A new non-hydrostatic coastal model for simulating waves at the Baltic coast

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www.reef3d.com

REEF3D : Open-Source Hydrodynamics

- Developed at the Department of Civil and Environmental Engineering, NTNU Trondheim

<u>Multiscale Framework:</u>
- high-order discretization (FDM)
- mesh with immersed boundary
- high-performance solvers
- consistent parallelization (MPI)

<u>Multiphysics for Hydraulic, Coastal, Offshore:</u>
- sediment transport
- floating bodies
- porous structures
- vegetation
- stratified flow

- Published under GNU GPL v3

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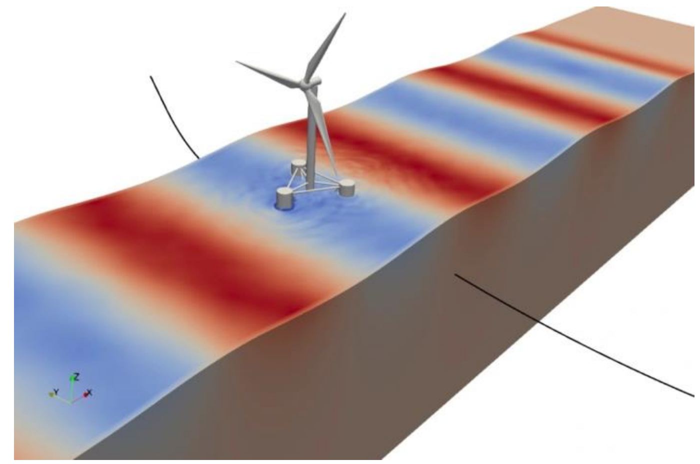
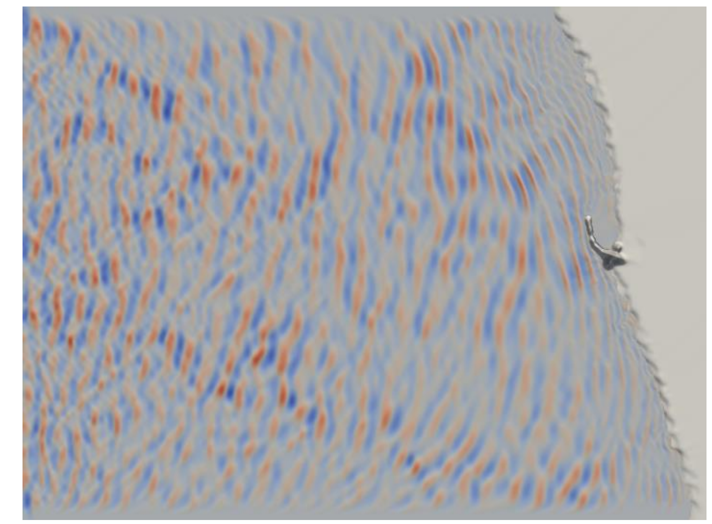
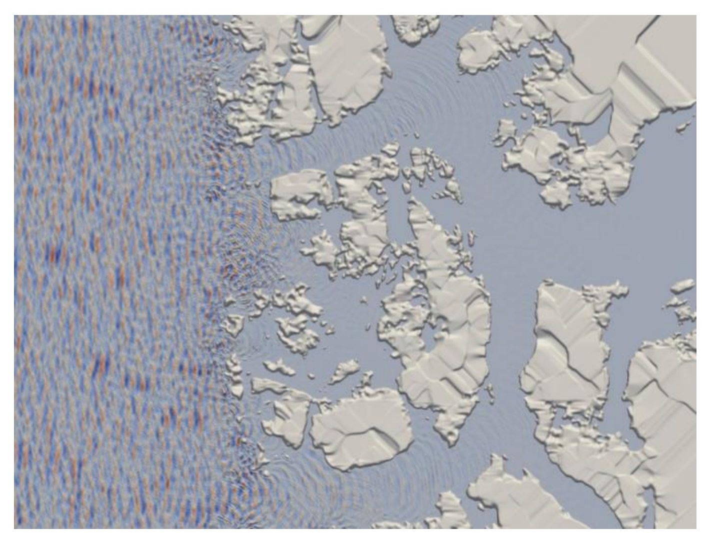


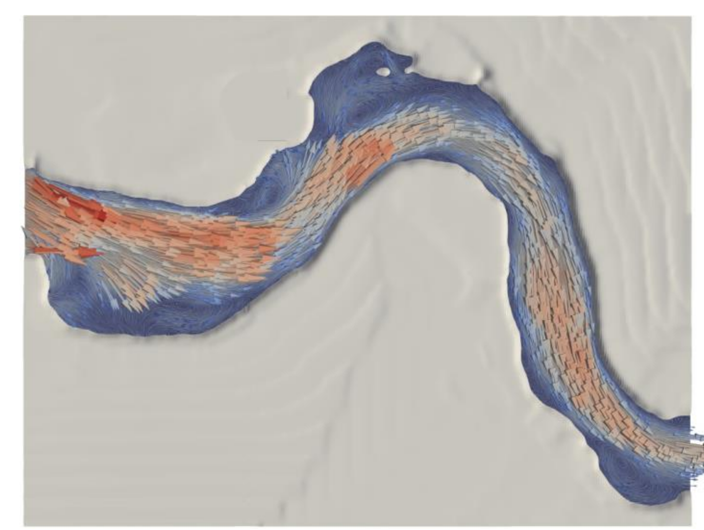
CFD Two-Phase Navier-Stokes Equations



NHFLOW Non-hydrostatic Navier-Stokes Equations

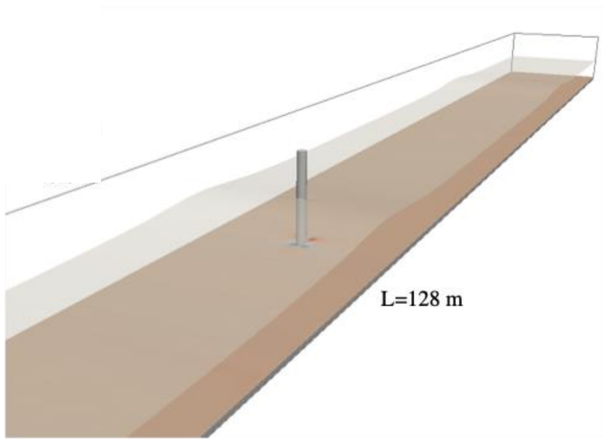


FNPF Fully Nonlinear Potential Flow

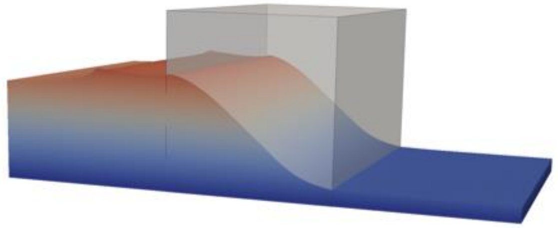


SFLOW Non-hydrostatic SWE

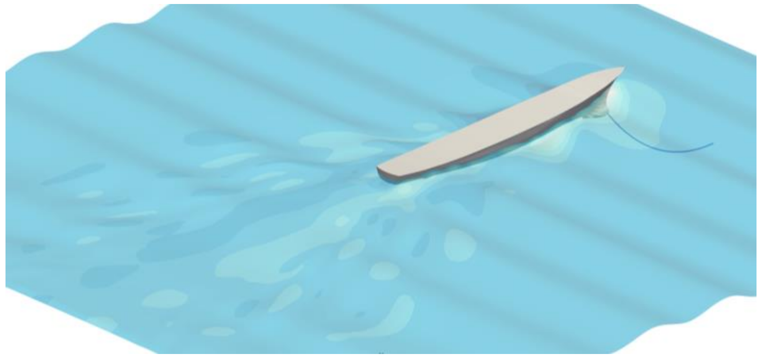
REEF3D::CFD - Hires Flow and Multiphysics



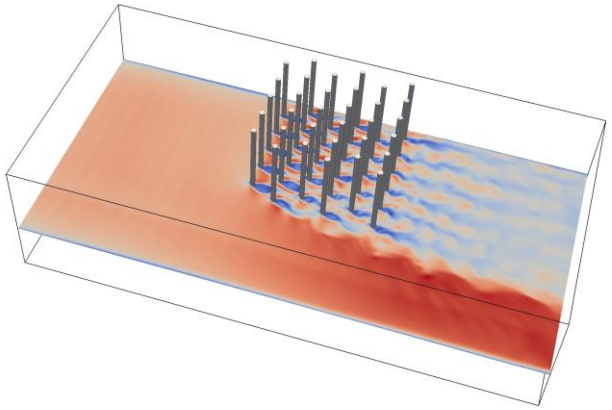
Sediment Transport
Local Scour
Arctic Erosion



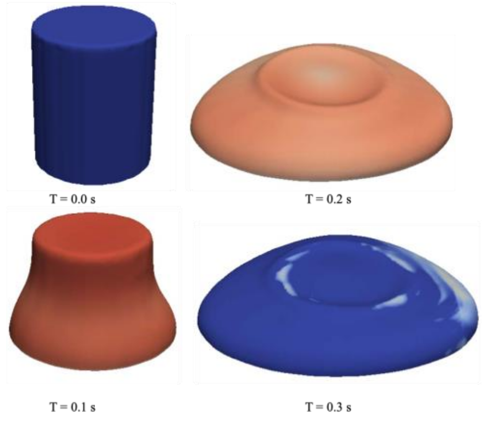
Porous Structures



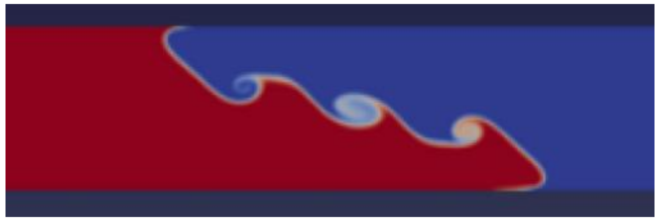
Floating Structures
6DOF
Mooring



Vegetation



Debris Flow
Granular Flow



Stratified Flow

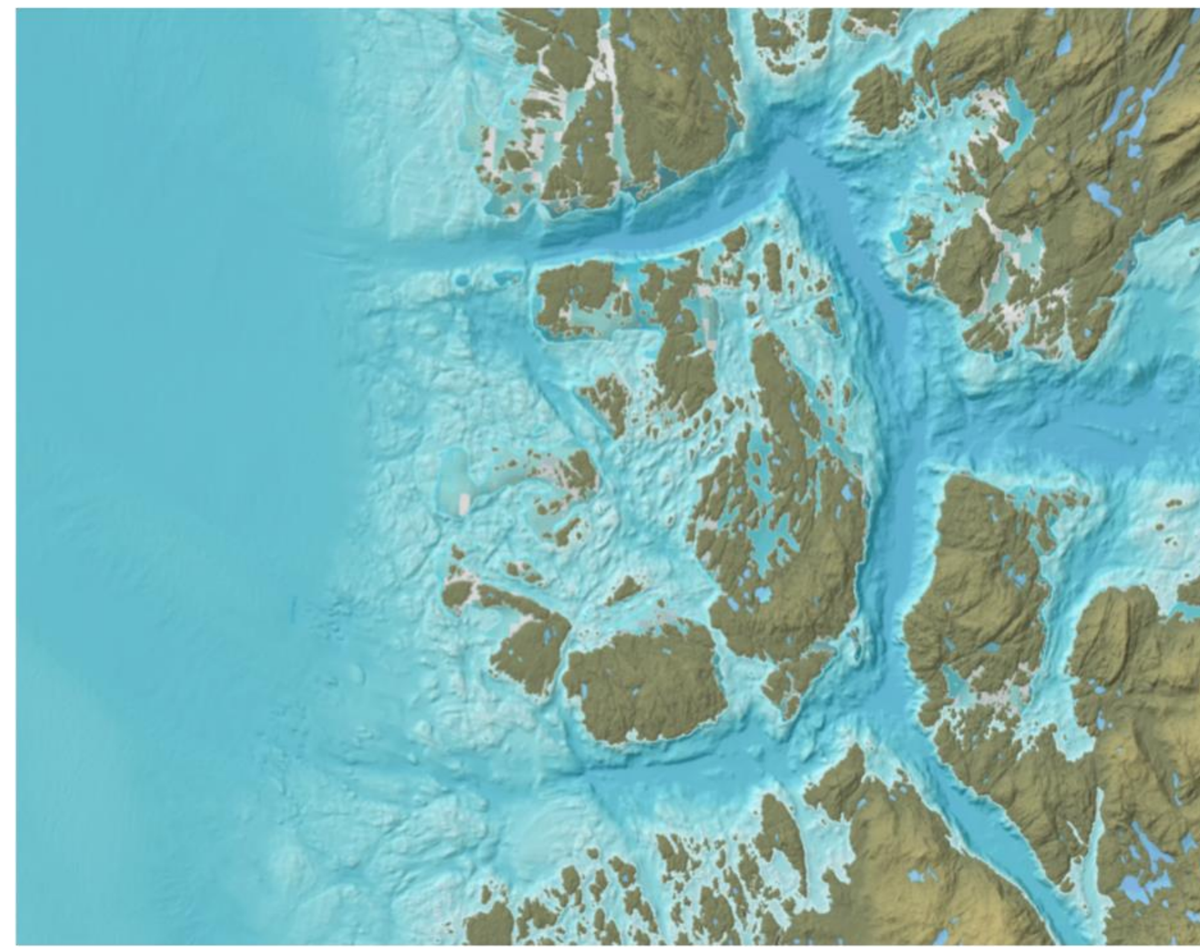
Typical North Sea and Baltic Sea Coasts

North Sea Föhr, Nordfriesland

Balitc Sea Gulf of Finland

Typical Norwegian Coast

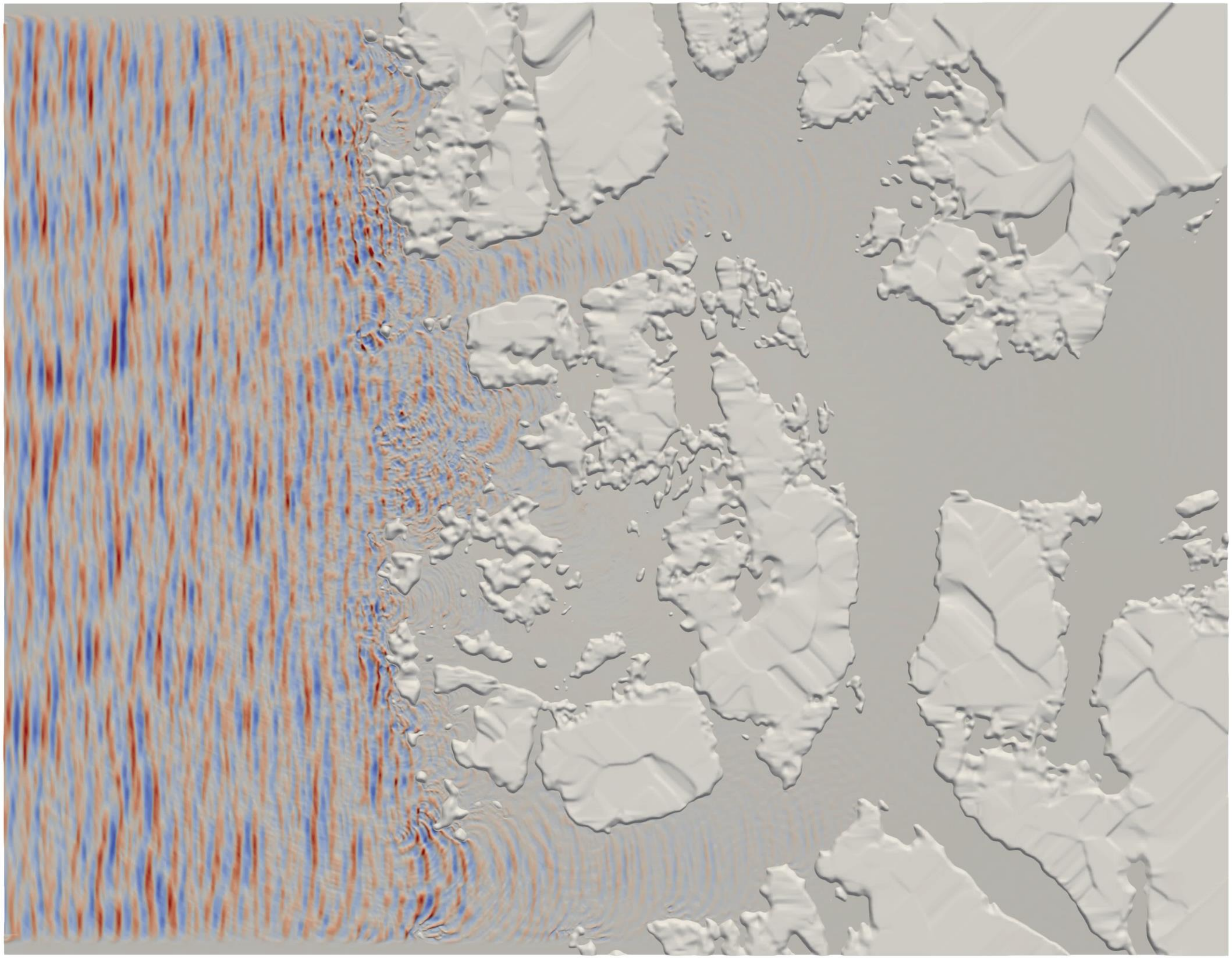
(a)



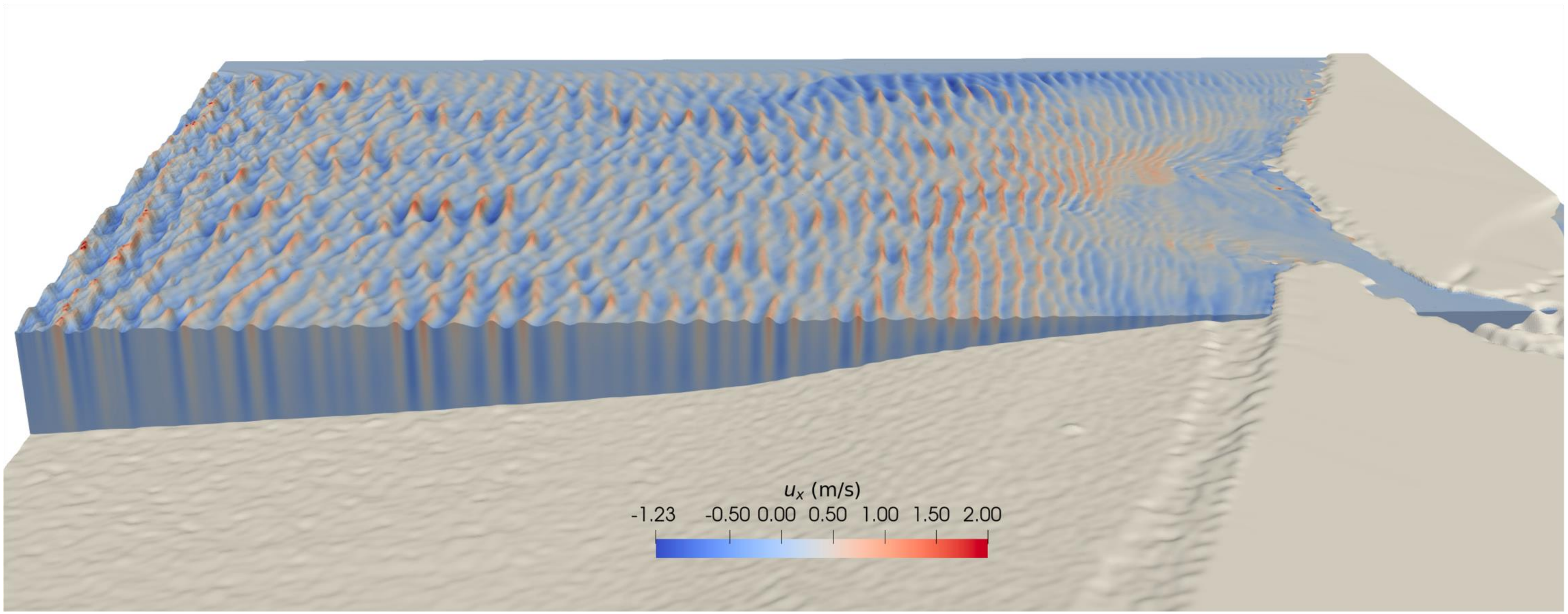
(b)

Bjørnafjord

FNPF: Bjørnafjord (35km x 45km)



Coastal Model: Required Processes



- waves
- currents
- sediment
- porous structures

Why NHFLOW?

	Dispersion	Wetting & Drying	Viscous effects	Breaking wave	2D/3D	Comp. cost
SFLOW	kd<1	dynamic	yes	kinematics	2D	cheap
FNPF	unlimited	static	no	kinematics	3D	cheap
NHFLOW	unlimited	dynamic	yes	kinematics	2D + 3D	cheap
CFD	unlimited	dynamic	yes	fully resolved	3D	expensive

NHFLOW - Governing Equations

$$\frac{\partial u_i}{\partial x_i} = 0$$

continuity

$$\frac{\partial h u_i}{\partial t} + u_j \frac{\partial h u_i}{\partial x_j} = -\frac{h}{\rho}\frac{\partial p}{\partial x_i} - h g_i$$

momentum

$$\frac{\partial h}{\partial t} + \frac{\partial h u_i}{\partial x_i} = 0$$

free surface

NHFLOW - Numerical implementation

$$\frac{\partial \mathbf{U}}{\partial t} = \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} + \frac{\partial \mathbf{G}(\mathbf{U})}{\partial x} + \frac{\partial \mathbf{H}(\mathbf{U})}{\partial x} = \mathbf{S}$$

$$\mathbf{F} = \begin{bmatrix} hu \\ hu^2 + \frac{1}{2} g\eta^2 + g\eta d \\ huv \\ huw \end{bmatrix} \quad \mathbf{G} = \begin{bmatrix} hv \\ huv \\ hu^2 + \frac{1}{2} g\eta^2 + g\eta d \\ huw \end{bmatrix} \quad \mathbf{H} = \begin{bmatrix} \omega \\ u\omega \\ v\omega \\ w\omega \end{bmatrix}$$

- **Godunov-type scheme:** HLL Riemann Solver with WENO reconstruction
  ➡ conservative & shock-absorbing

- pressure correction projection method (Poisson: hypre’s BiCGStab + GMG)
- 2nd-order TVD Runge Kutta
- Domain Decomposition and MPI

Solution of the Poisson Equation

Poisson Eq. for the pressure correction

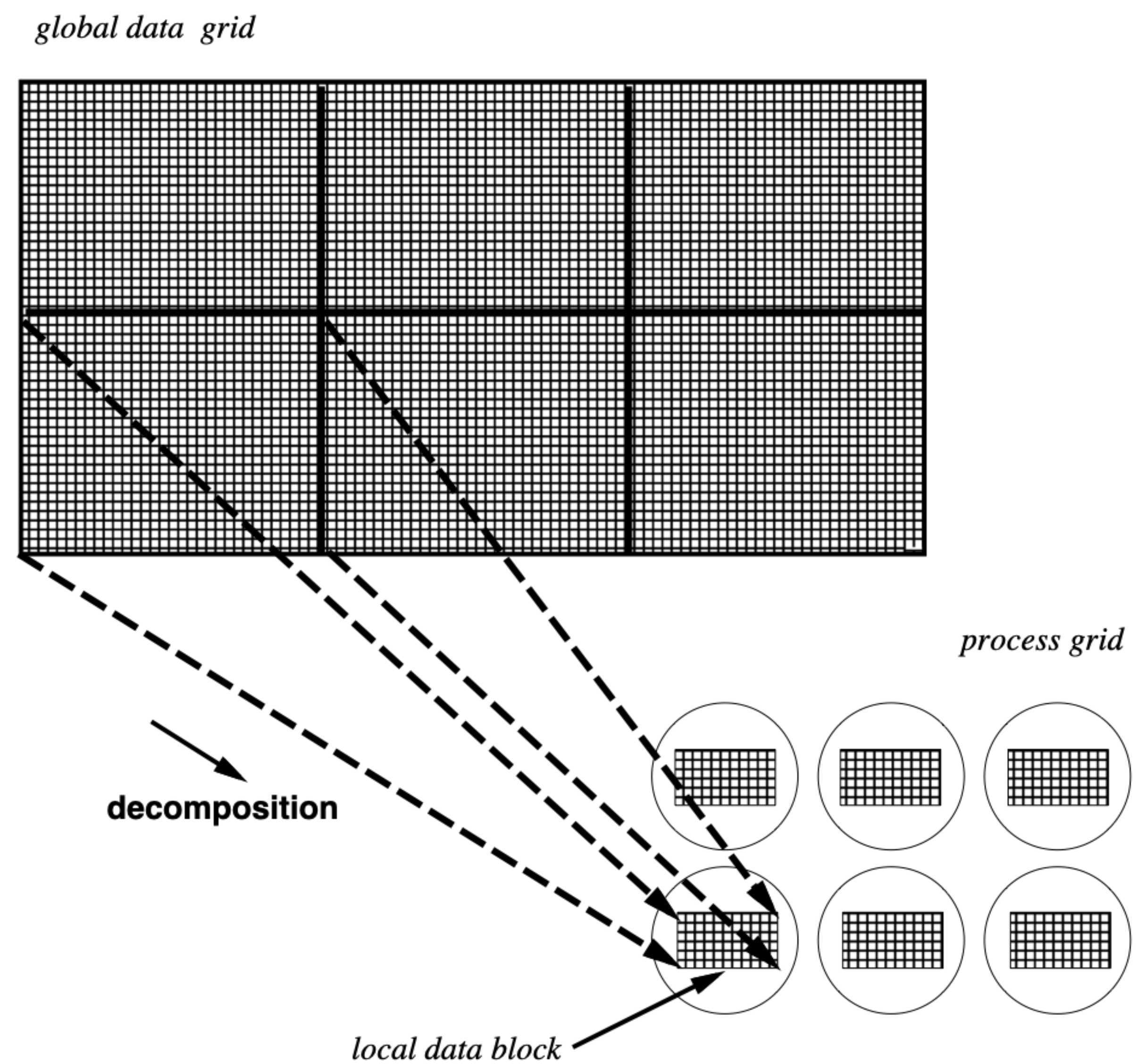
$$\Delta p = \nabla u$$

→ $$Ax = f$$

system of linear Equations

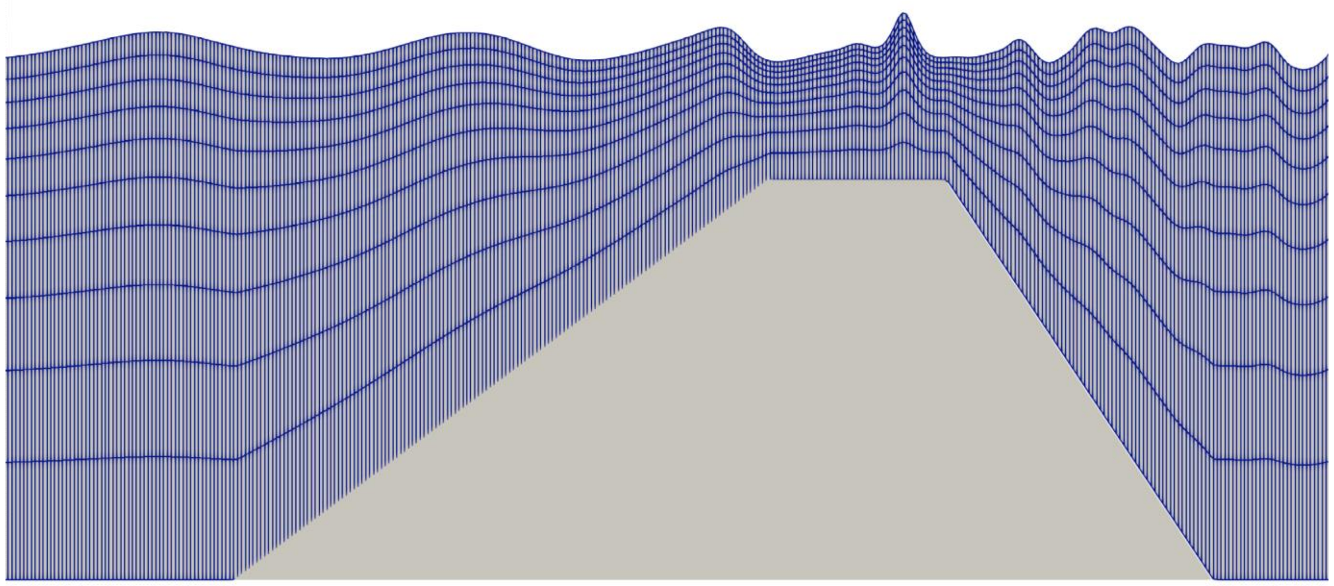
→ hypre: BiCGStab + PFMG

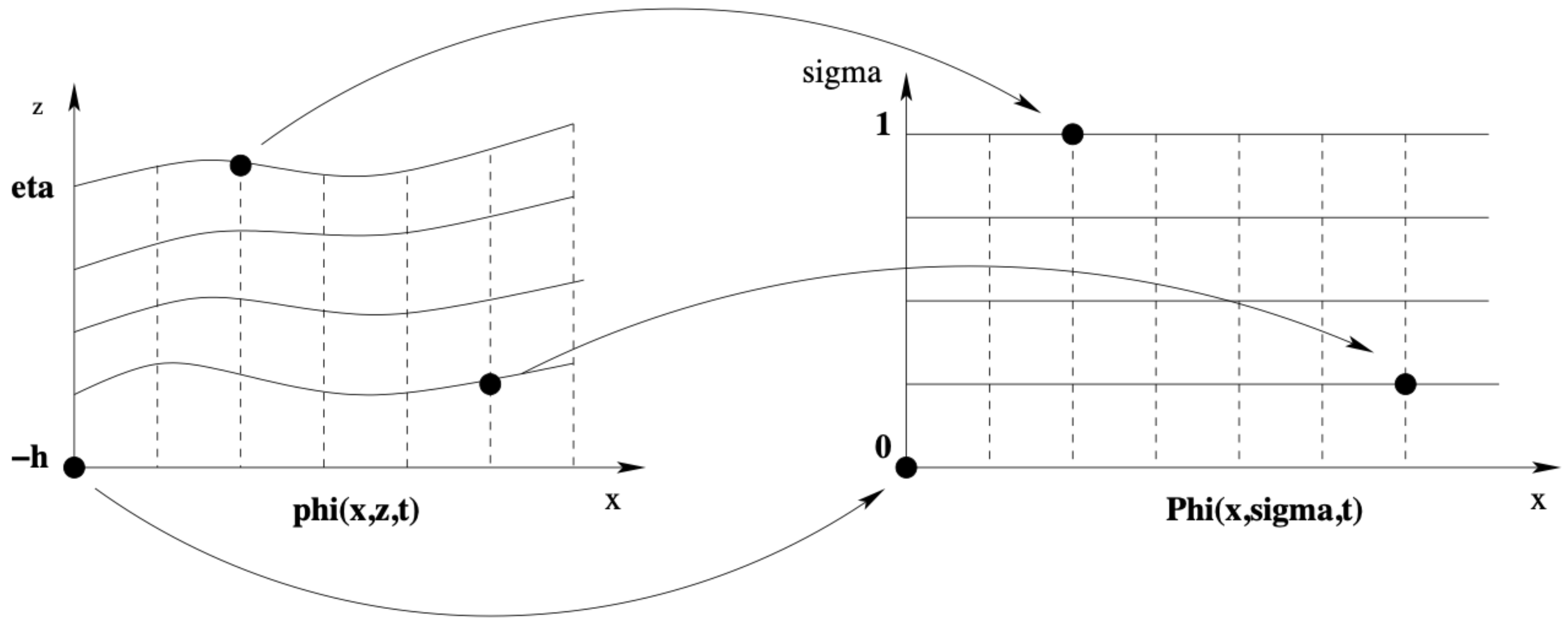
HPC: domain decomposition + MPI



NHFLOW - σ-grid

$$\sigma = \frac{z + h(x,y,t)}{d(x,y)}$$





NHFLOW - Wetting & Drying / Breaking Waves

<u>wetting & drying:</u>

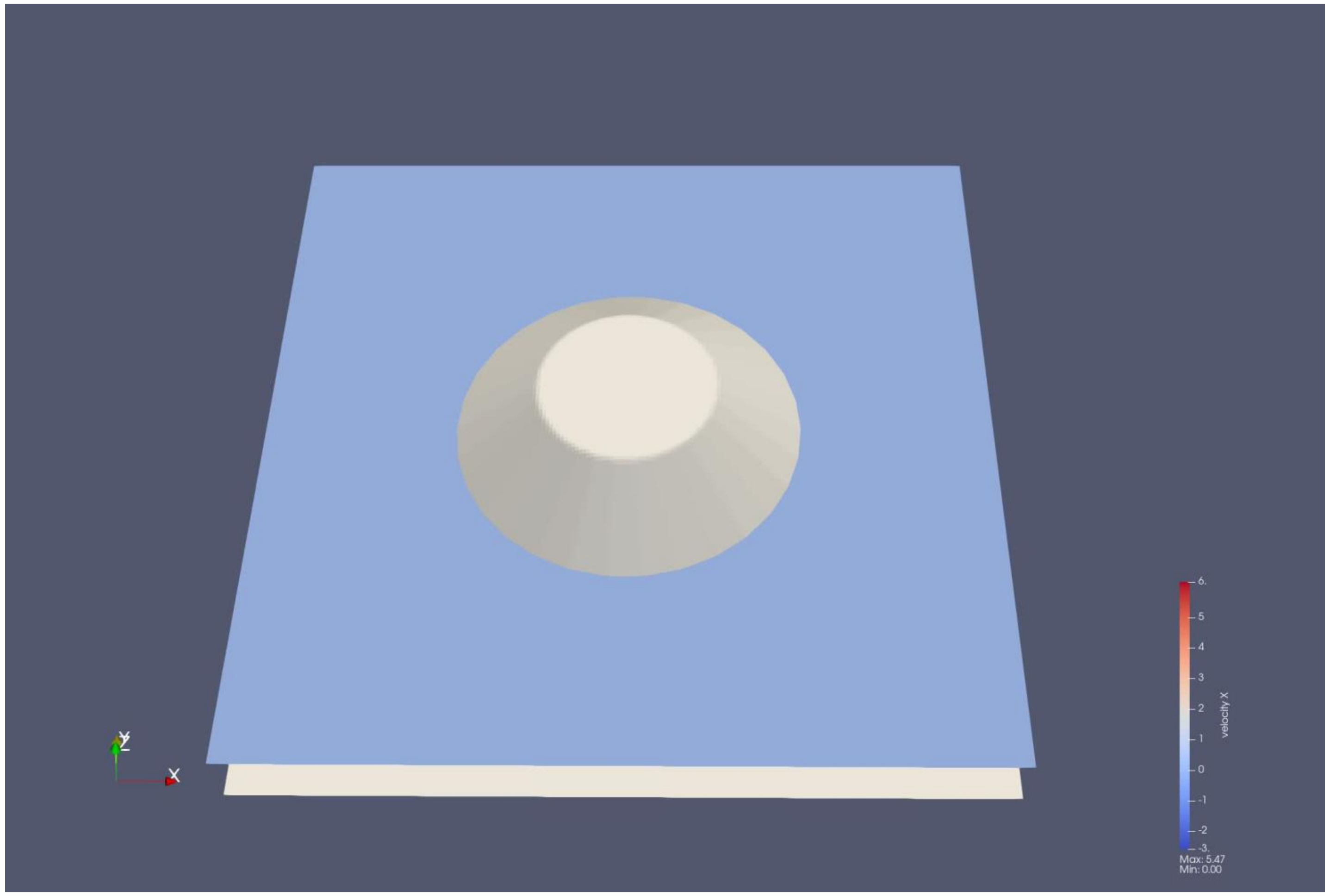
- maintain minimum water level

$$wet_{ij} = 0 \quad if \quad \eta_{ij} < \eta_{neighbor}$$

$$wet_{ij} = 1 \quad if \quad \eta_{ij} > \eta_{neighbor}$$

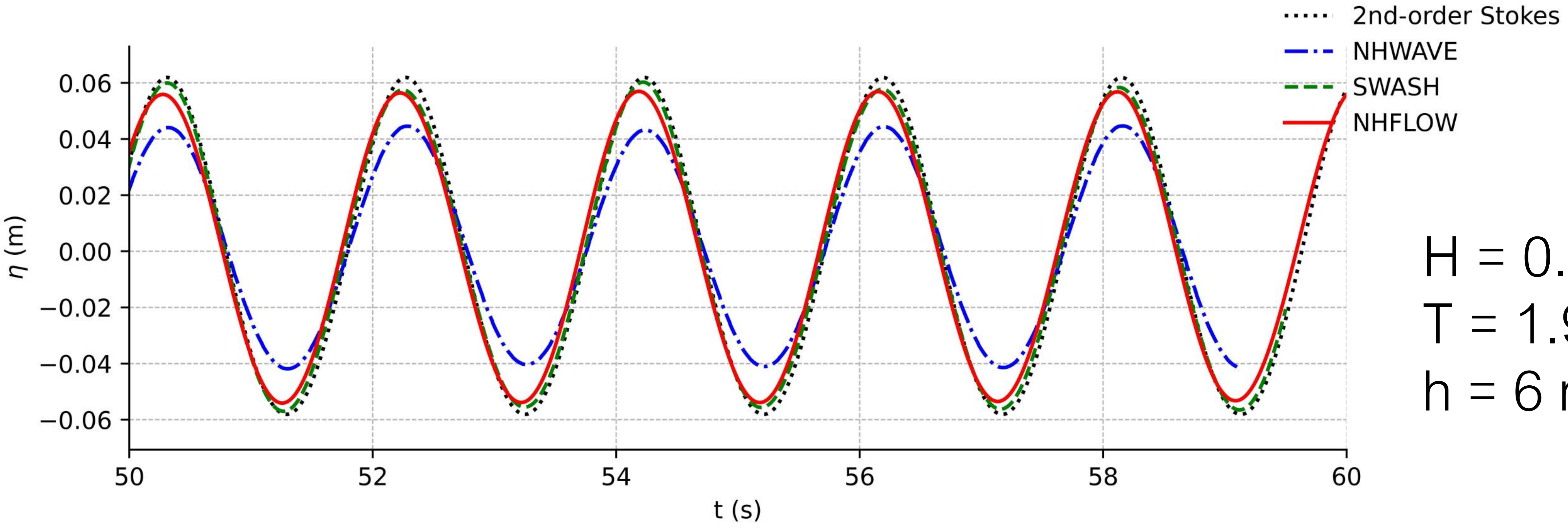
<u>breaking:</u>

- no additional treatment due to shock-absorbing scheme



vertical scale: 5x
contour: u-velocity

Benchmark: Stokes wave with kd = 6.28

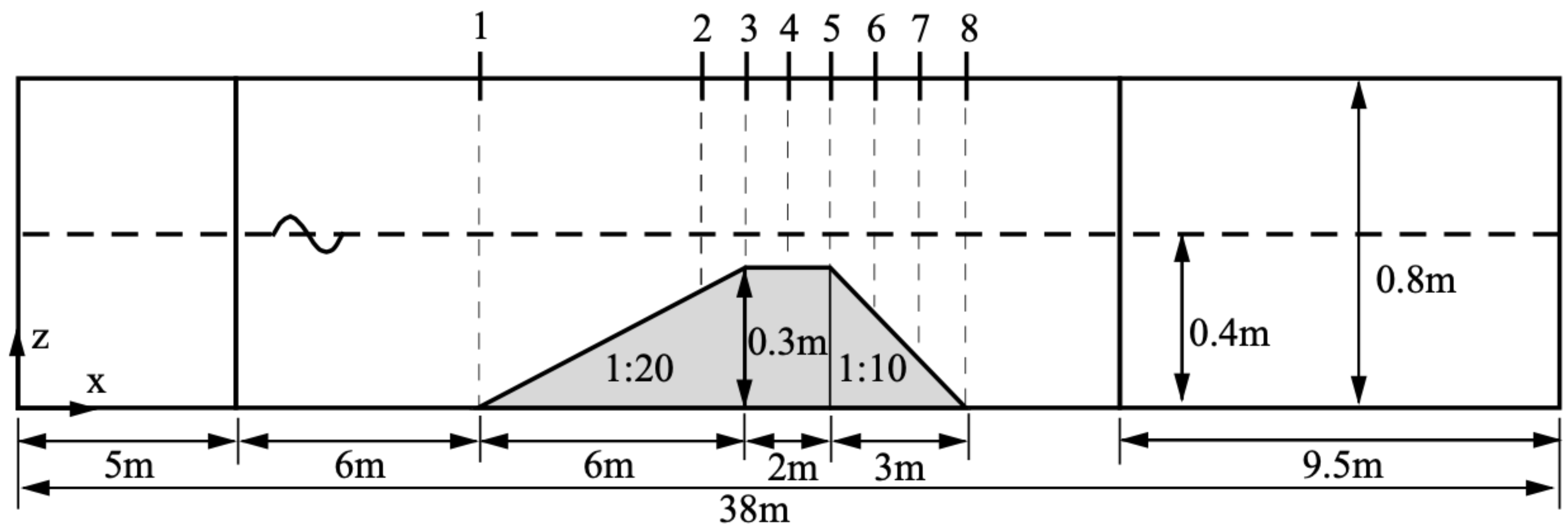


H = 0.06 m
T = 1.96 s
h = 6 m

	Discretization	Pressure	Mesh
SWASH	primitive variable / staggered	pressure correction	960 x 3
NHWAVE	Godonov-type / shock absorbing	projection method	1920 x 5
NHFLOW	Godonov-type / shock absorbing	pressure correction	1920 x 5

Beji & Battjes: Submerged Bar

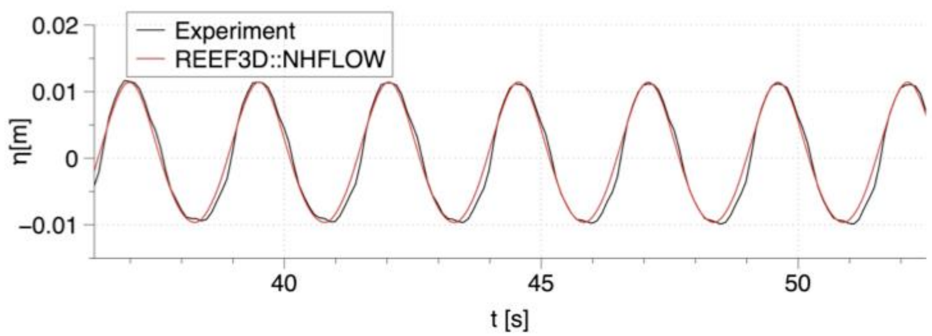
Wave Input
- H = 0.021m
- T = 2.525s
- wave theory: 2nd-order Stokes



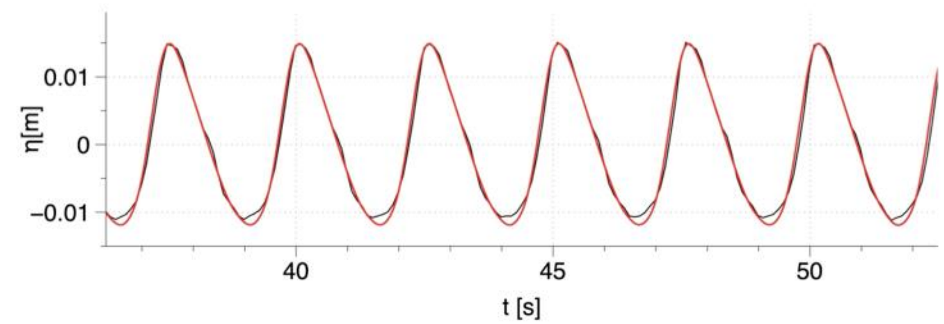
Setup
- mesh: 1400 x 2
- dx = 0.025 m
- CFL = 0.5

vertical scale: 50x
contour: w-velocity

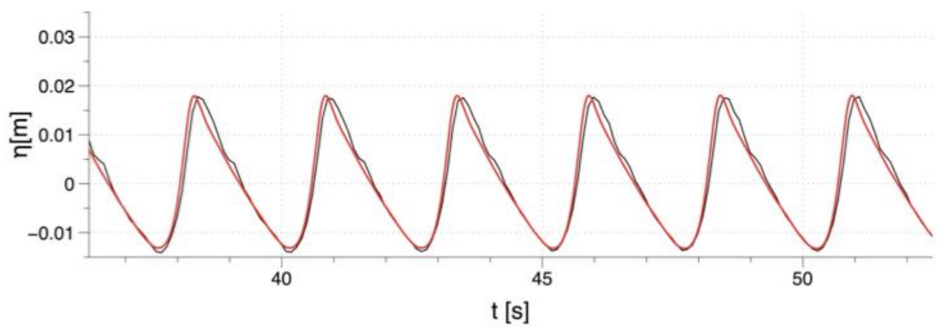
Beji & Battjes: Submerged Bar



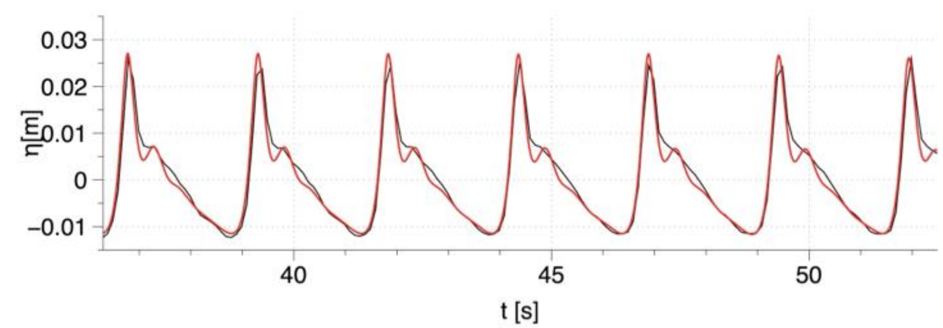
(a) gage 1



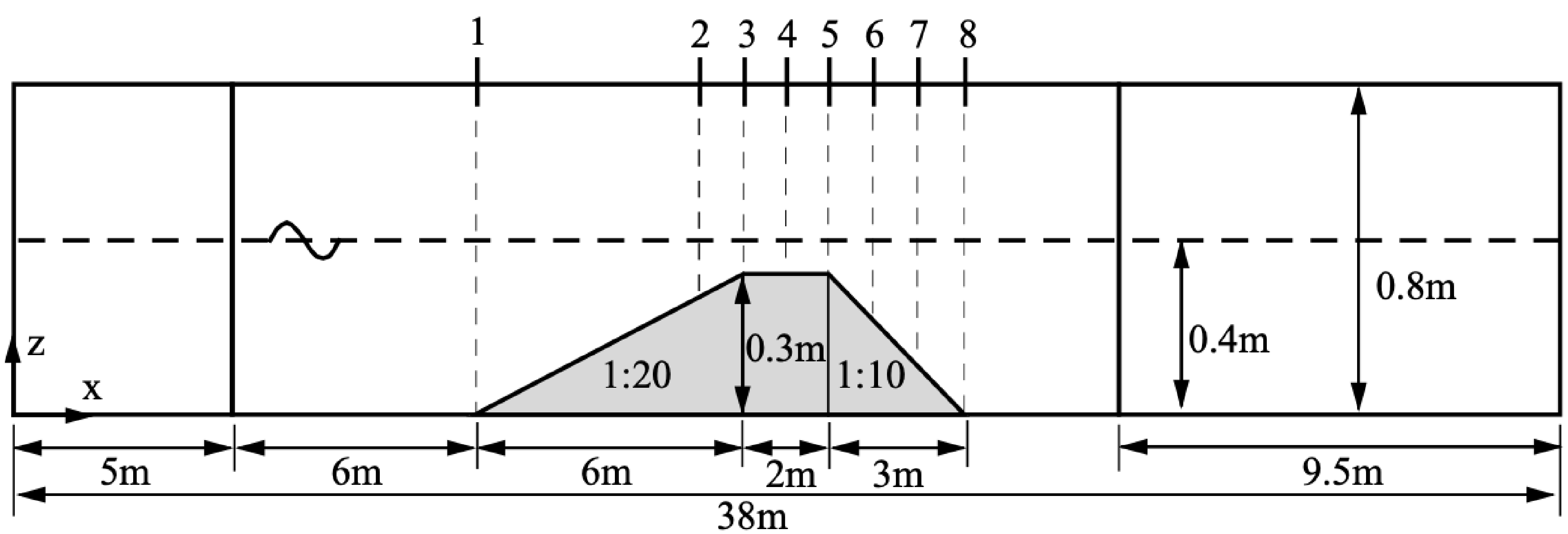
(b) gage 2



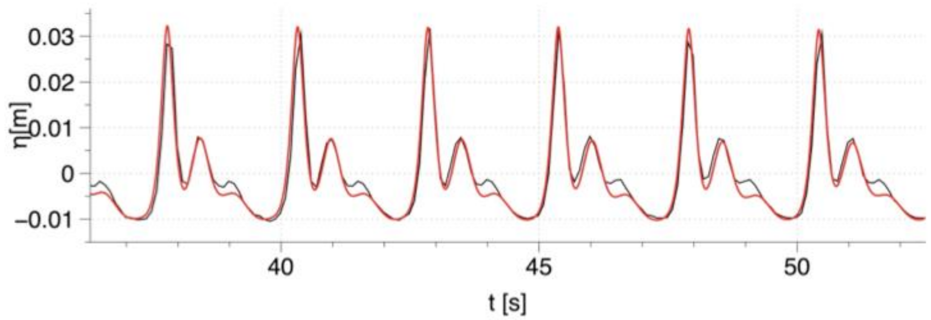
(c) gage 3



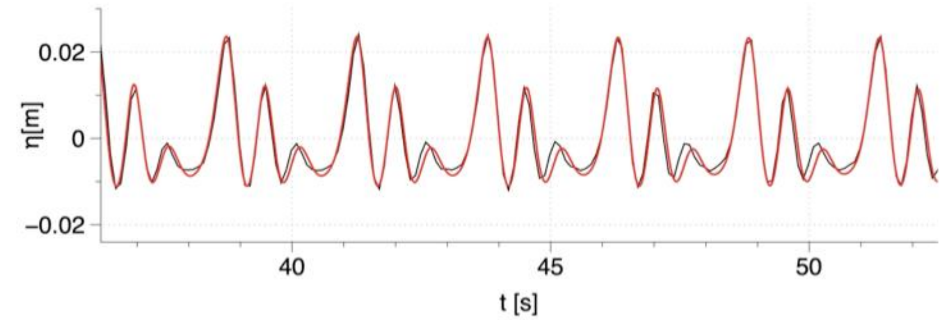
(d) gage 4



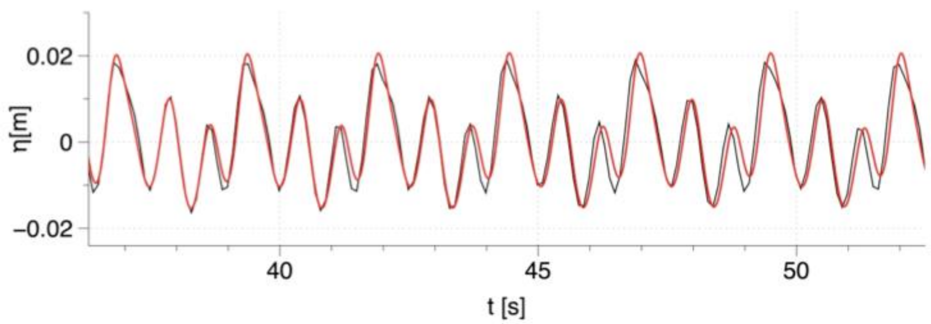
Beji & Battjes: Submerged Bar



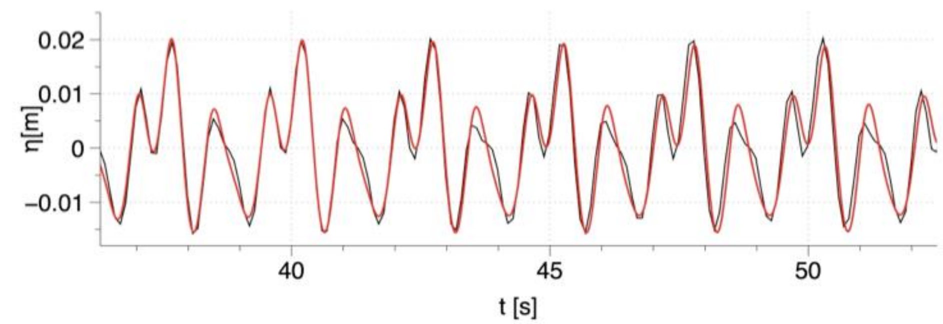
(e) gage 5



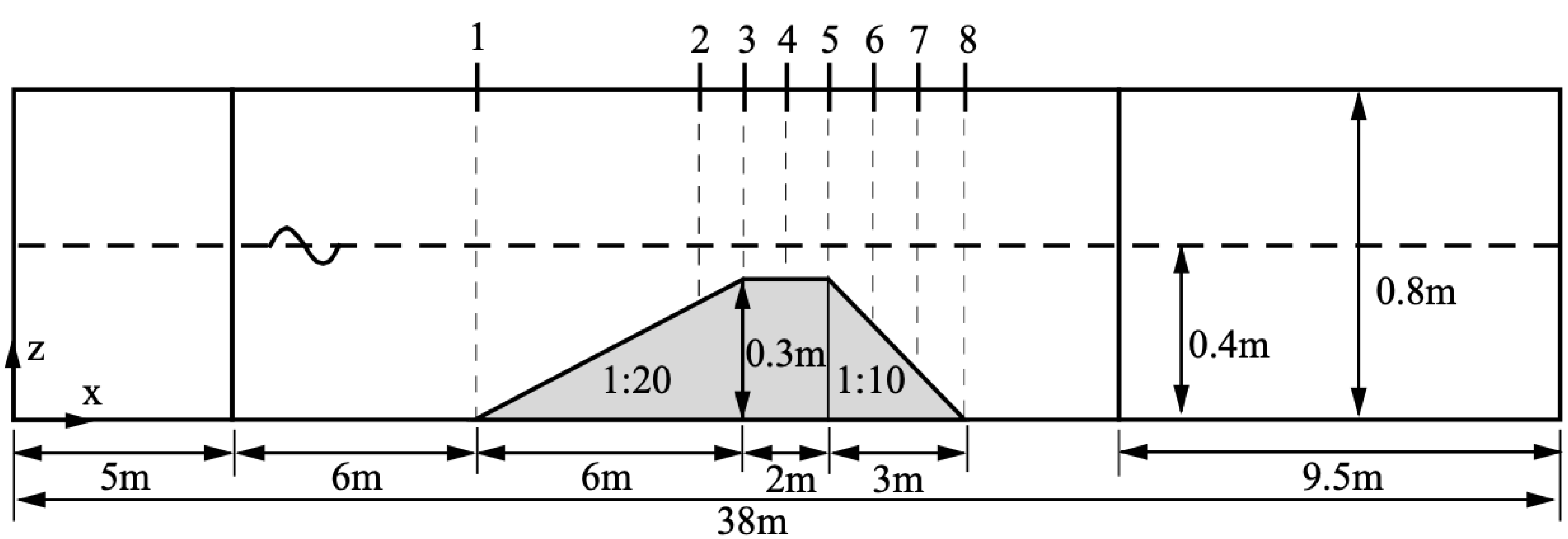
(f) gage 6



(g) gage 7



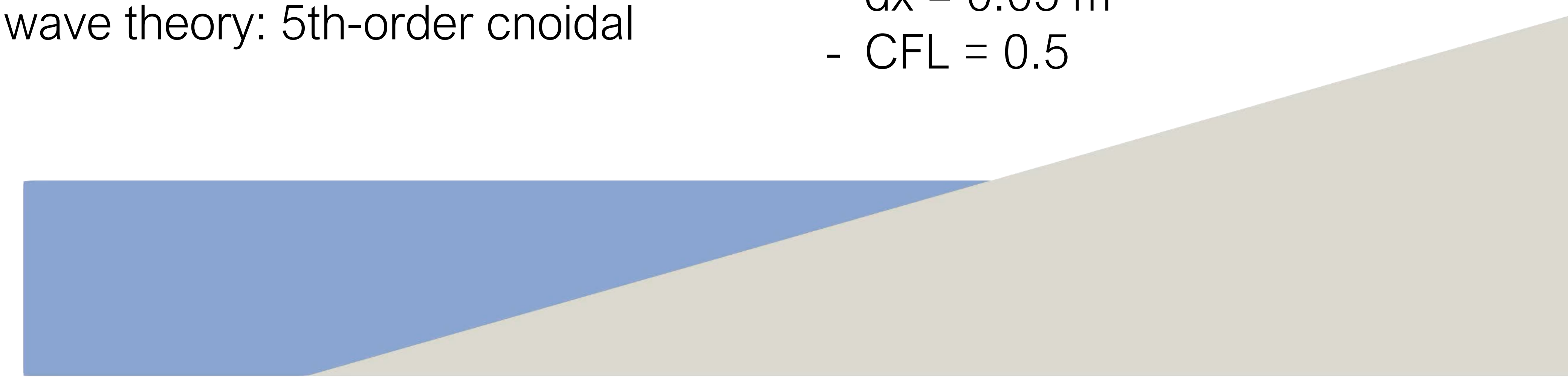
(h) gage 8

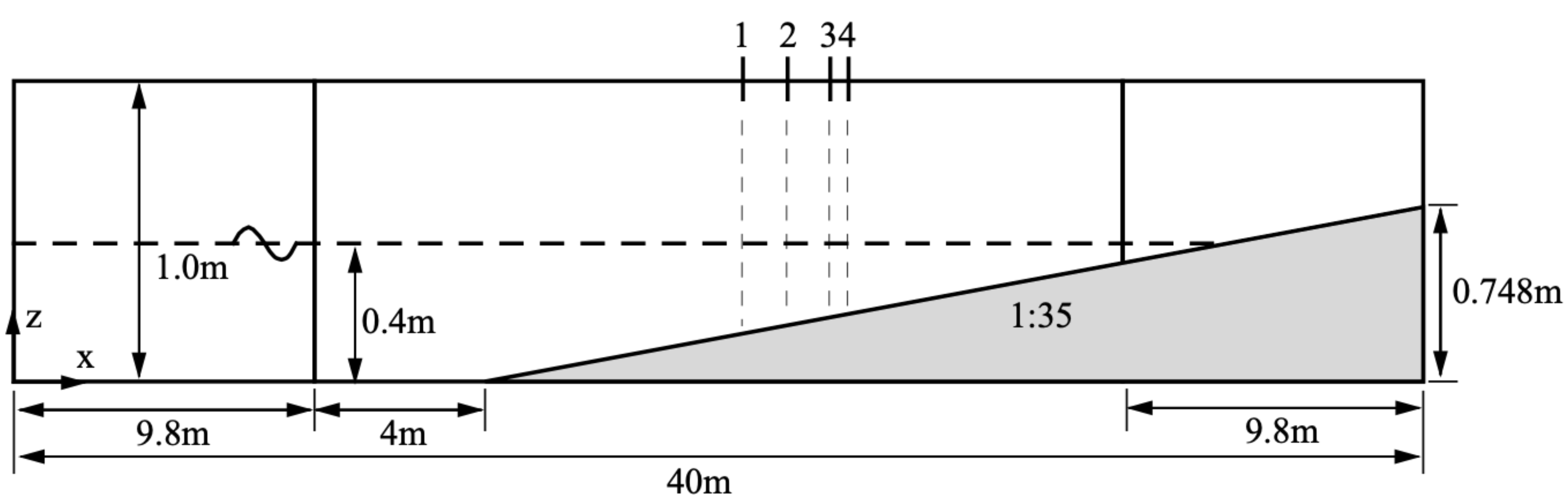


Ting&Kirby: Breaking Waves

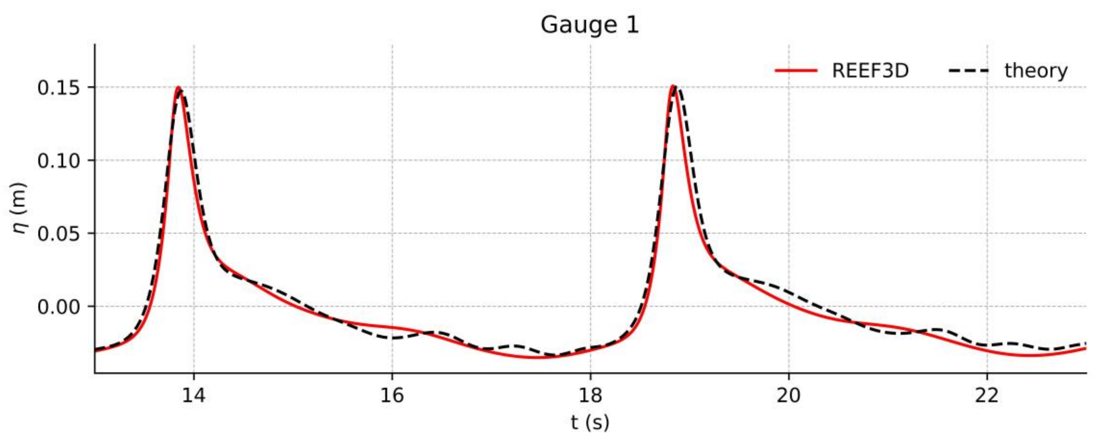
Wave Input
- H = 0.021m
- T = 2.525s
- wave theory: 5th-order cnoidal

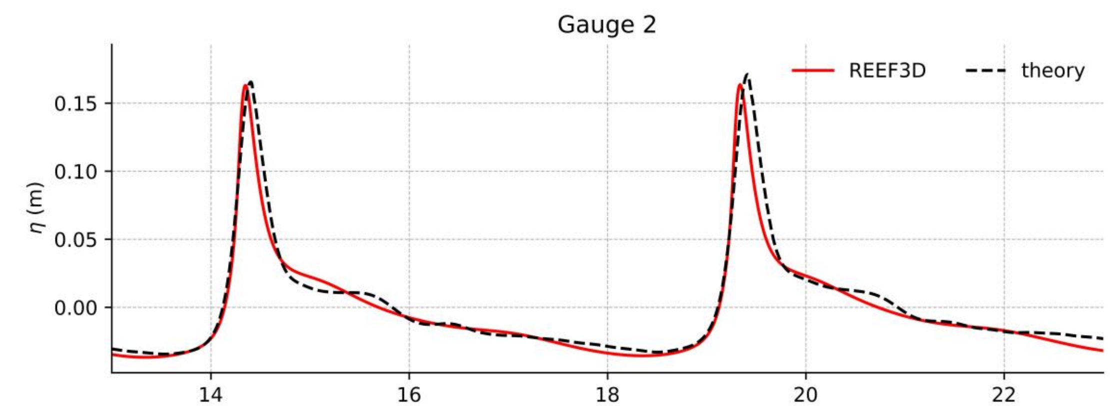
Setup
- mesh: 640 x 5
- dx = 0.05 m
- CFL = 0.5

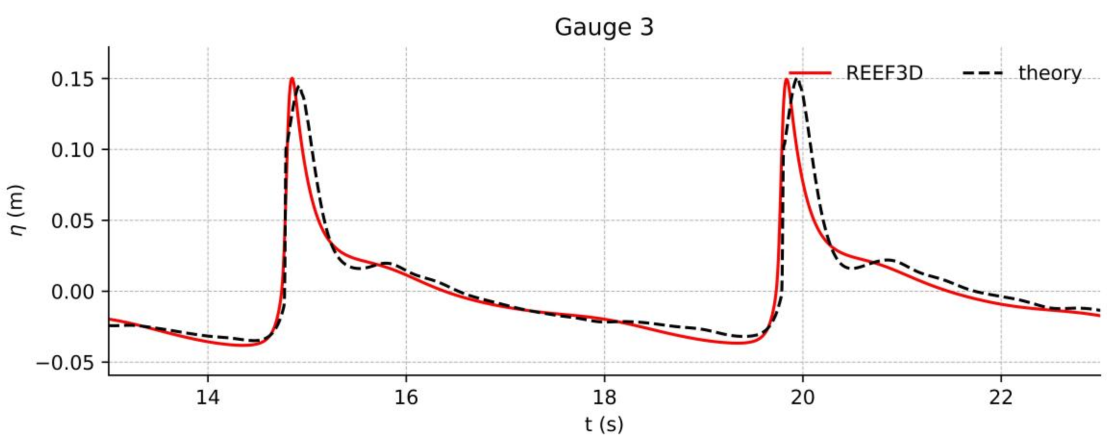


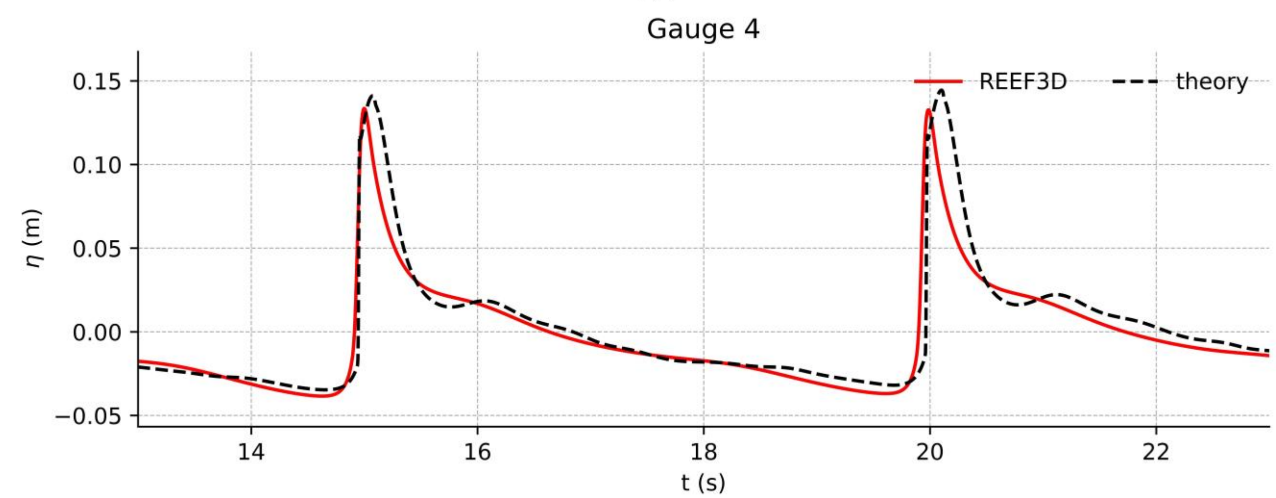


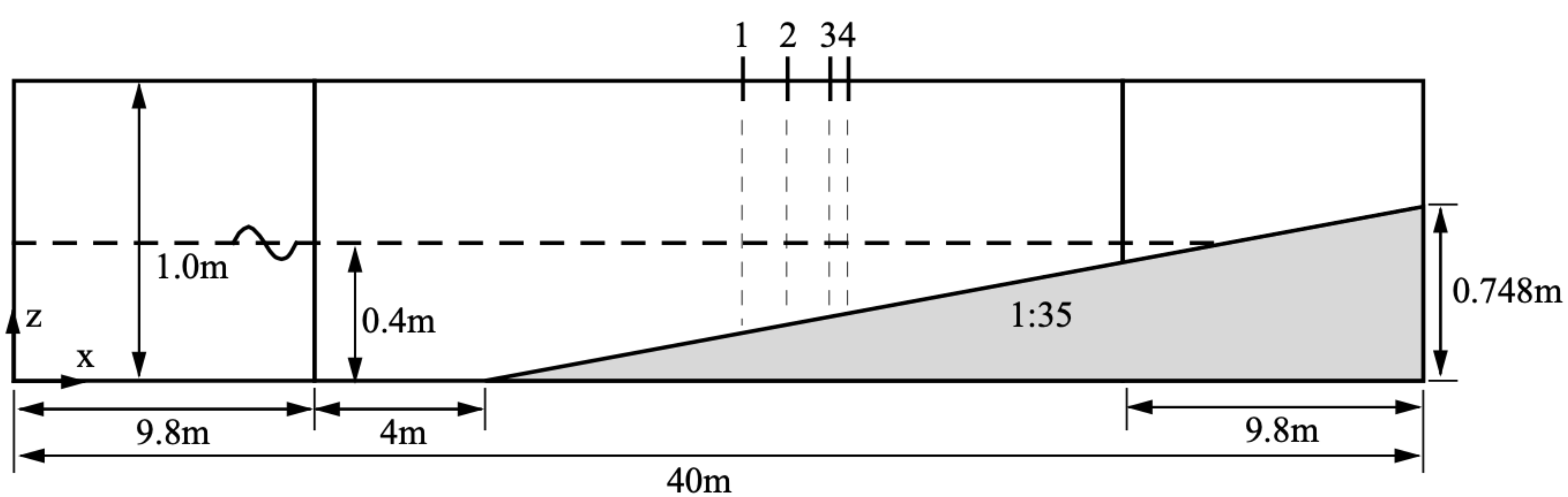
Ting&Kirby: Breaking Waves



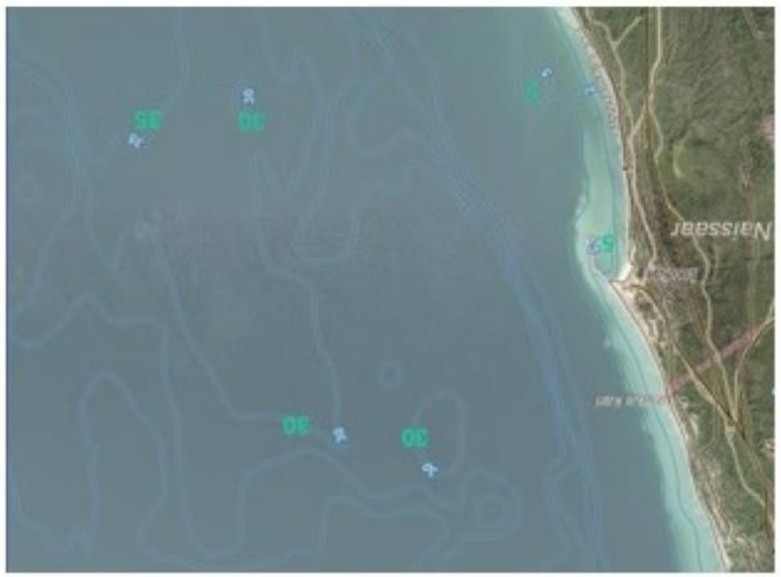


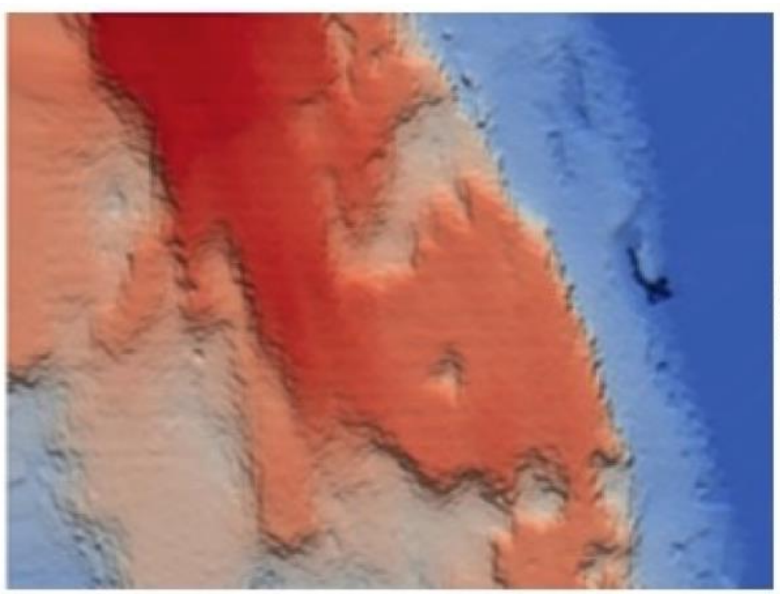


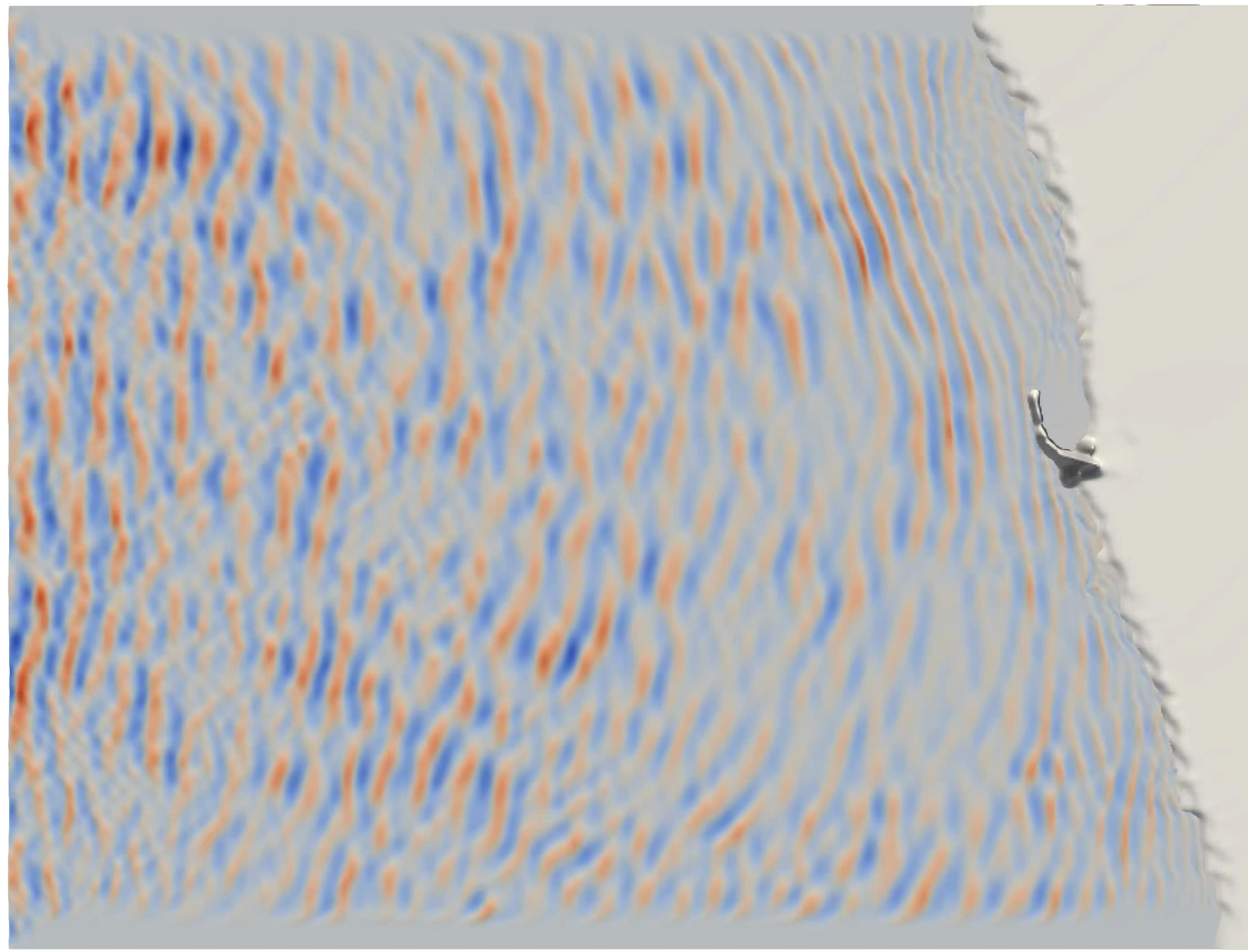




Naissaar Harbor, Estonia



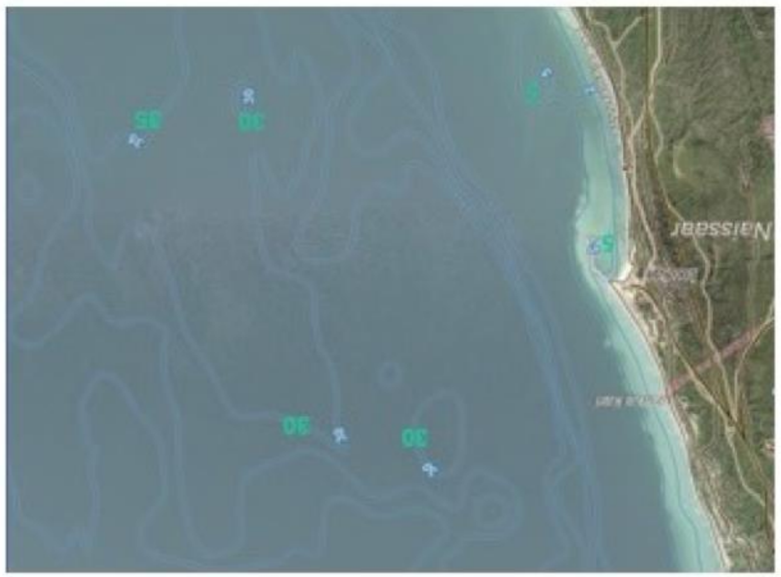


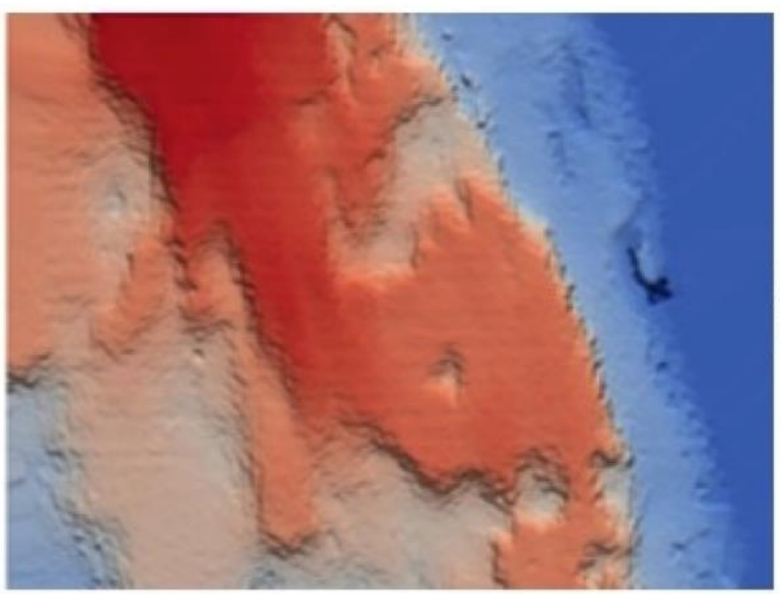


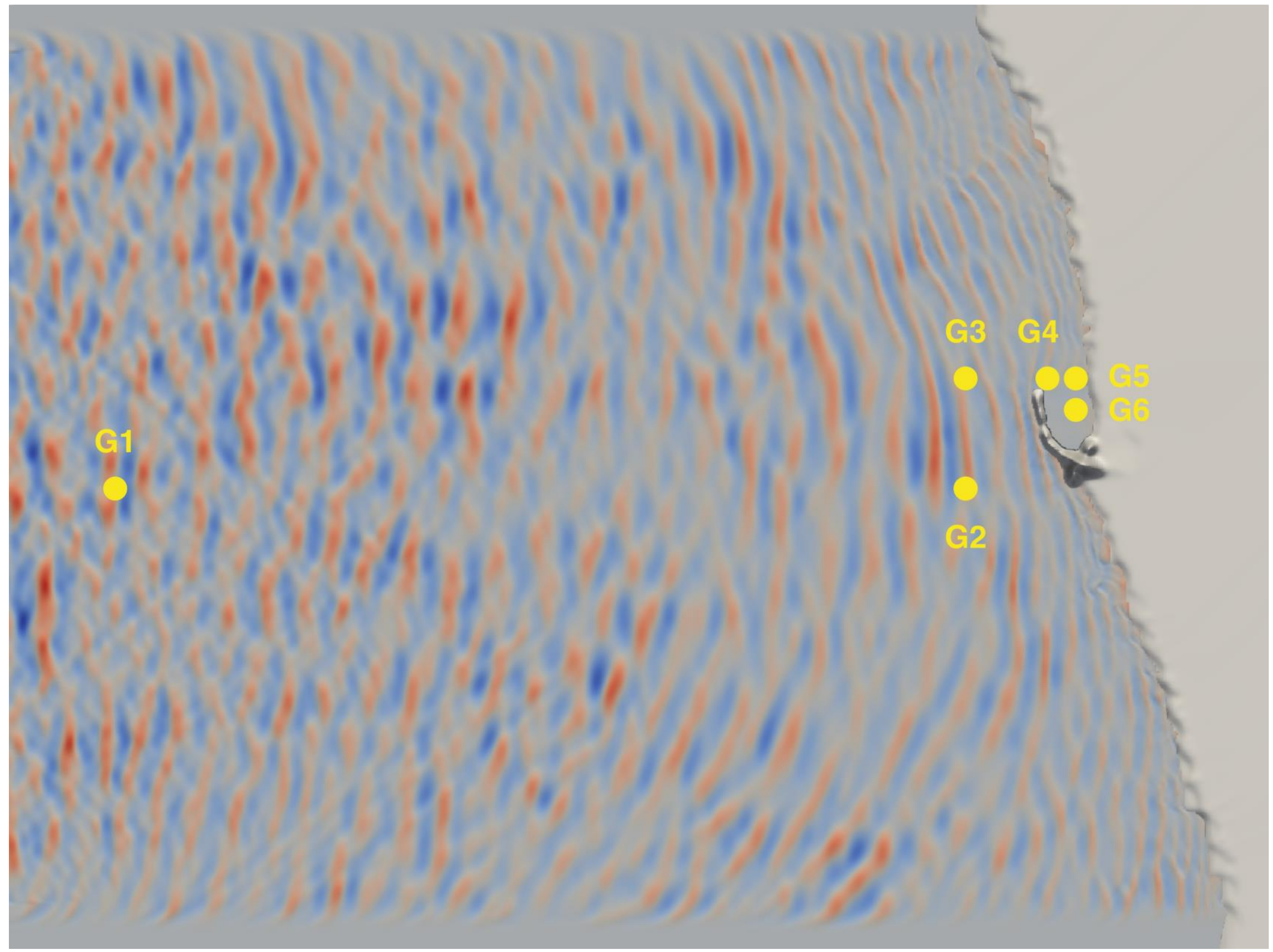
Wave Input
- Hs = 1.42 m
- T = 10.0 s
- wave theory: short-crested irregular waves

Setup
- mesh: 800 x 600 x 5
- 2.4 mil. cells

Naissaar Harbor, Estonia







Wave Input
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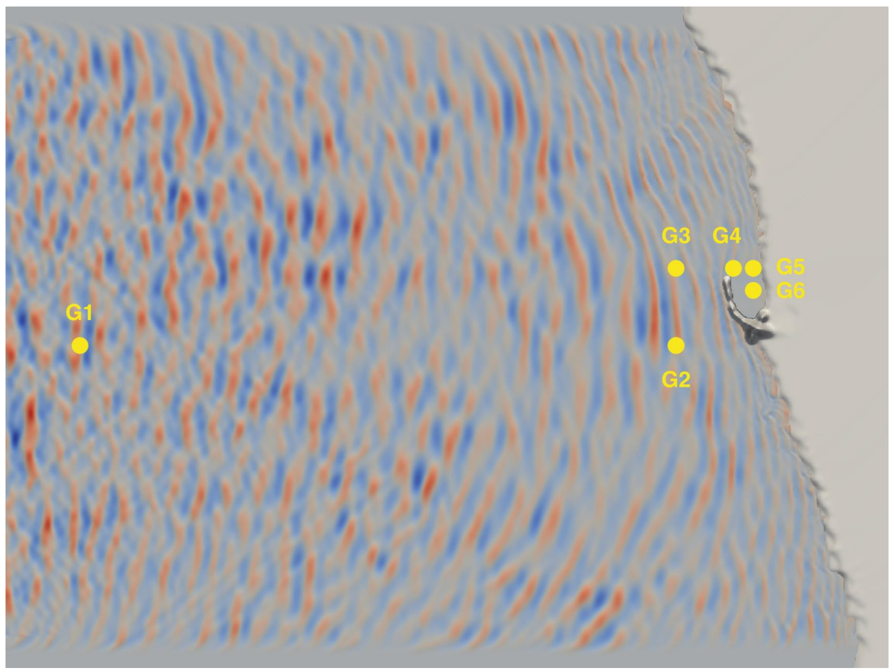
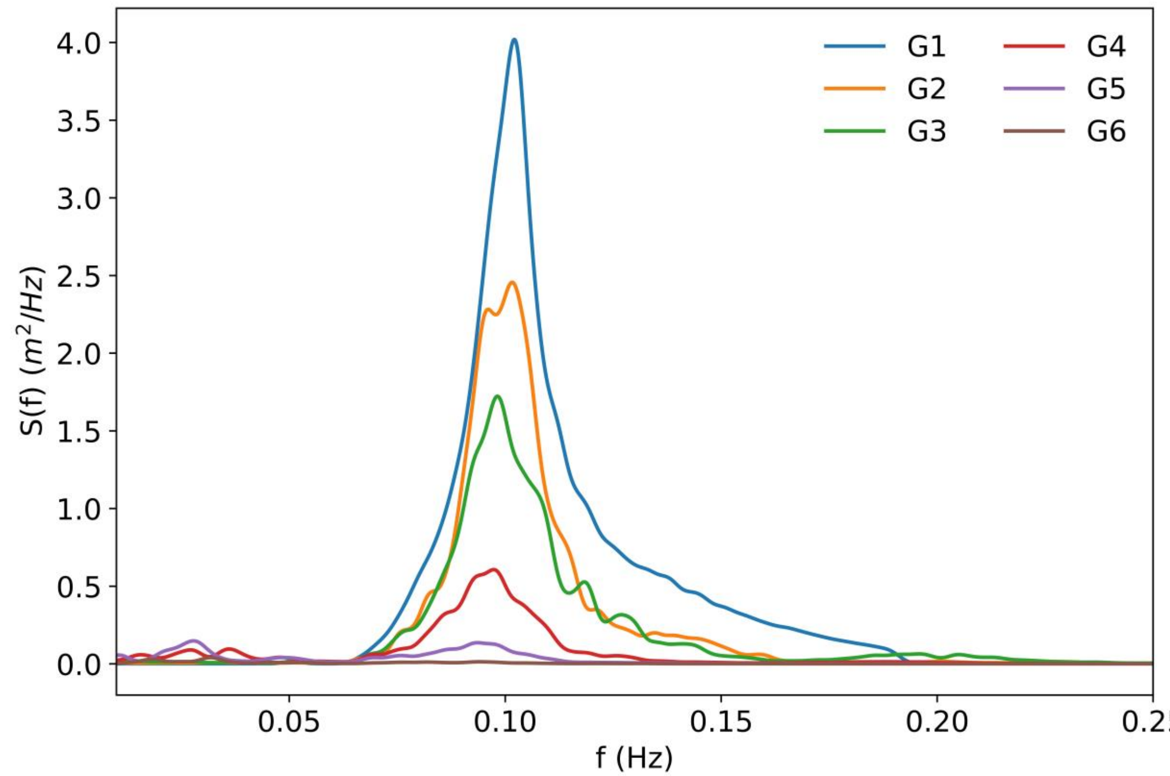
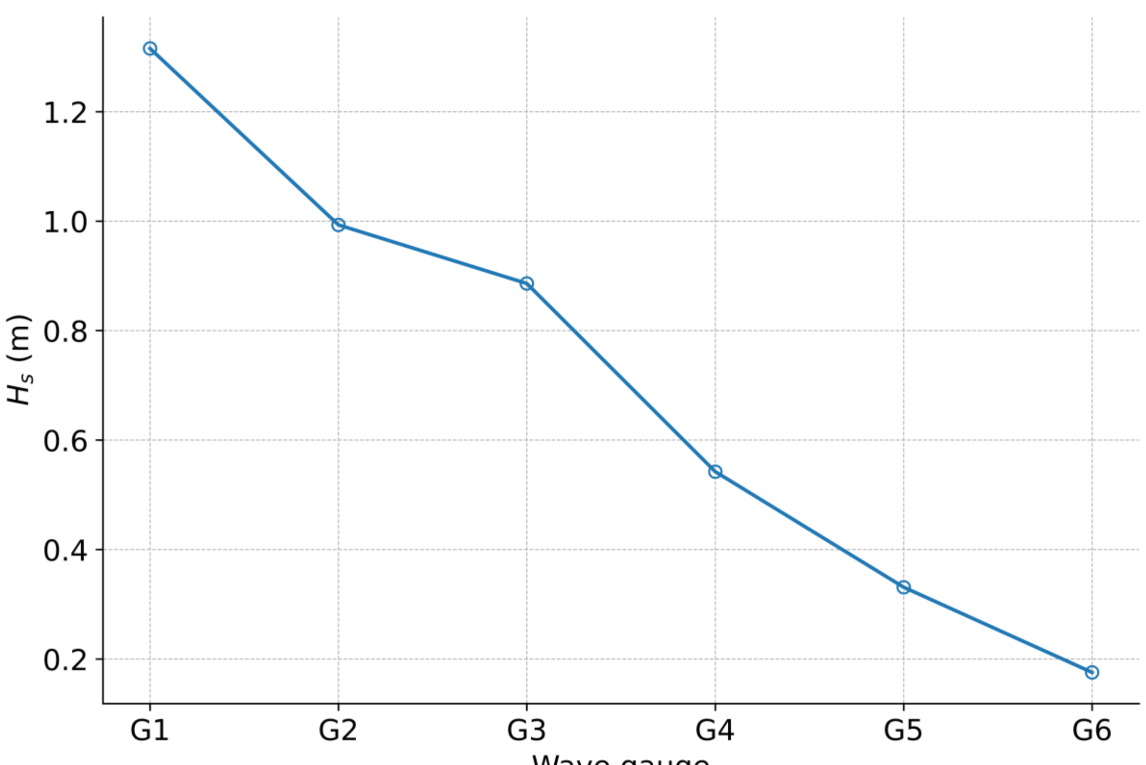
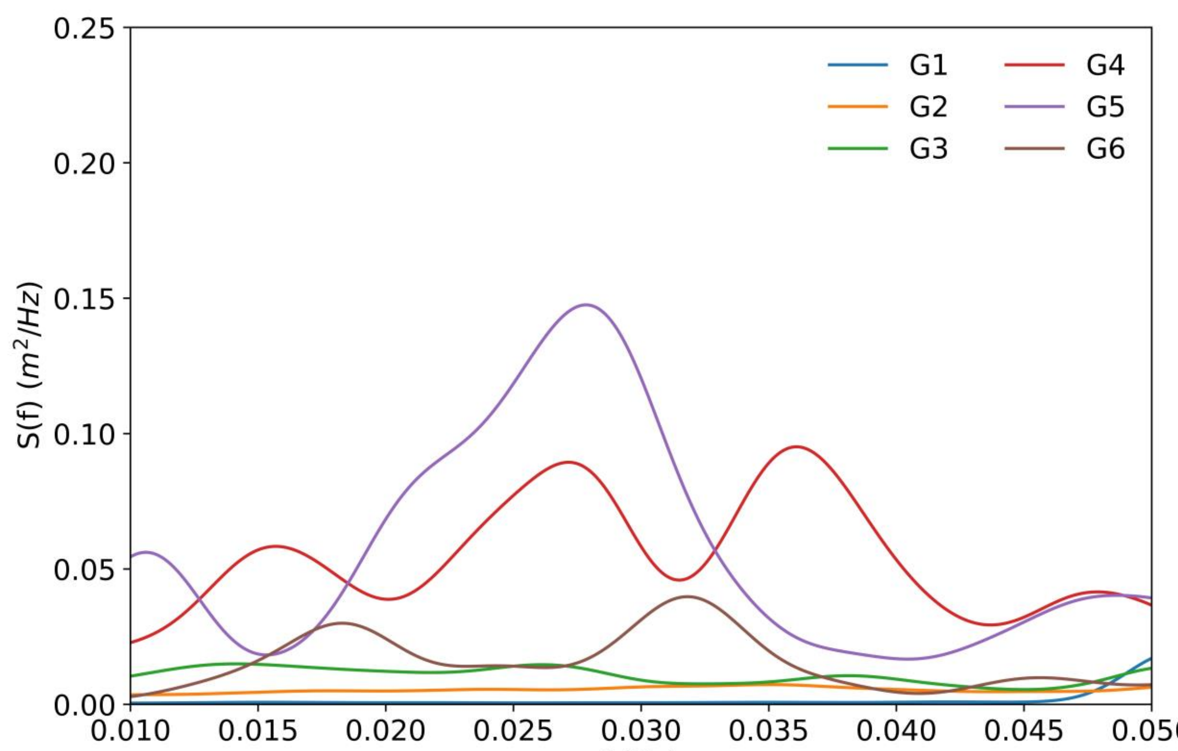
Naissaar Harbor, Estonia





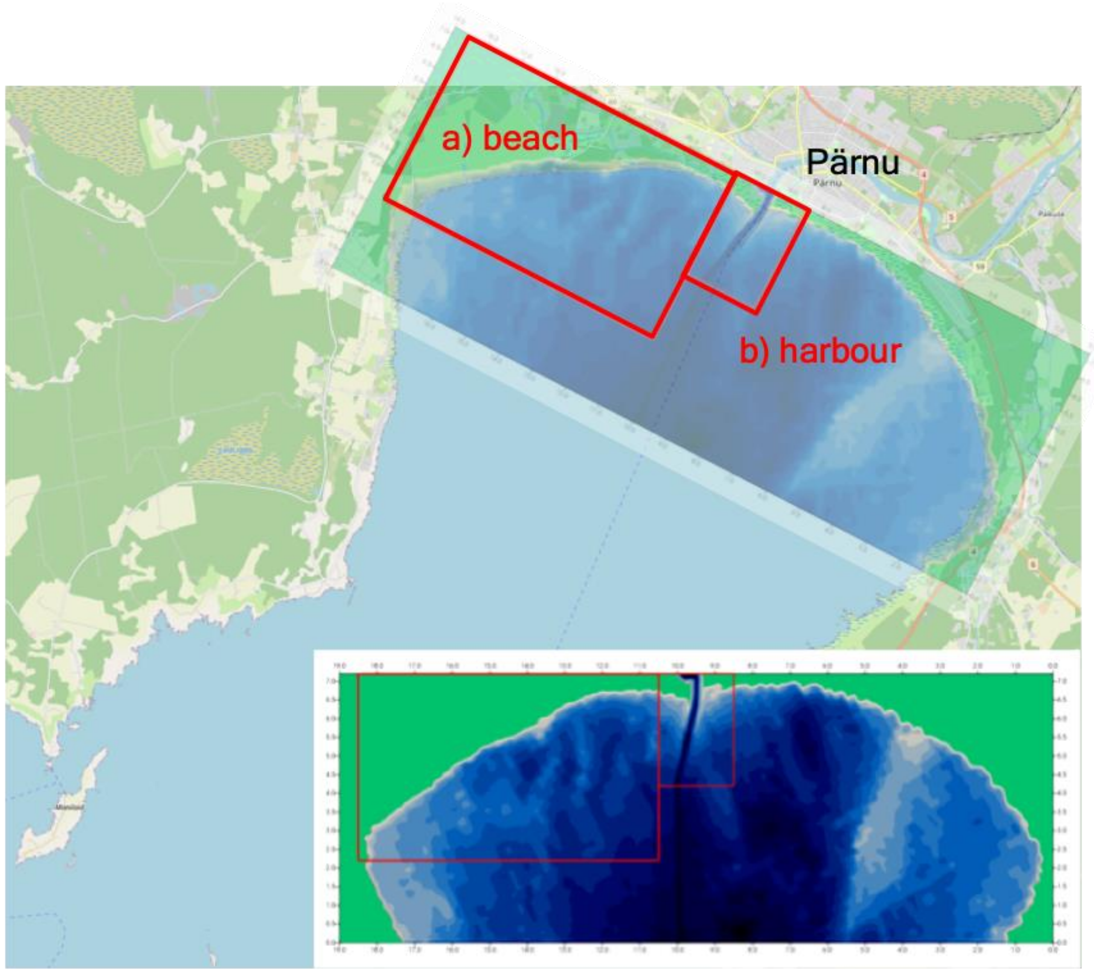
wave spectra

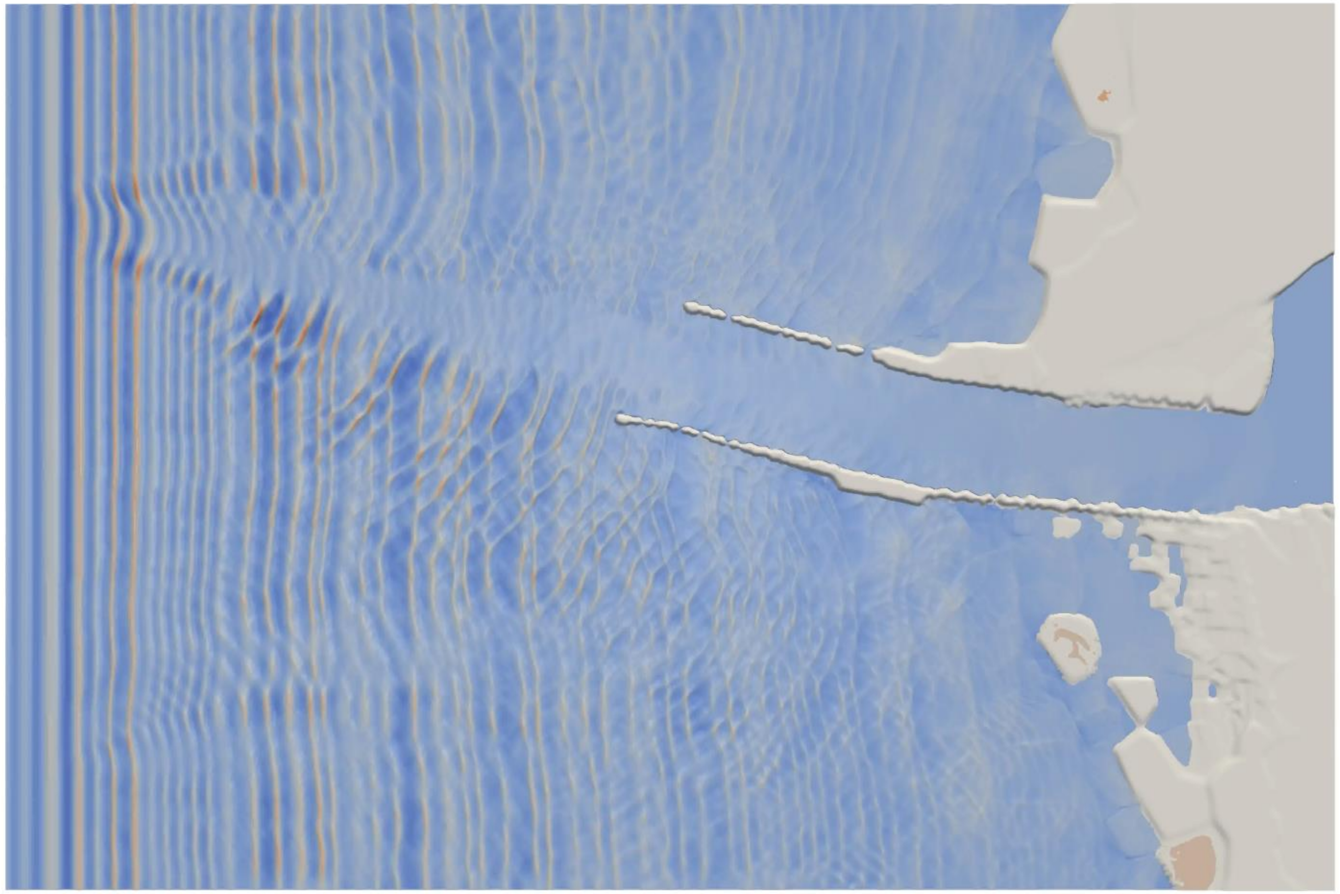




low frequency part

Pärnu - Outlook





Processes
- waves
- current
- sediment transport

Ericeira - Surf Wave Modeling

- Ericeira (Portugal): Unique location for surfing, one of the top spots in the world
- 9 different beaches
- EEA Grant

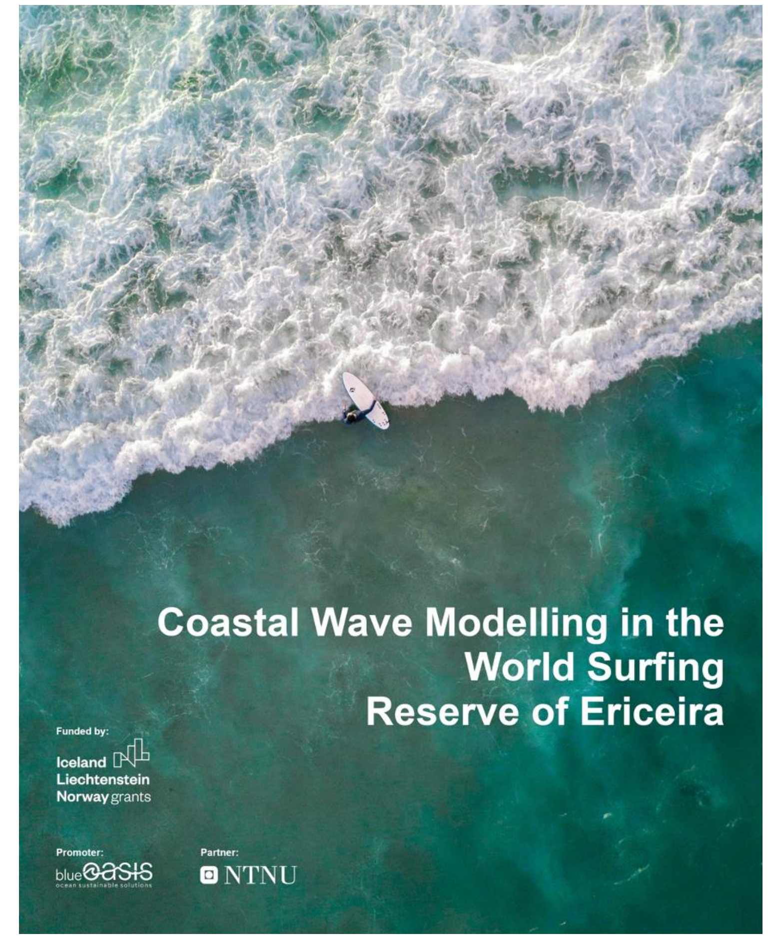
Objective

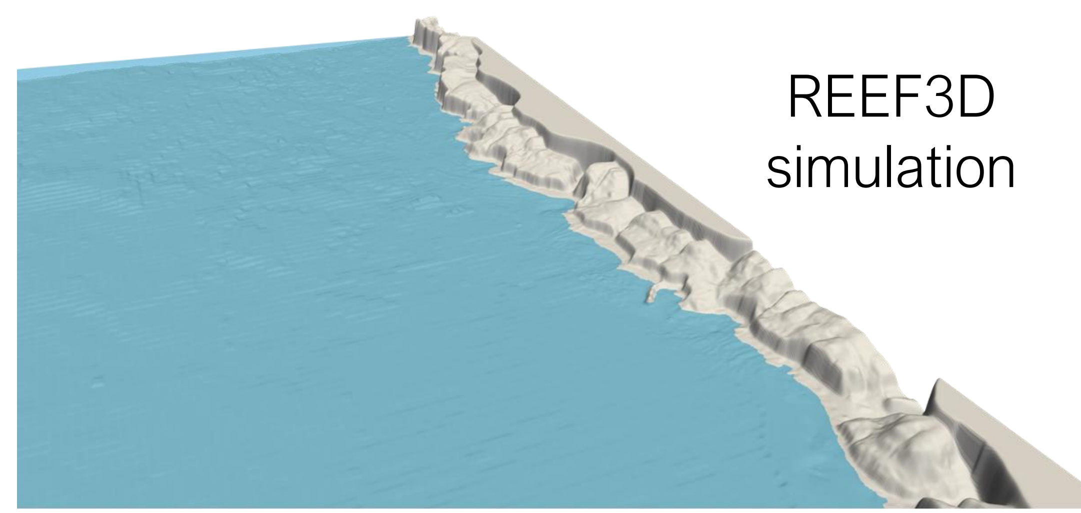
- predict wave conditions for the different beaches with REEF3D
- build a tool to predict surf waves
- <u>partner:</u> blueOasis, Ericeira Surf Clube

blueOasis
ocean sustainable solutions

ERICEIRA
SURFCLUBE

NTNU





REEF3D
simulation

Ericeira - Surf Wave Modeling

Wave Input

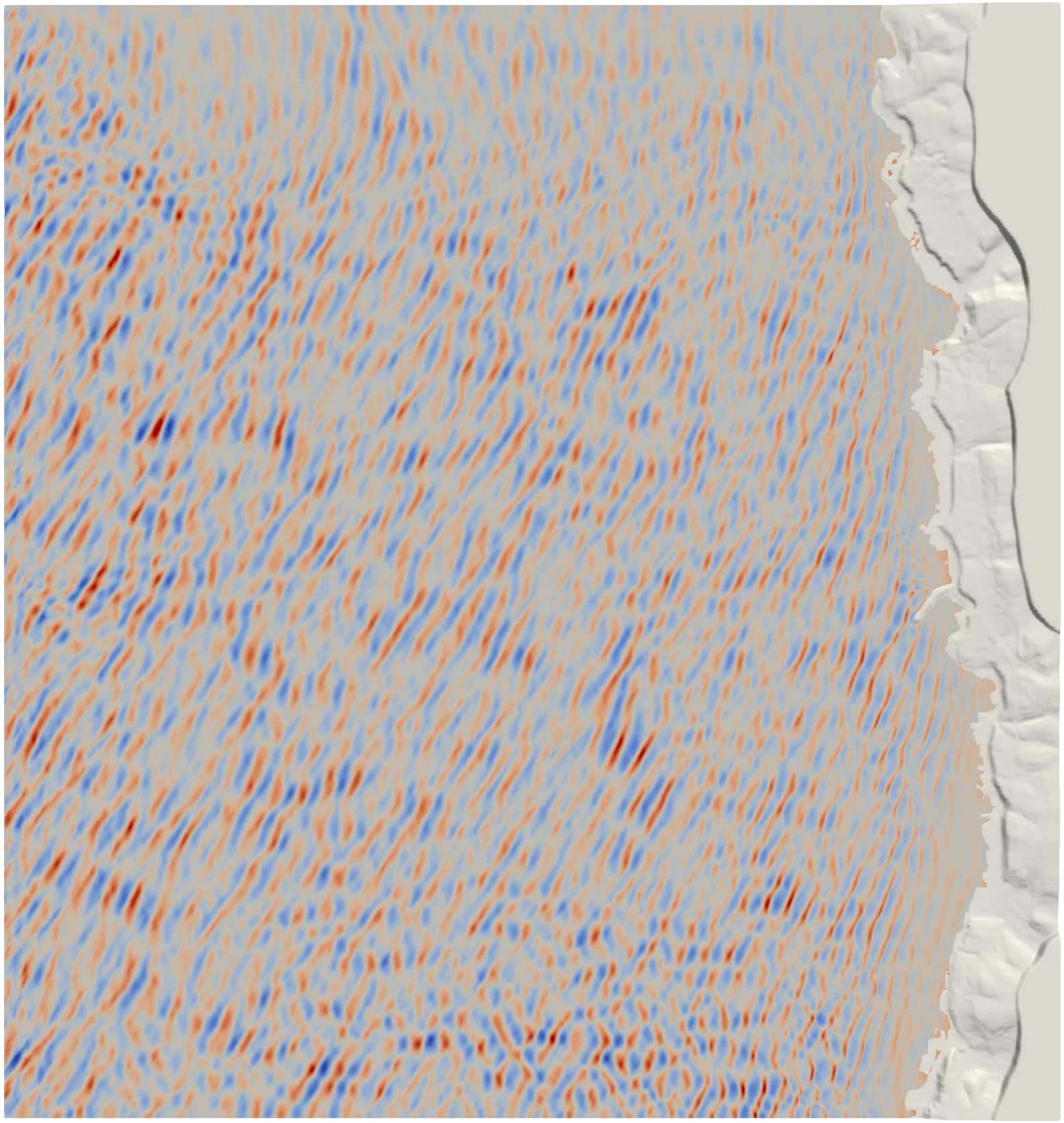
- Hs = 4.0m
- T = 12.0 s
- wave theory: short-crested irregular waves

Setup

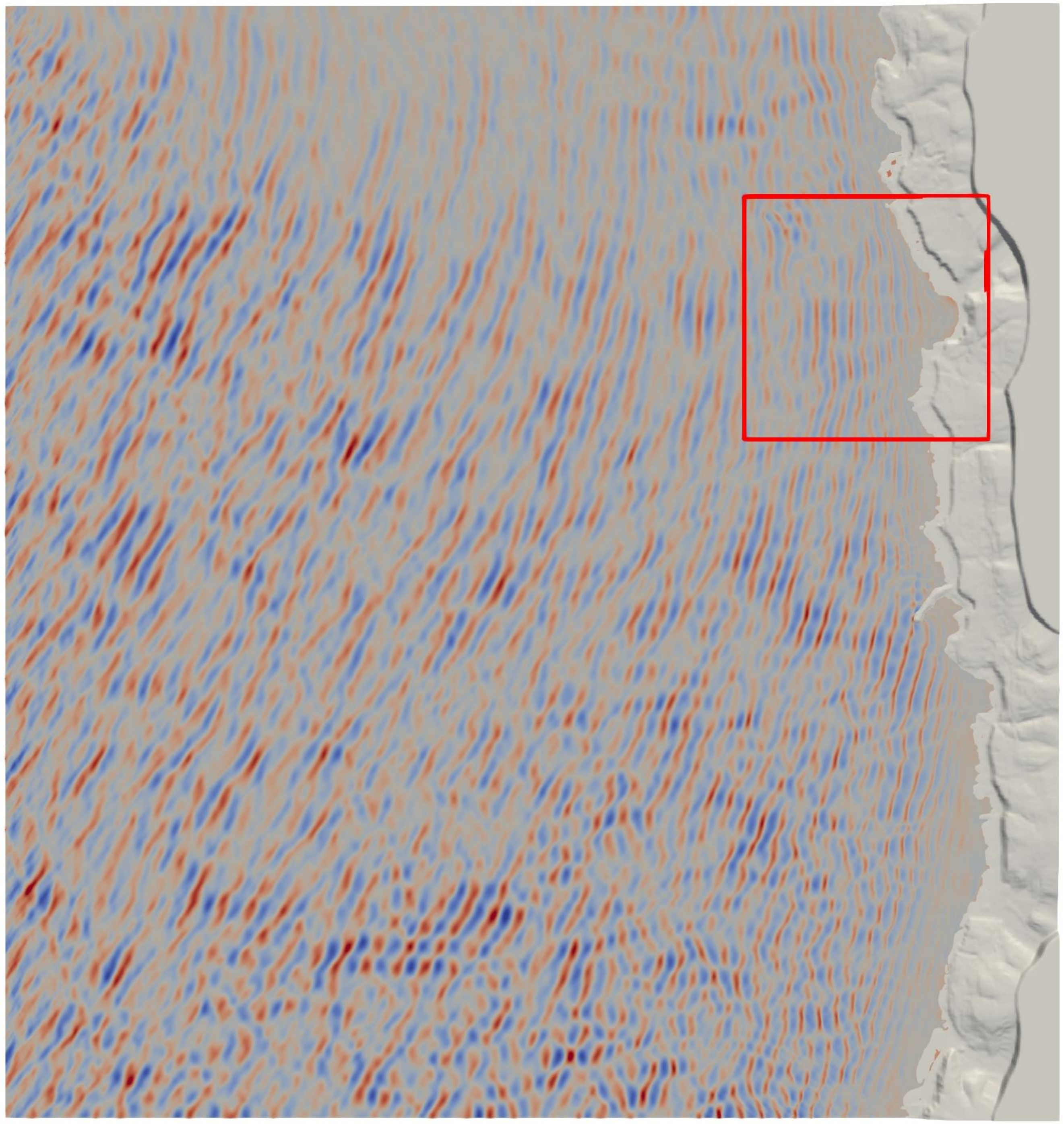
- 8.7 km x 9.1 km
- mesh: 1300 x 1377 x 5
- 8.95 mil. cells
- dx = 6.7 m

Bathymetry

- EMODNet (115m)
- LiDAR for coast (15m)



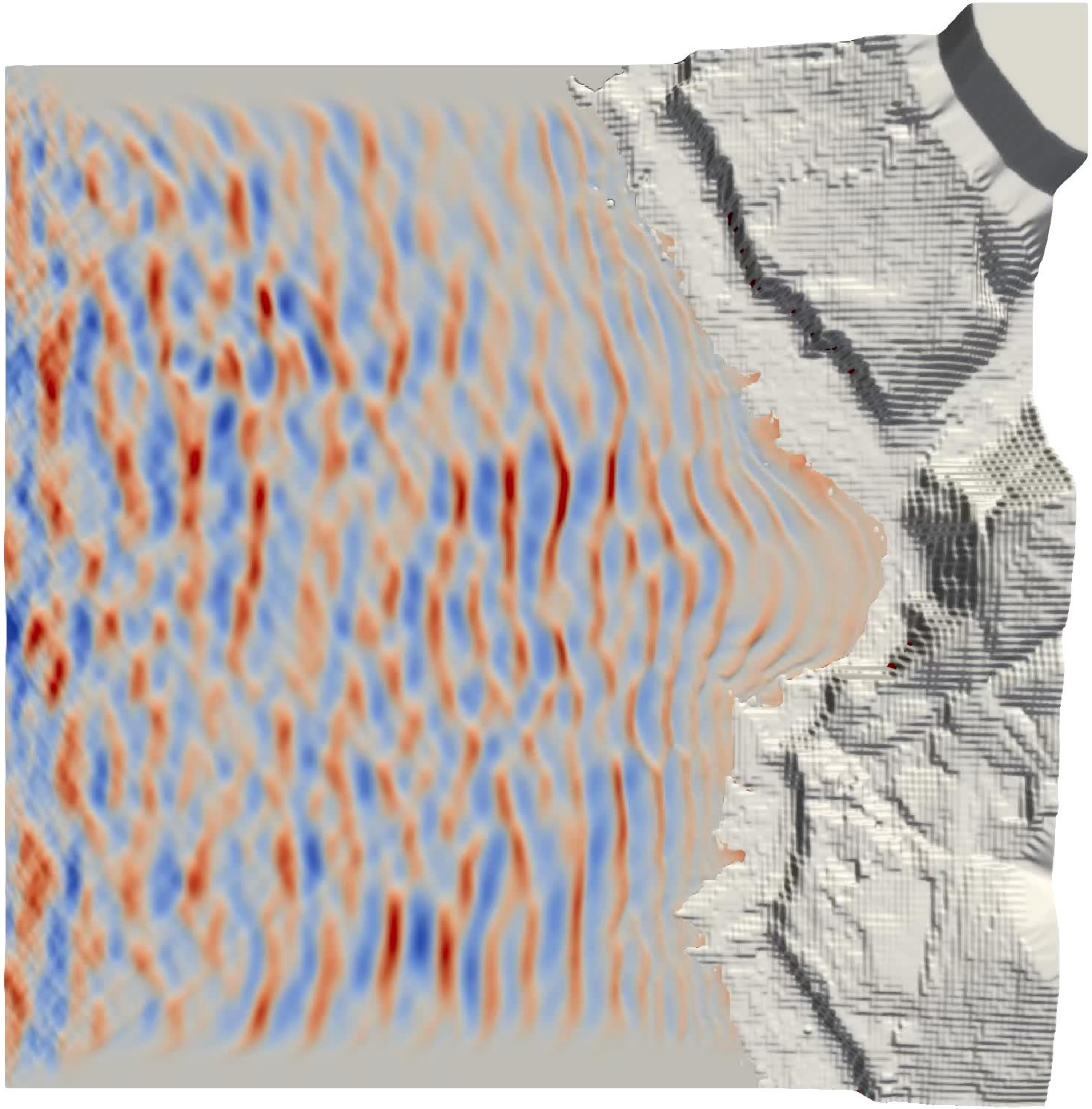
Ericeira: Praia de Ribeira d'Ilhas



Ericeira: Praia de Ribeira d'Ilhas

Wave Input
- Hs = 3.0m
- T = 10.0 s
- wave theory: short-crested irregular waves

Setup
- 2 km x 2 km
- mesh: 500 x 500 x 5
- 1.25 mil. cells
- dx = 4.0 m



Conclusions & Outlook

Conclusions

- new non-hydrostatic model REEF3D::NHFLOW
- very good dispersion (from deep to shallow)
- dynamic coastline: wetting & drying
- stable breaking wave behavior
- efficient: parallel and low number of cells needed
- accurate: HLL-Riemann with WENO reconstruction

Outlook

- more Validation
- Current
- Sediment
- Porous Media / VRANS
- Immersed structures
- Ship wave generator
- Hydrodynamic Coupling: NHFLOW to CFD

Acknowledgement

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