ICCE 2018

36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018

Baltimore, Maryland | July 30 – August 3, 2018

The State of the Art and Science of Coastal Engineering

Numerical Simulation Of Interactions Between Water Waves And Moored-Floating Breakwater

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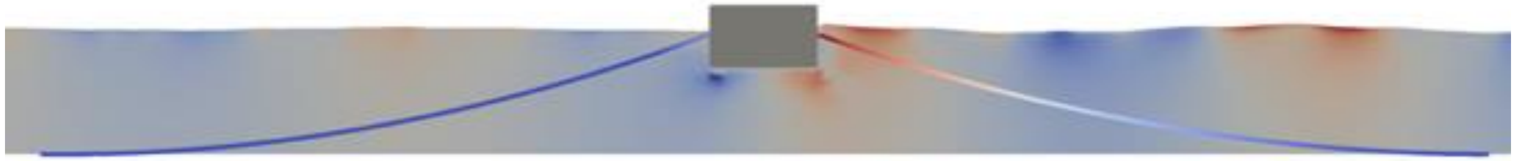
Objectives

- Modelling the influence of mooring systems on the motion of breakwaters
  - Complex FSI including flexible structures

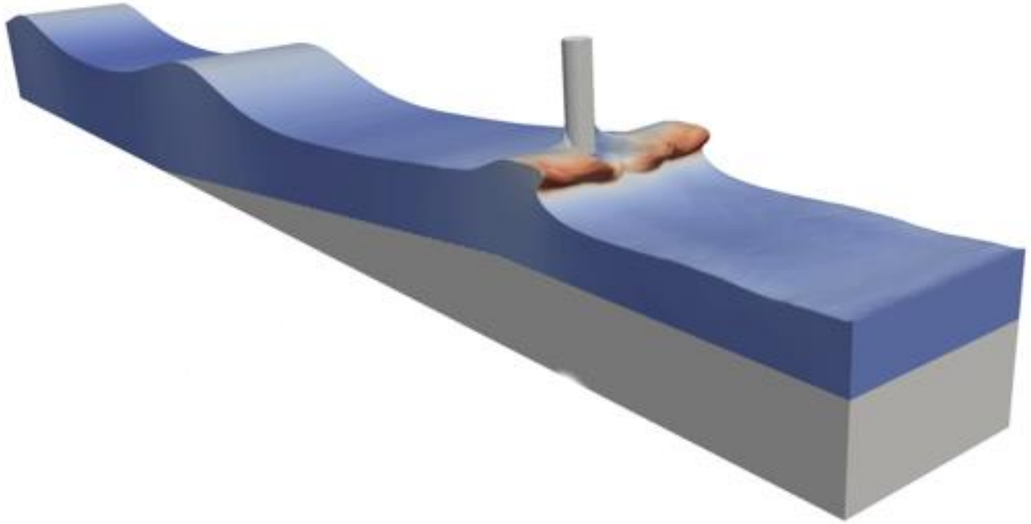
- CFD
  - Accurate wave modelling
  - Non-linear wave-structure interaction
  - Viscous effects around the body

- Implementation of 6DOF algorithm
- Implementation of mooring system



REEF3D: Open Source CFD Solver

- Developed at the Marine Civil Engineering Group, Department of Civil and Transport Engineering, NTNU Trondheim, Norway
- 3D numerical wave tank
  - Free Surface Flows
  - Wave Hydrodynamics
  - Wave Forces
  - Fluid-Structure Interaction
- MPI parallelized C++ code
- Published under GNU GPL v3



Governing Equations

- Incompressible RANS and continuity equations in non-conservative form

$$\frac{\partial u_i}{\partial x_i} = 0,$$
$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \cdot \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + g_i,$$

- Level-Set Method for capturing the free surface

$$\Phi(\boldsymbol{x}, t)\begin{cases} > 0 & \text{if } \boldsymbol{x} \in \text{phase 1} \\ = 0 & \text{if } \boldsymbol{x} \in \Gamma \\ < 0 & \text{if } \boldsymbol{x} \in \text{phase 2} \end{cases}, \ |\nabla \Phi| = 1$$

$$\frac{\partial \mathit{\Phi}}{\partial t} + u_j \frac{\partial \mathit{\Phi}}{\partial x_j} = 0.$$

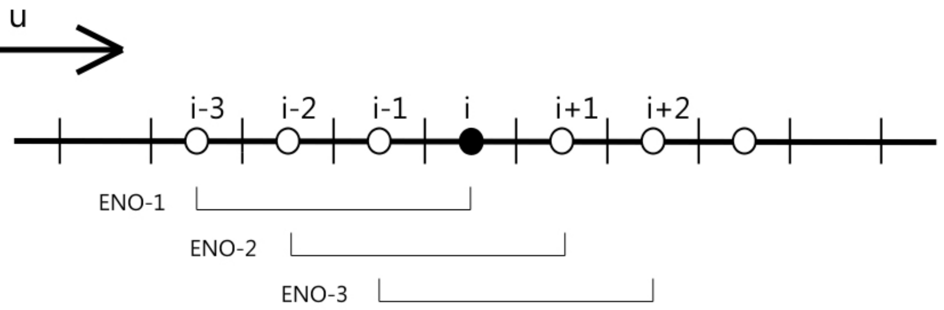
- Reinitialisation after each step to keep Φ a signed distance function

Numerical Discretisation

- Finite Difference Method on Cartesian grid
- Convection terms: 5th-order accurate WENO scheme
  - Non-oscillatory behaviour near large gradients
  - Keeps high-order accuracy in comparison to TVD schemes

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

$$U^{\pm}_{i+1/2} = \omega_1^{\pm}U^{1\pm}_{i+1/2} + \omega_2^{\pm}U^{2\pm}_{i+1/2} + \omega_3^{\pm}U^{3\pm}_{i+1/2}$$



- Diffusion terms: Implicit discretisation for stability and efficiency reasons
- Temporal terms in momentum equation: 3rd-order TVD Runge-Kutta scheme
  - Adaptive time steps based on CFL criterion

Fluid Solution Algorithm

- Staggered grid
  - Tight velocity-pressure coupling
  - Avoiding parasitic currents above the free surface

- Chorin's projection method for incompressible flows
  - Poisson equation for pressure
  - Velocity satisfies continuity equation after correction

- Implicit boundary treatment
  - Ghost cell immersed boundary method
  - Extrapolation of solution in solid regions
  - High stability through numerical simplicity

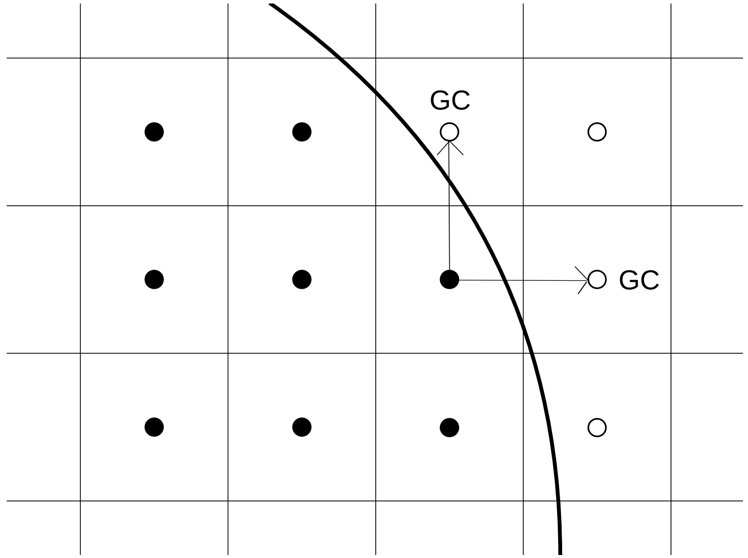
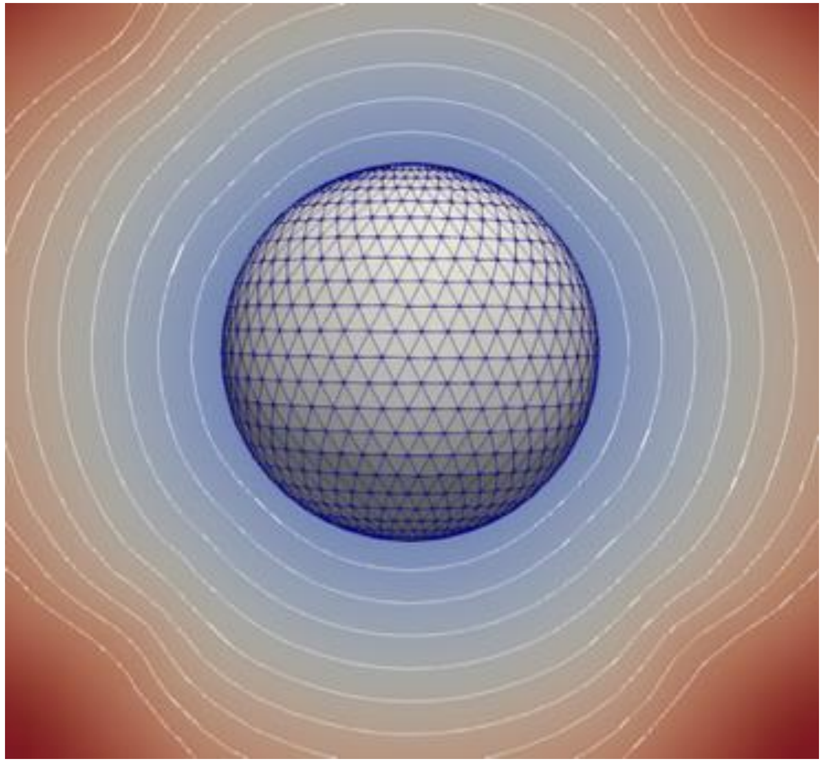


Illustration of GC-IBM

6DOF Algorithm

- Geometry described by triangular mesh
- Implicit description of rigid bodies
    - Ray-tracing algorithm for closest distance information
    - Signed distance function around body using reinitialisation algorithm

- Advantages:
    - No moving or overset meshes
    - High numerical stability
    - Fast and parallelised process



Contour of level set function around moving body

6DOF Algorithm: Rigid Body Dynamics

- Body moves as rigid body in 6DOF
    - Translational motion from Newton's law

$$\begin{pmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \end{pmatrix} = \frac{1}{m} \cdot \begin{pmatrix} F_{x_1,\mathbf{x}} \\ F_{x_2,\mathbf{x}} \\ F_{x_3,\mathbf{x}} \end{pmatrix}$$

$$I_x \ddot{\xi}_1 + \dot{\xi}_2 \dot{\xi}_3 \cdot (I_z - I_y) = M_{1,\boldsymbol{\xi}},$$
$$I_y \ddot{\xi}_2 + \dot{\xi}_1 \dot{\xi}_3 \cdot (I_x - I_z) = M_{2,\boldsymbol{\xi}},$$
$$I_z \ddot{\xi}_3 + \dot{\xi}_1 \dot{\xi}_2 \cdot (I_y - I_x) = M_{3,\boldsymbol{\xi}}.$$

    - Rotational motion in principal, body-fixed coordinate system

$$\mathbf{I} = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} = \begin{bmatrix} mr_x^2 & 0 & 0 \\ 0 & mr_y^2 & 0 \\ 0 & 0 & mr_z^2 \end{bmatrix} \qquad \mathbf{M}_{\boldsymbol{\xi}} = \left(M_{1,\boldsymbol{\xi}}, M_{2,\boldsymbol{\xi}}, M_{3,\boldsymbol{\xi}}\right)^{\mathcal{T}} = \mathbf{J}_1^{-1} \cdot \mathbf{M}_{\mathbf{x}}$$

$$\mathbf{J}_1 = \begin{bmatrix} cx_6 cx_5 & -sx_6 cx_4 + cx_6 sx_5 sx_4 & sx_6 sx_4 + cx_6 cx_4 sx_5 \\ sx_6 cx_5 & cx_6 cx_4 + sx_4 sx_5 sx_6 & -cx_6 sx_4 + sx_5 sx_6 cx_4 \\ -sx_5 & cx_5 sx_4 & cx_5 cx_4 \end{bmatrix}$$

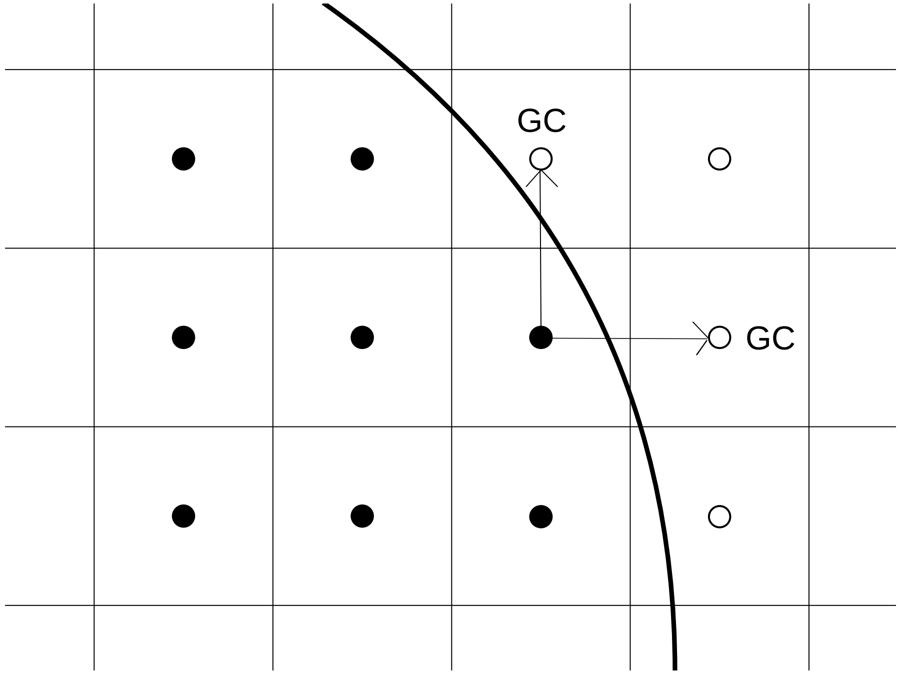
- System is solved explicitly using an AB-scheme

6DOF Algorithm: Coupling

- Weak coupling without sub-iterations
- Ghost cell immersed boundary method
  - Interface velocity from body dynamics
  - Interpolation of staggered velocity components
  - Pressure gradient from velocities

$$\boldsymbol{u} = \dot{\boldsymbol{x}} + \boldsymbol{r} \times \dot{\boldsymbol{\xi}}$$

$$\frac{\partial p}{\partial x_i} = -\frac{1}{\rho}\frac{du_i}{dt}$$

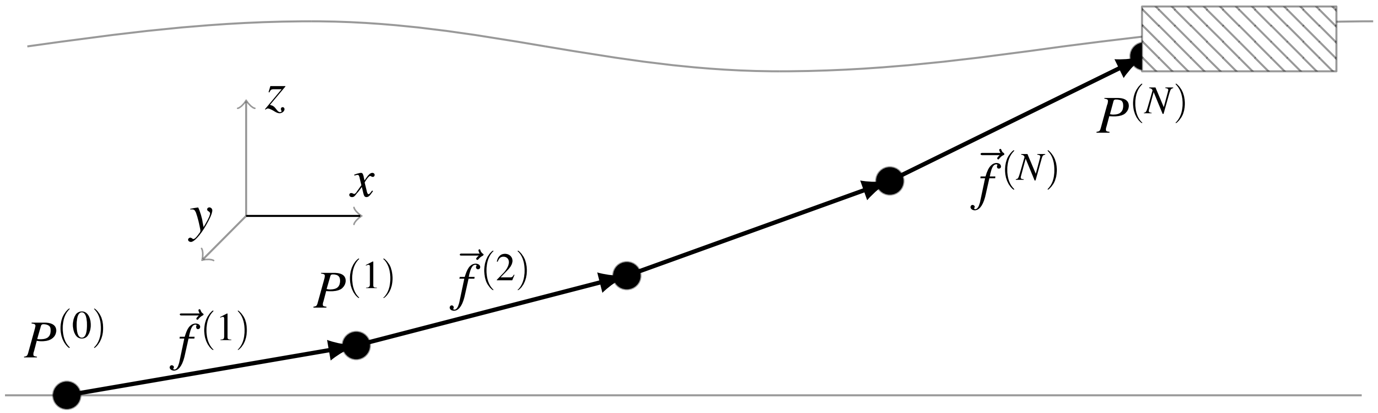


- Preventing pressure oscillations during solid/fluid change
  - Extrapolation of fluid values to solid region

Quasi-Static Mooring Model

- Analytical models lack flexibility for general application
- Simple numerical model in order to keep efficiency
    - Quasi-static motion
    - Explicit coupling as additional forces and moments

- Tension Element Method
    - Neglecting bending stiffness
    - Elastic material
    - Discretisation in mass points
    - Here: just gravity forces



Quasi-Static Mooring Model

- Static force equilibrium at each point

$$\vec{f}^{(\nu+1)} F_T^{(\nu+1)} - \vec{f}^{(\nu)} F_T^{(\nu)} = -\vec{F}_G^{(\nu)} \qquad \vec{F}_G^{(\nu)} = q\vec{g} \cdot \left(\frac{a^{(\nu)} + a^{(\nu+1)}}{2} \right), \quad \nu = 1, \ldots, N-1$$

- System of equations is solved for unit normal vectors of bars

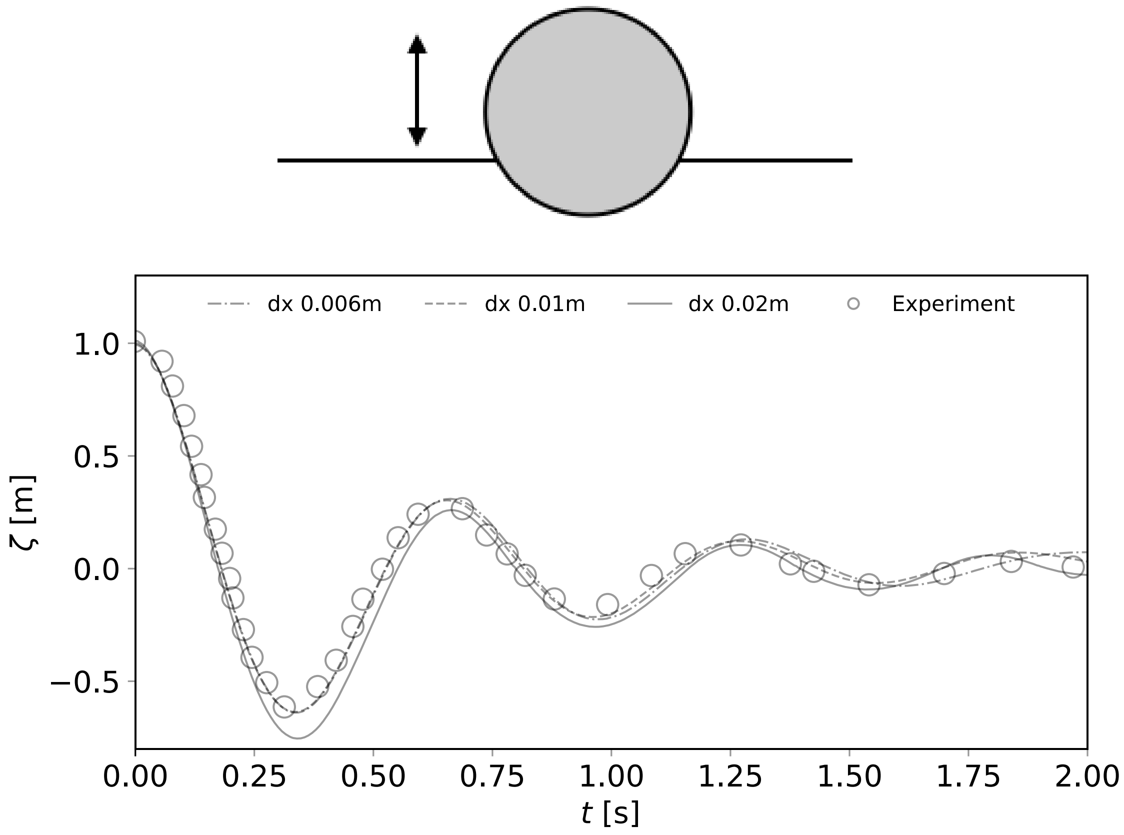
$$\mathbf{A} \cdot \mathbf{F} = \mathbf{B}, \qquad \mathbf{A} = \begin{pmatrix} \mathbf{T} \\ \mathbf{L} \end{pmatrix} \qquad \mathbf{B} = \begin{pmatrix} -\mathbf{G} \\ \vec{c} \end{pmatrix}$$

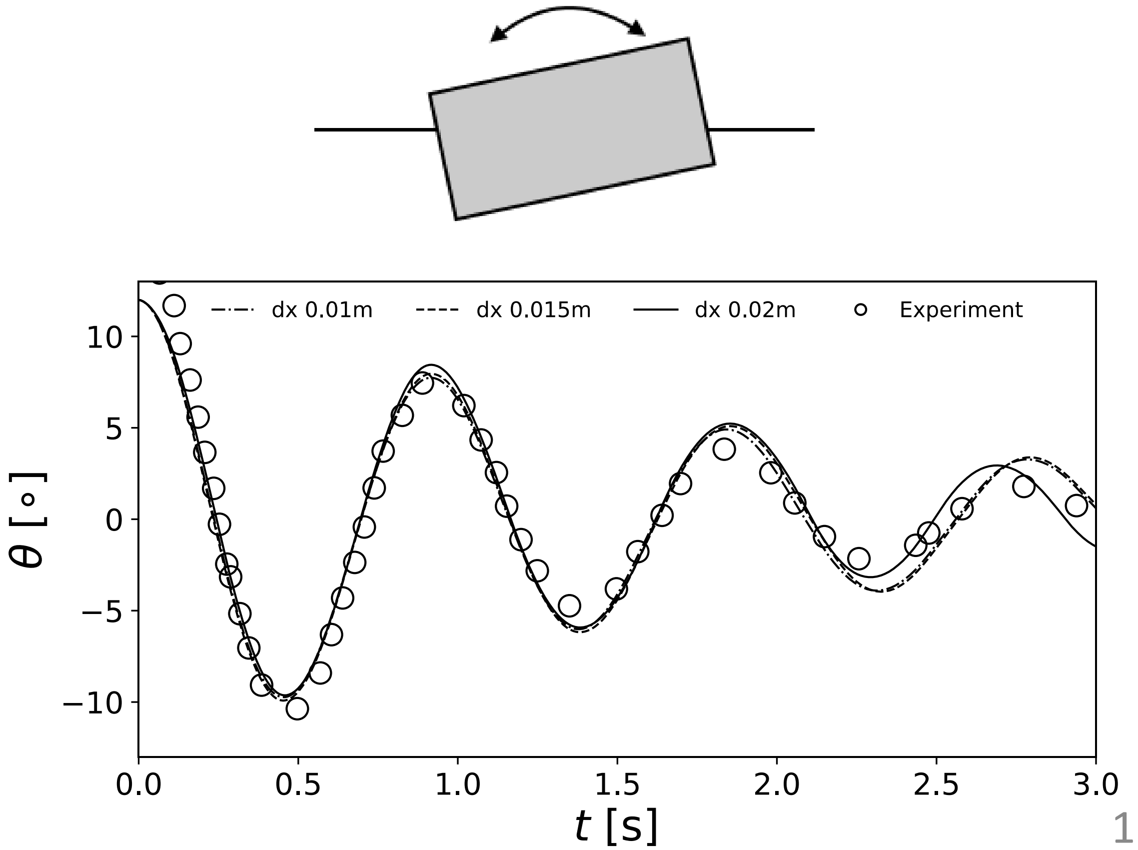
$$\sum_{\nu=1}^{N+1} \vec{f}^{(\nu)} a^{(\nu)} = \vec{c}$$

- Geometrical constraint to close system and control physics
    - Bar lengths a as function of stiffness
- System solved using successive approximation

2D Decay Tests

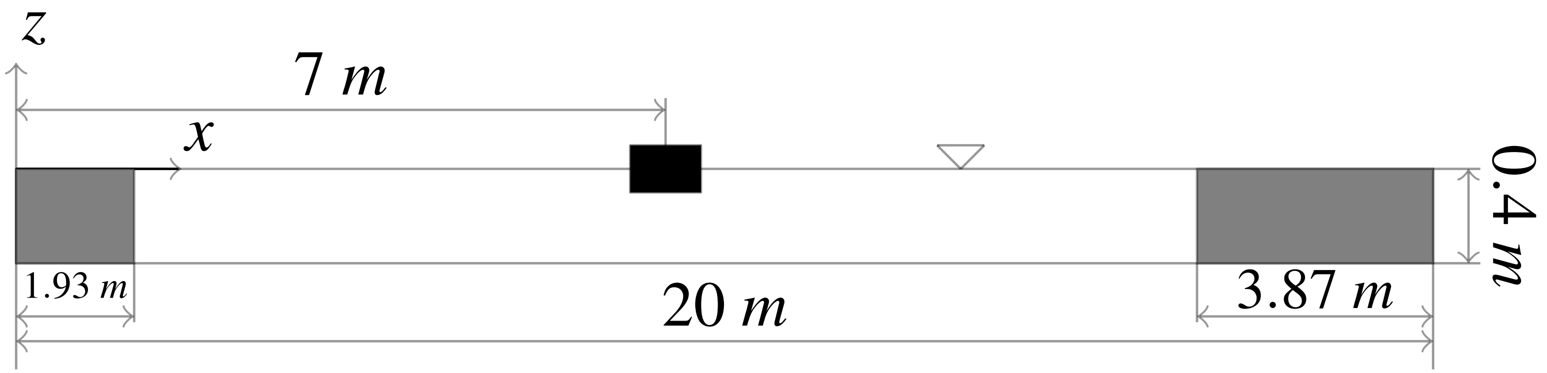
- Single motion calculations
- Good convergence to experimental data



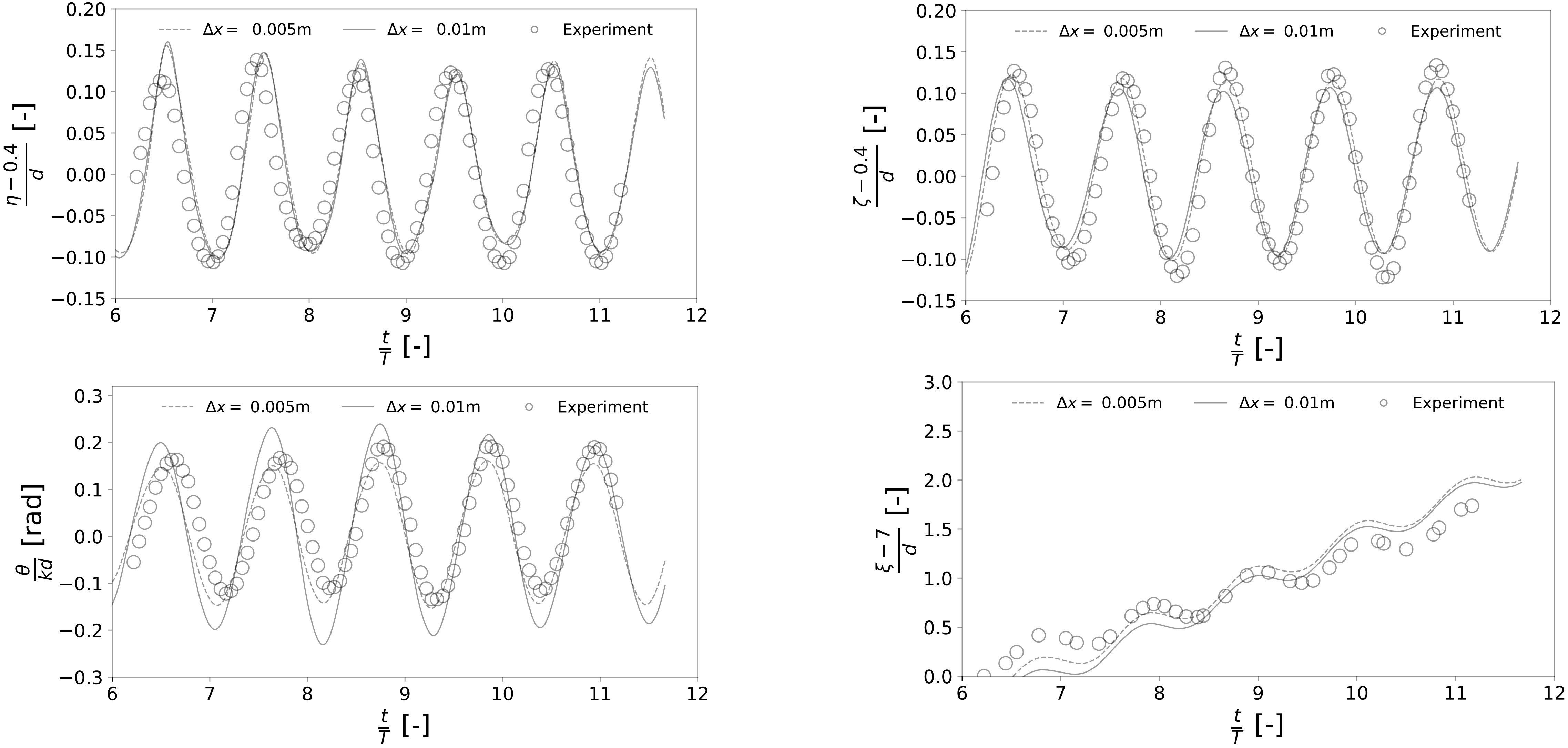


2D Breakwater Motion in Waves

- Experiments from Ren et al., 2015, Applied Ocean Research
- 2D barge:
  - ρ = 500 kg/m^3
  - h = 0.2 m
  - l = 0.3 m
- Incoming waves:
  - ƛ = 1.936 m
  - H = 0.04 m
  - T = 1.2 s



2D Breakwater Motion in Waves



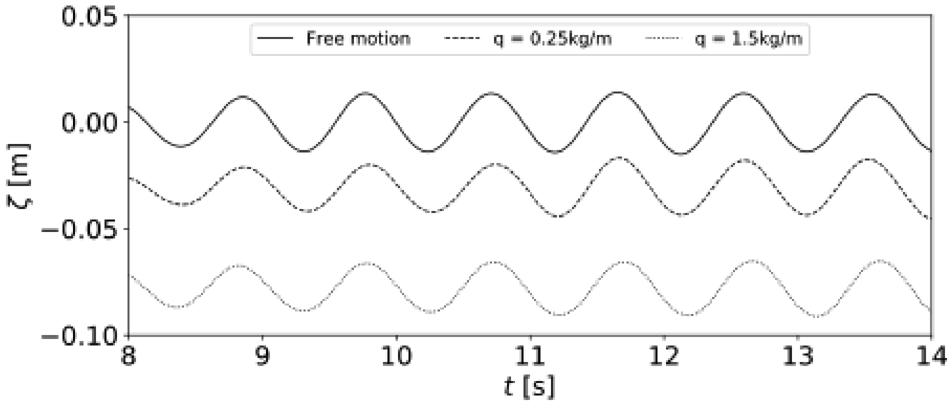
2D Moored Breakwater Motion in Waves

- Comparison of free-floating barge with moored-floating barge
  - Mooring system of two mooring lines
  - Two different line configurations with different specific weight

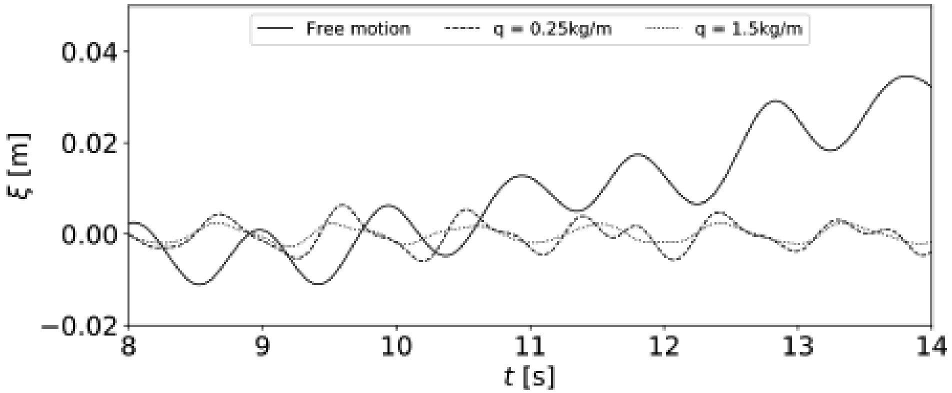
Colours shows u_x in the fluid and tension forces in the lines

2D Moored Breakwater Motion in Waves

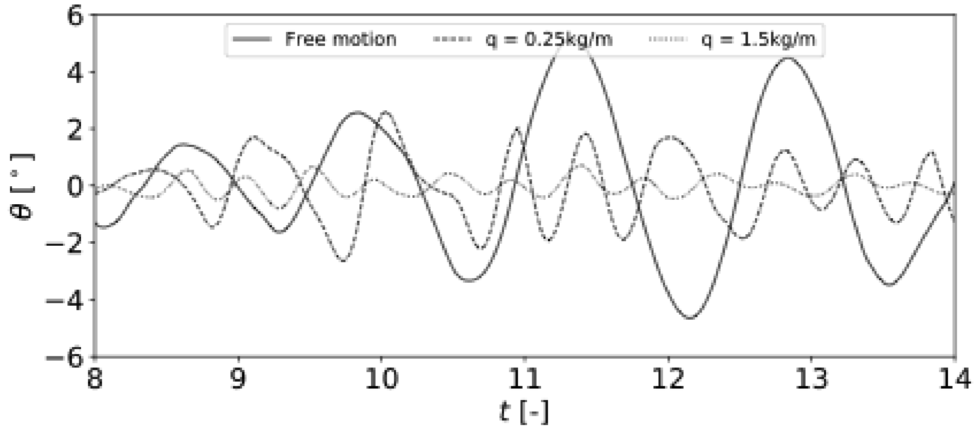
- Comparison of the three motions of freedom



(a) HEAVE MOTION.



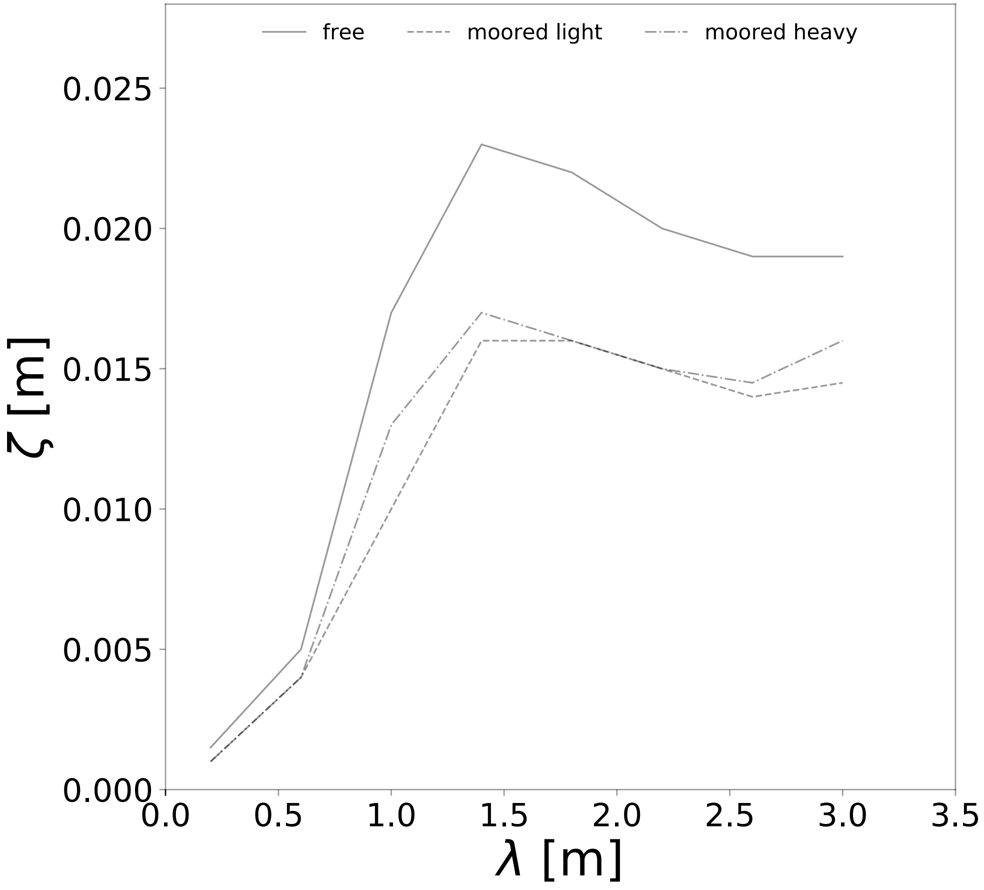
(b) SURGE MOTION.

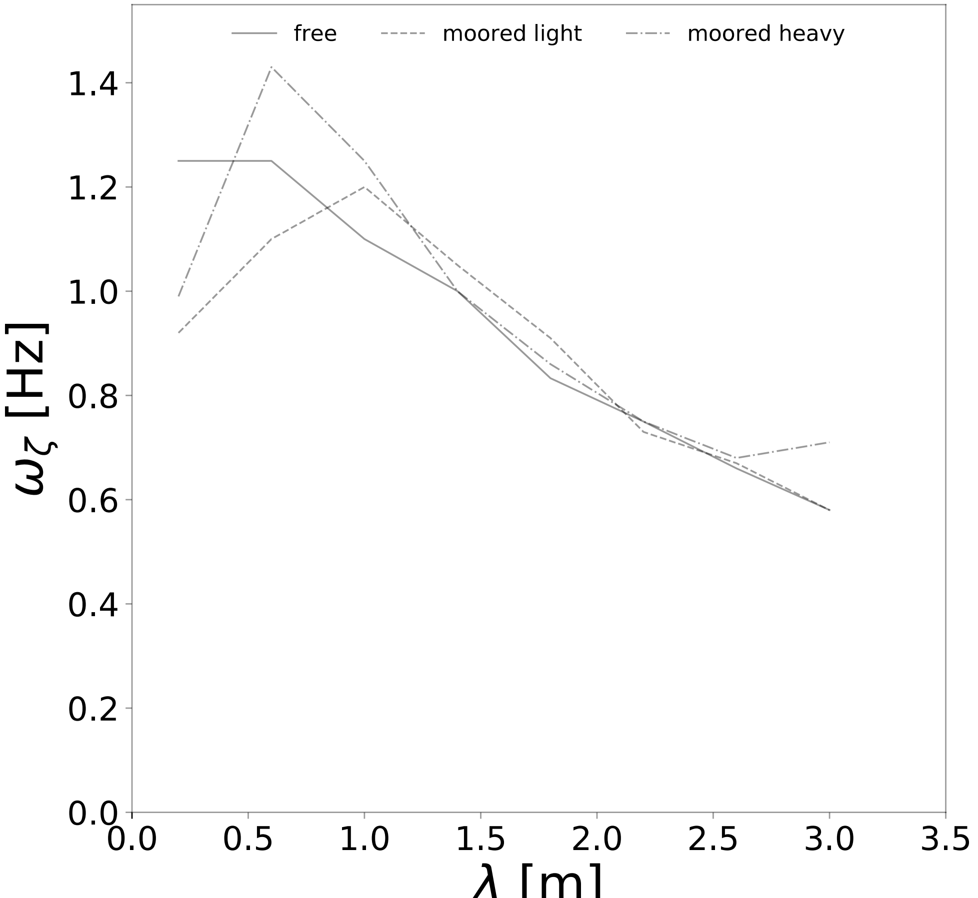


(c) PITCH MOTION.

2D Moored Breakwater Motion in Waves

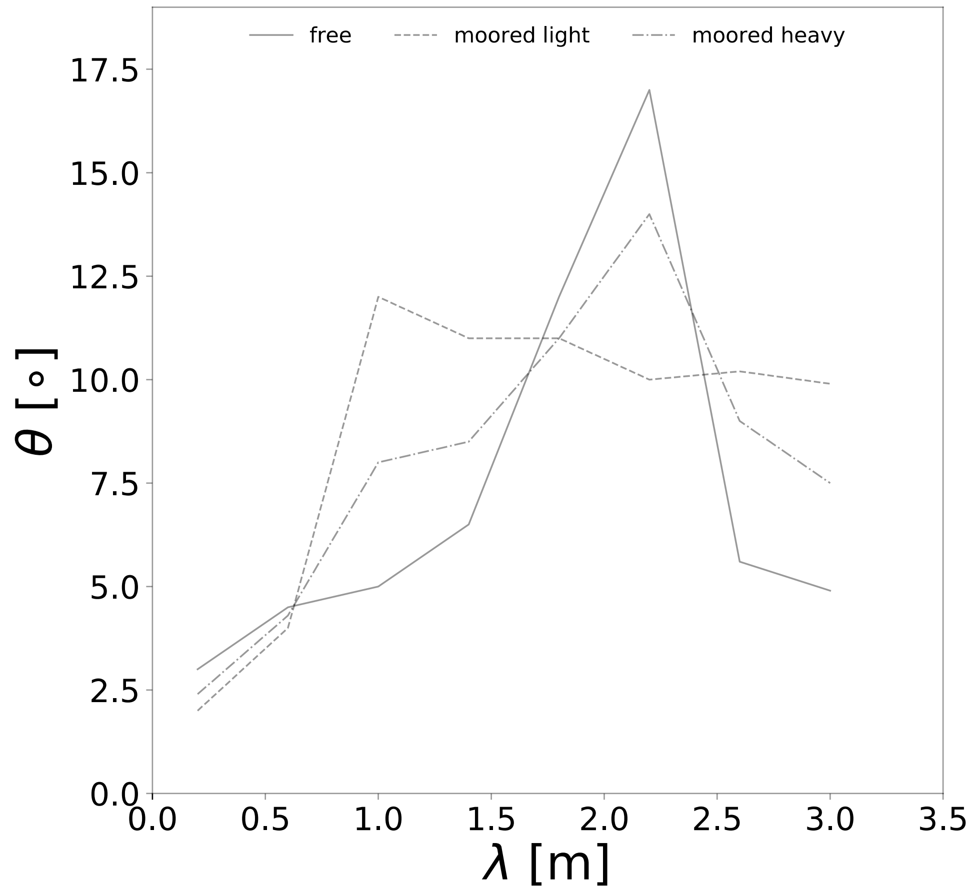
- Influence of different mooring systems on heave motion in waves of different wave lengths
  - Decreasing amplitude irrespective to weight
  - Changing frequency near eigenfrequency

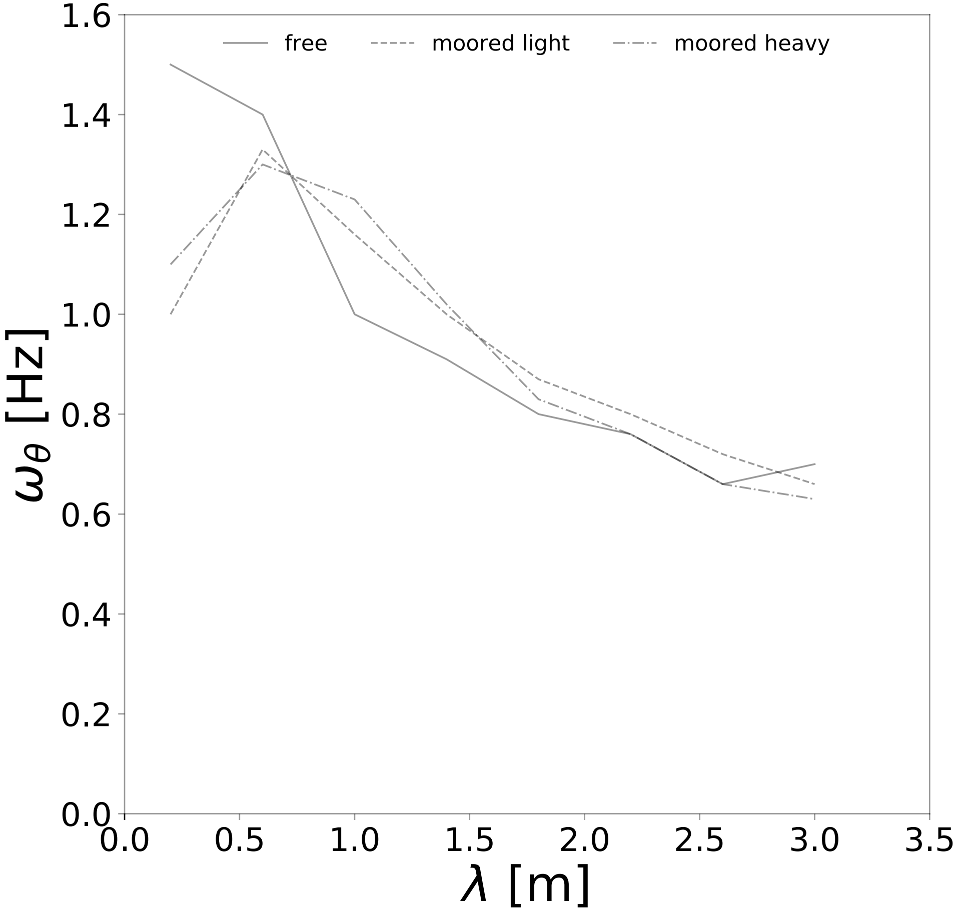




2D Moored Breakwater Motion in Waves

- Influence of different mooring systems on <u>pitch</u> motion in waves of different wave lengths
  - Changing amplitudes over wave length
  - Changing frequencies at small wave lengths





Conclusion

- 6DOF Algorithm
    - Based on ghost cell immersed boundary method
    - Weakly coupled algorithm shows good convergence

- Mooring model
    - Coupled to 6DOF algorithm through forces
    - Quasi-static algorithm for efficient calculations
    - Suitable for slack and tensed configurations

- Mooring systems influence all motions of the breakwater in both amplitude and frequency
    - Surge: Weight decreases the motion
    - Heave: Amplitude of motion mainly depends on the angle at the mooring point
    - Pitch: Weight can significantly influence the behaviour at different wave lengths