Numerical Simulation of Wave Hydrodynamics with a Focus on Wave Structure Interaction

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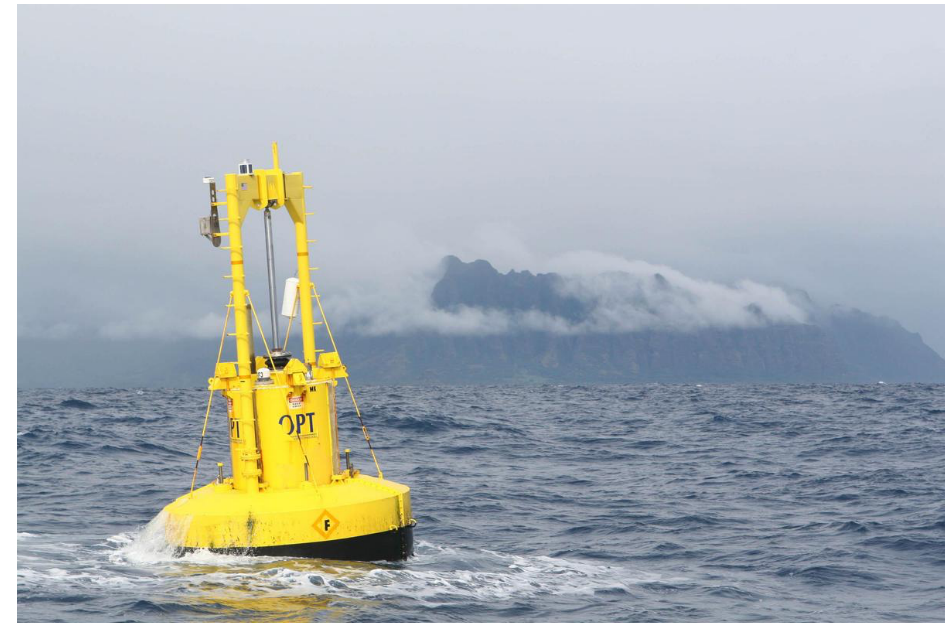
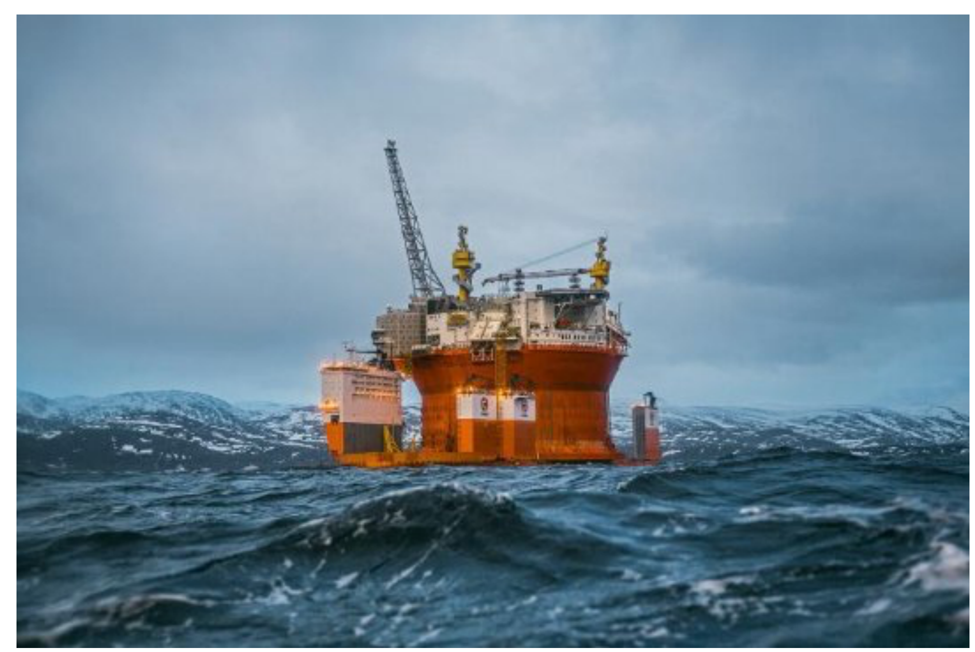
Wave Structure Interaction : Offshore Energy

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

WSI : Transportation & Aquaculture

Coastal Transportation Infrastructure

OceanFarm 1 in the Ocean Basin

E39: Floating Bridges

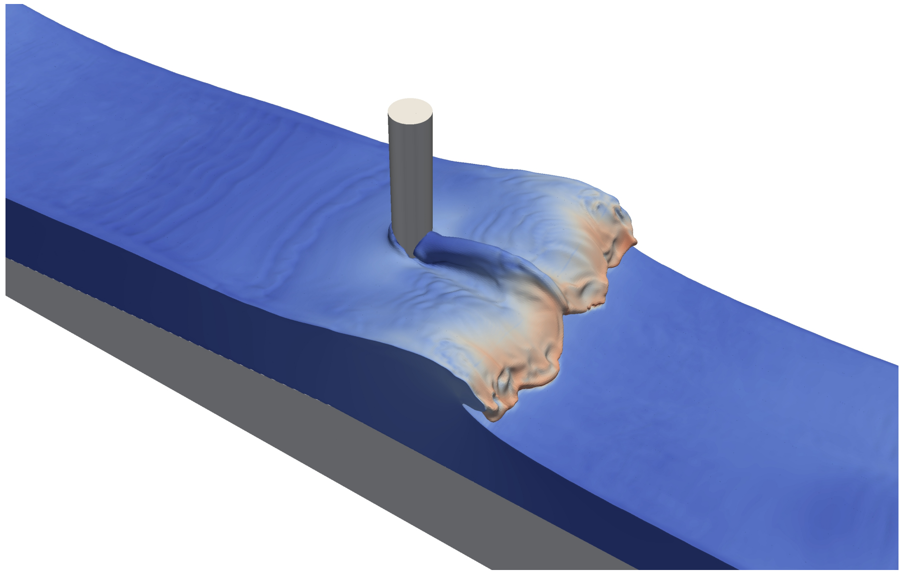
OceanFarm 1

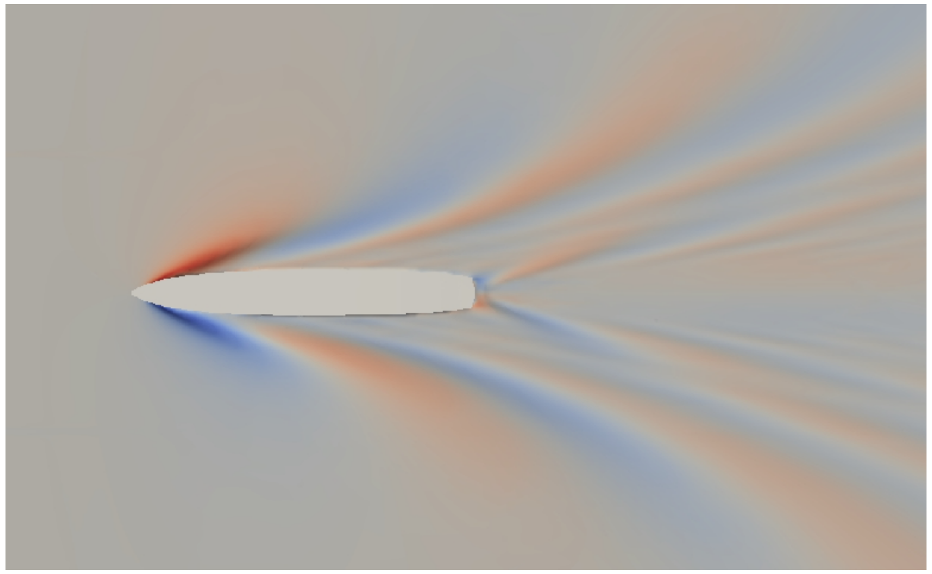
REEF3D::CFD

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

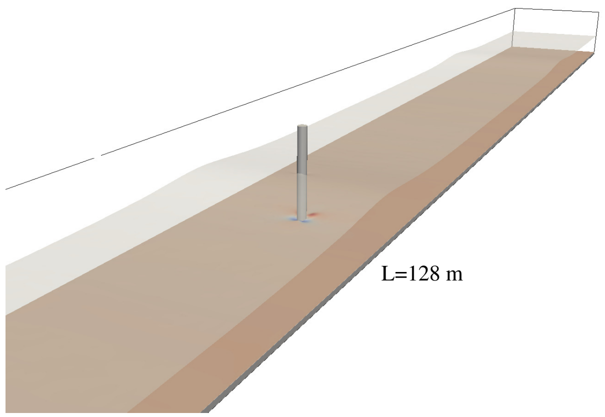
- **Focus on:**
  - Free Surface Flows
  - Wave Hydrodynamics
  - Wave Structure Interaction
  - Floating Structures
  - Open Channel Flow
  - Sediment Transport

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

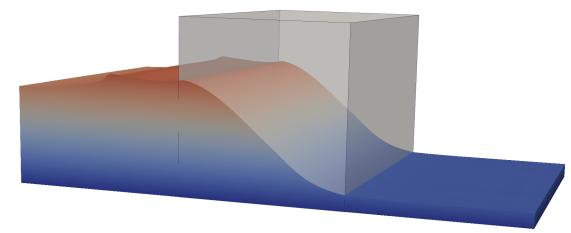




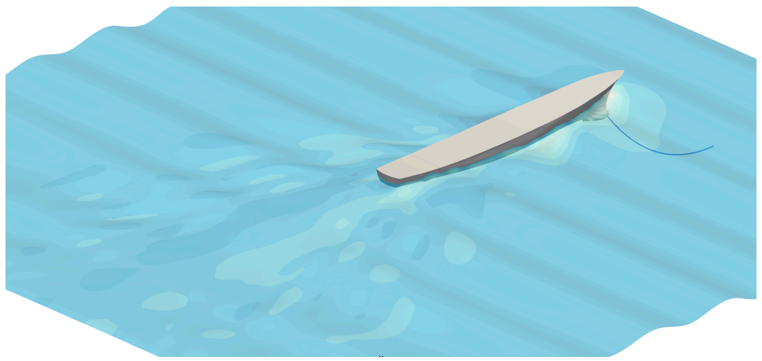
REEF3D::CFD : Multiphysics Extensions



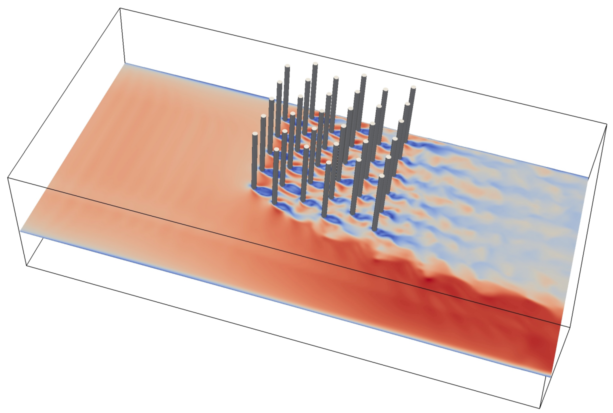
Sediment Transport
Local Scour
Arctic Erosion



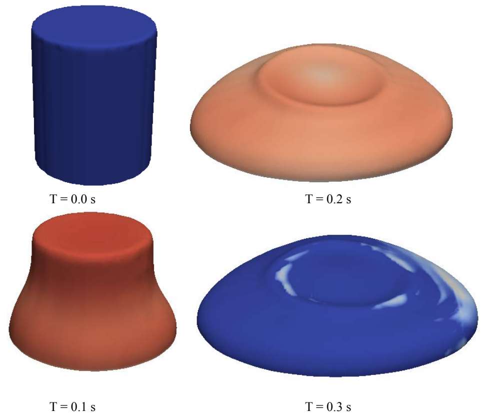
Porous Structures



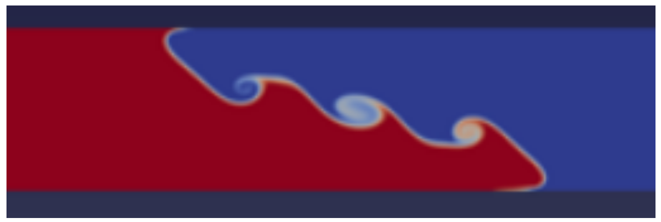
Floating Structures
6DOF
Mooring



Vegetation



Debris Flow
Granular Flow

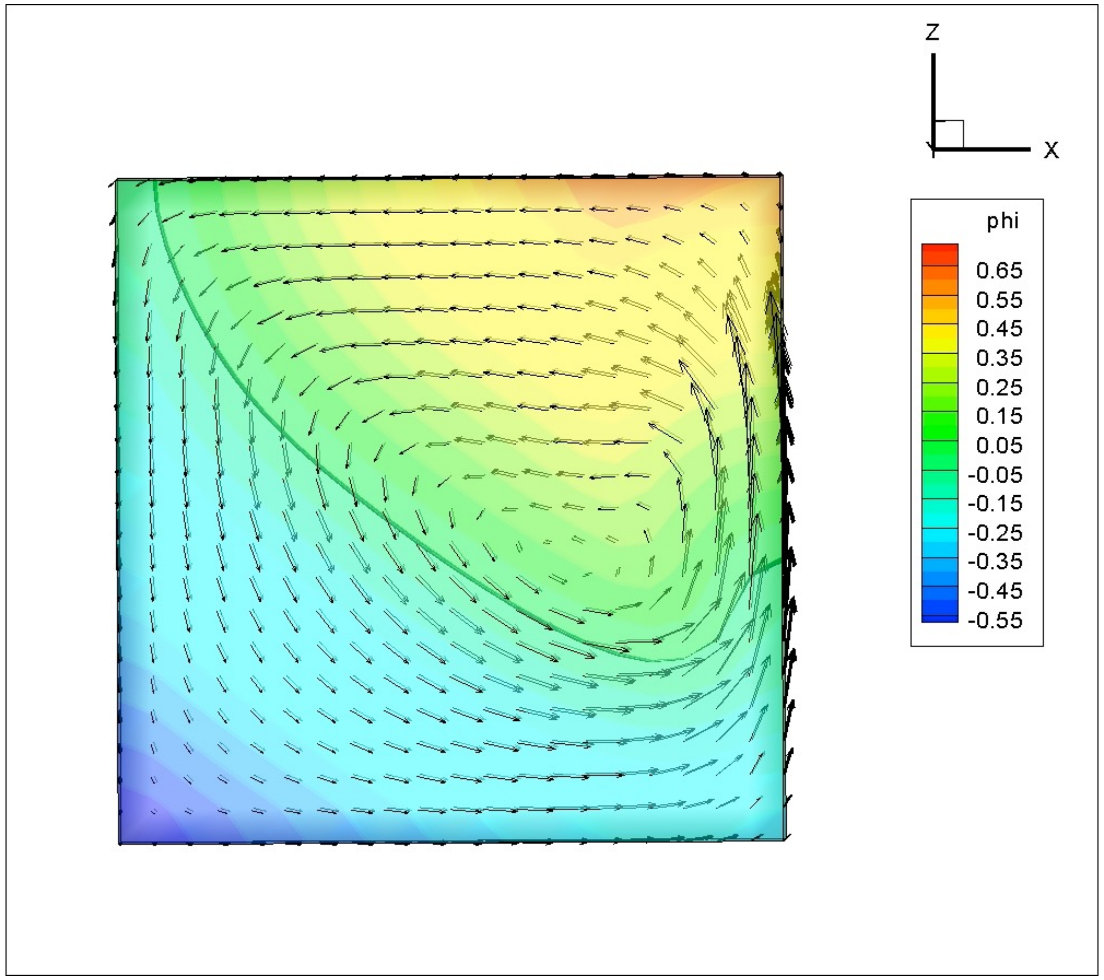


Stratified Flow

Level Set Equation : A Signed Distance Function

$$\phi(\vec{x},t)\begin{cases} >0 \; if \; \vec{x}\in phase\,1 \\ =0 \; if \; \vec{x}\in \Gamma \\ <0 \; if \; \vec{x}\in phase\,2 \end{cases} \quad , |\nabla\phi| = 1$$

$$\phi_t + \vec{u}\cdot\nabla\phi = 0$$



Governing Equations

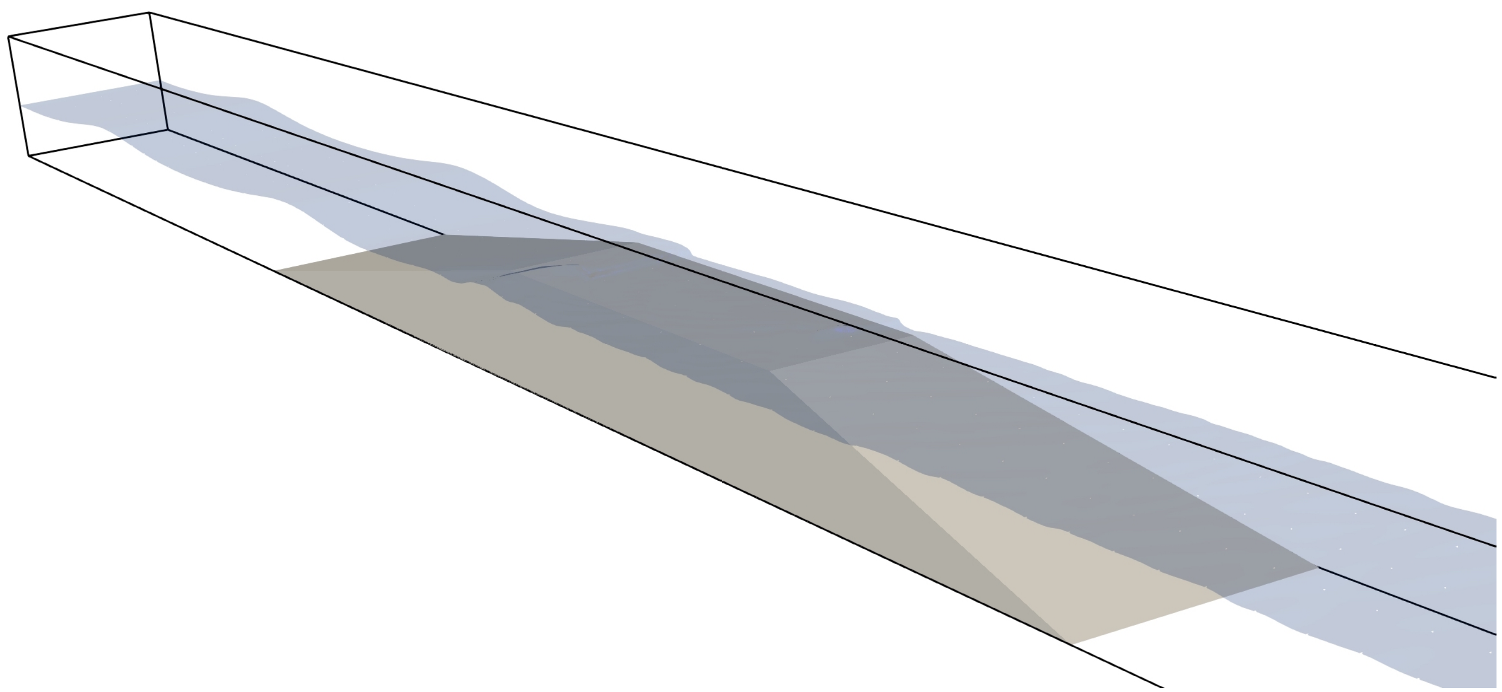
Incompressible RANS Equations:

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

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + g_i$$

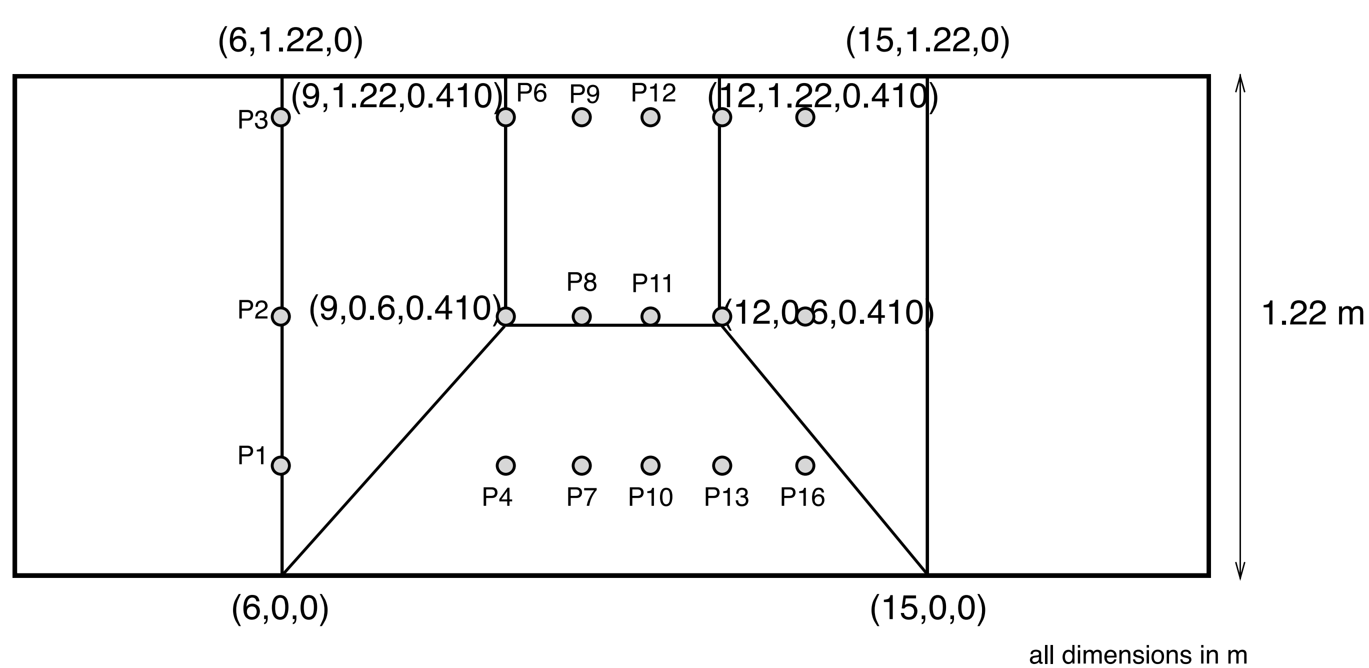
- Temporal Discretization: **RK3**
- Spatial Discretization: **WENO**
- Pressure Solution: **projection method + multigrid**
- Turbulence Modeling: **RANS or LES**
- Mesh: **non-uniform, immersed boundary**

Wave Hydrodynamics: 3D Breaking Waves on Reef



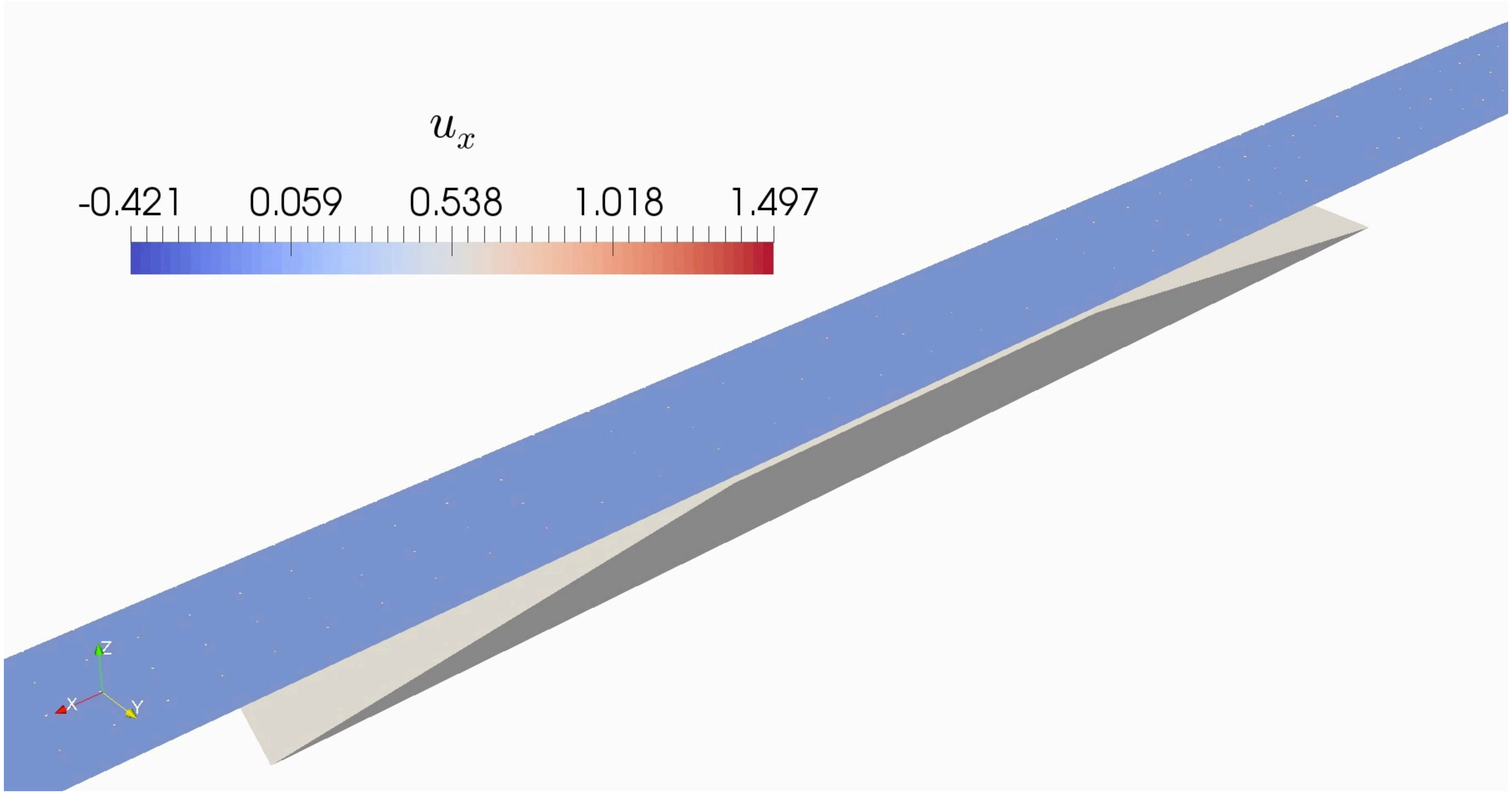
Collaboration with Prof. Seiffert, Florida Atlantic

Experiments design based on CFD input

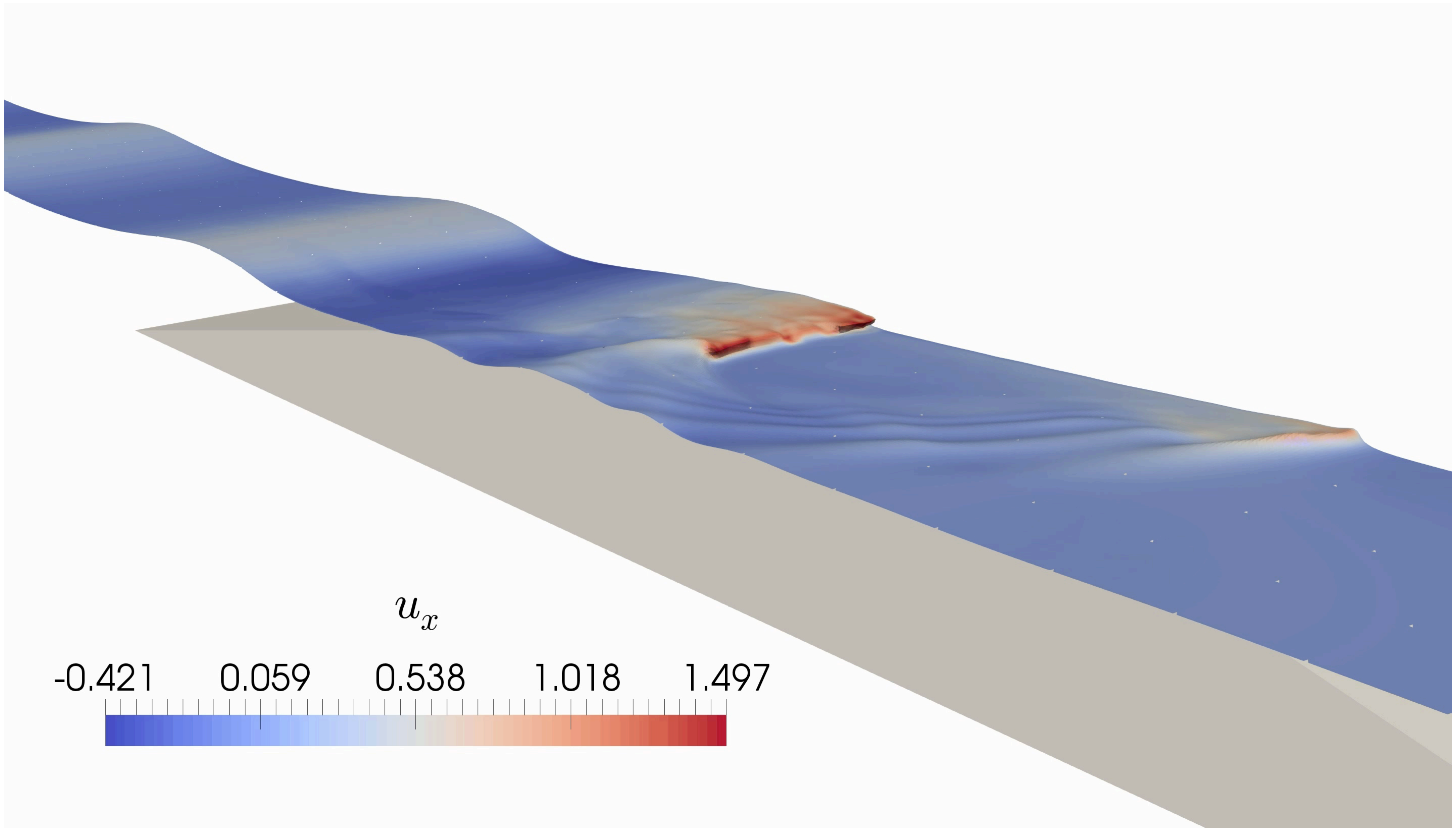


Reef Case 13

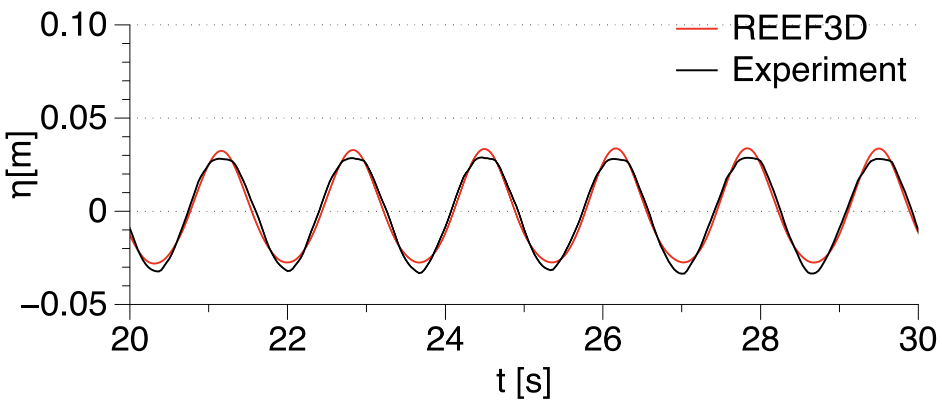
H=0.10, L=4m, d=0.460



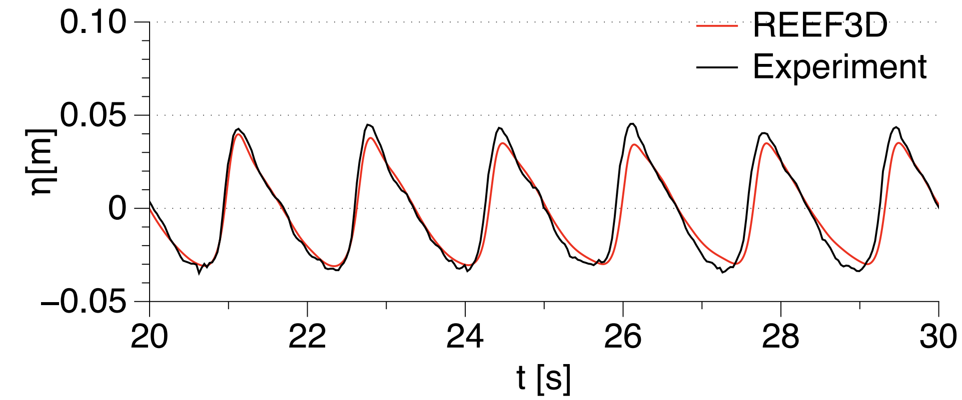
Reef Case 13 - Close-Up



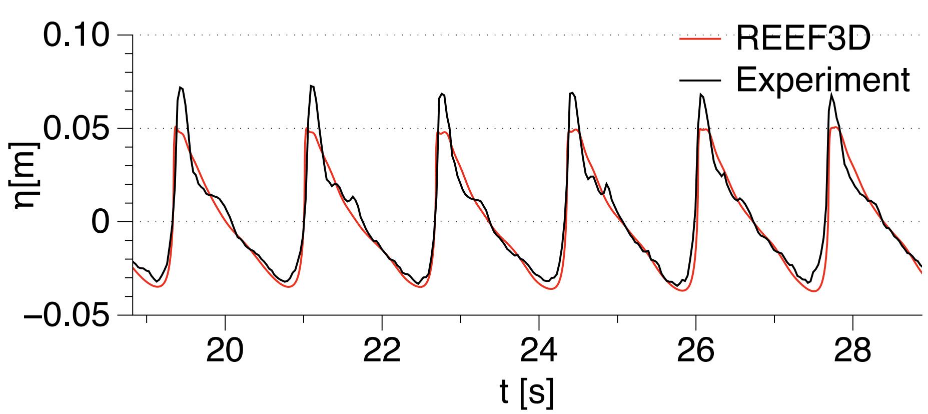
H_0=0.06 m, T_0=1.67 s



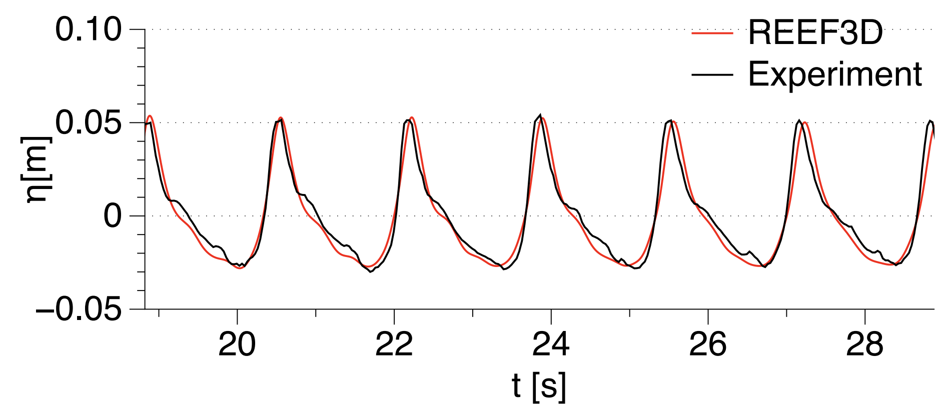
incident wave at -0.114 m from the toe



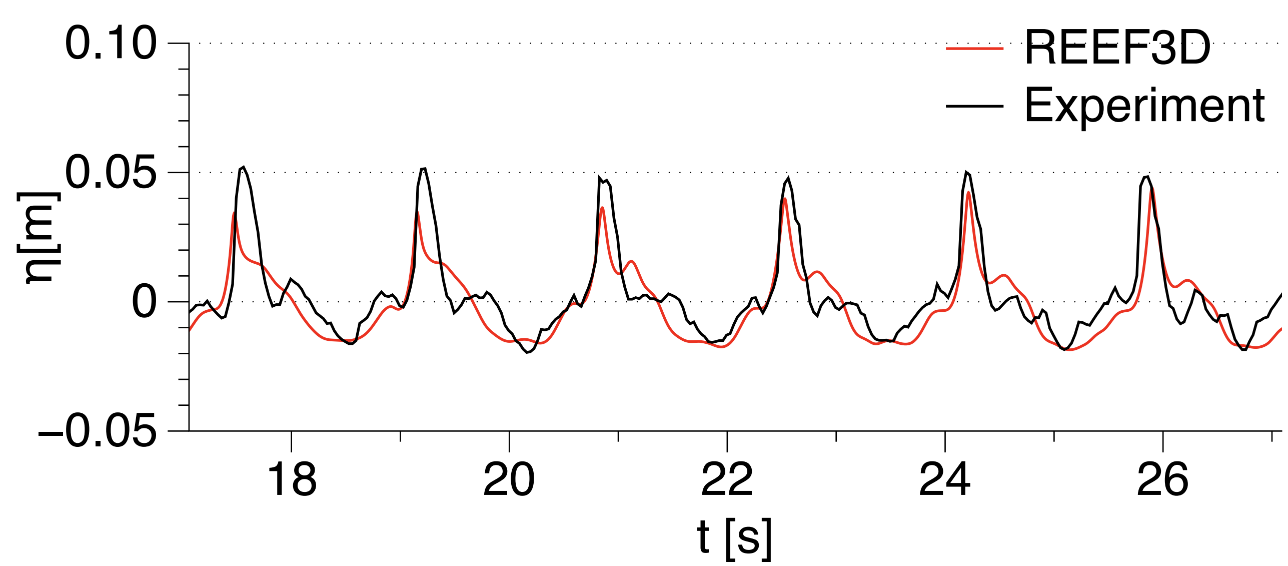
on the slope at -0.196 m from the crest



on flat bed at +0.165 m from crest

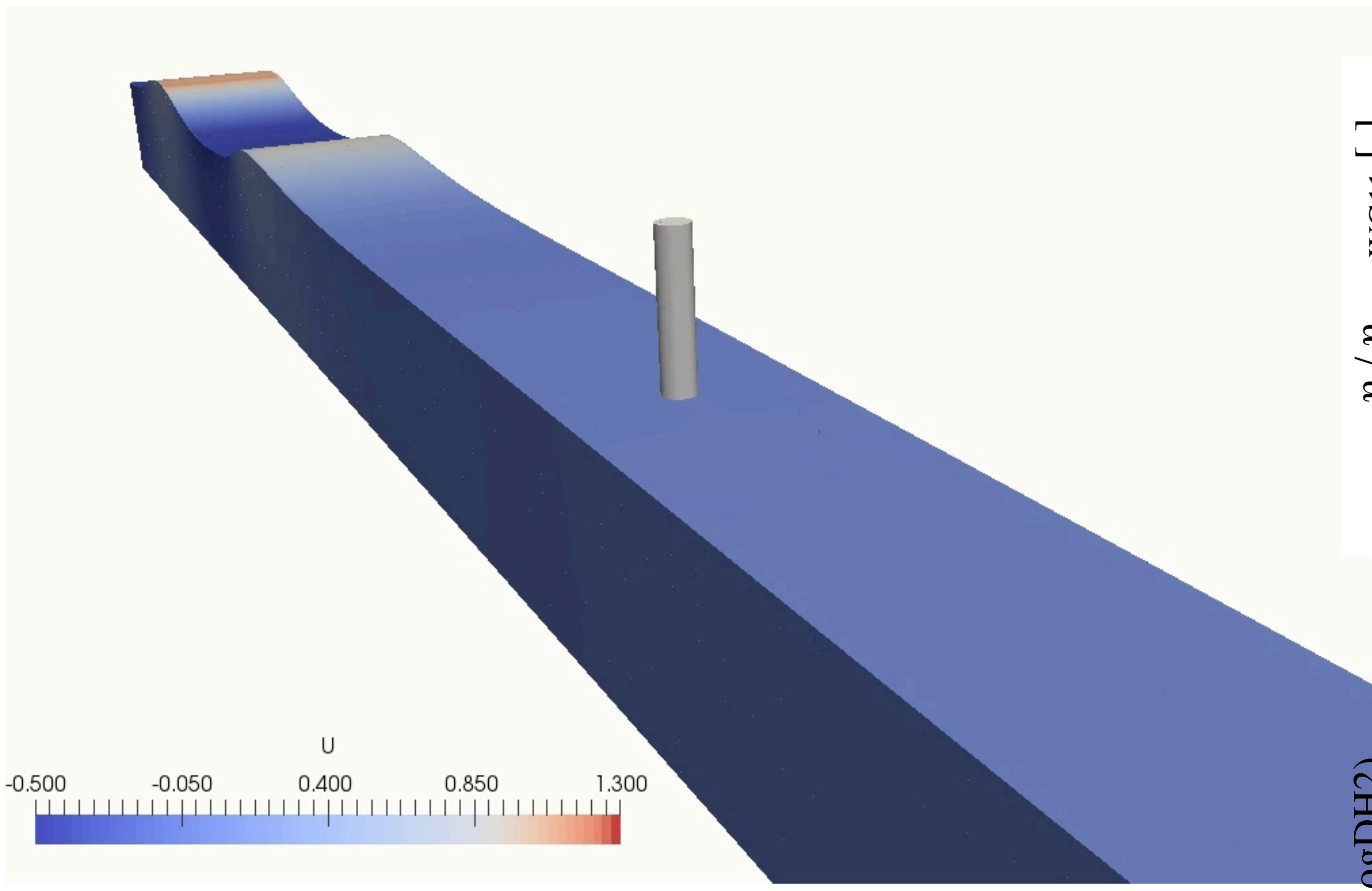


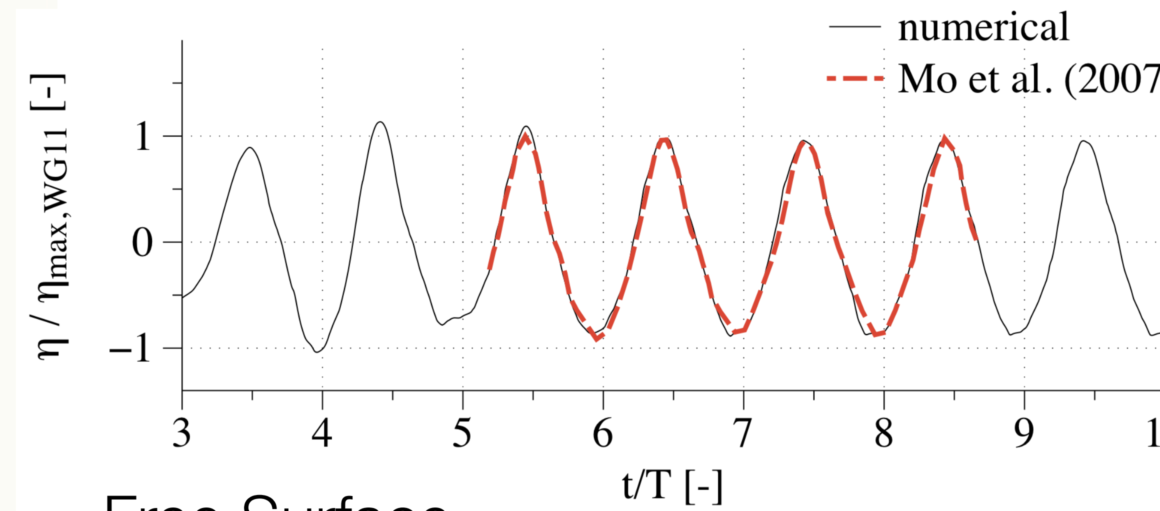
on flat bed at +0.114 m from crest



on leeward slope at +0.196 m from leeward crest

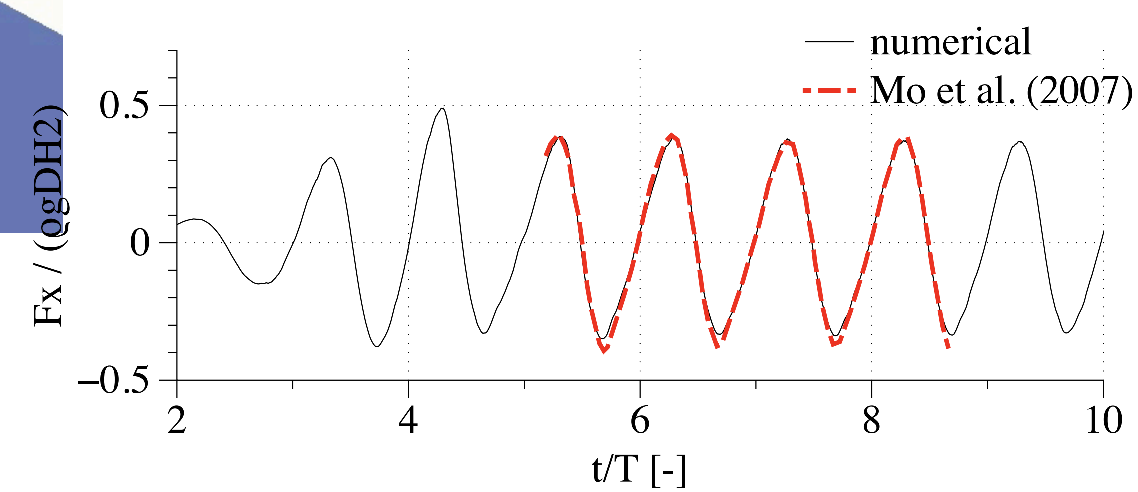
Wave Structure Interaction: Non-Breaking Waves





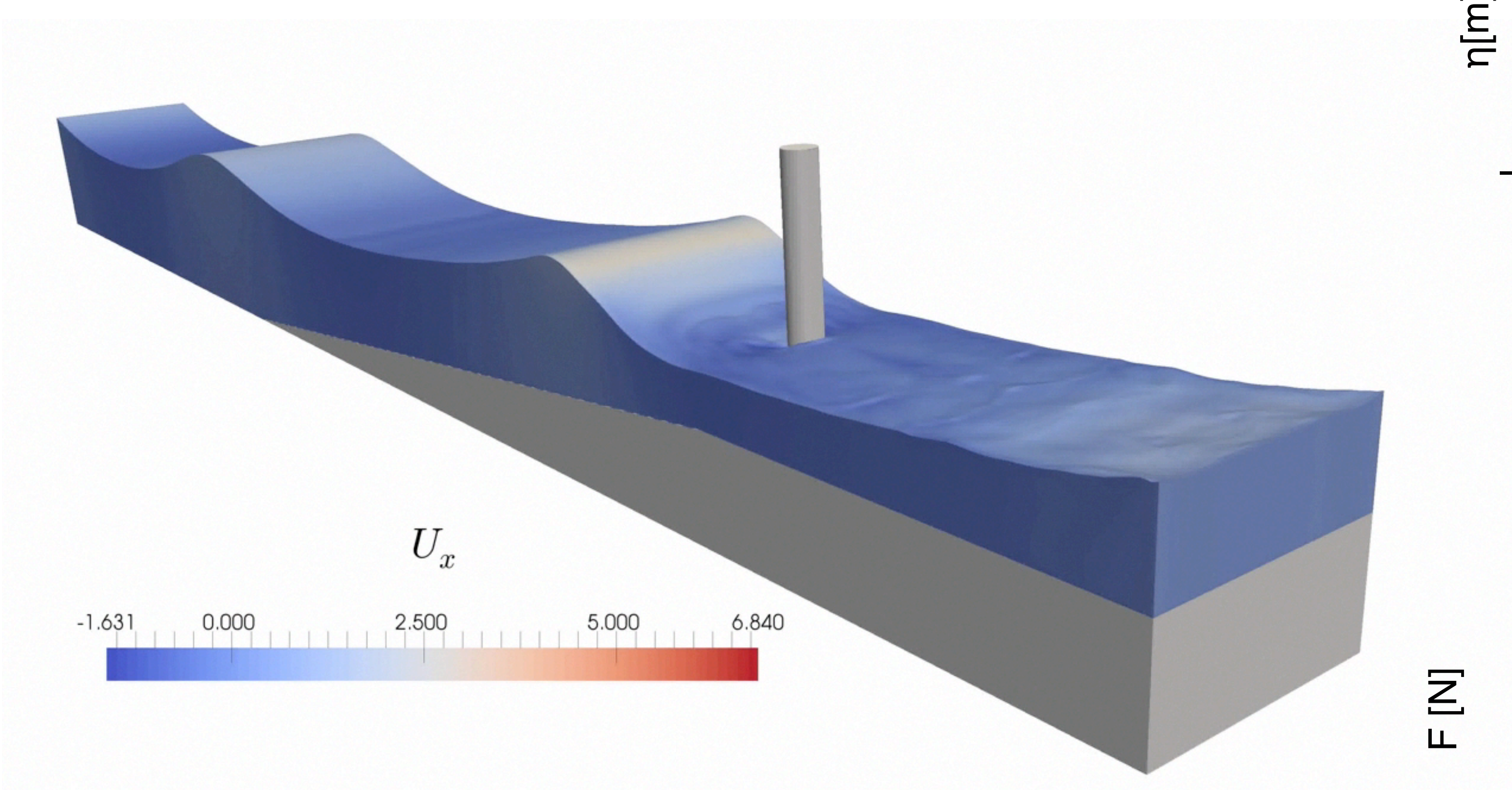
Free Surface

Experiment: GWK - Mo et al. 2007, JE

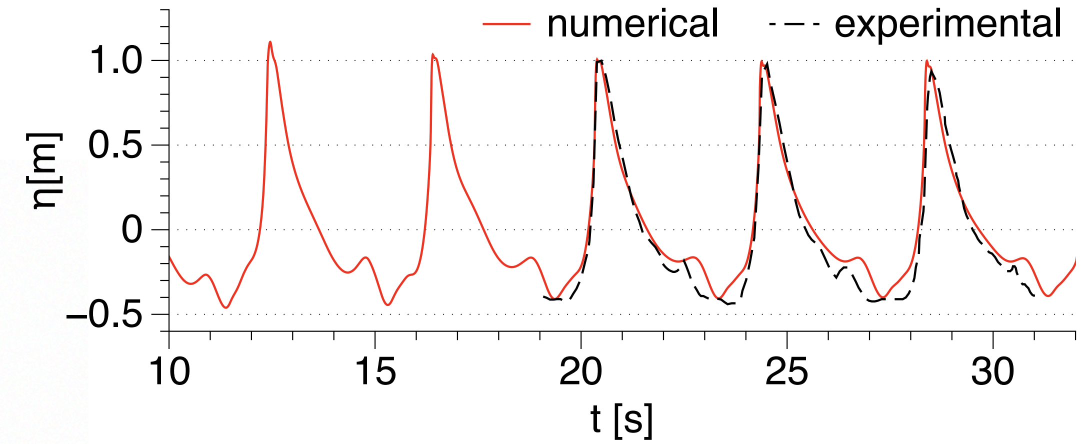


Force

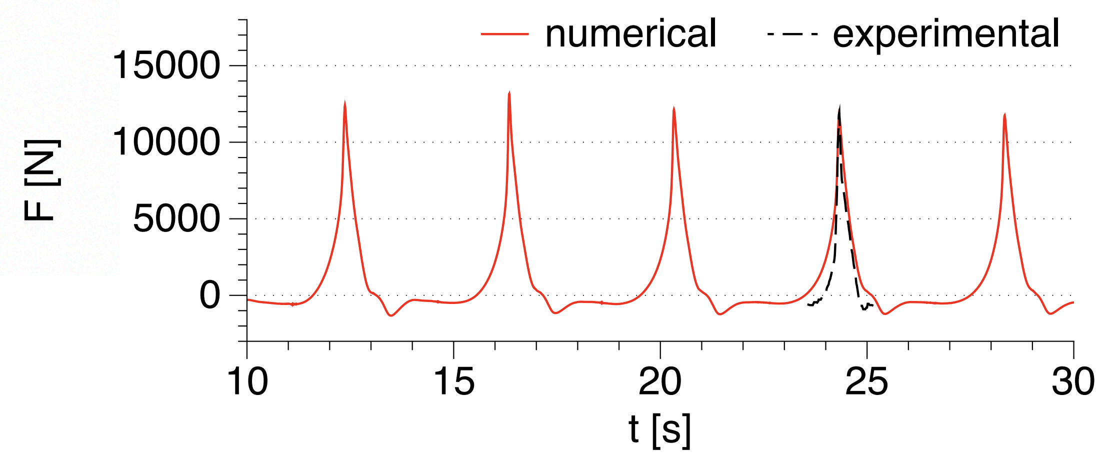
Wave Structure Interaction: Breaking Waves



Experiment: GWK - Irschik et al. 2002, ICCE



Free Surface

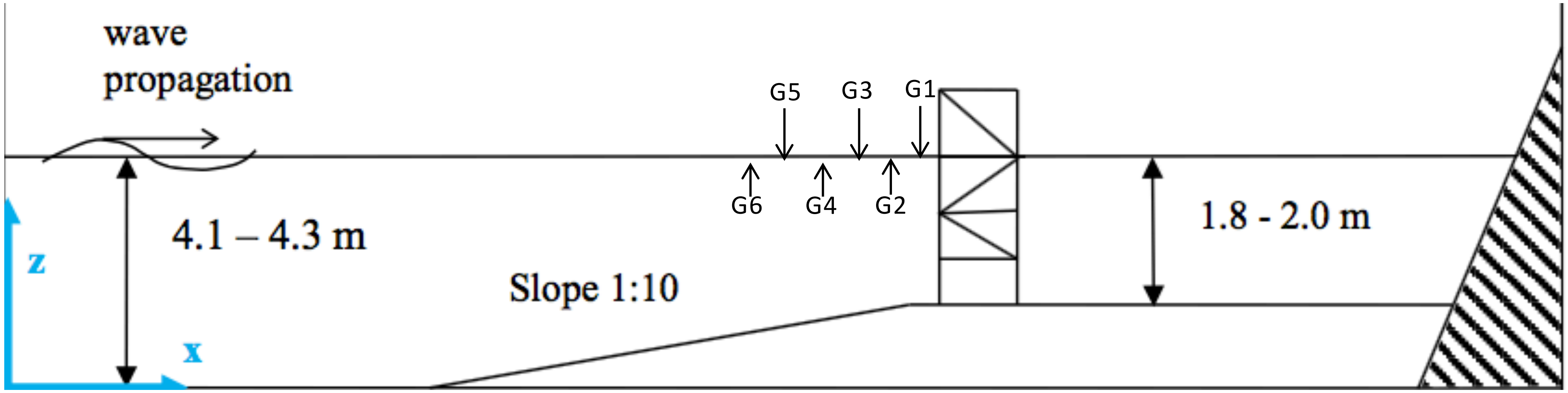


Wave Force

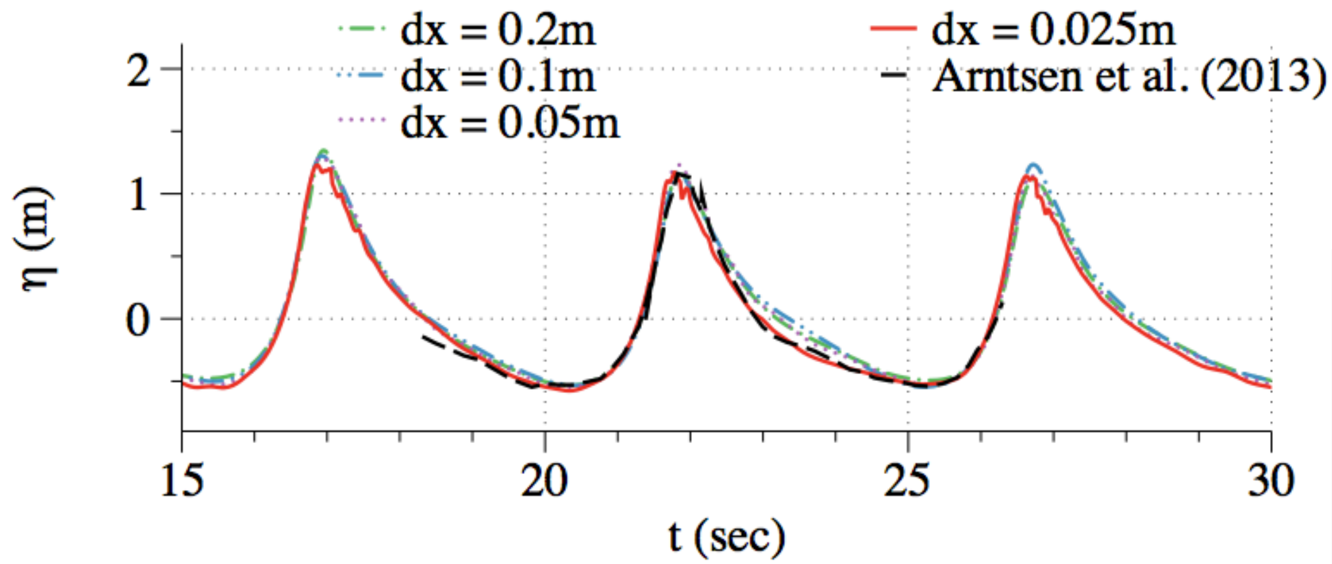
Jacket Structures : WaveSlam

WaveSlam Jacket in GWK

Slamming Event



WaveSlam : 2D breaking



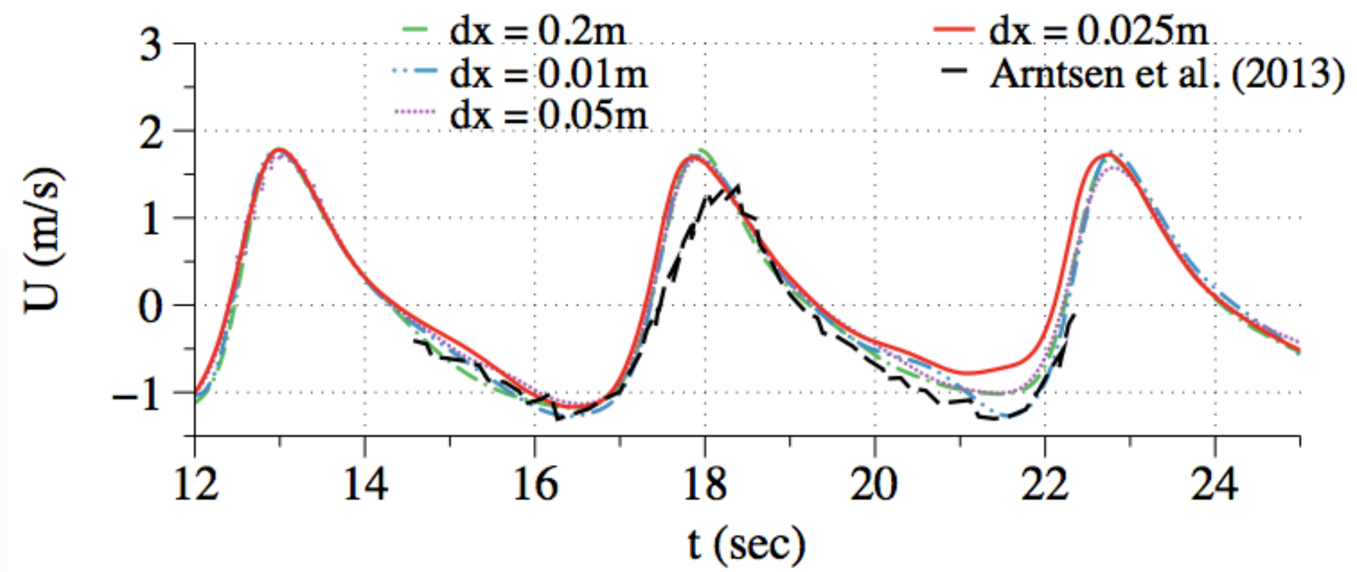
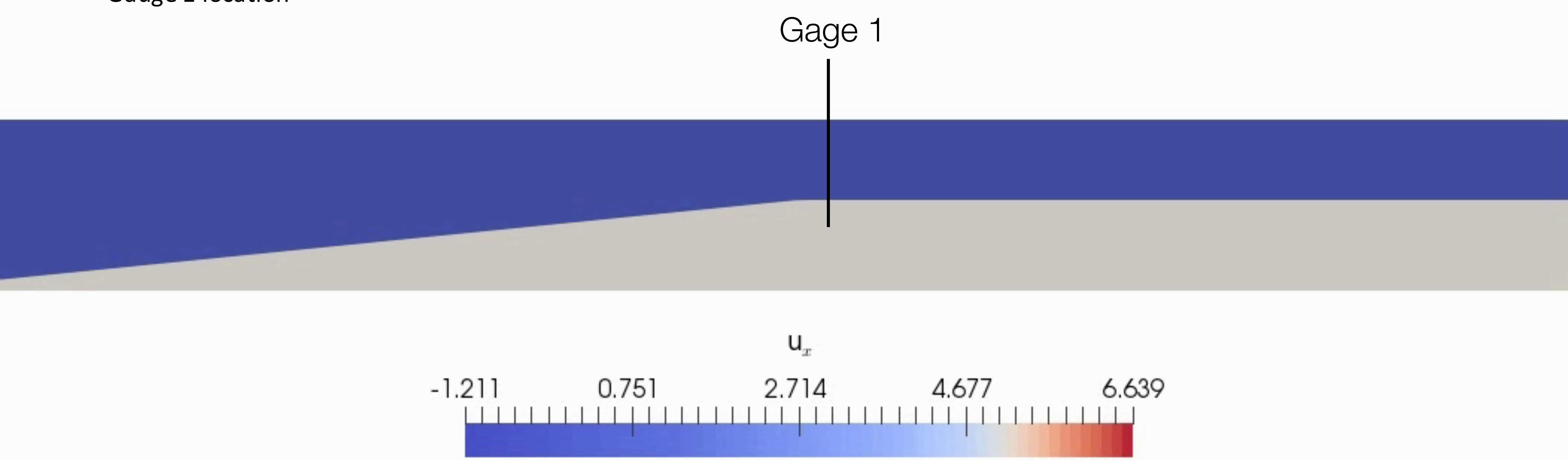
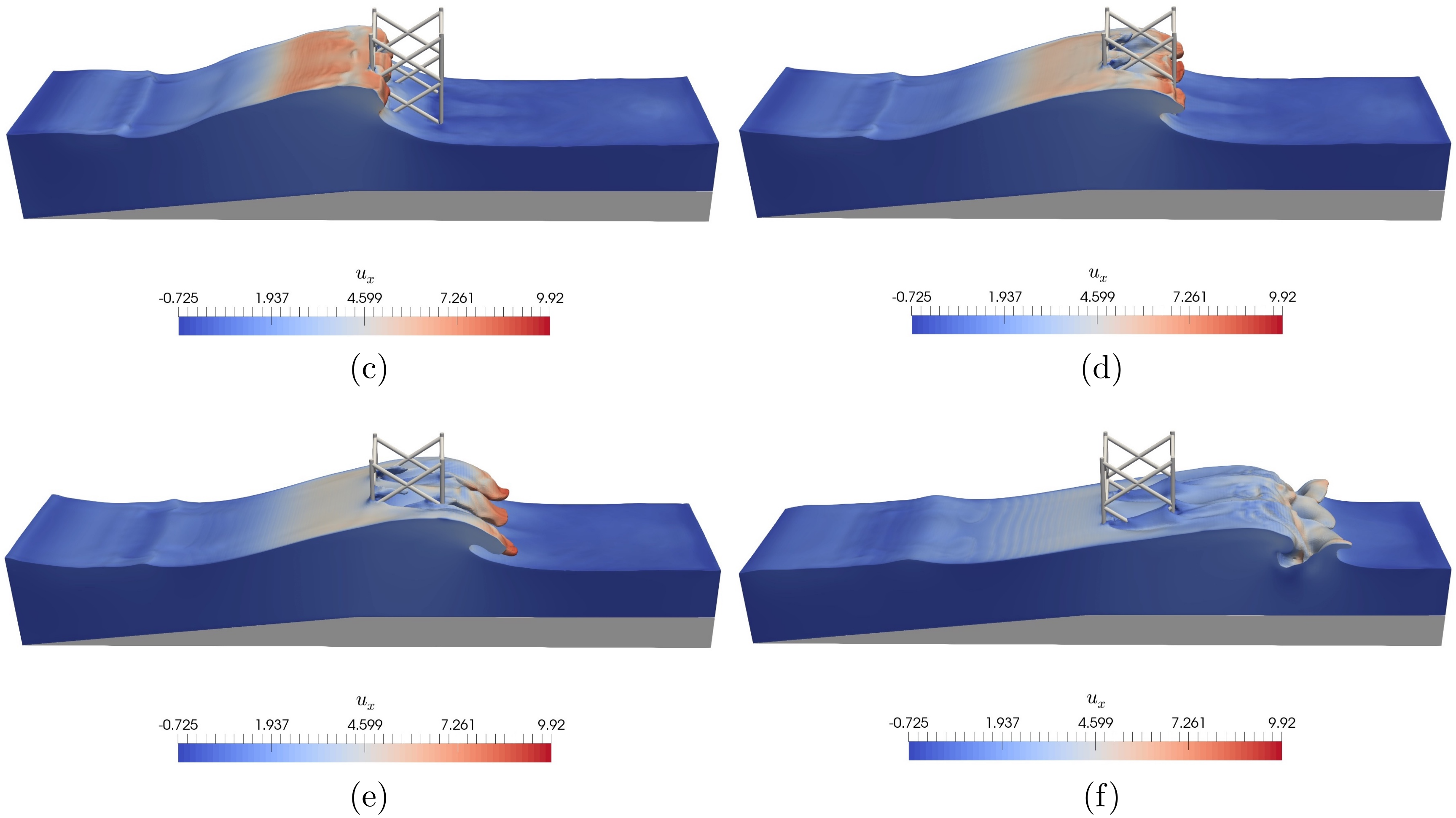
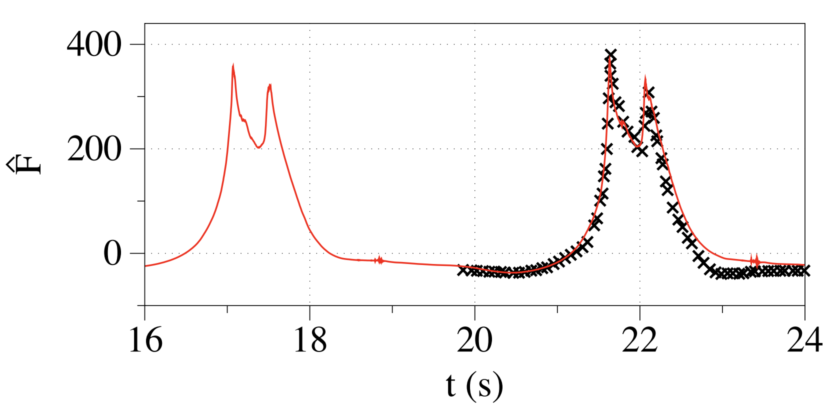


Fig. 10. Comparison of the free surface elevation (a) and horizontal particle velocities (b) of numerical results with experimental at Gauge 1 location



WaveSlam: Breaking Wave Forces

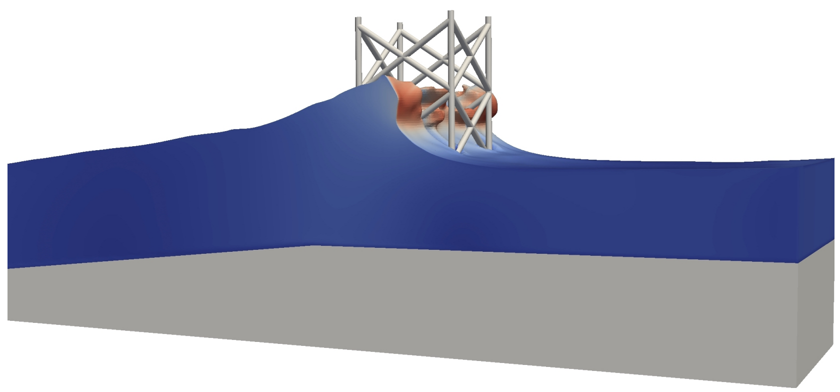


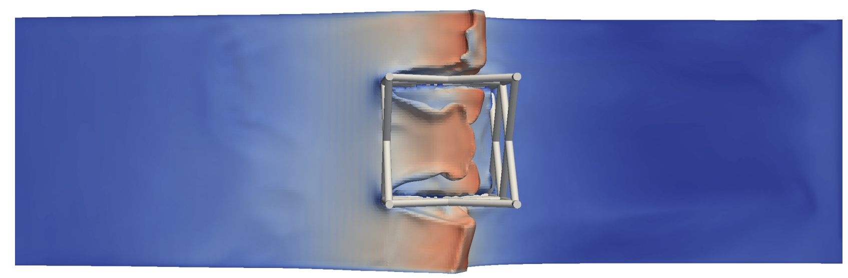


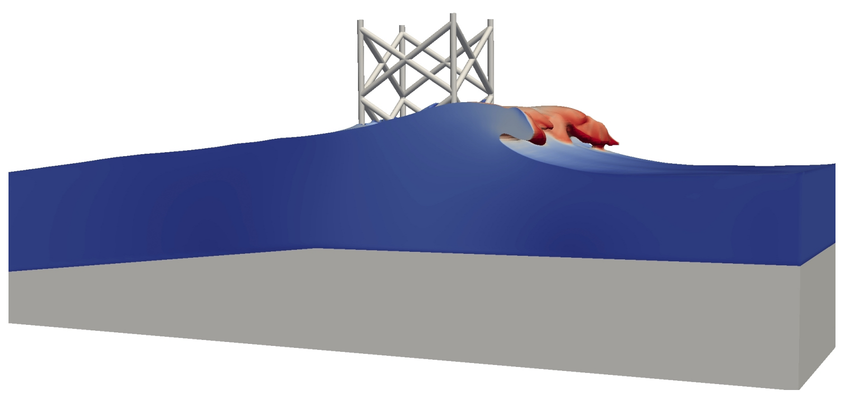
x_b = 0.9m
d = 4.3m
H = 1.7m
T = 4.6s
s = 0.05

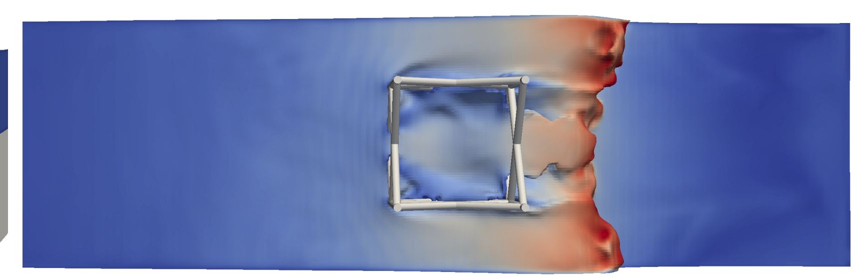
Num (dx=0.05m) **x** Experiment

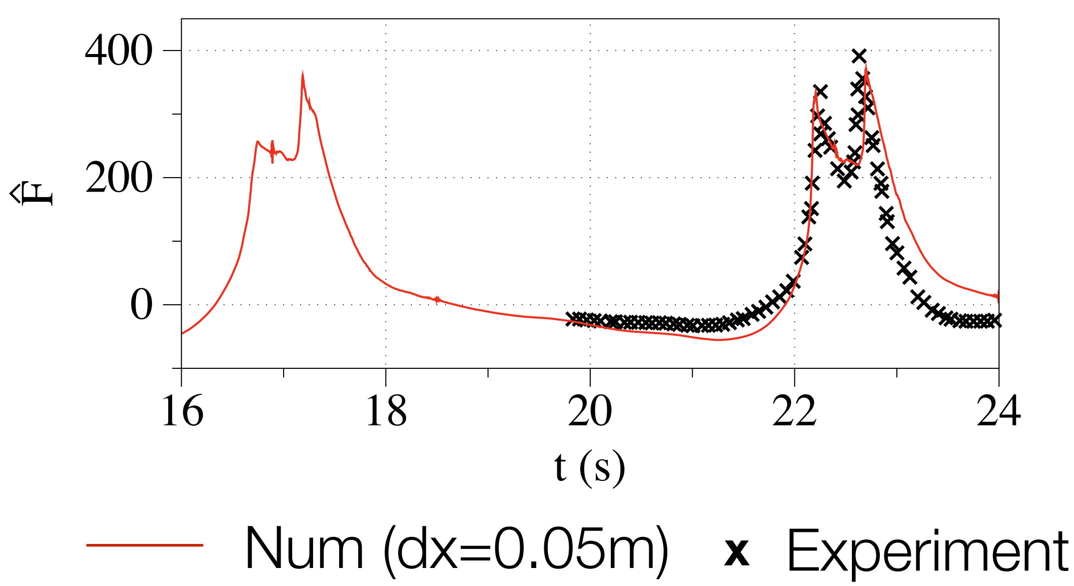
WaveSlam: Breaking Wave Forces











x_b = 1.5m

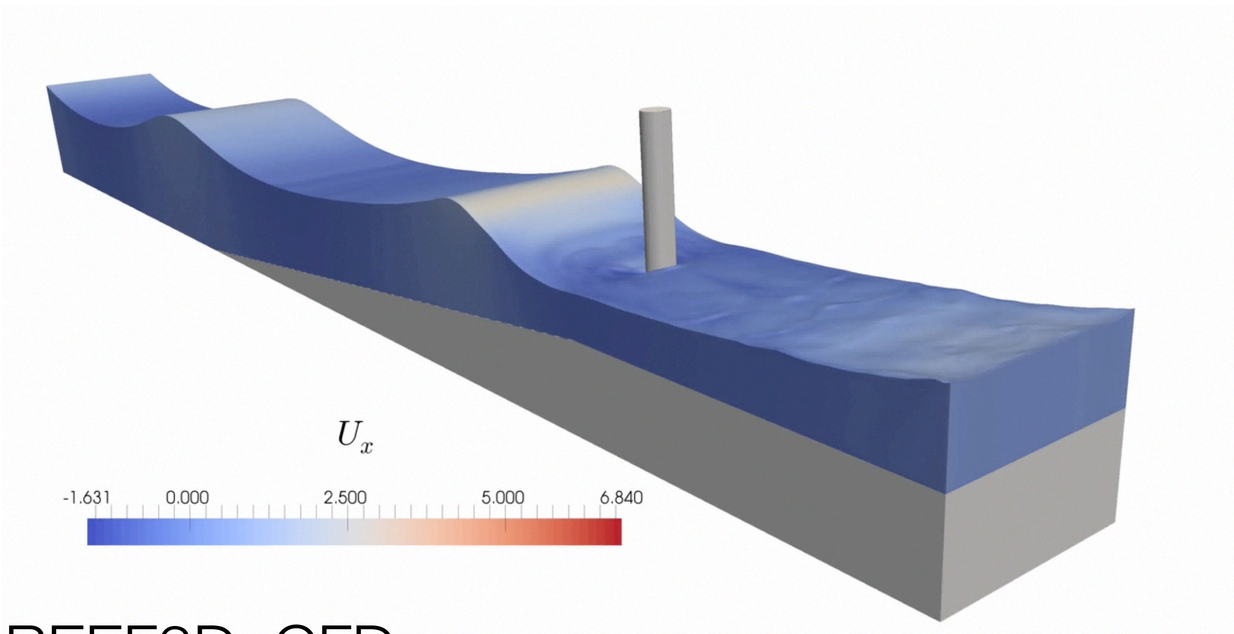
d = 4.3m

H = 1.6m

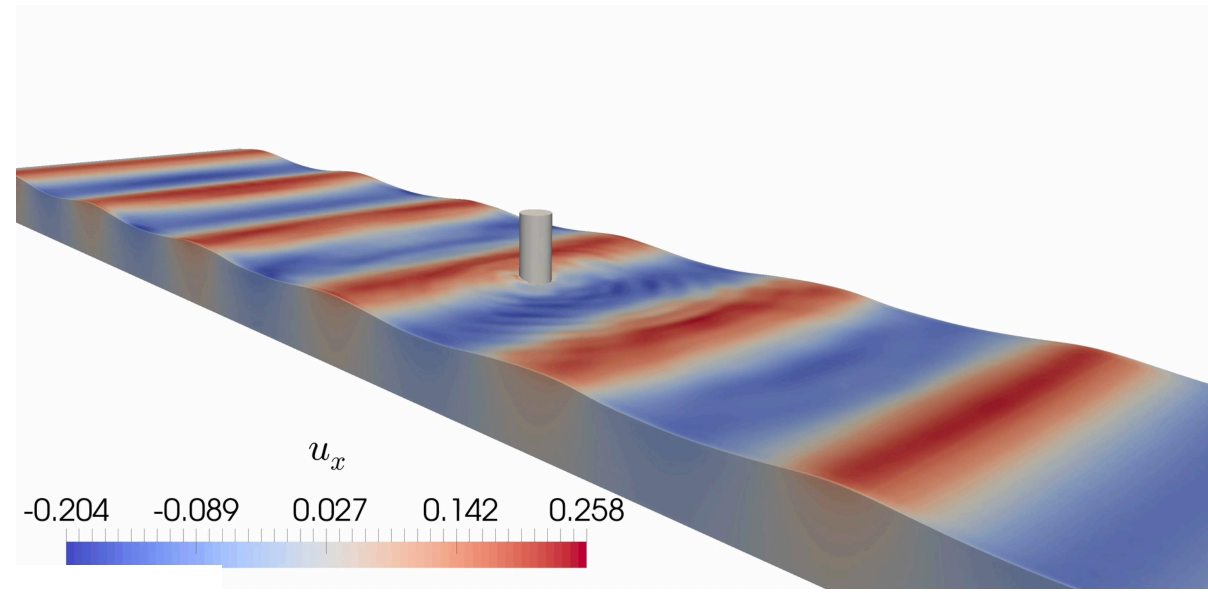
T = 5.55s

s = 0.03

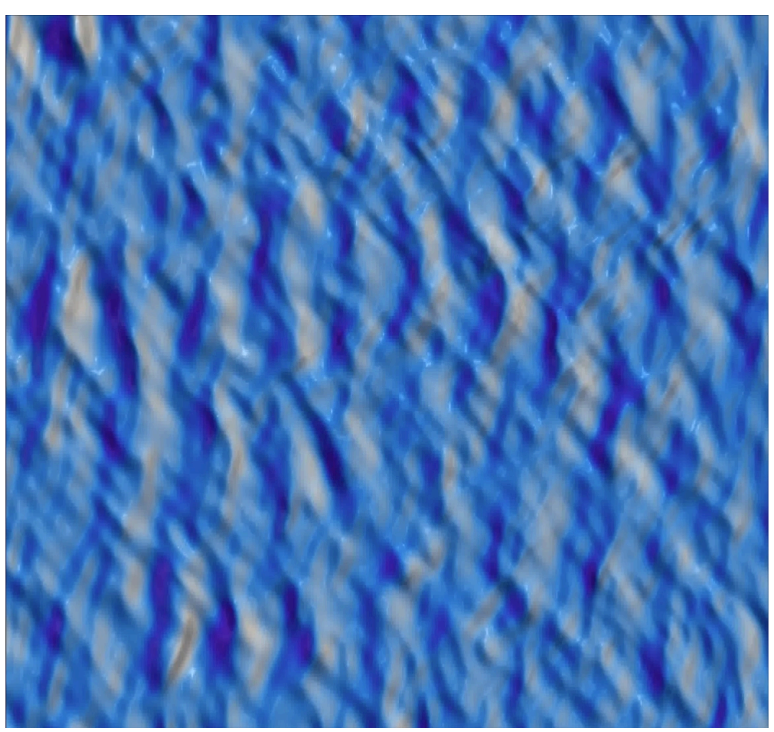
REEF3D : Open-Source Hydrodynamics



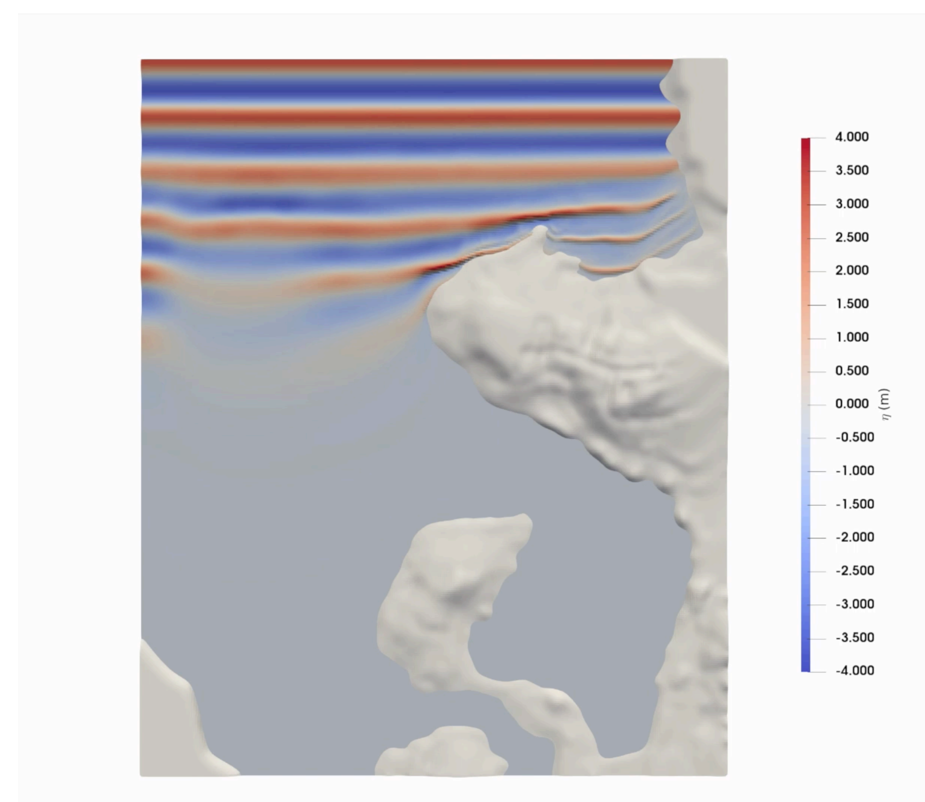
REEF3D::CFD



REEF3D::NSEWAVE



REEF3D::FNPF



REEF3D::SFLOW

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

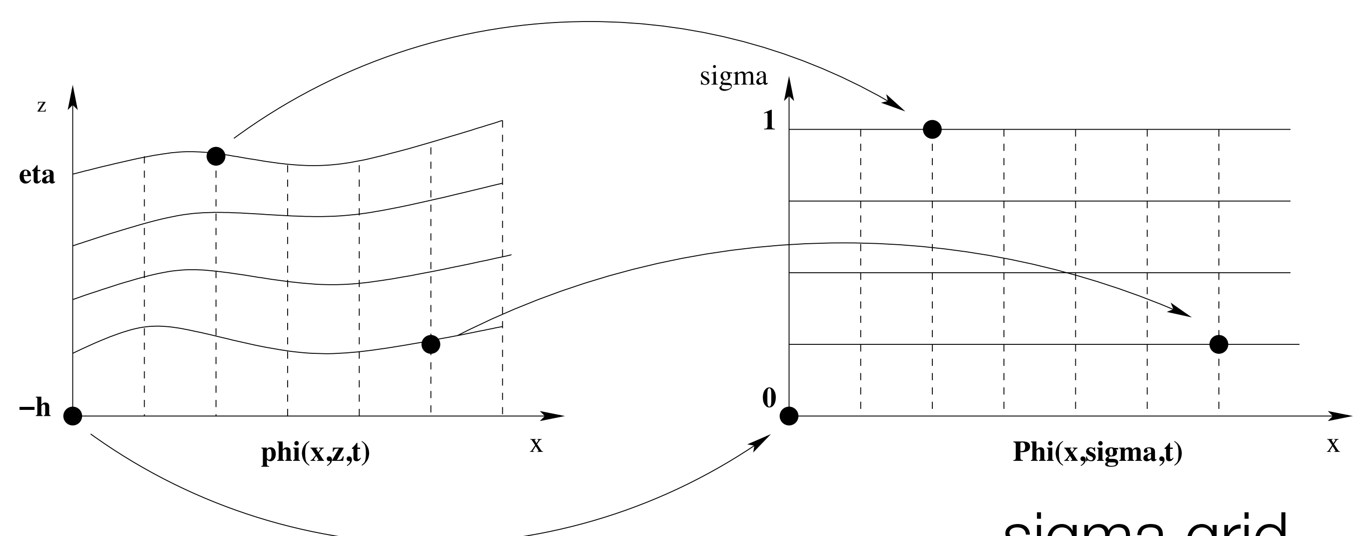
$$\frac{\partial\widetilde{\Phi}}{\partial t}=-\frac{1}{2}\left(\frac{\partial^2\widetilde{\Phi}}{\partial x^2}+\frac{\partial^2\widetilde{\Phi}}{\partial y^2}-\widetilde{w}^2\left(1+\frac{\partial^2\eta}{\partial x^2}+\frac{\partial^2\eta}{\partial y^2}\right)\right)-g\eta$$

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

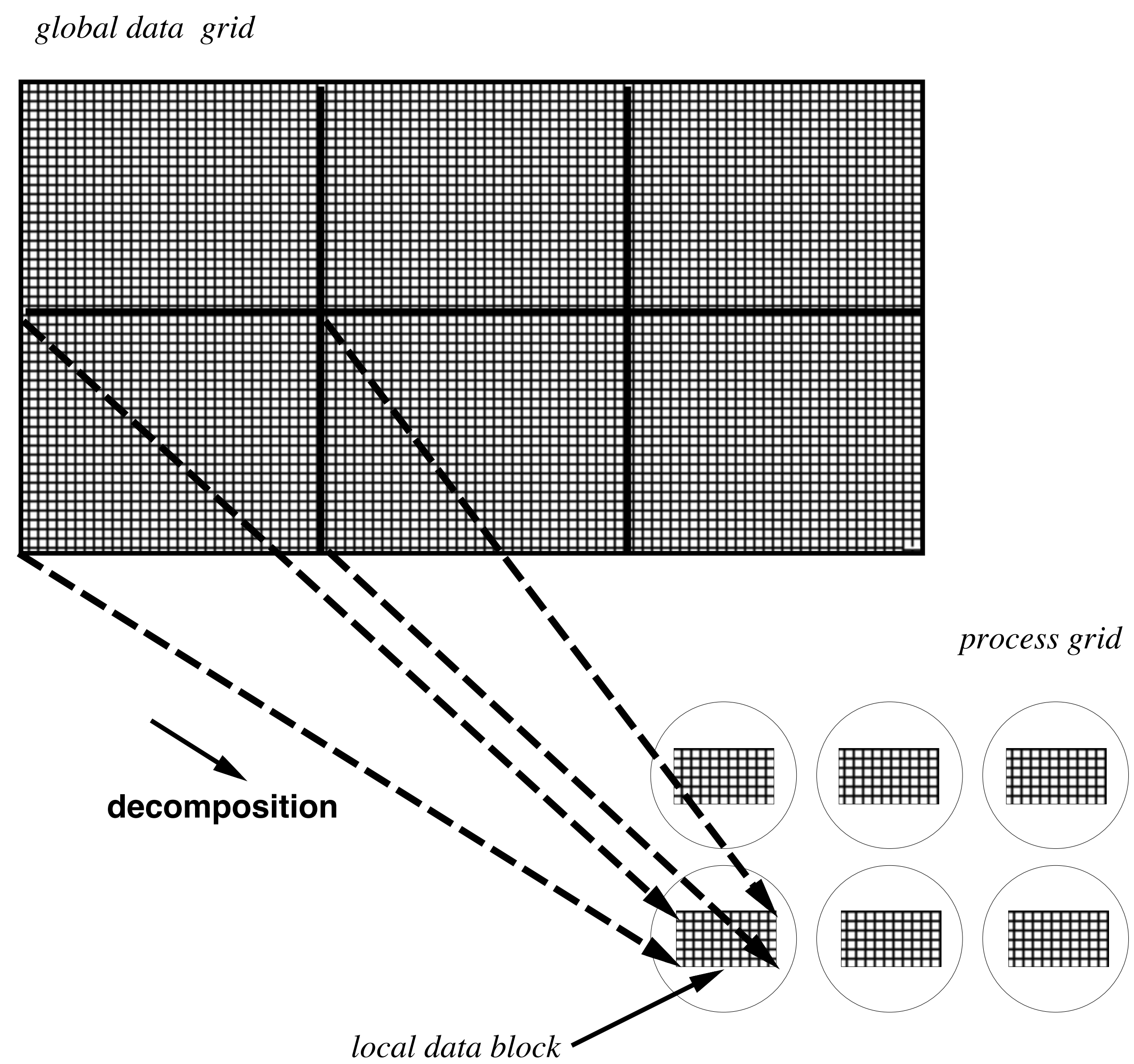
<u>Lapace Eq. for the potential</u>

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

→ $Ax = 0$
system of linear Equations

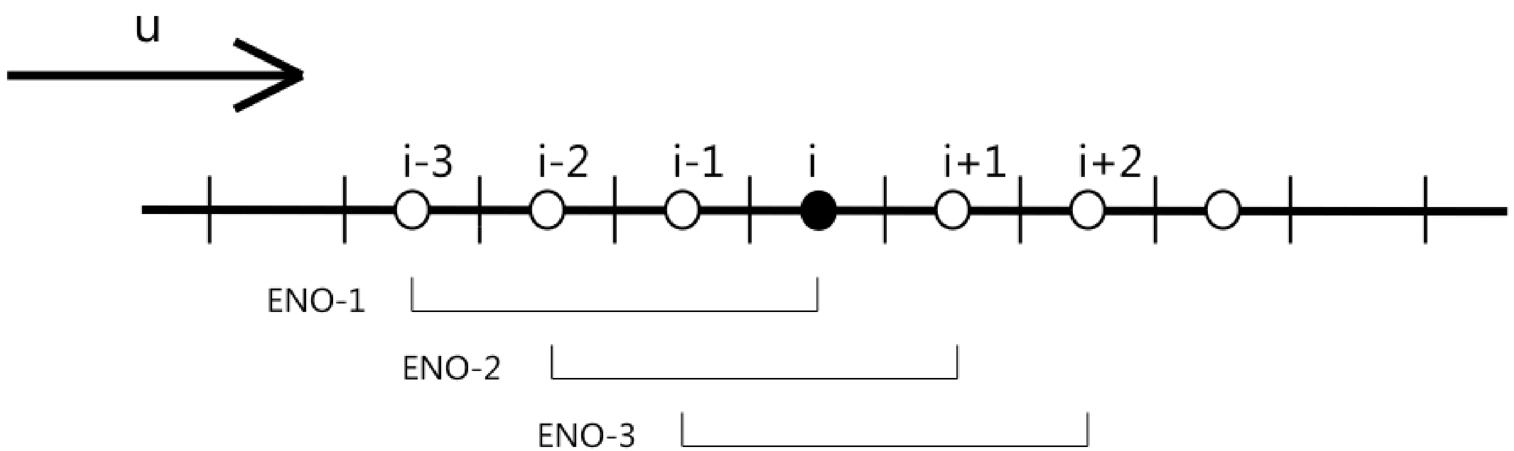
→ hypre: BiCGStab + PFMG

HPC: domain decomposition



FSFBC: Spatial Discretization

Convection Discretization: Conservative 5th-order WENO



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

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

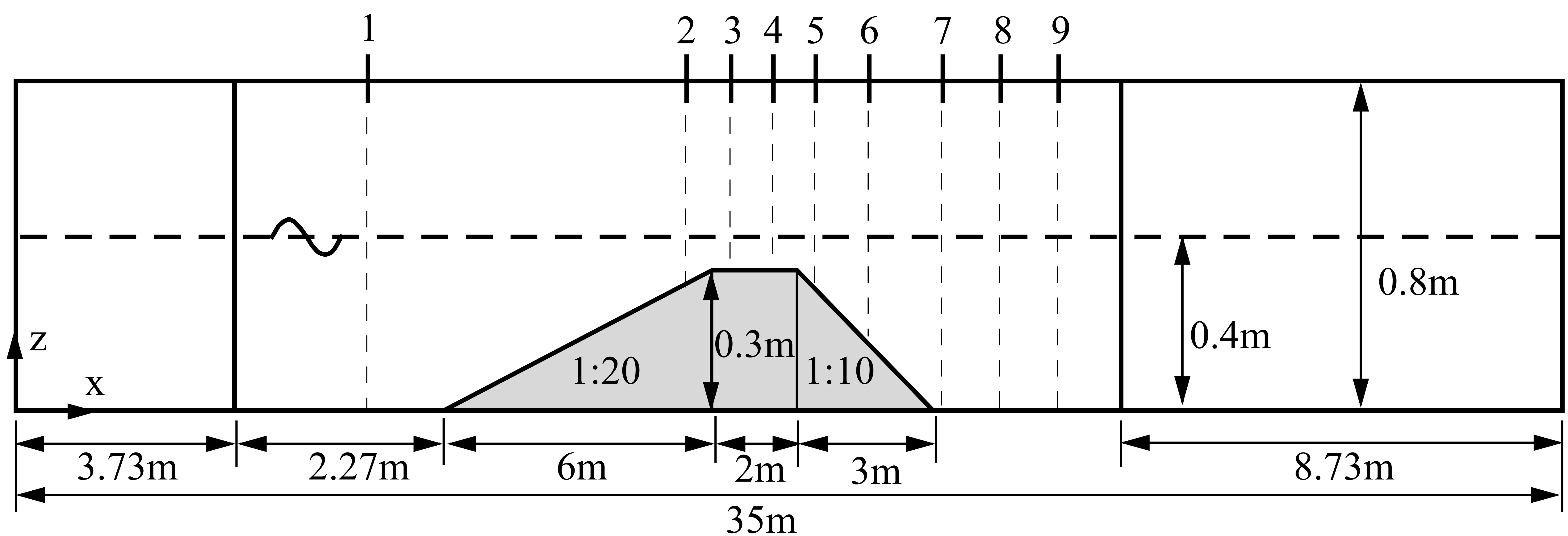
$$U^{\pm}_{i+1/2} = \omega^{\pm}_1 U^{1\pm}_{i+1/2} + \omega^{\pm}_2 U^{2\pm}_{i+1/2} + \omega^{\pm}_3 U^{3\pm}_{i+1/2}$$

Beji & Battjes: Submerged Bar - FNPF vs CFD

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

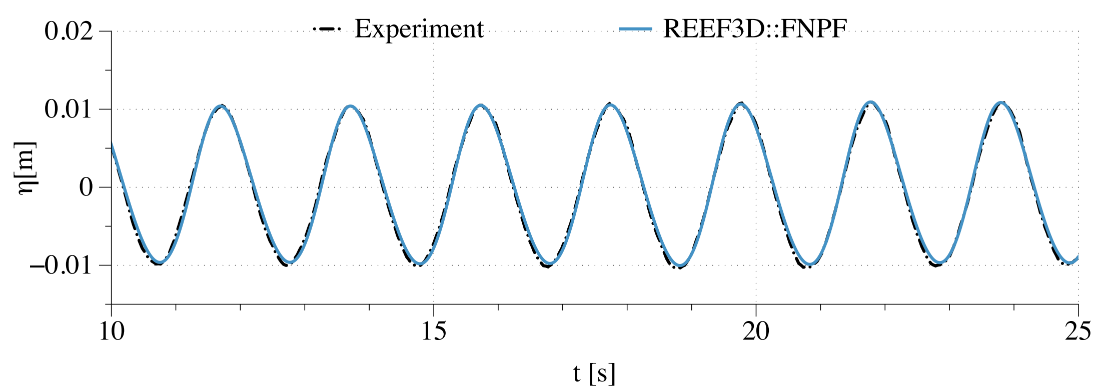
FNPF
- mesh: 800 x 10 = 8.000 cells

CFD
- mesh: 6000 x 160 = 960.000 cells

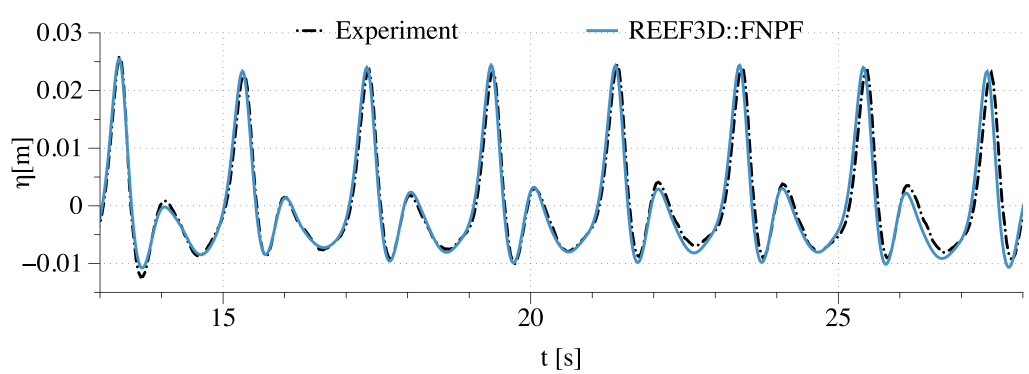


Beji & Battjes: Submerged Bar

FNPF

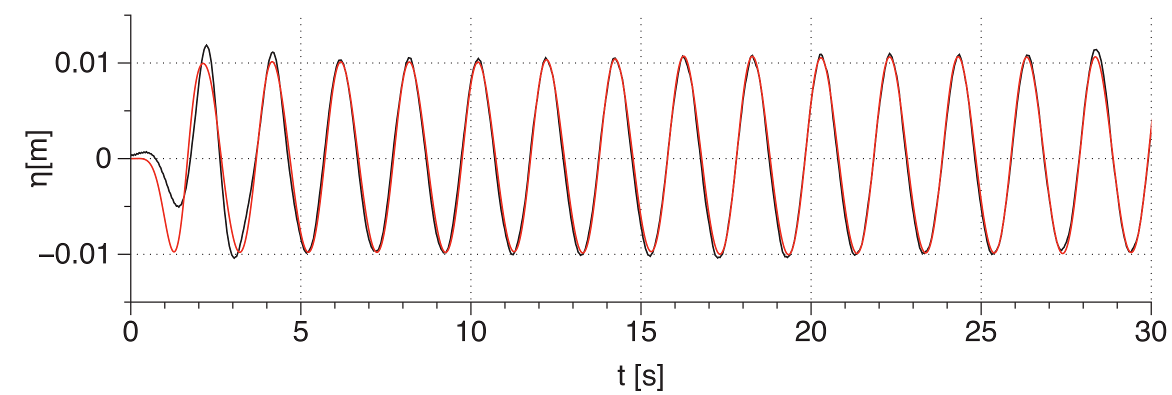


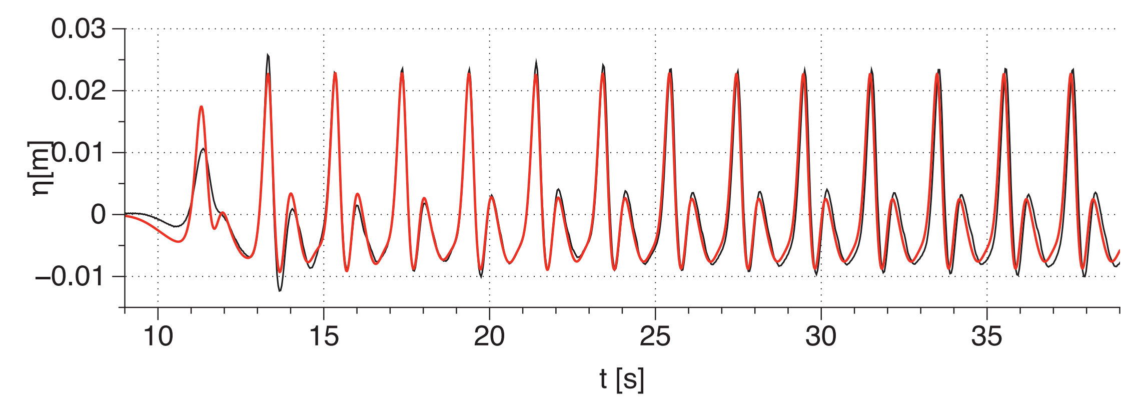
(a) wave gauge 1 at $x = 4.0$ m

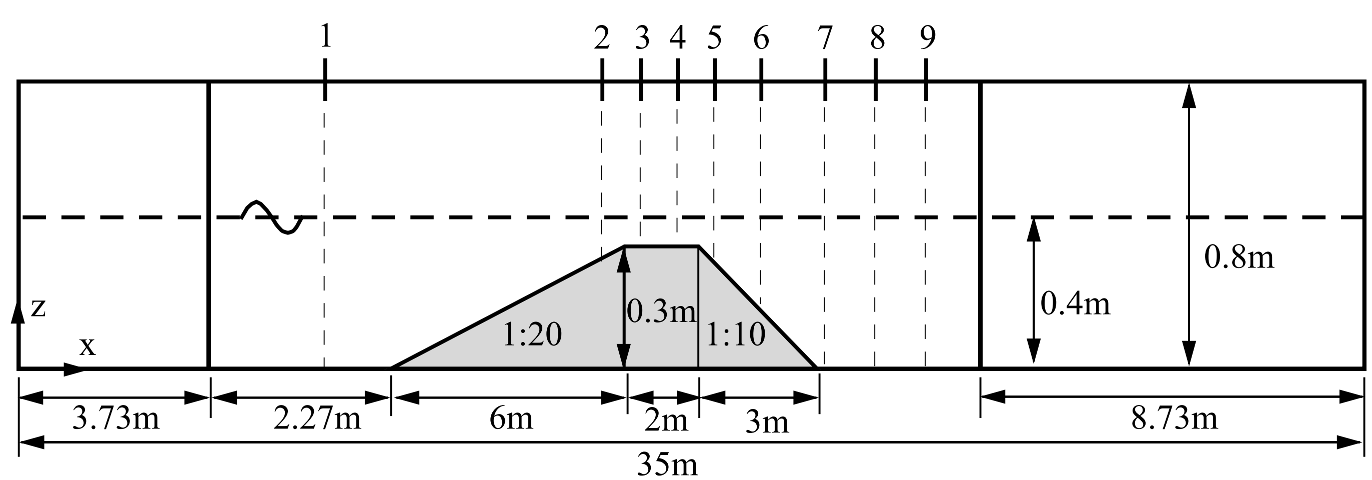


(e) wave gauge 5 at $x = 14.5$ m

CFD

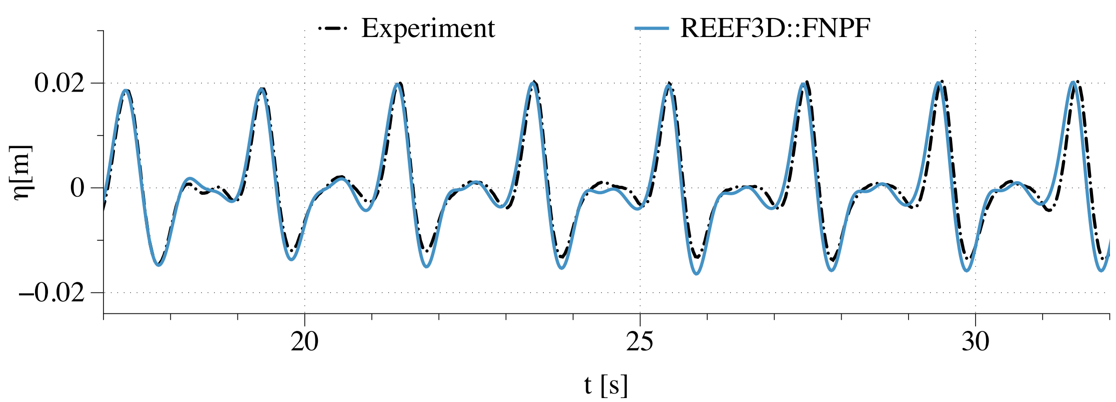




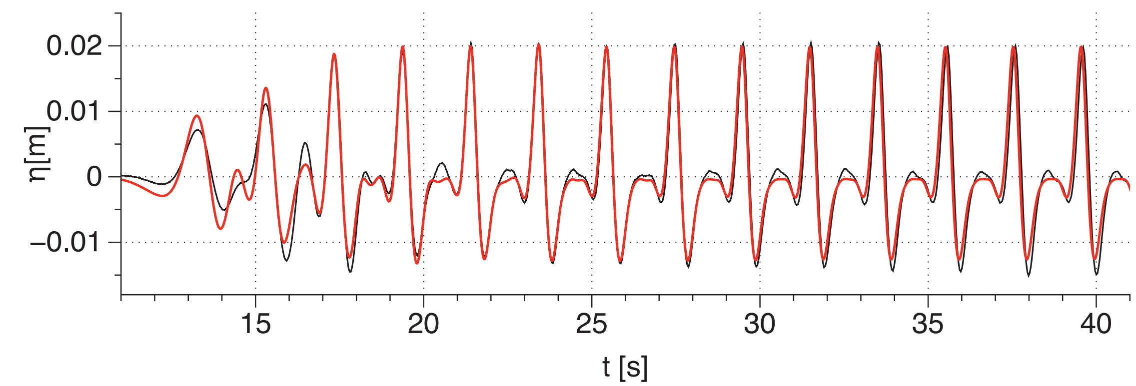


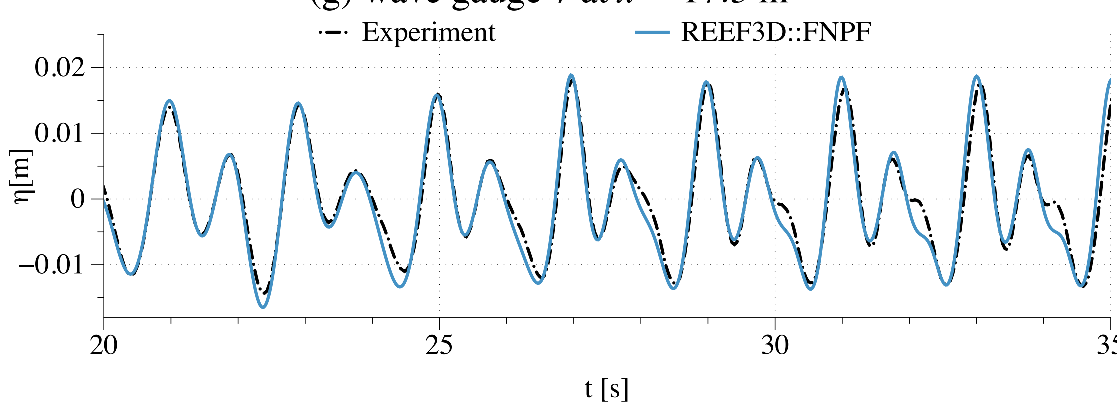
Beji & Battjes: Submerged Bar

FNPF | **CFD**

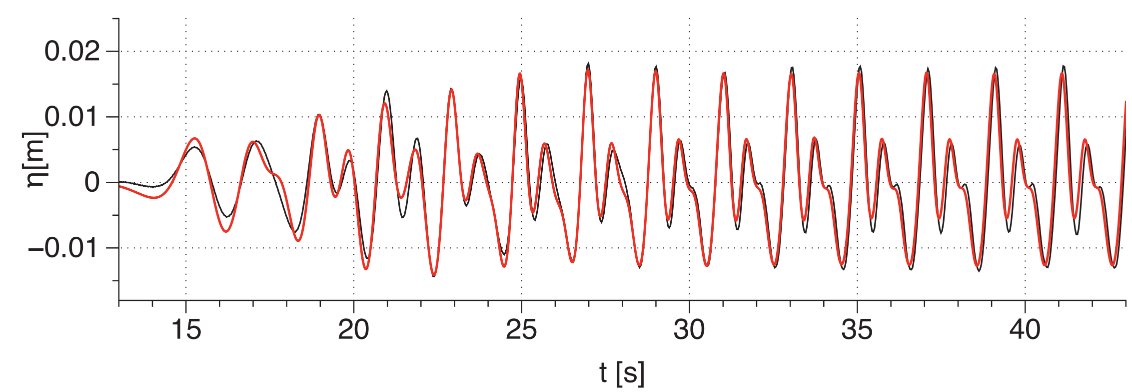


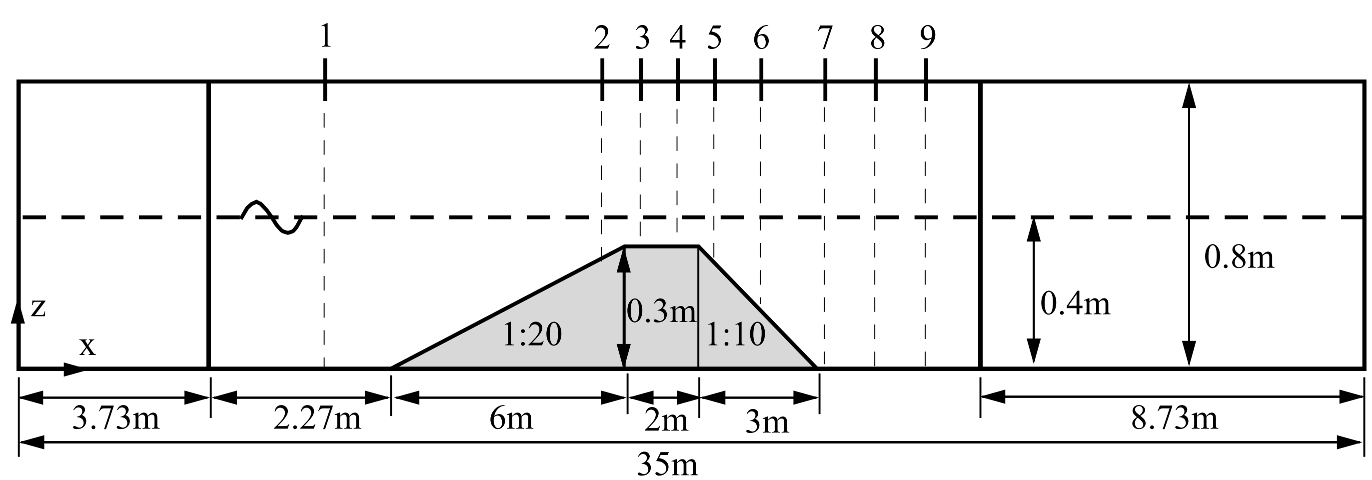
(g) wave gauge 7 at $x = 17.3$ m





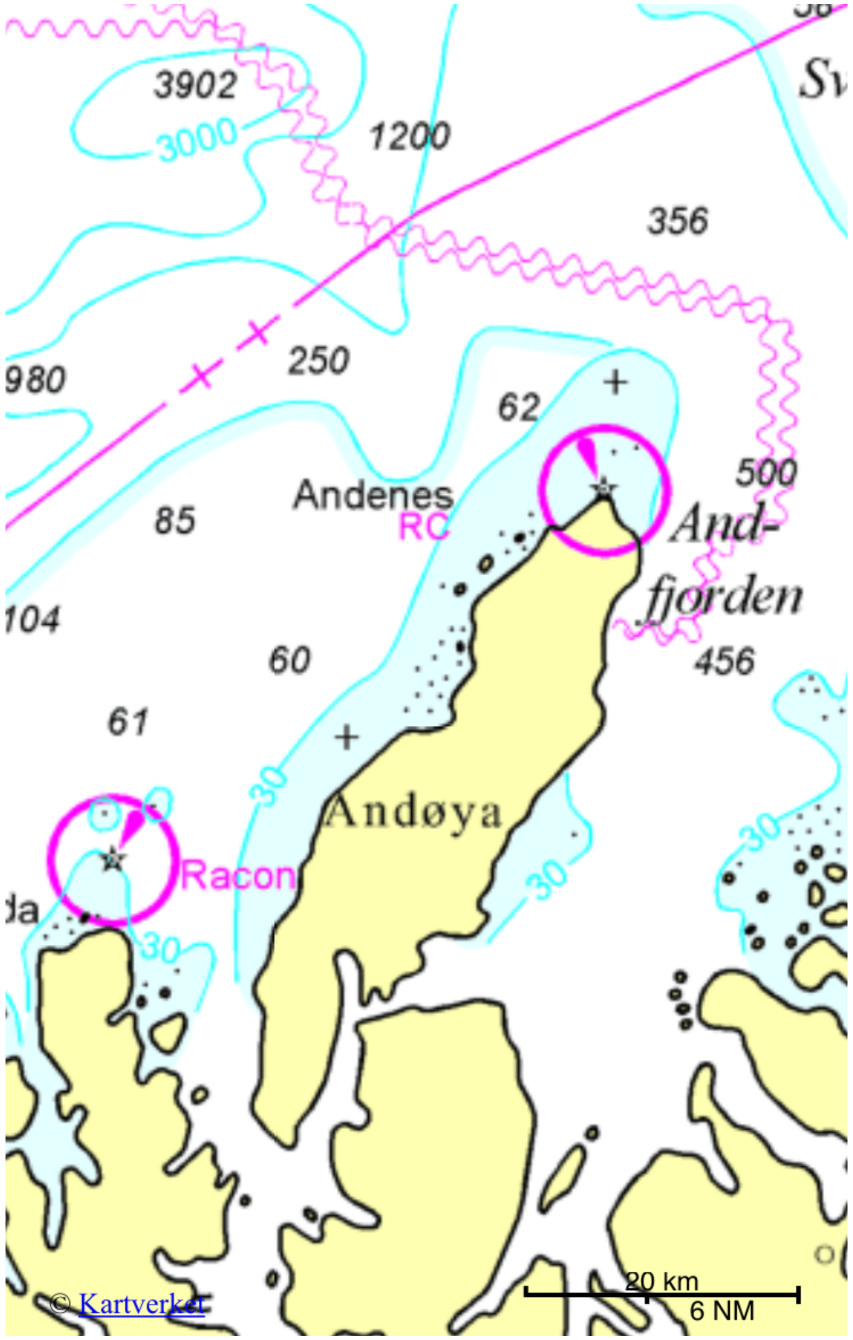
(i) wave gauge 9 at $x = 21.0$ m





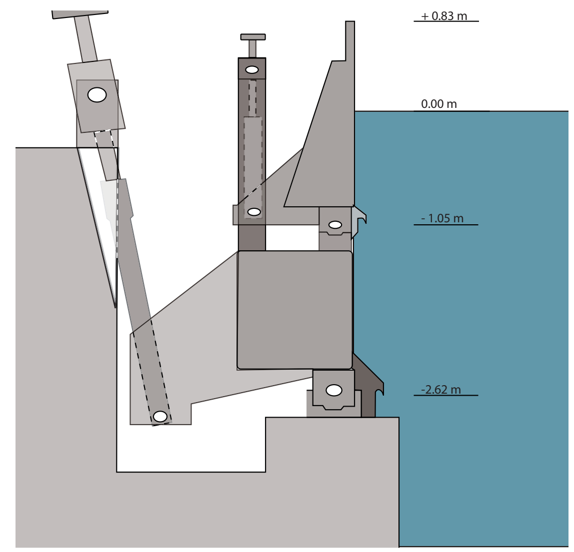
Typical Norwegian Coast

Andenes, Versterålen Archipelago

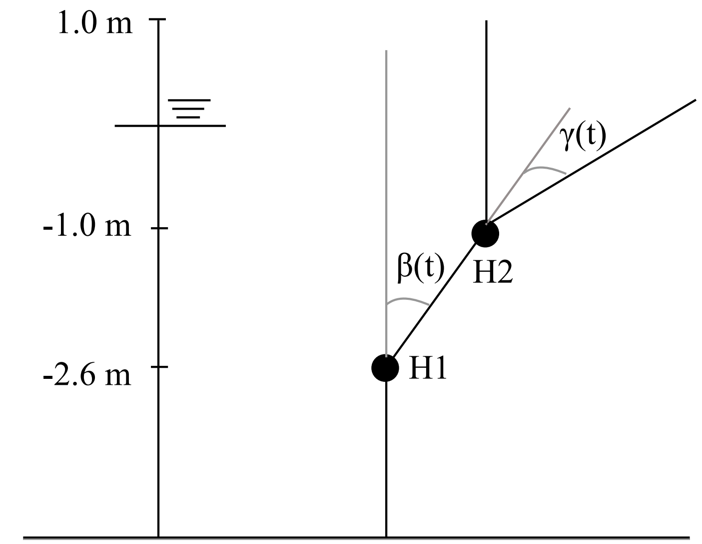


Bichromatic Waves (full tank 250m)

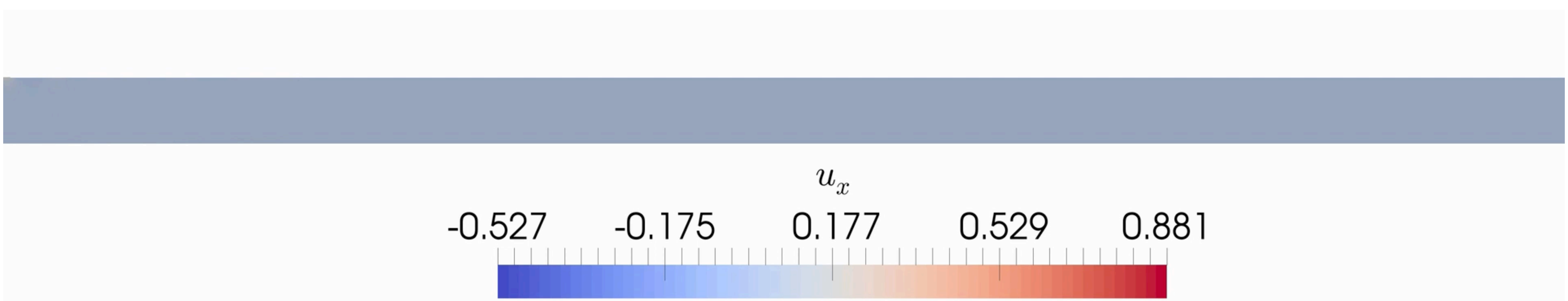
- Experiments: C. Pakozdi, 2014
- Experimental Wave Flume:
  - SINTEF Ocean (Marintek)
  - L = 250 m
  - d = 10.0 m
- Bichromatic waves
  - T_1 = 2.1s
  - T_2 = 1.6s
- 2D grid: 250m x 10m
  - 2500 x 25 = 62.500 cells



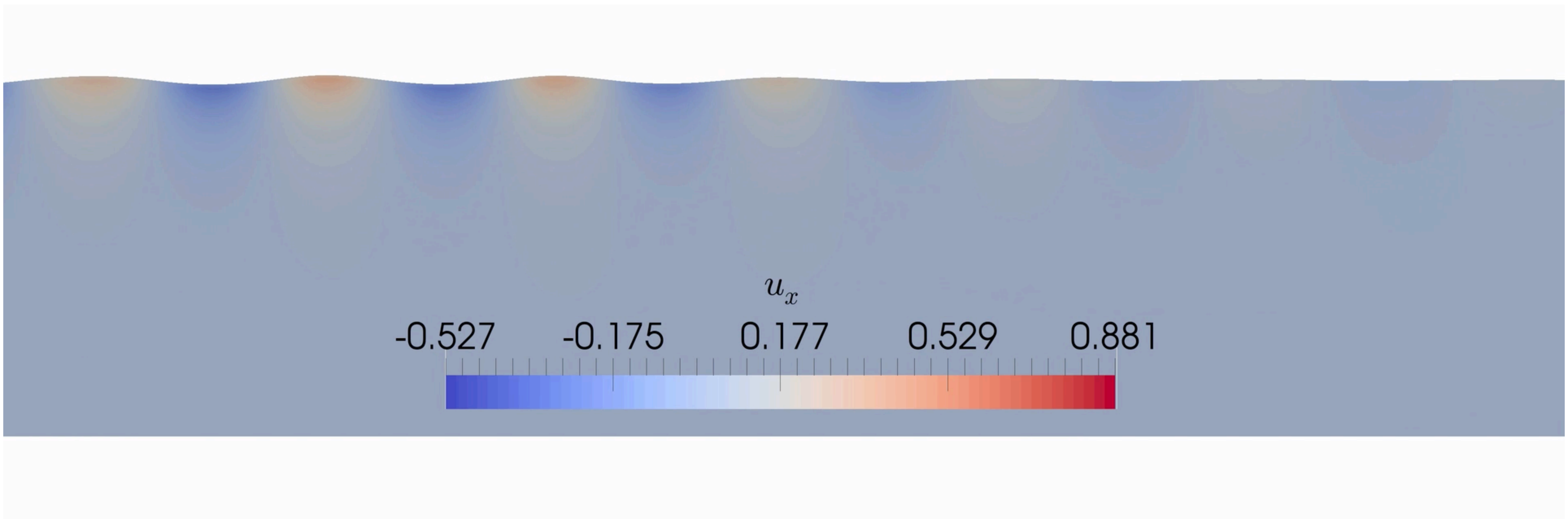
Experimental wavemaker



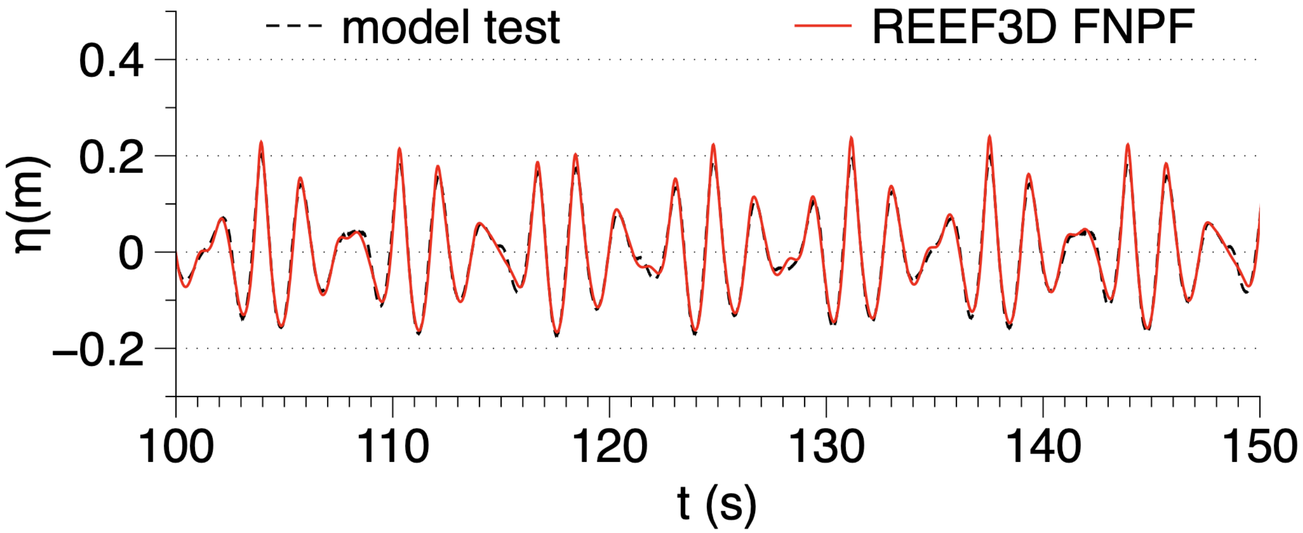
Numerical wavemaker



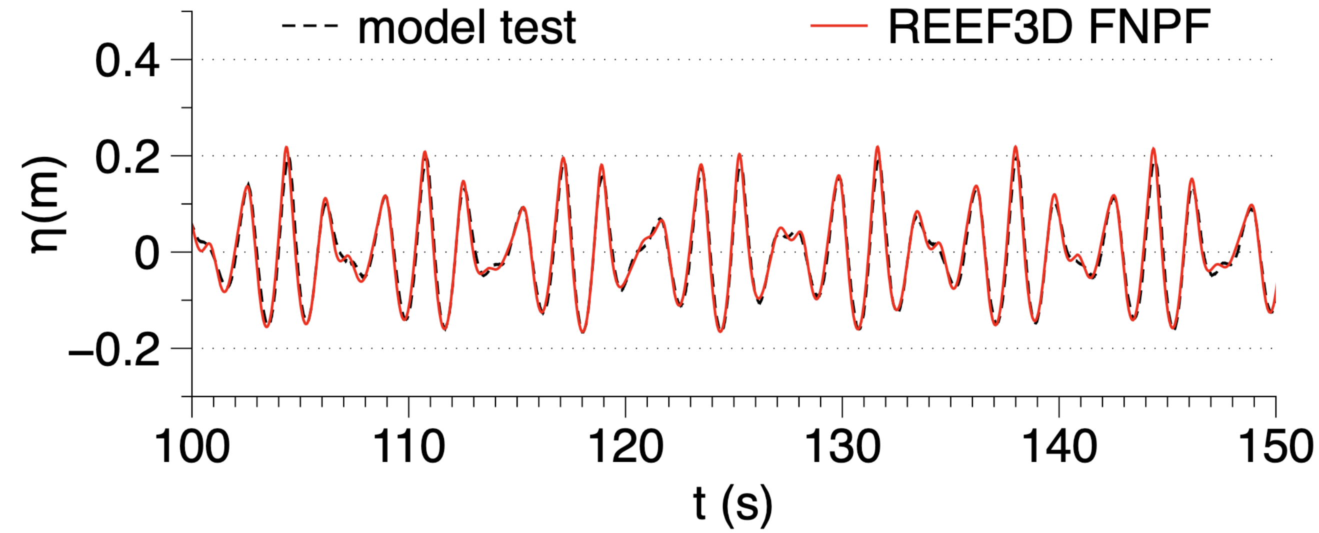
Bichromatic waves (portion of NWT)



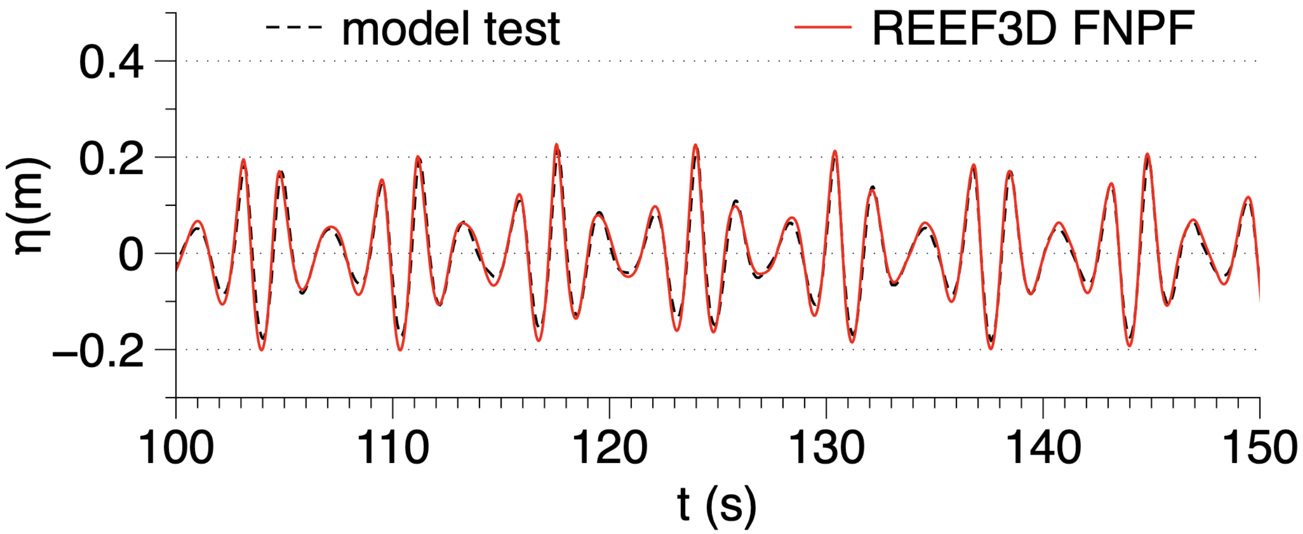
Bichromatic Waves



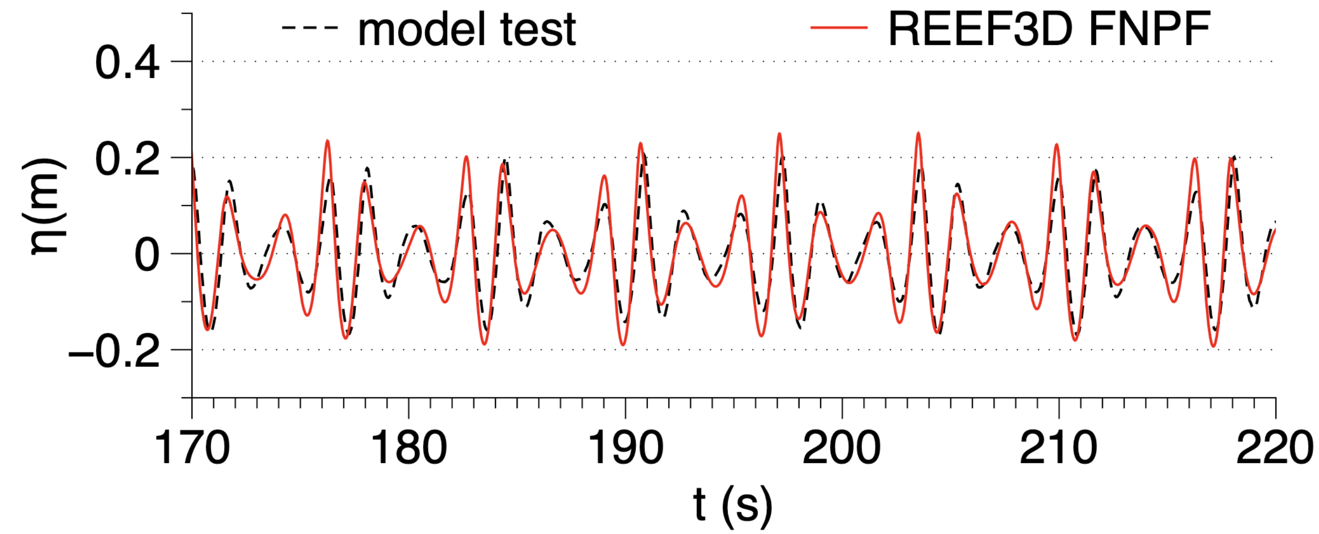
x = 10 m



x = 40 m

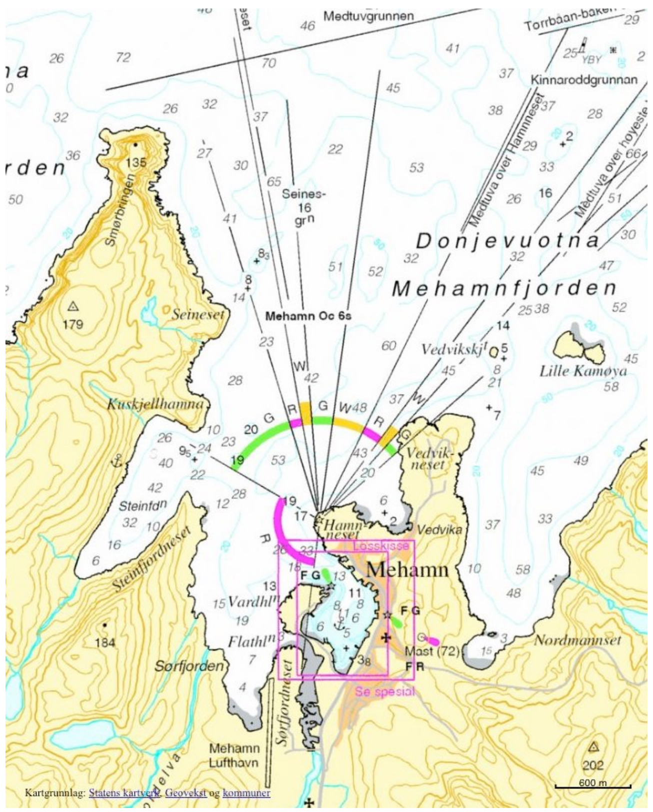


x = 70 m



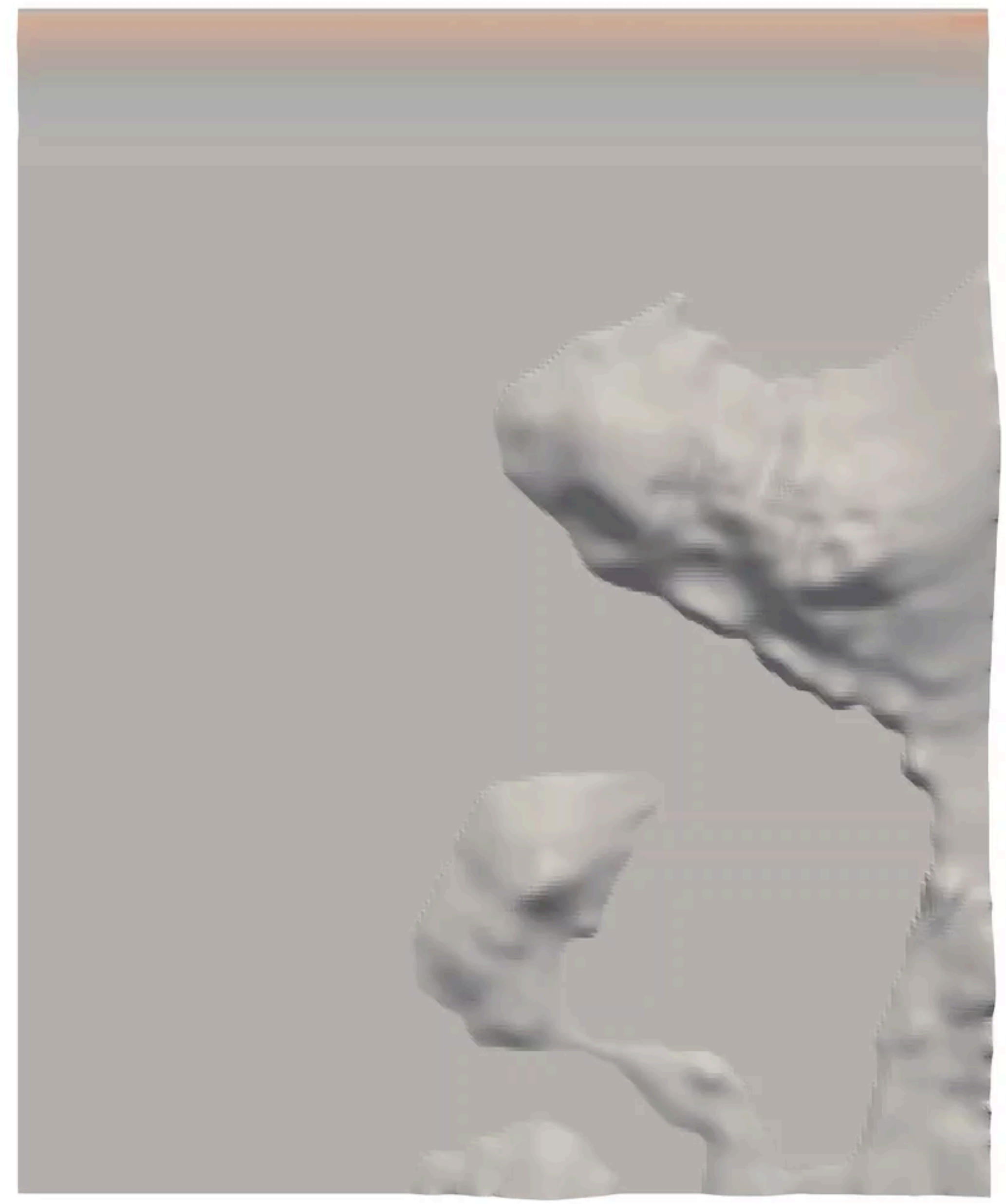
x = 160 m

Coastal Modeling: Mehamn



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

FNPF includes
- wetting/drying
- breaking



Conclusions

- **REEF3D Open-Source Hydrodynamics :**

  → Phase-resolved Waves on all Scales

- Coastal / Marine / Hydraulic Engineering

- <u>Ongoing FNPF:</u>
  - structures
  - wave communication protocol (WCP) for consistent coupling

- <u>Outlook FNPF:</u>
  - floating
  - mooring