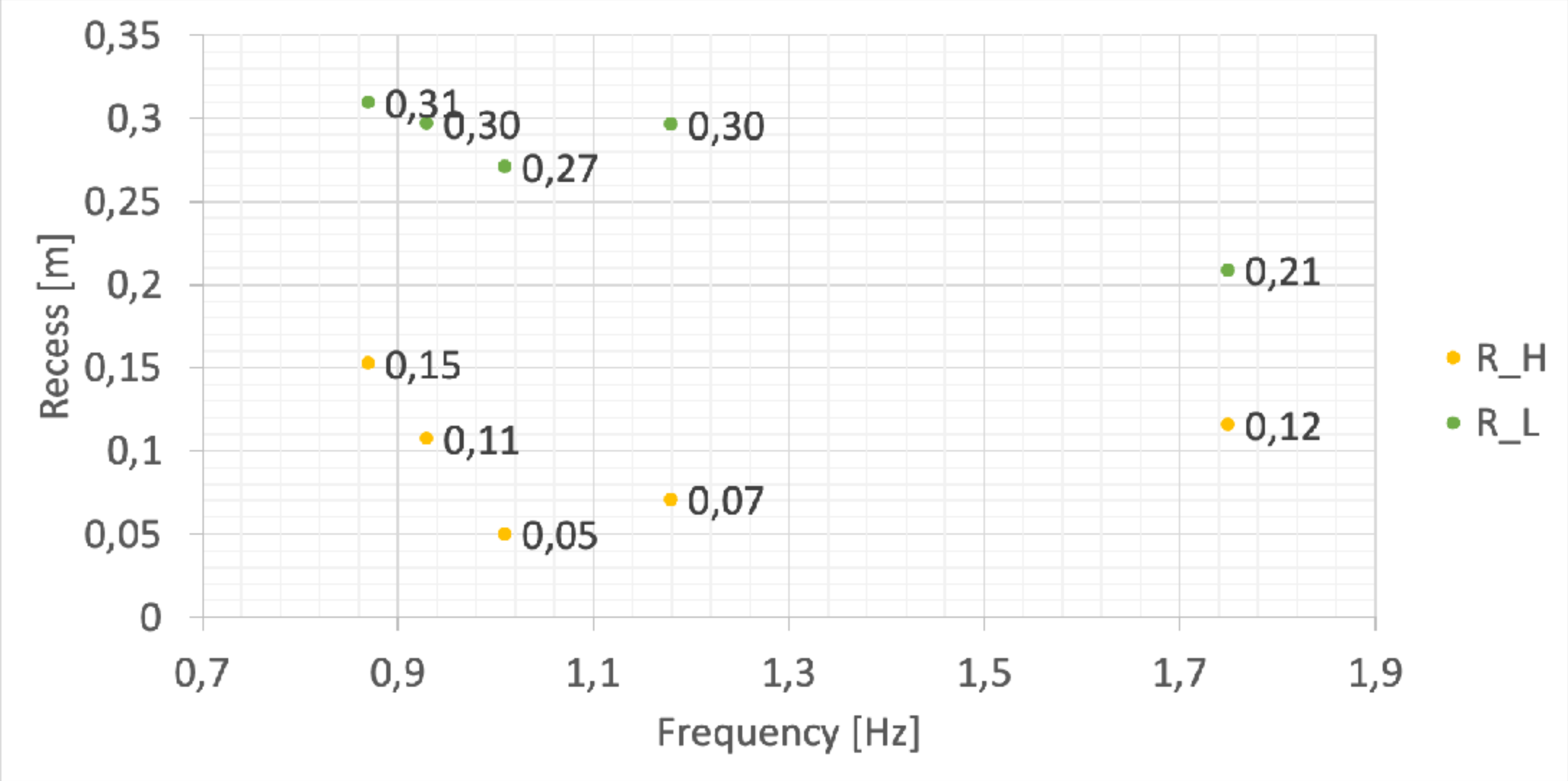
2. Build a Response Surface Model (RSM), a statistical meta-model represented by a function obtained from the interpolation of the outputs. The RSM meta-model can give many more virtual designs (e.g., 5000 designs)
3. Find the few best designs among the virtual ones that make the Pareto Front
4. Run the SPH simulation with the same parameters as the best virtual designs selected; compare the virtual outputs with SPH outputs (relative error below 15%)

Optimization Results:

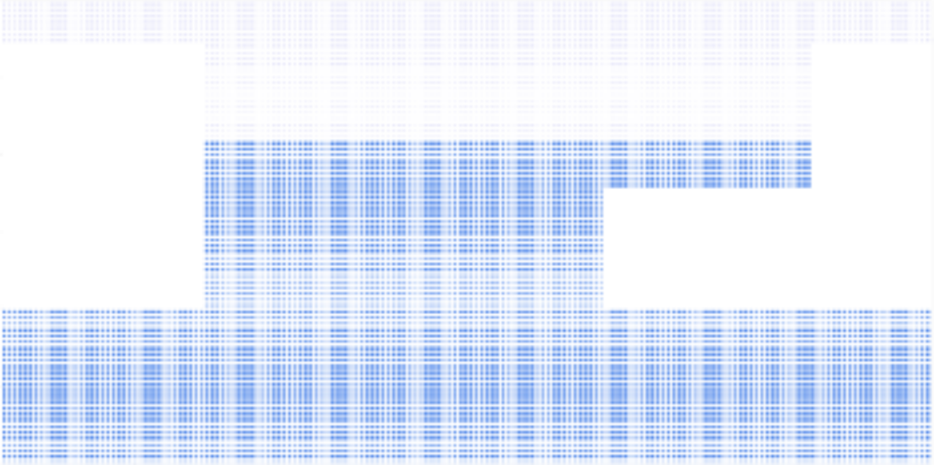
Frequency values [0.87 ; 0.93 ; 1.01 ; 1.18 ; 1.75] Hz

RH range 0.05 - 0.163 m

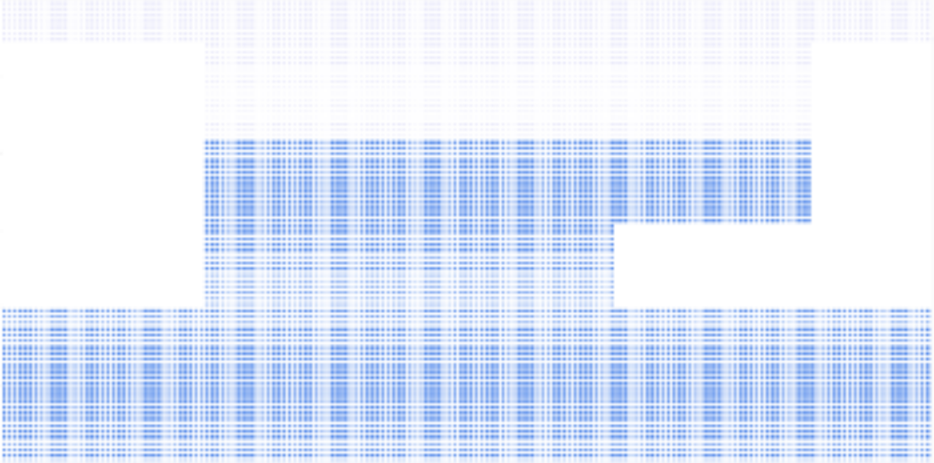
RL range 0.1 - 0.41 m



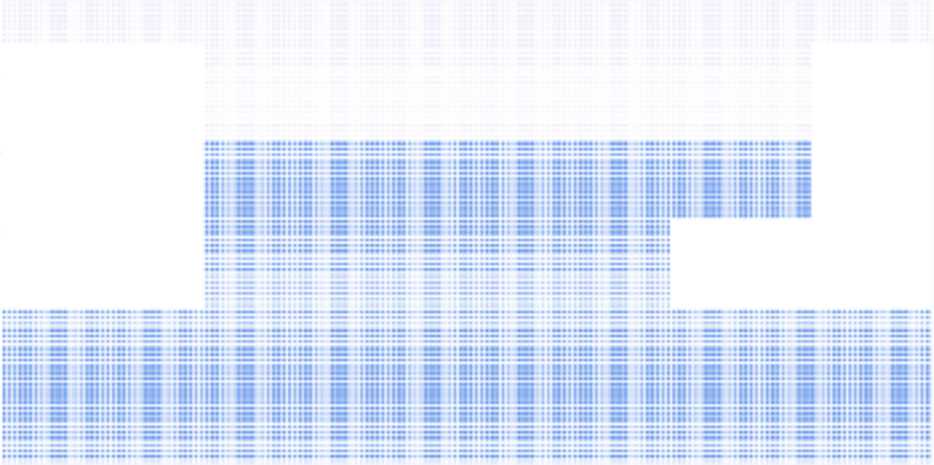
0.87 Hz



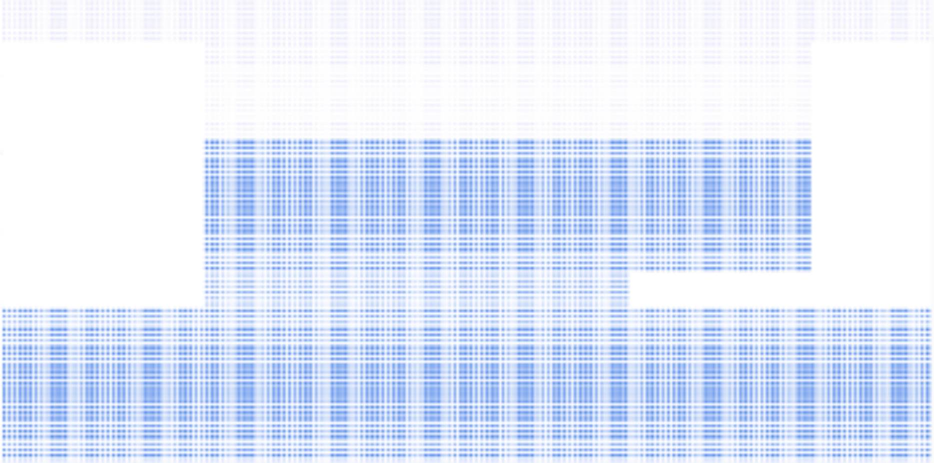
0.93 Hz



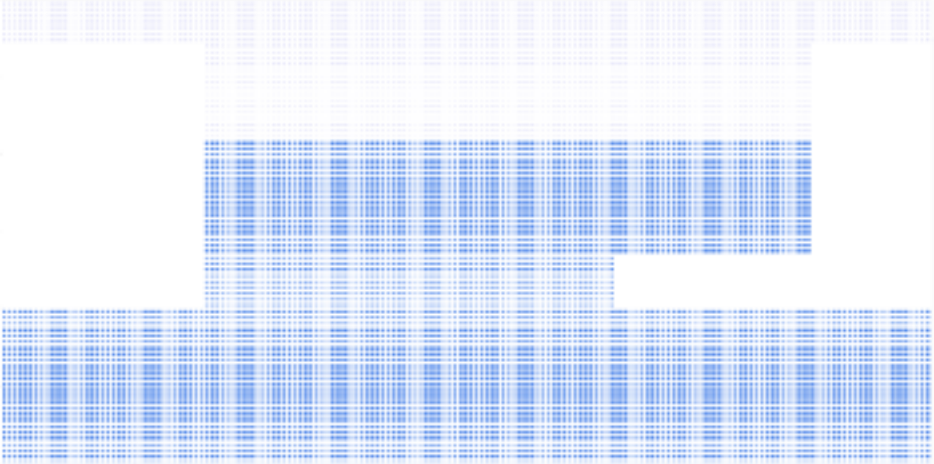
1.01 Hz



1.18 Hz



1.75 Hz



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Conclusions

- Modified viscous force works nicely for benchmarks involving viscosity (and density) jumps across the interface
- The SPH code validated for sloshing and further adapted to study the moon pool case
- Optimization of the moon pool case performed by coupling the in-house code with modeFRONTIER software

Future work

- Further developments are needed for the implementation of inlet and outlet boundary conditions
- In the in-house code, further developed during the project, the boundary treatment and the complex geometries revealed problematic to be simulated.
- Both issues are considered among the Great Challenges in the SPH community

Thank you

Institute of Fluid-Flow Machinery Polish Academy of Sciences

ESTECO SpA

European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie Action ITN-EID grant agreement No 813948