REEF3D::FNPF

Efficient Phase-Resolved Wave Modeling for the Norwegian Coast

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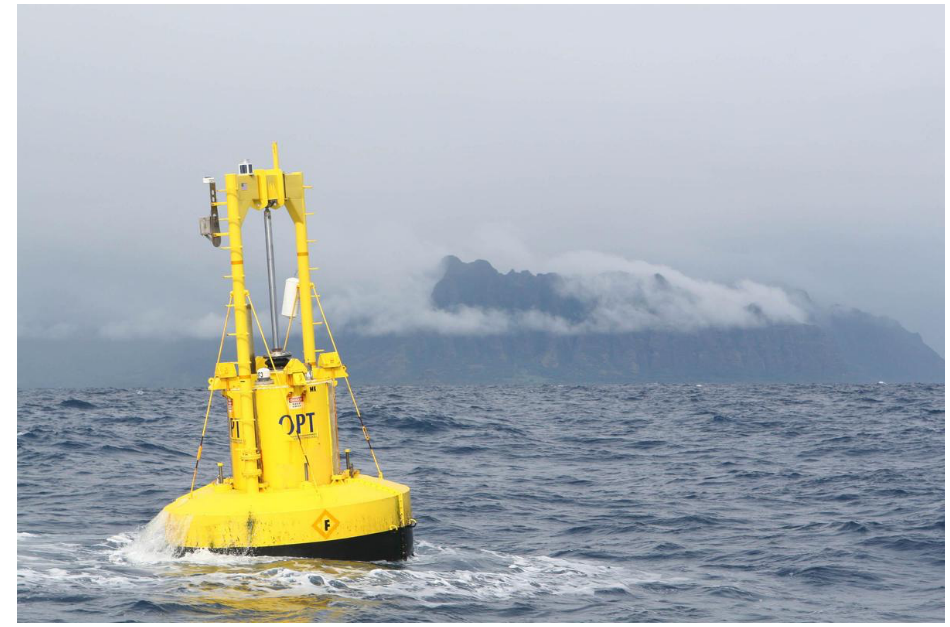
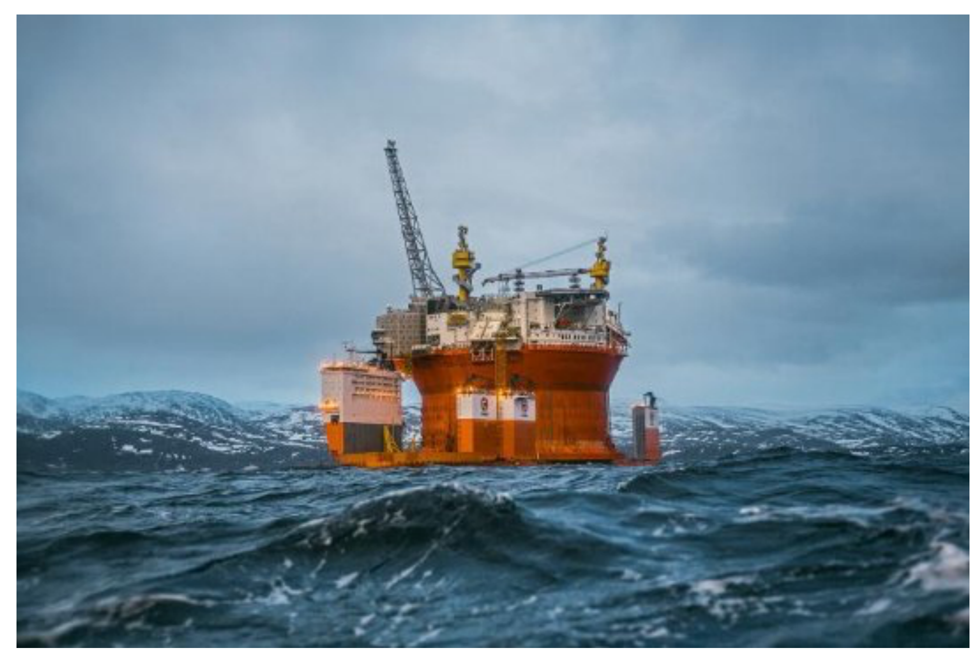
Motivation for Wave Modeling : Offshore Energy

Offshore Wind Energy: Wave Force, Local Scour



Ocean Wave Energy: Wave Climate, Wave Forces

Offshore Structures: Wave Force, Green Water



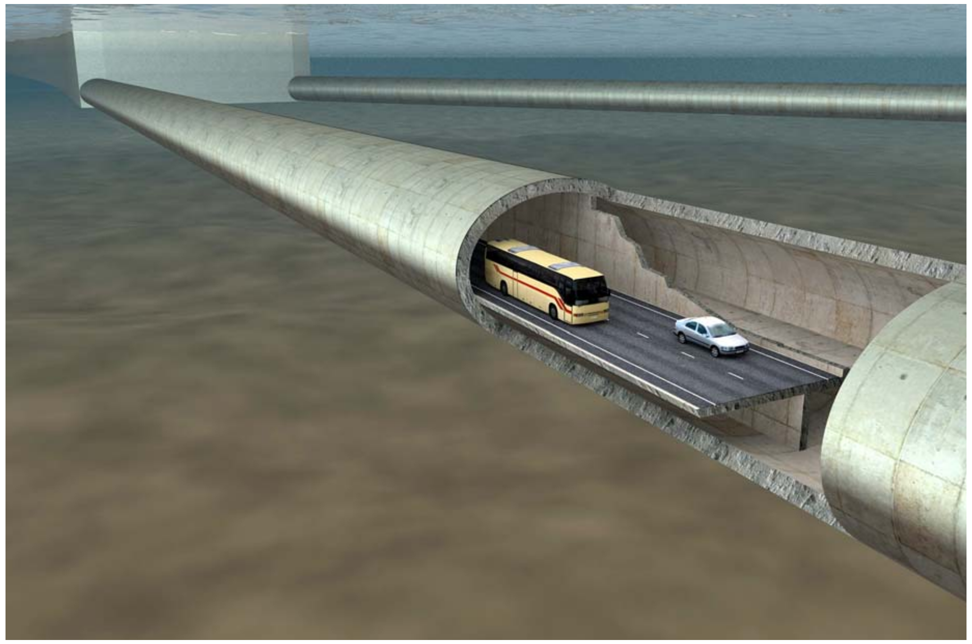
Offshore Structures: Floating, Mooring, Ice

Motivation for Wave Modeling : Transportation

Coastal Transportation Infrastructure

Harbour: e.g. Sirevåg

E39: Floating Bridges



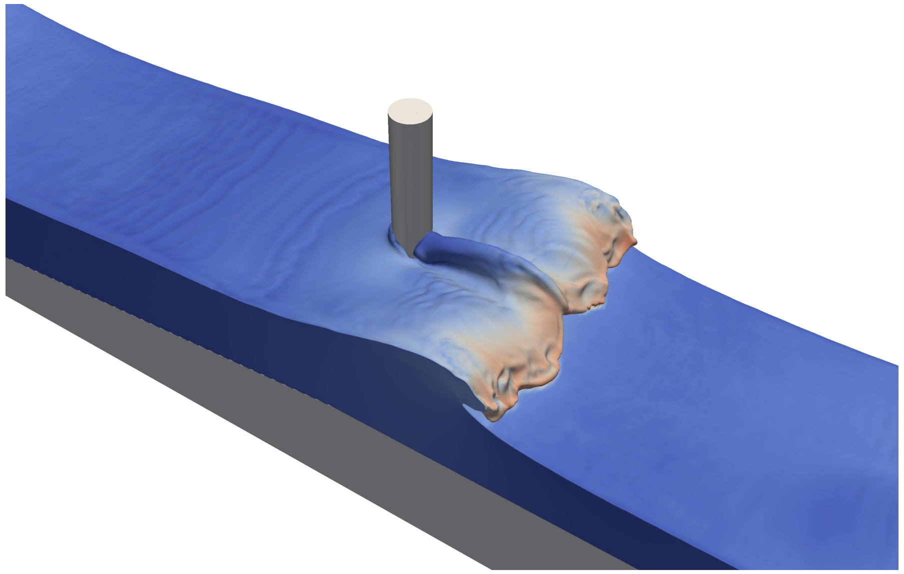
E39: Floating Tunnels

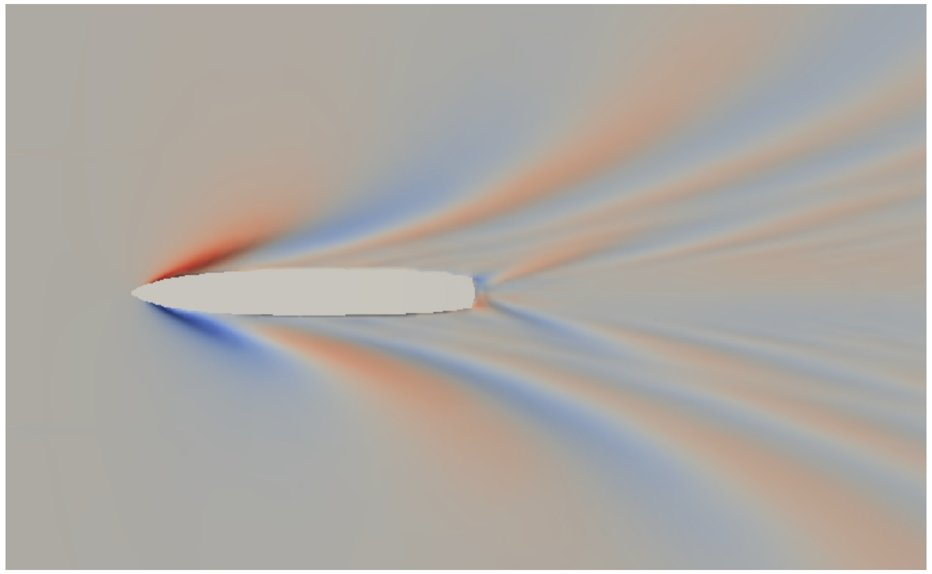
REEF3D::CFD

- **Solves:**
  - Full 3D Navier-Stokes Equations
  - Free Surface: Two-Phase Flow - Water & Air
  - Turbulence

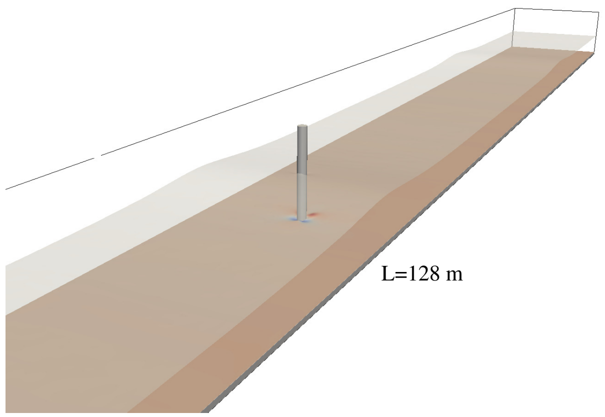
- **Focus on:**
  - Free Surface Flows
  - Wave Hydrodynamics
  - Wave Structure Interaction
  - Floating Structures
  - Open Channel Flow
  - Sediment Transport

- **The Code:**
  - C++ (modular & extensible)
  - Parallel Computing / HPC
  - Open-Source
  - Developed at the Department of Civil and Environmental Engineering, NTNU Trondheim

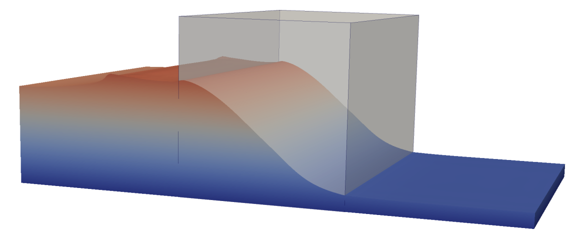




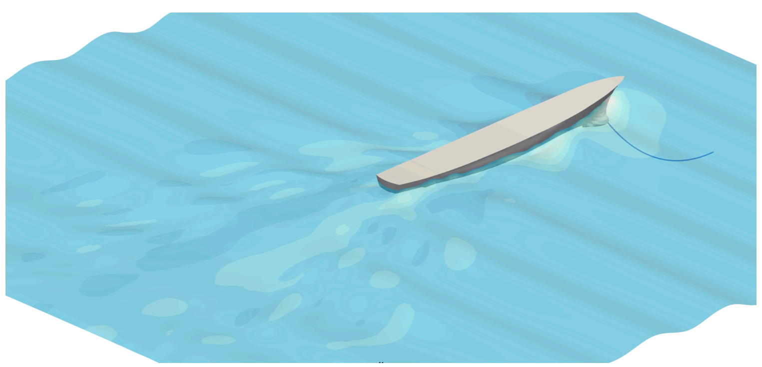
REEF3D::CFD : Multiphysics Extensions



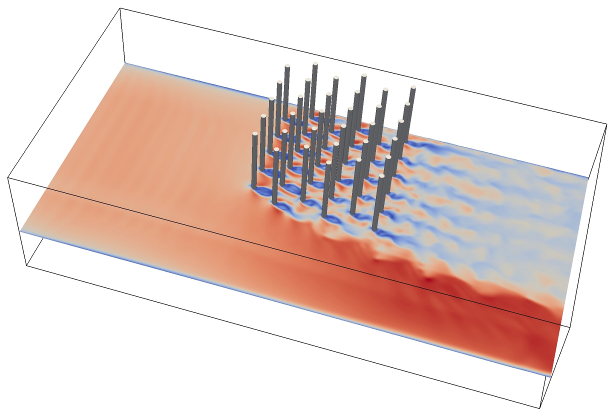
Sediment Transport
Local Scour
Arctic Erosion



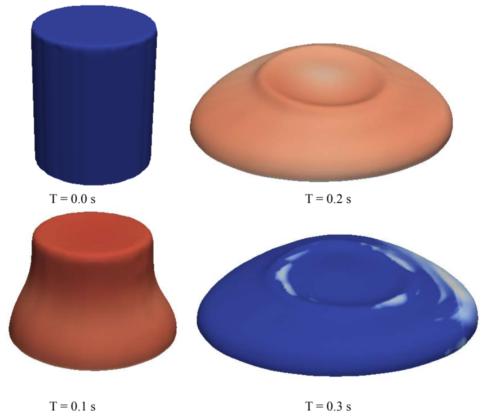
Porous Structures



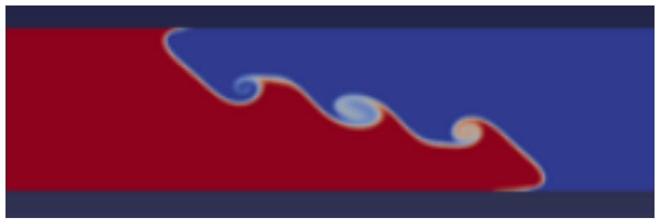
Floating Structures
6DOF
Mooring



Vegetation

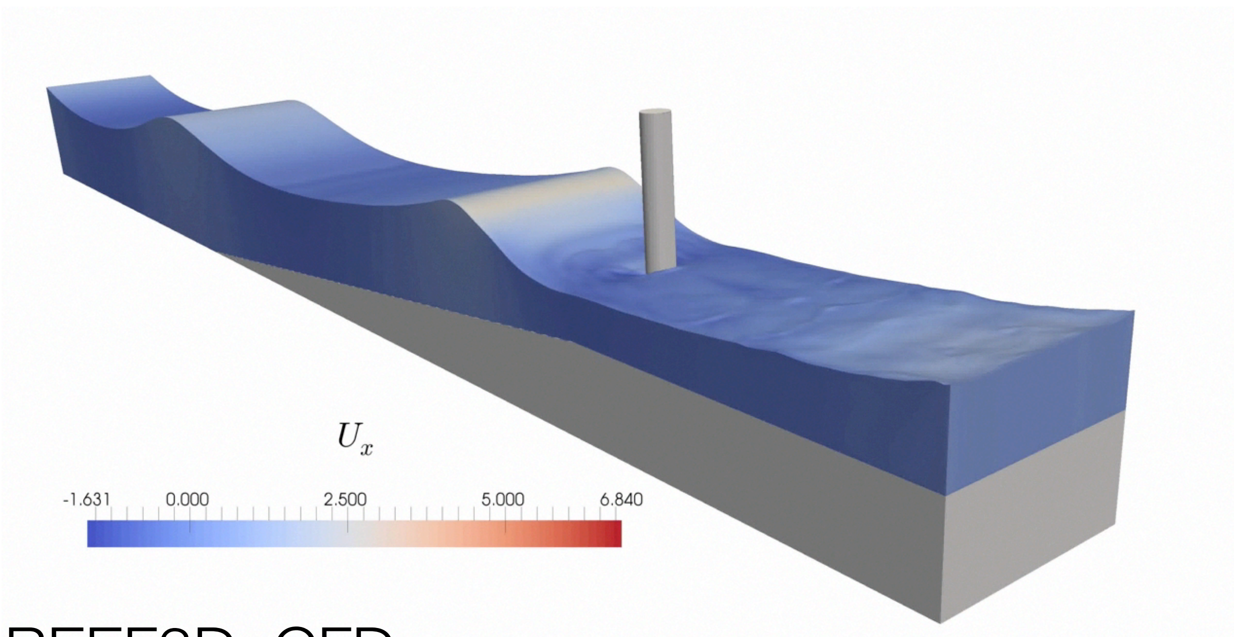


Debris Flow
Granular Flow

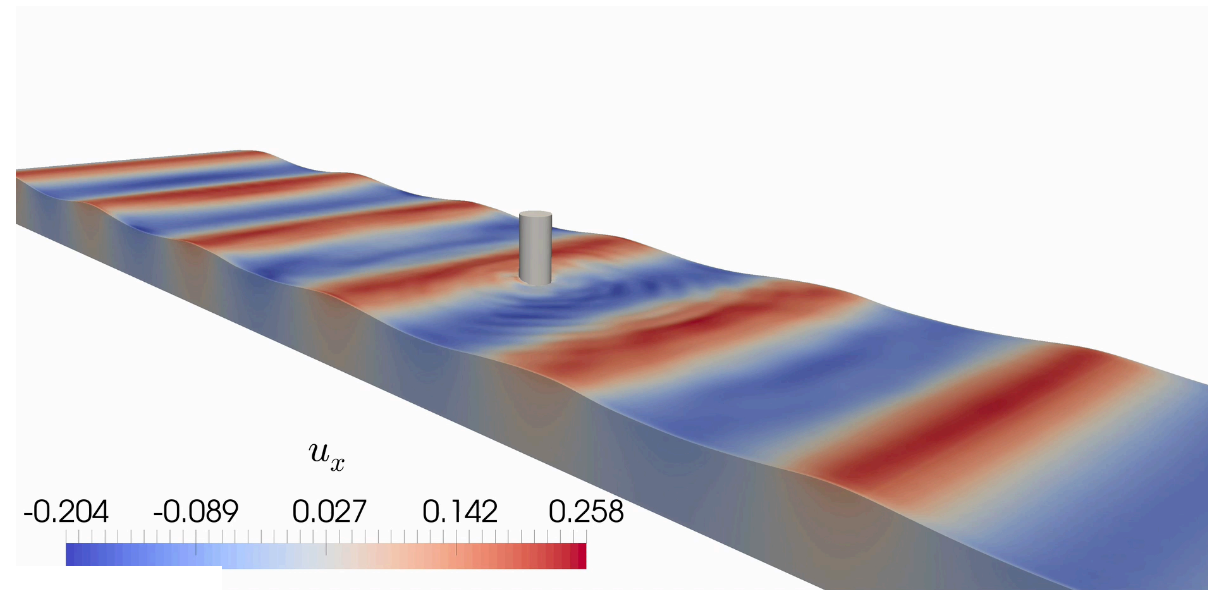


Stratified Flow

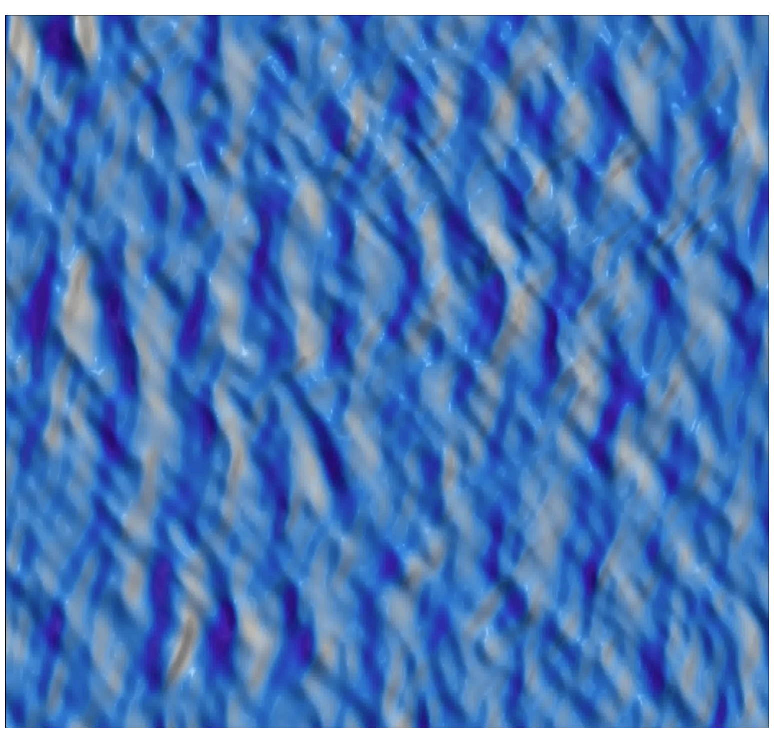
REEF3D : Open-Source Hydrodynamics



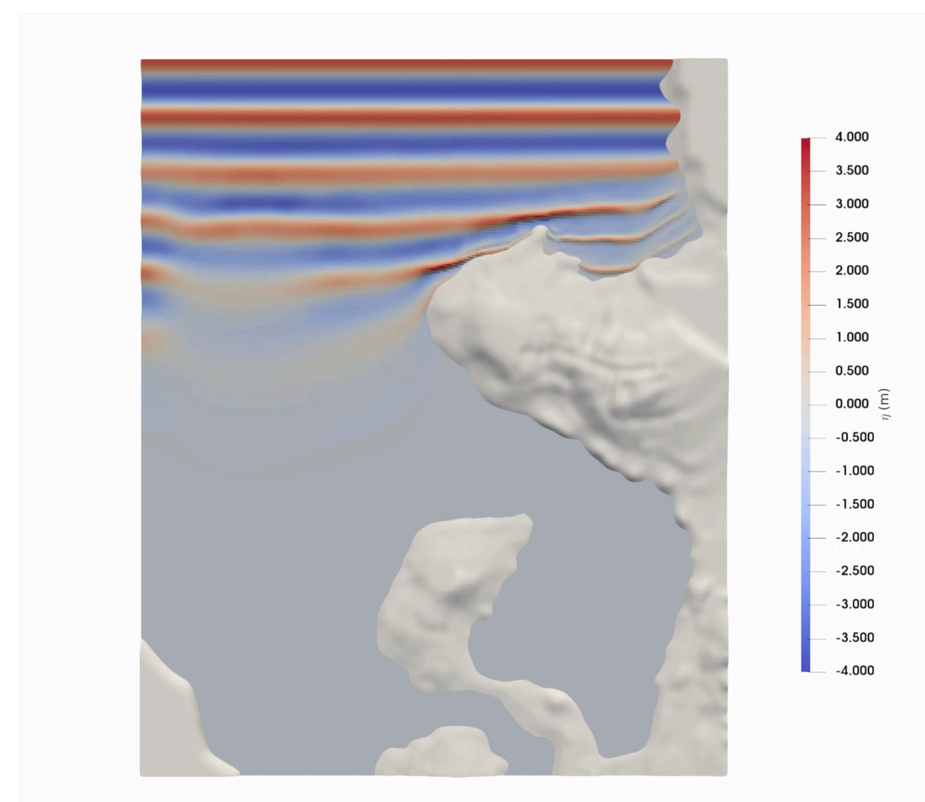
REEF3D::CFD



REEF3D::NSEWAVE



REEF3D::FNPF



REEF3D::SFLOW

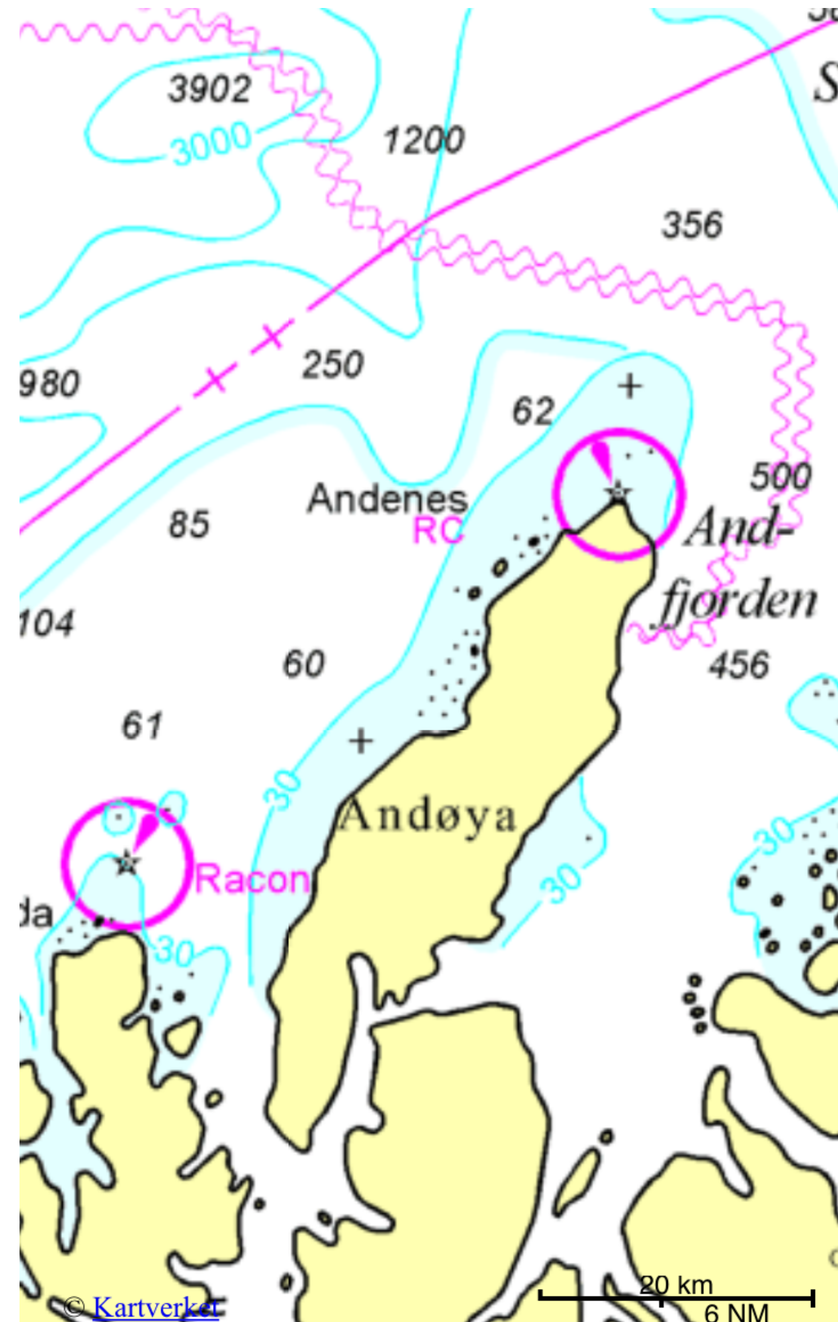
Typical North Sea Coast

Northern Germany

Föhr, Northern Friesland

Typical Norwegian Coast

Andenes, Versterålen Archipelago



FNPF Governing equations

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0$$

Laplace Equation

$$\frac{\partial \eta}{\partial t} = -\frac{\partial \eta}{\partial x}\frac{\partial \widetilde{\Phi}}{\partial x} + \frac{\partial \eta}{\partial y}\frac{\partial \widetilde{\Phi}}{\partial y} + \widetilde{w}\left(1 + \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2}\right)$$

kinematic FSFBC

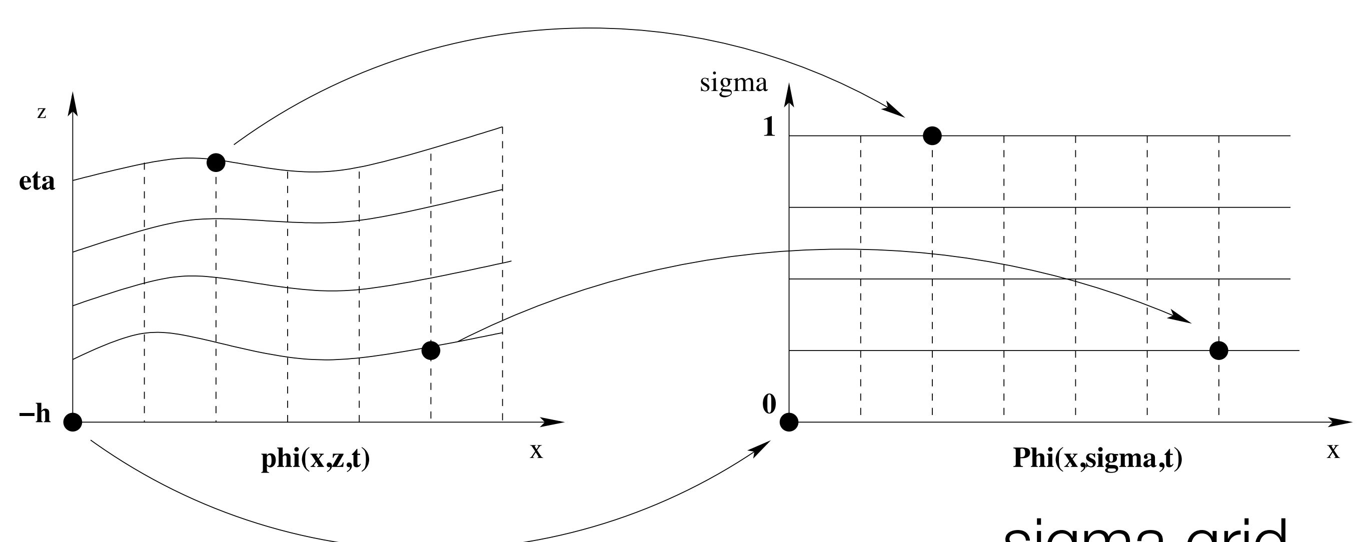
$$\frac{\partial \widetilde{\Phi}}{\partial t} = -\frac{1}{2}\left(\frac{\partial^2 \widetilde{\Phi}}{\partial x^2} + \frac{\partial^2 \widetilde{\Phi}}{\partial y^2} - \widetilde{w}^2\left(1 + \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2}\right)\right) - g\eta$$

dynamic FSFBC

$$\frac{\partial \Phi}{\partial z} + \frac{\partial h}{\partial x}\frac{\partial \Phi}{\partial x} + \frac{\partial h}{\partial y}\frac{\partial \Phi}{\partial y} = 0, \;\; z = -h.$$

kinematic bed BC

$$\sigma = \frac{z + h(\mathbf{x})}{\eta(\mathbf{x},t) + h(\mathbf{x})}$$



sigma grid

Solution of the Laplace Equation

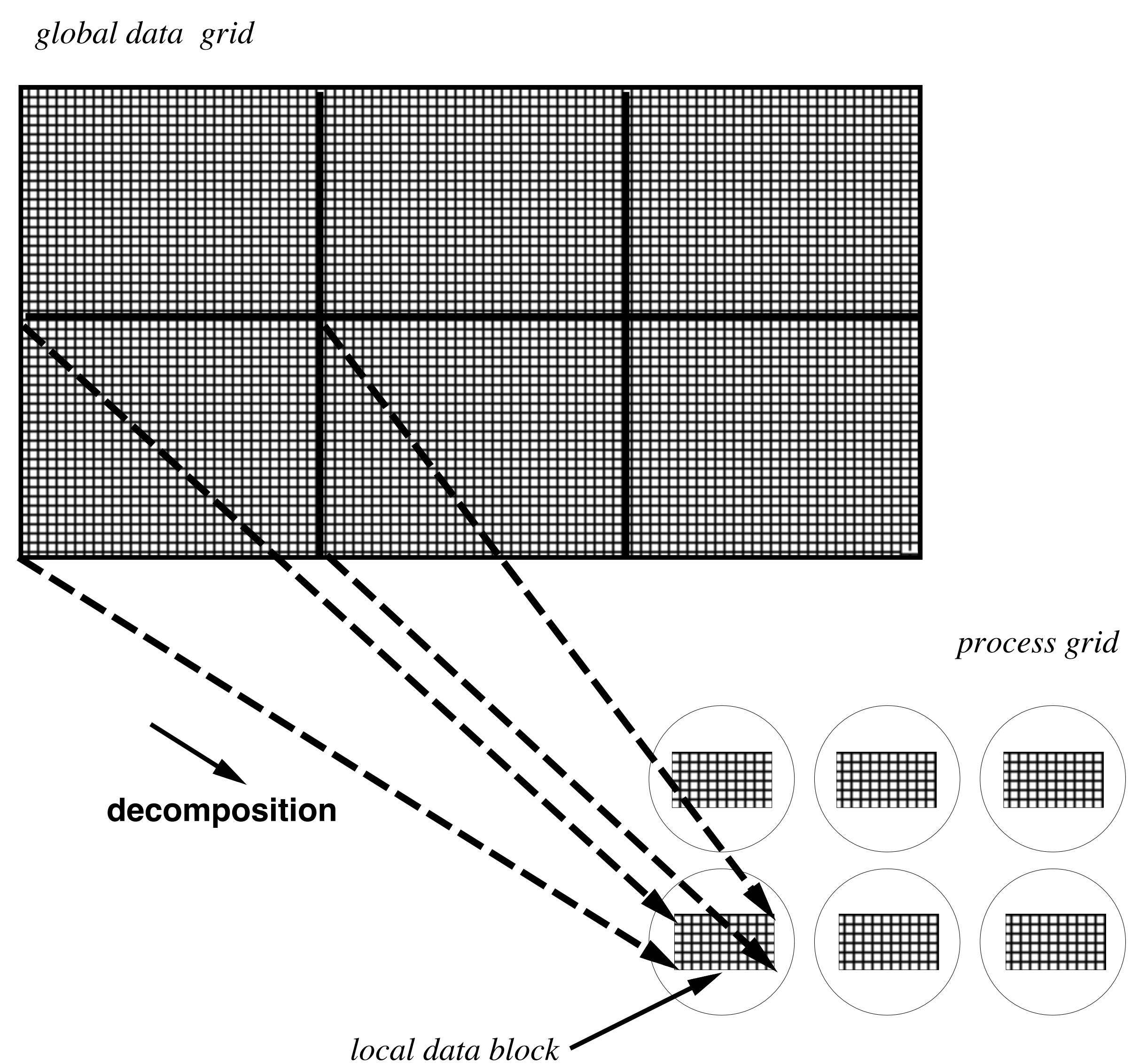
Lapace Eq. for the potential

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} + \frac{\partial^2\Phi}{\partial z^2} = 0$$

→ $Ax = 0$
system of linear Equations

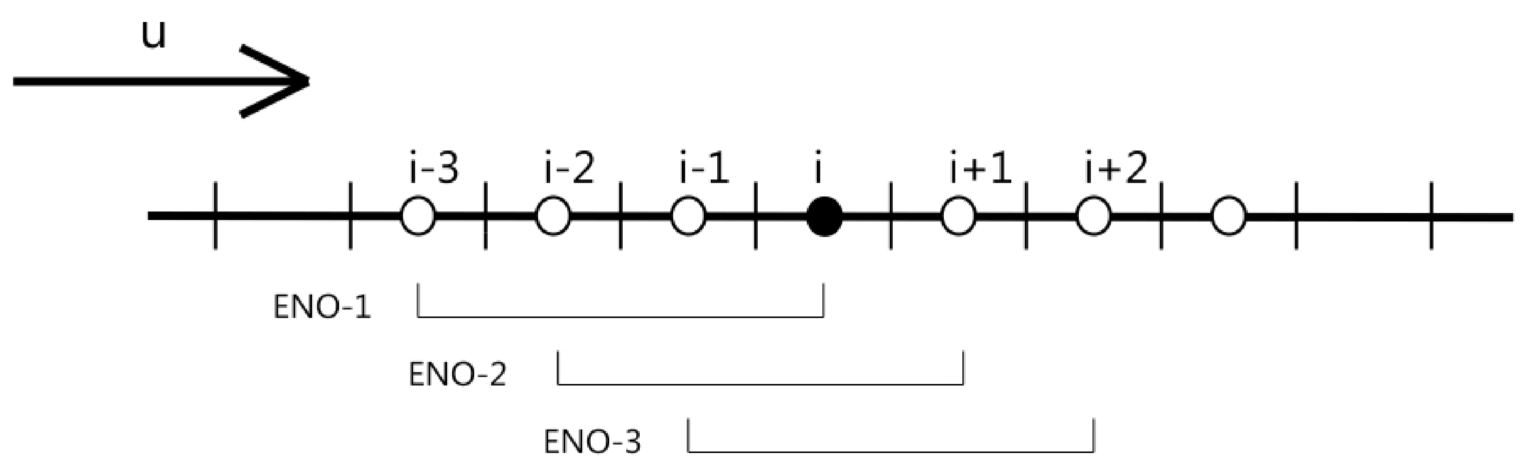
→ hypre: BiCGStab + PFMG

HPC: domain decomposition



FSFBC: Spatial Discretization

Convection Discretization: Conservative 5th-order WENO



$$U\frac{\partial U}{\partial x} \approx \frac{1}{\Delta x}\left(\tilde{U}_{i+1/2}U_{i+1/2} - \tilde{U}_{i-1/2}U_{i-1/2}\right)$$

$$U^{\pm}_{i+1/2} = \omega^{\pm}_{1}U^{1\pm}_{i+1/2} + \omega^{\pm}_{2}U^{2\pm}_{i+1/2} + \omega^{\pm}_{3}U^{3\pm}_{i+1/2}$$

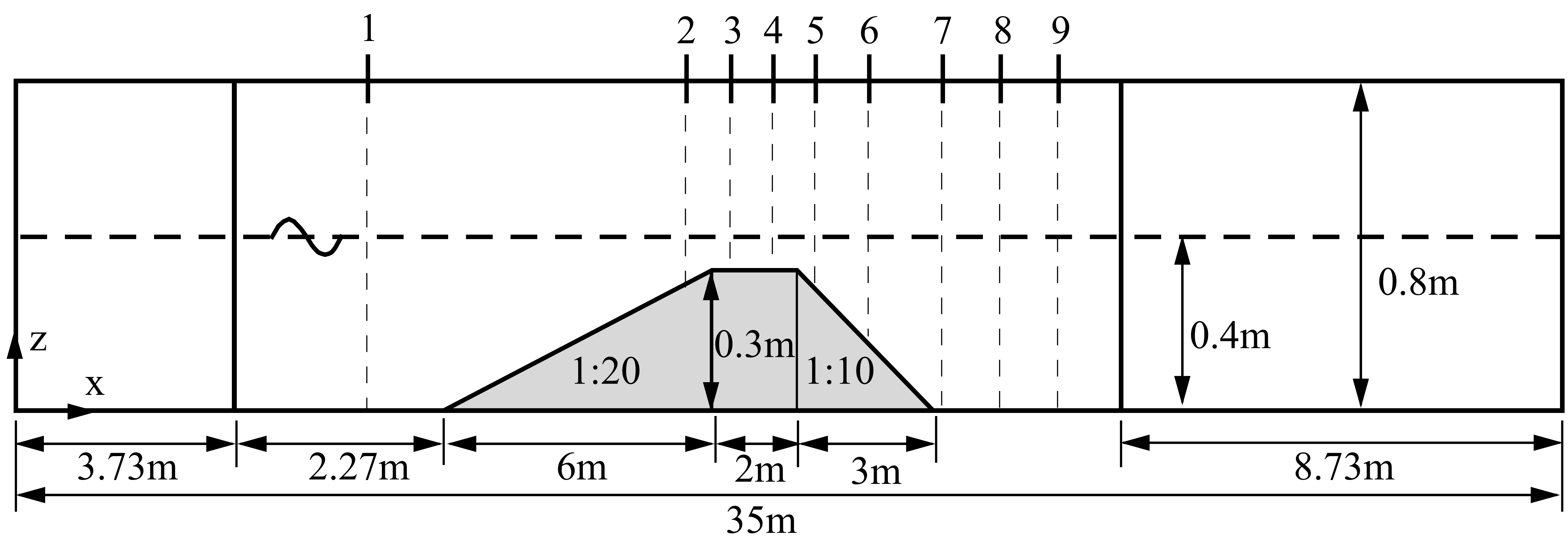
- can handle large gradient
- high accuracy
- maintains the sharpness of the extrema

Beji & Battjes: Submerged Bar - FNPF vs CFD

Wave Input
- H = 0.02m
- T = 2.0s
- wave theory: linear waves

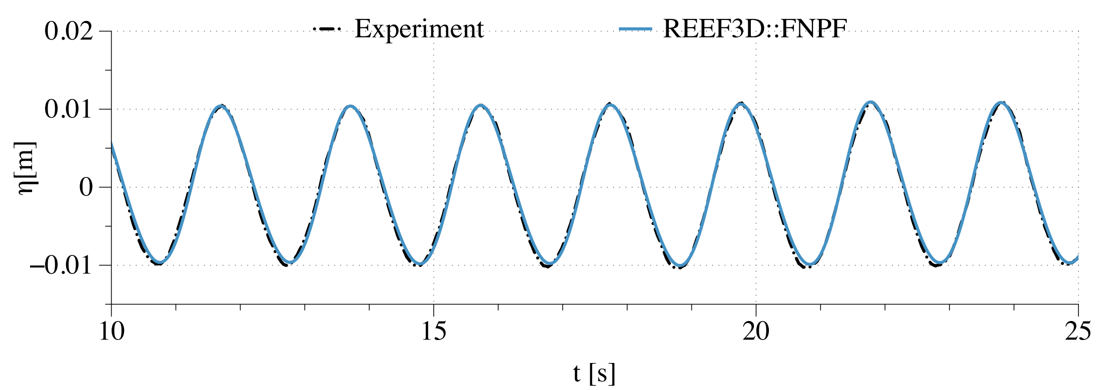
FNPF
- mesh: 800 x 10 = 8.000 cells

CFD
- mesh: 6000 x 160 = 960.000 cells

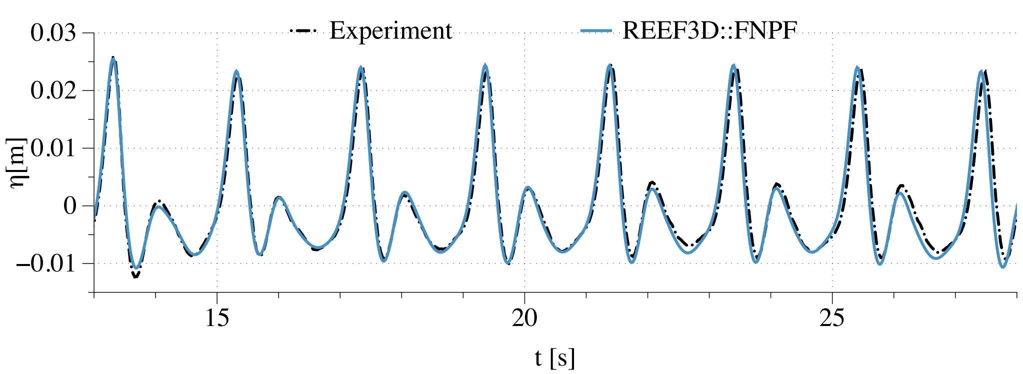


Beji & Battjes: Submerged Bar

FNPF

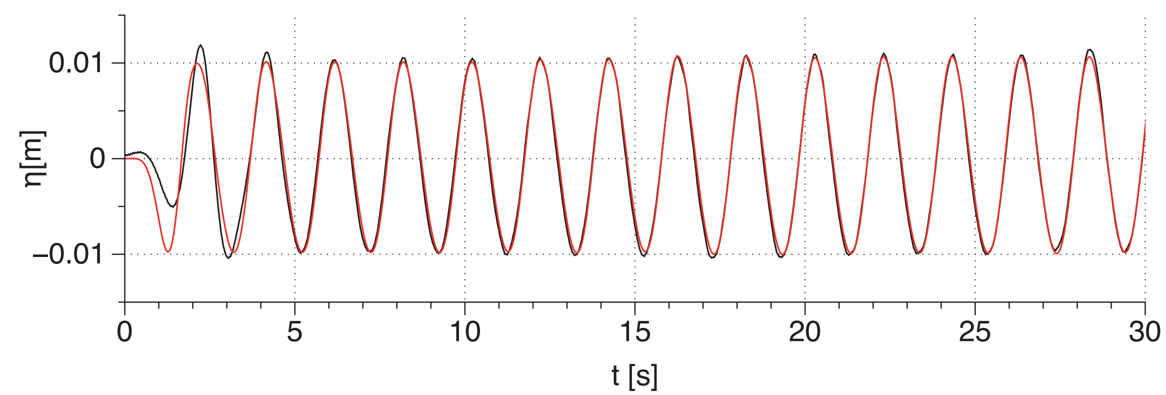


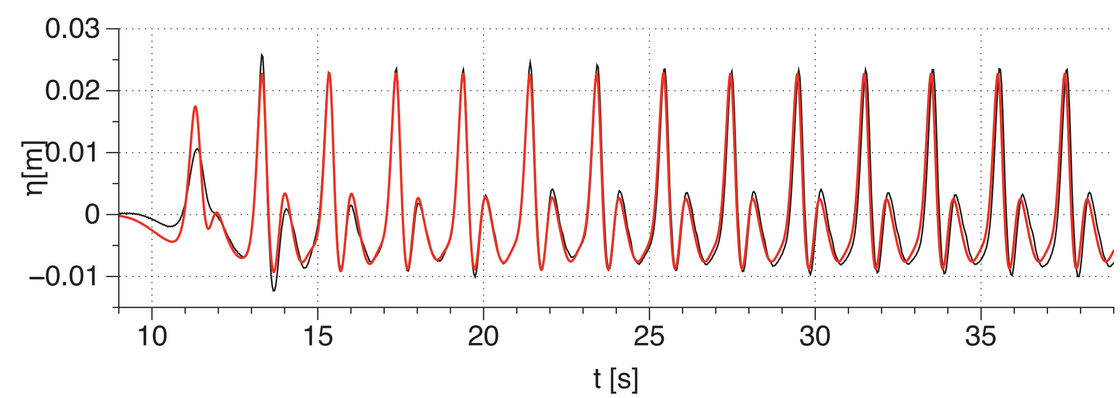
(a) wave gauge 1 at $x = 4.0$ m

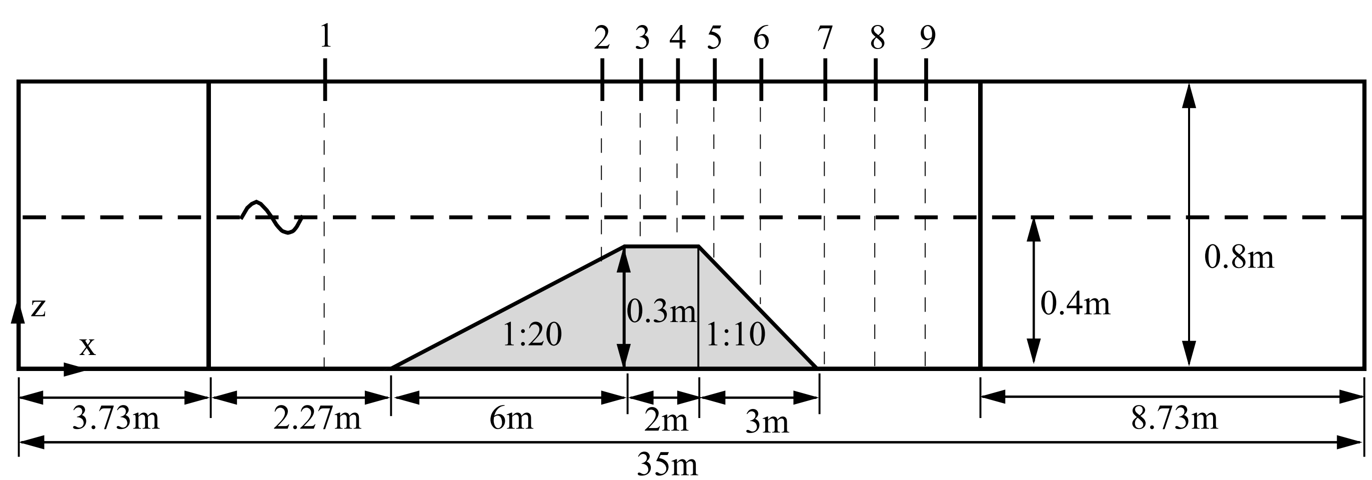


(e) wave gauge 5 at $x = 14.5$ m

CFD

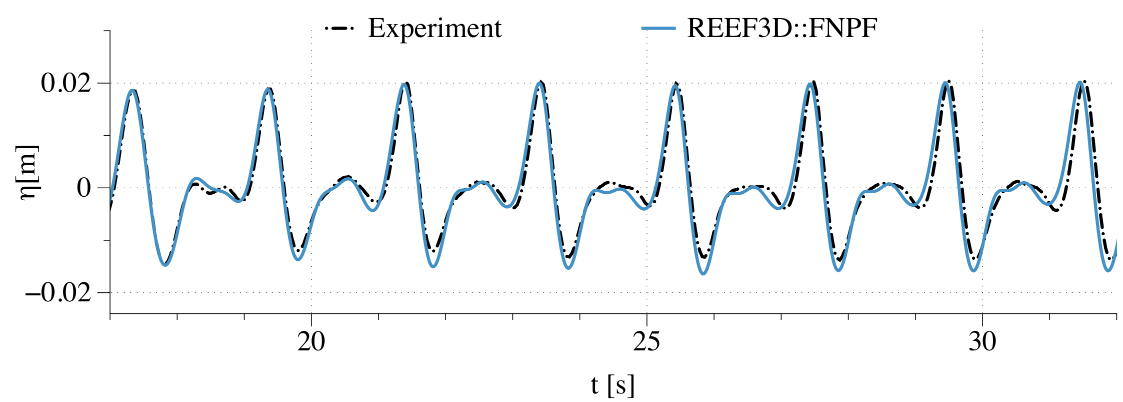




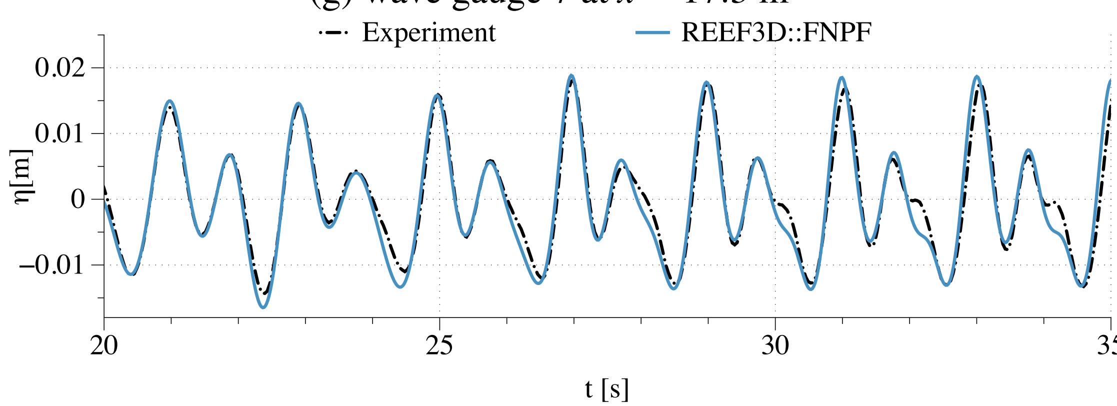


Beji & Battjes: Submerged Bar

FNPF

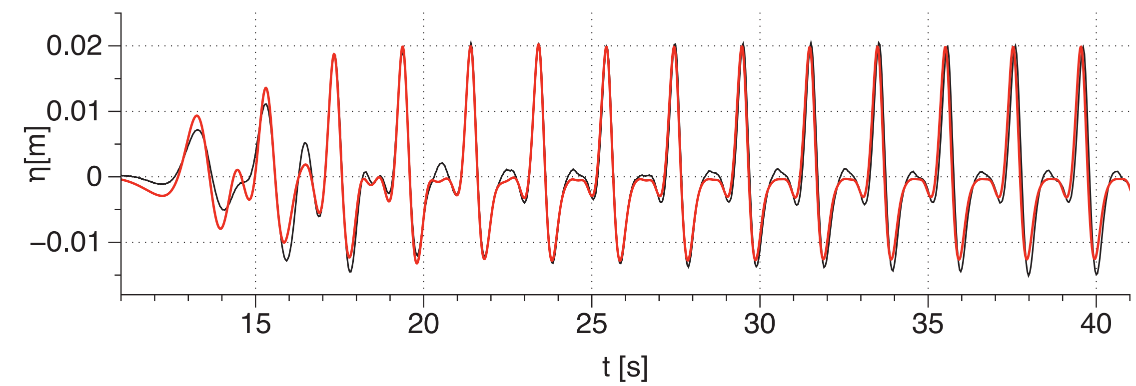


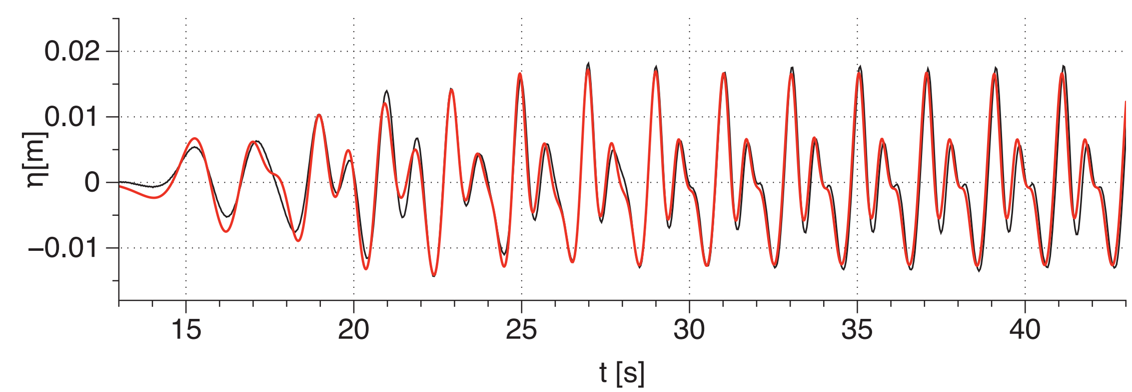
(g) wave gauge 7 at $x = 17.3$ m

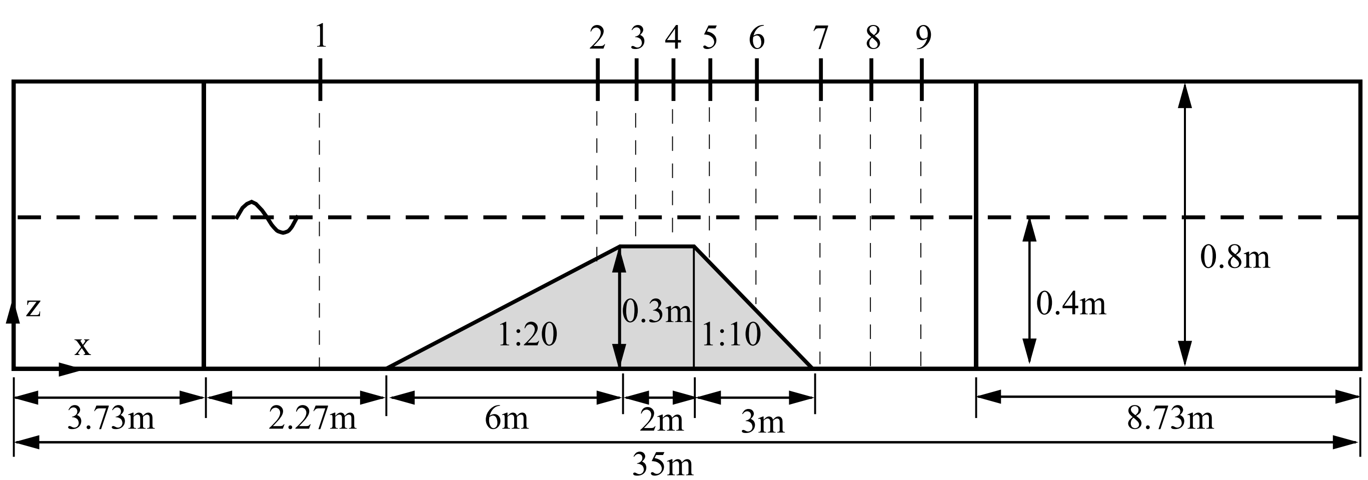


(i) wave gauge 9 at $x = 21.0$ m

CFD

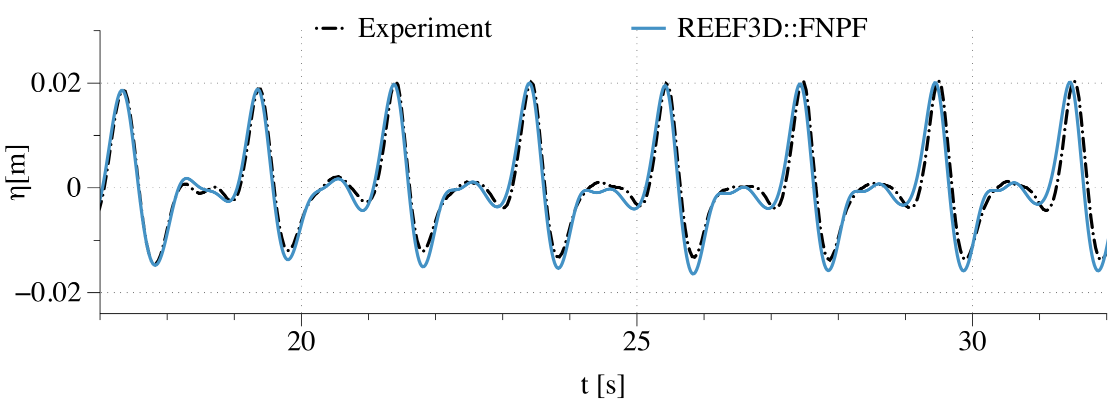




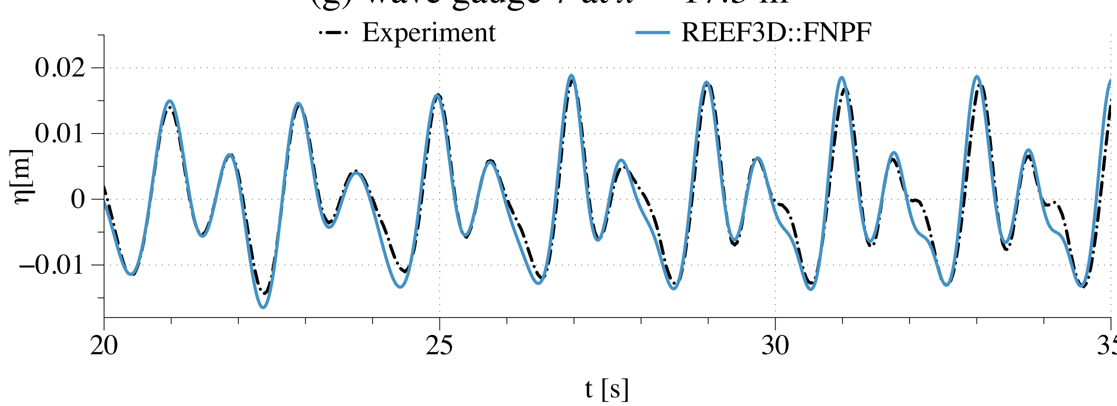


Beji & Battjes: FNPF vs Non-Hydrostatic SWE

FNPF

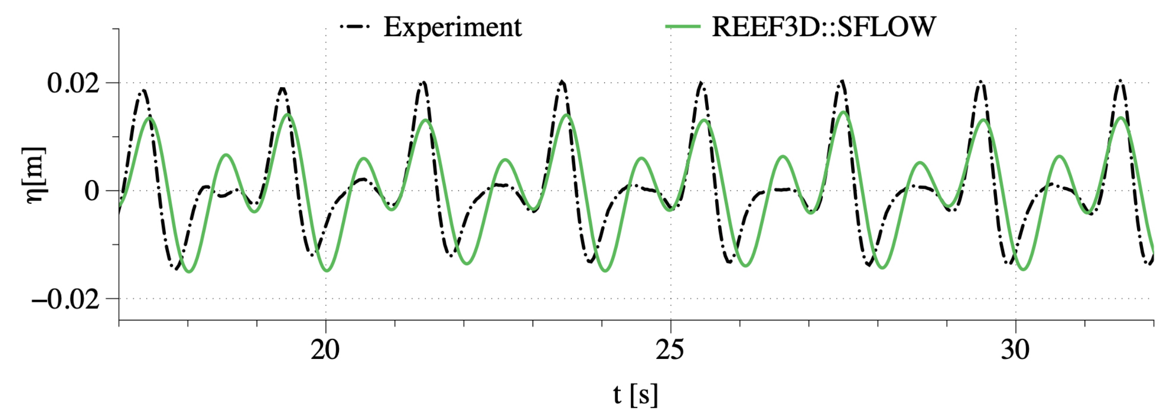


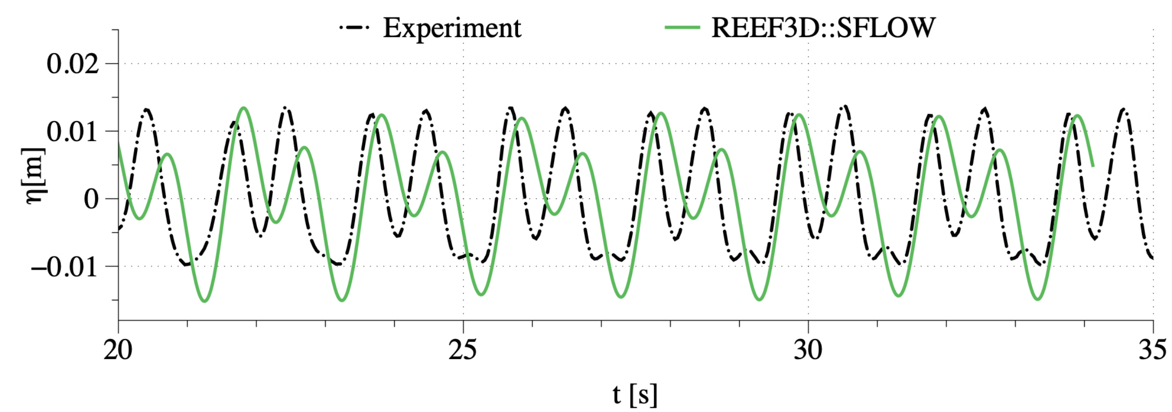
(g) wave gauge 7 at $x = 17.3$ m

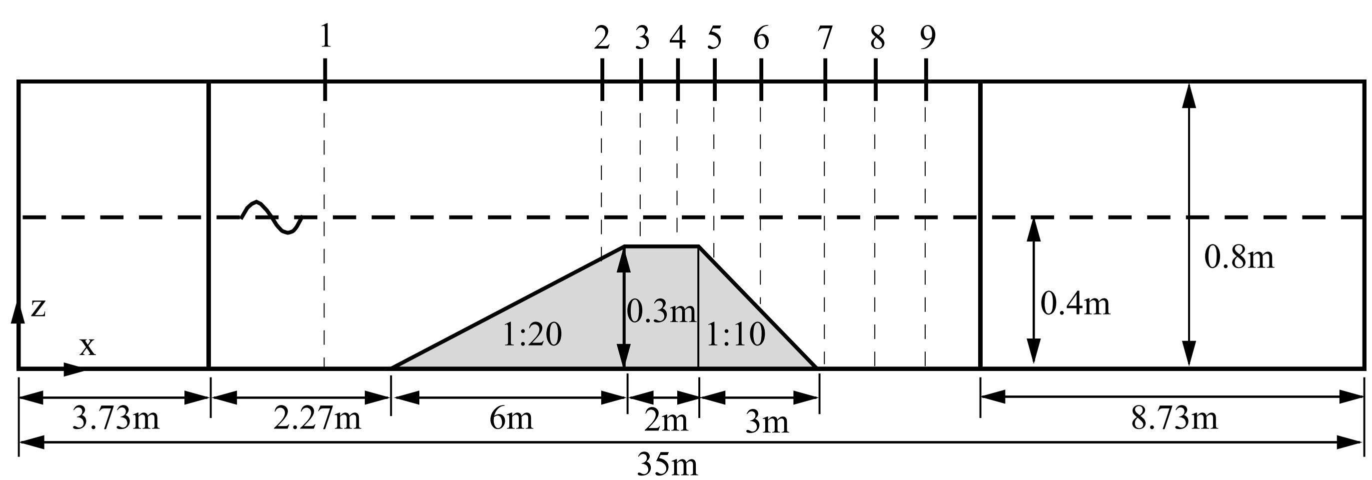


(i) wave gauge 9 at $x = 21.0$ m

SFLOW (2D)



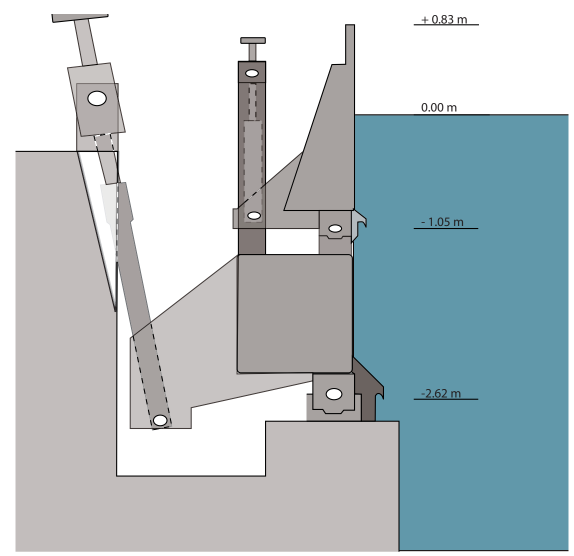




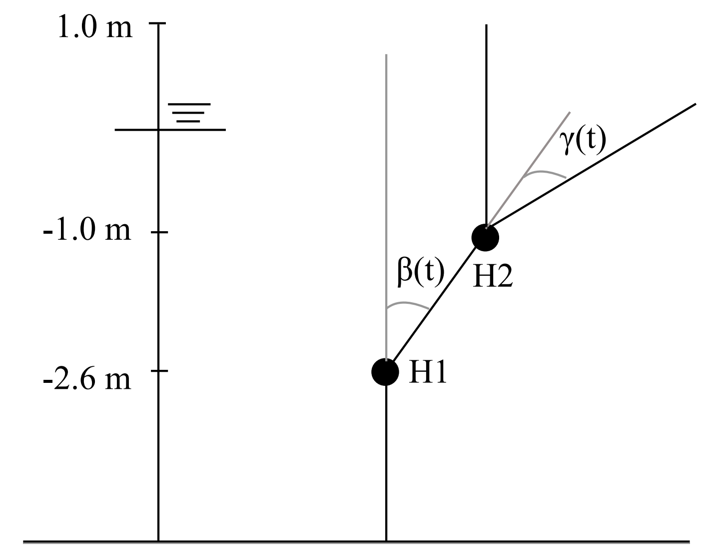
Bichromatic Waves (full tank 250m)

- Experiments: C. Pakozdi, 2014

- Experimental Wave Flume:
  - SINTEF Ocean (Marintek)
  - L = 250 m
  - d = 10.0 m
- Bichromatic waves
  - T_1 = 2.1s
  - T_2 = 1.6s

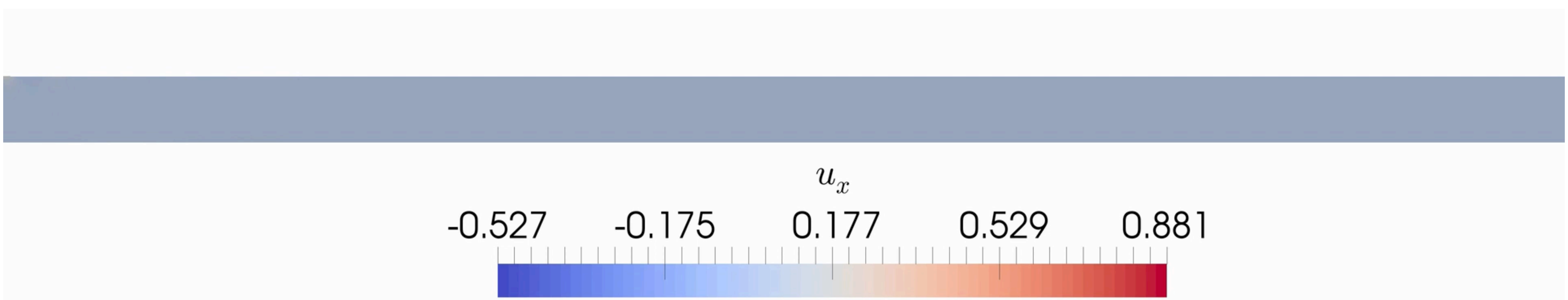


Experimental wavemaker

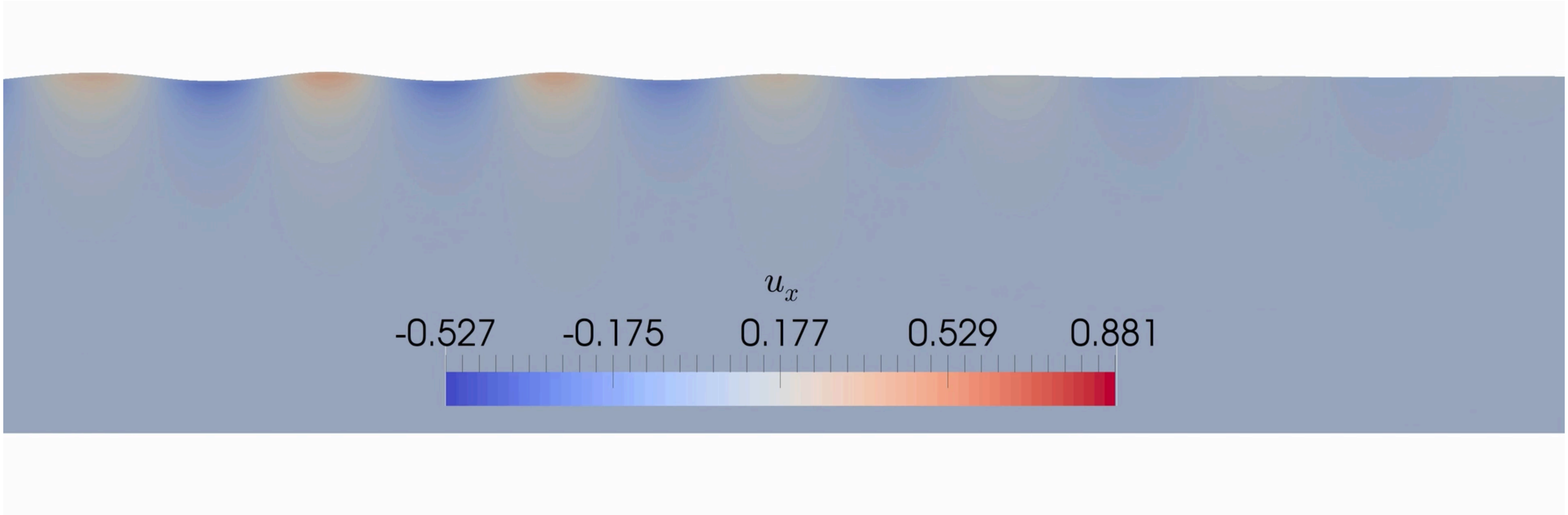


Numerical wavemaker

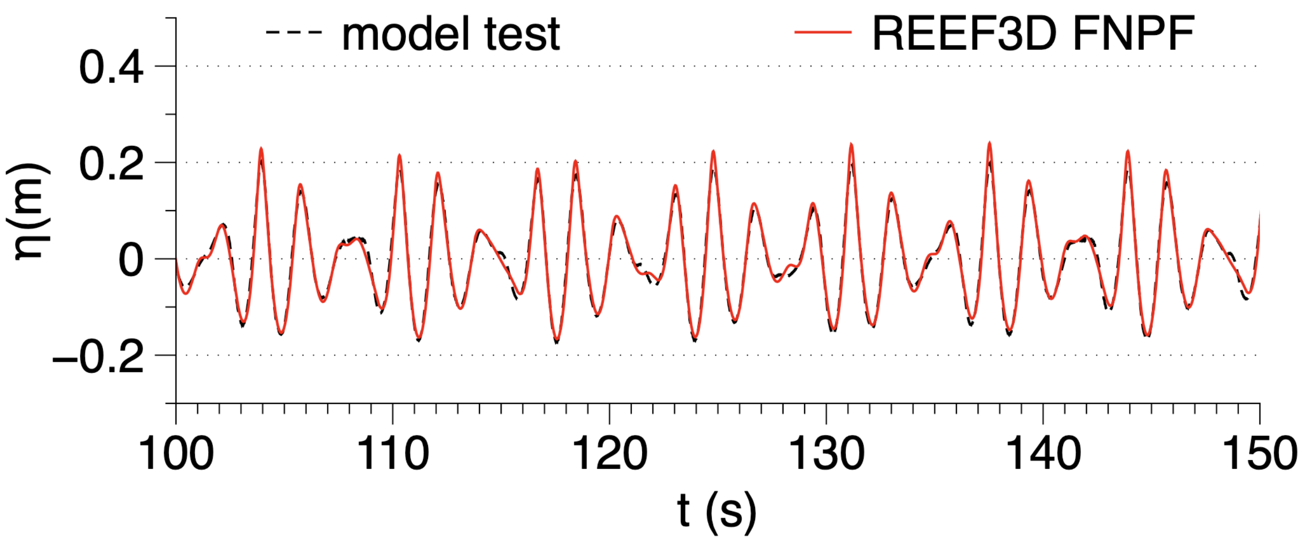
- 2D grid: 250m x 10m
  - 2500 x 25 = 62.500 cells



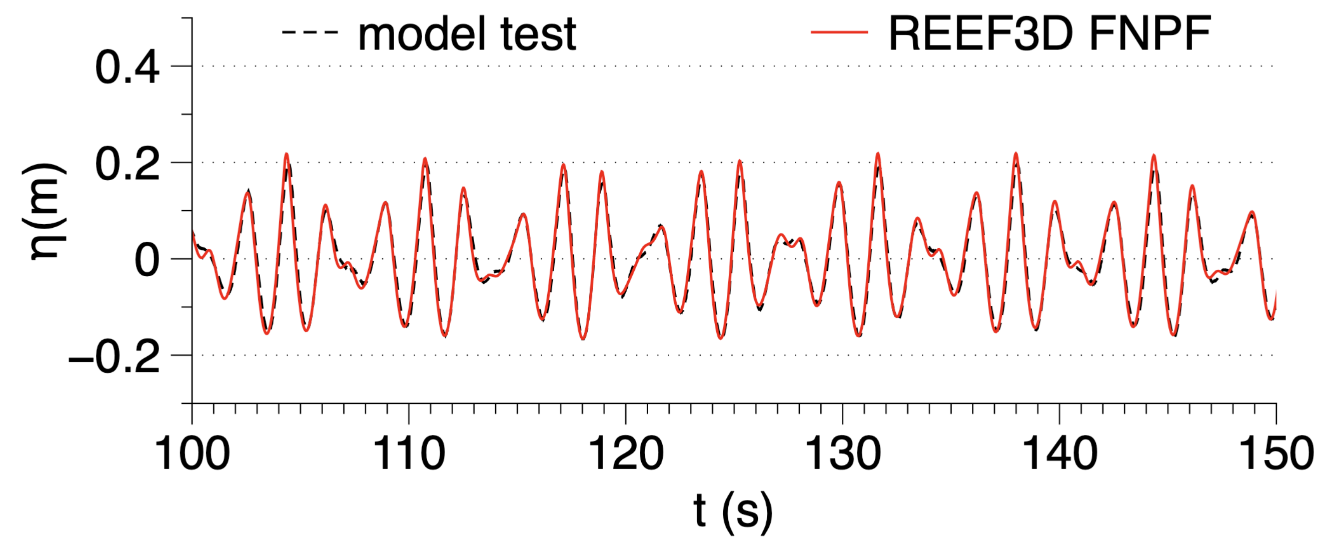
Bichromatic waves (portion of NWT)



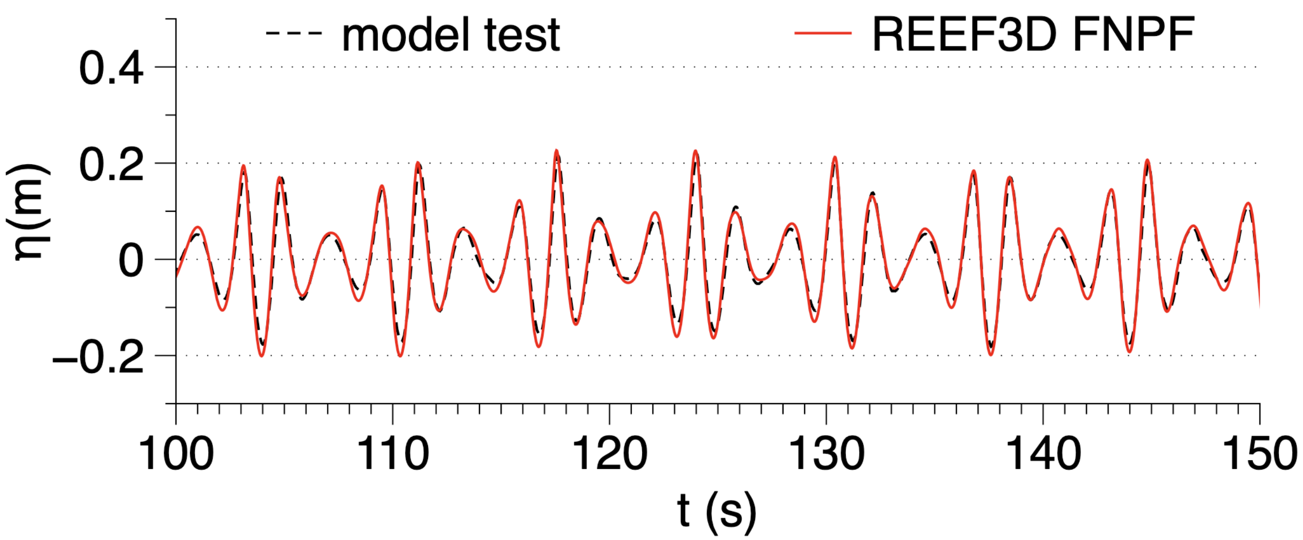
Bichromatic Waves



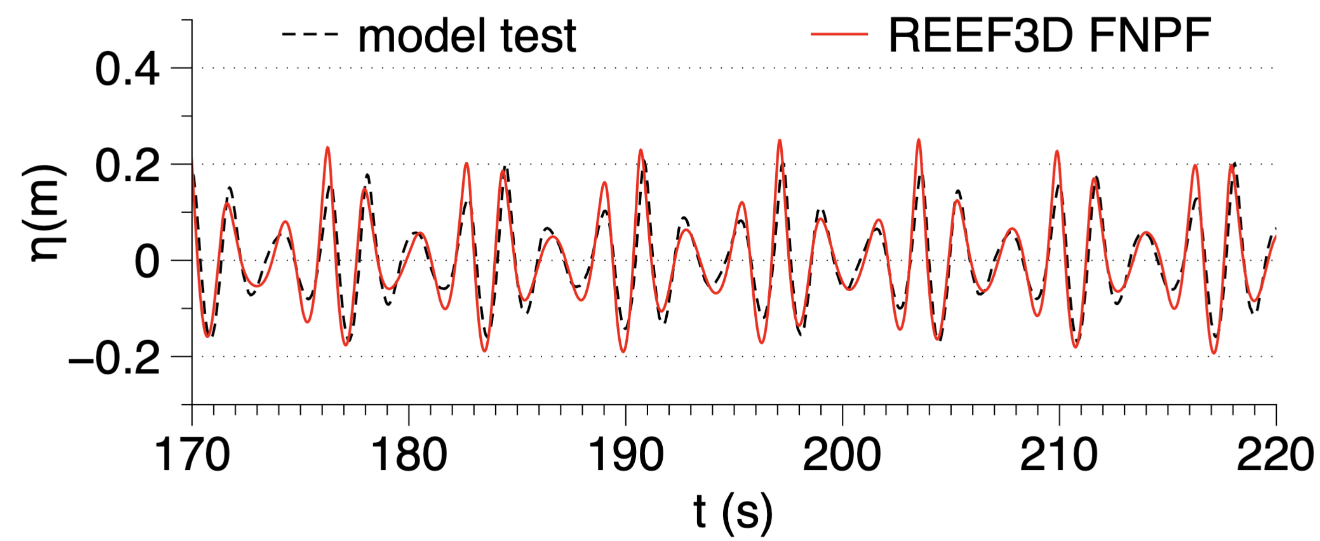
x = 10 m



x = 40 m

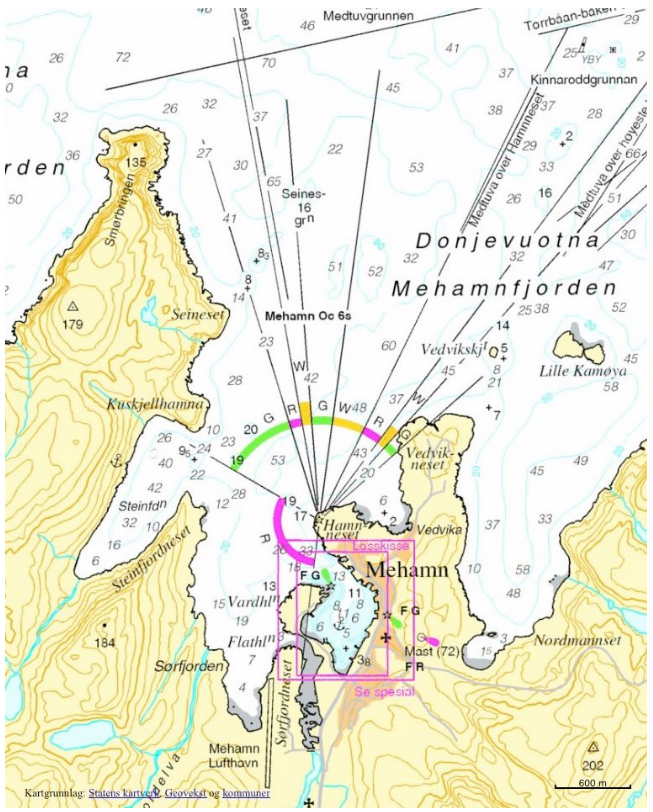


x = 70 m



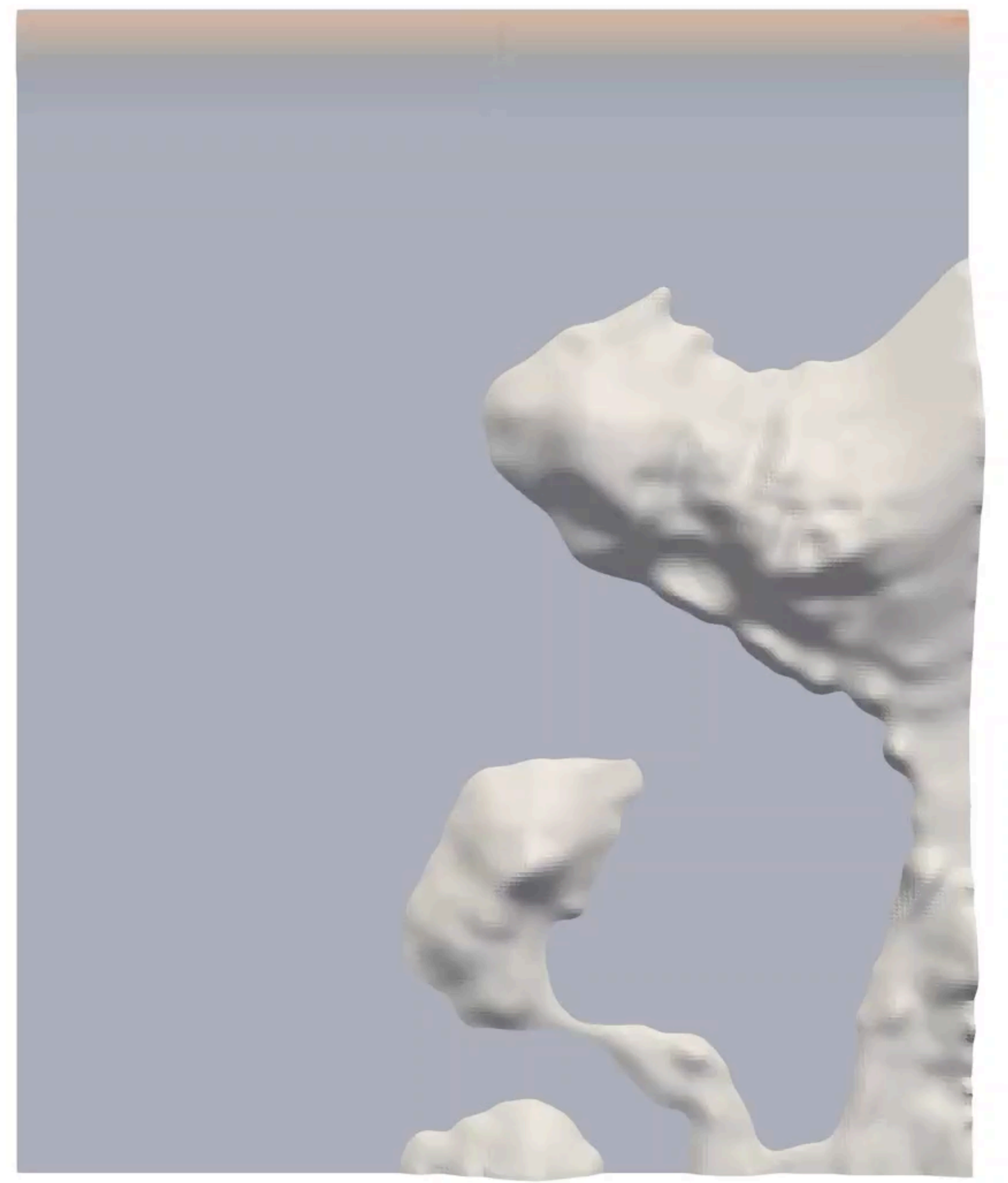
x = 160 m

Coastal Modeling: Mehamn



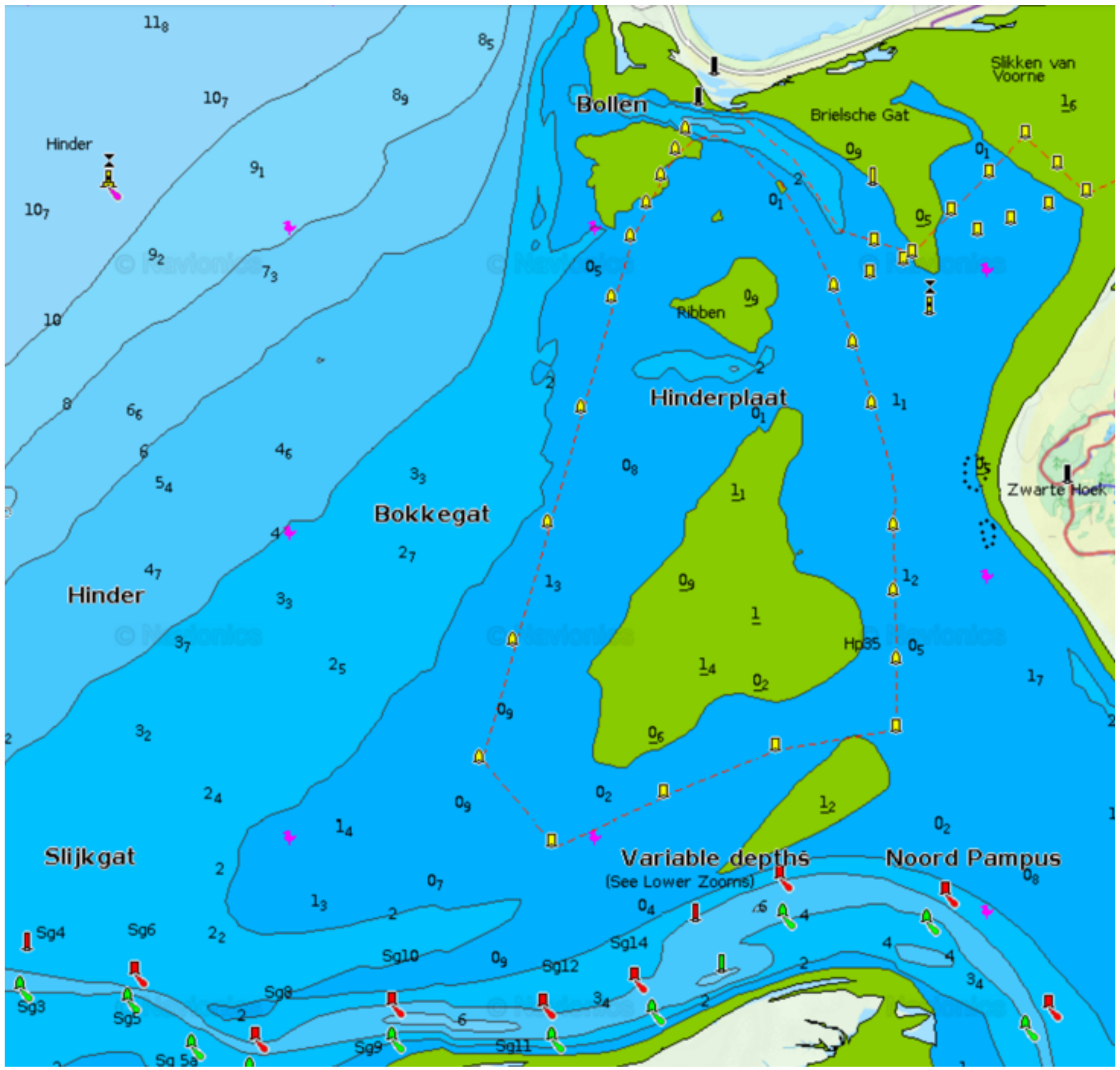
Input wave
H = 3.5 m
T = 14 s
Regular wave

FNPF includes
- wetting/drying
- breaking

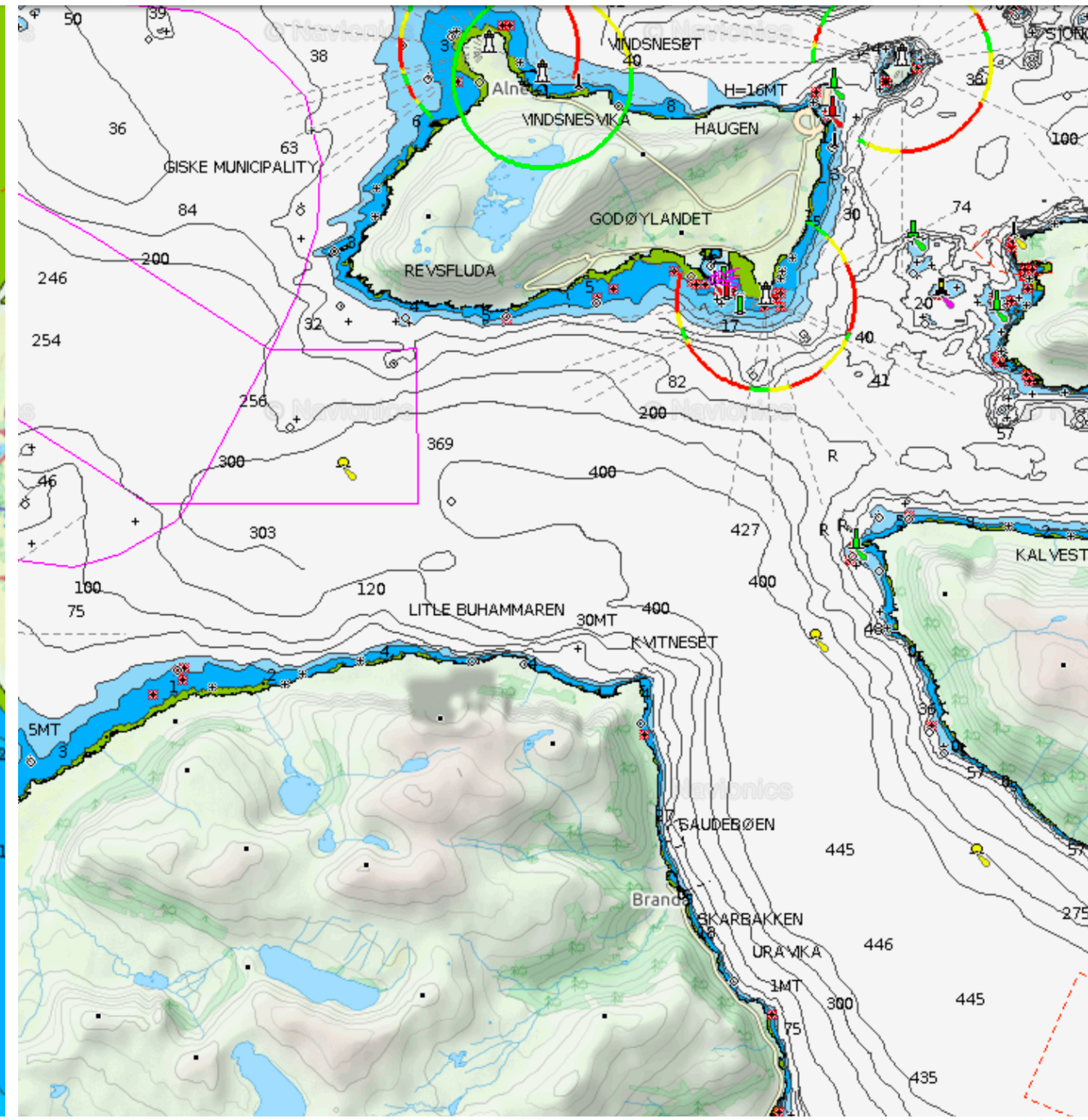


playback speed 10x

Example: Floating Bridge in Sulafjord

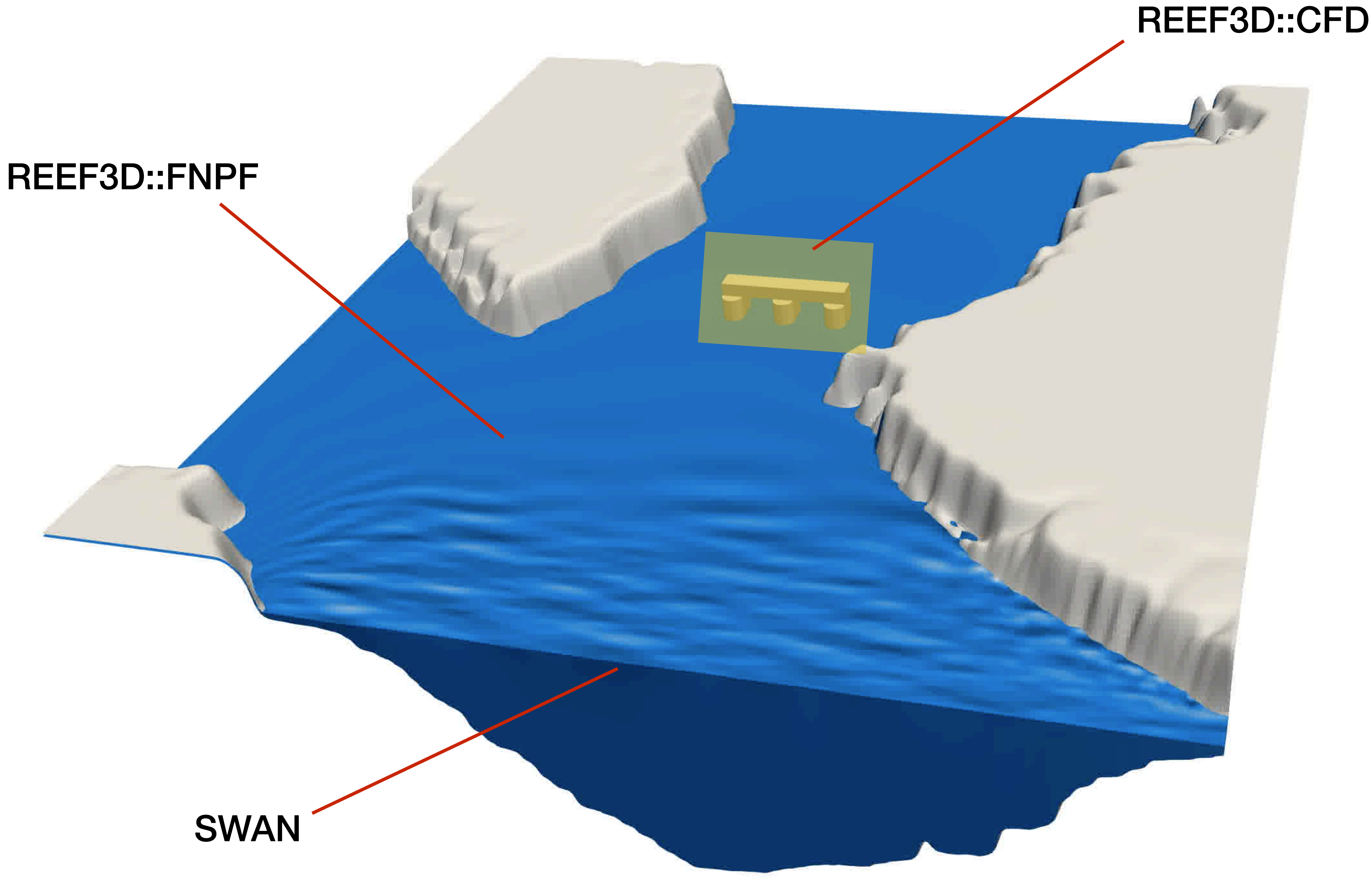


Haringvliet, Netherlands



Sulafjorden, Norway

Example: Floating Bridge in Sulafjord



Conclusions

- **REEF3D Open-Source Hydrodynamics :**
  → Phase-resolved Waves on all Scales

- Coastal / Marine / Hydraulic Engineering

- Ongoing FNPF:
  - structures
  - wave communication protocol (WCP) for consistent coupling

- Outlook FNPF:
  - floating
  - mooring