Ringing and impulsive excitation from steep and breaking waves
Results from the Wave Loads project

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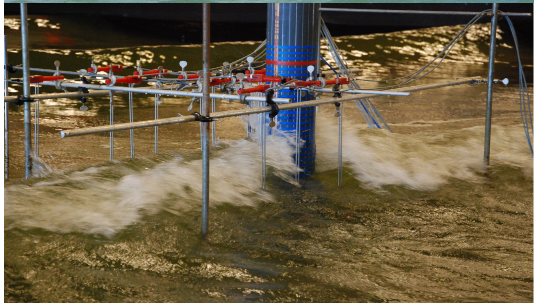
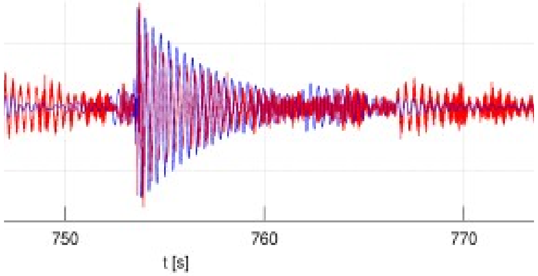
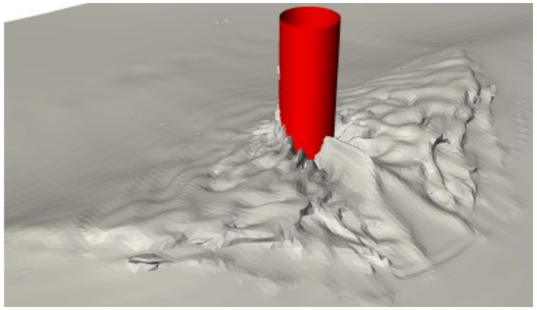
Ringing and impulsive excitation from steep and breaking waves

Results from the Wave Loads project







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Department of Mechanical Engineering

The Wave Loads project

ForskEL. DTU Wind Energy, DTU Mech. Engng., DHI. 2010-2013.

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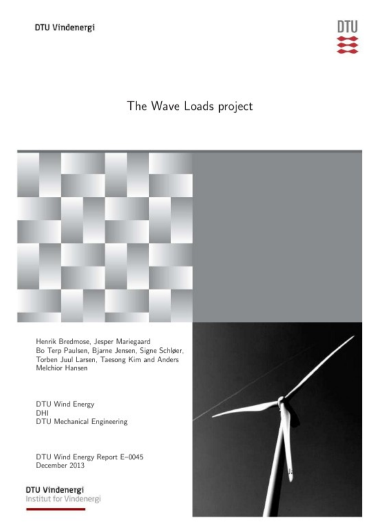

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The Wave Loads project

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December 2013

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Hydrodynamic loads

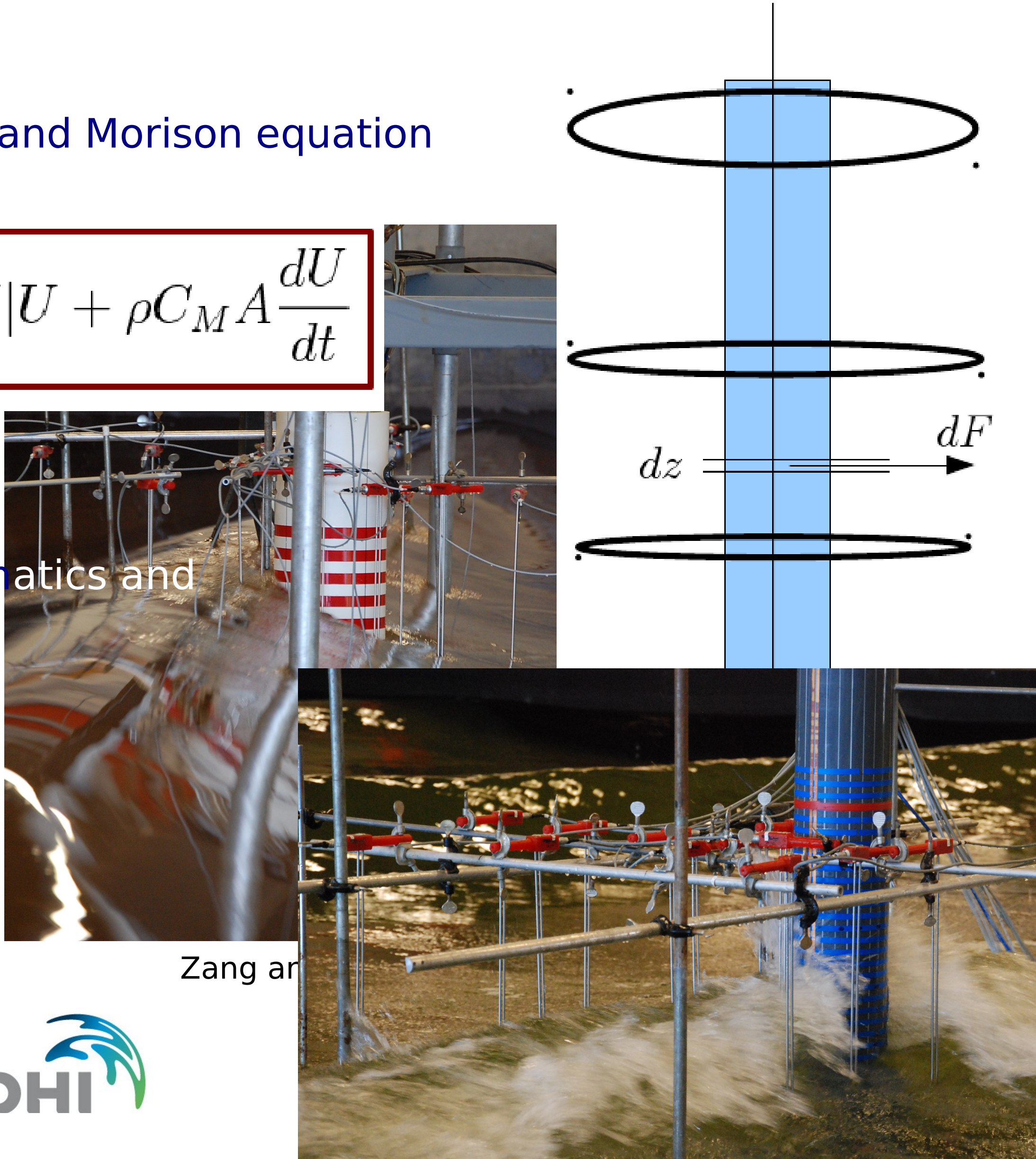
Simplest: Linear wave kinematics and Morison equation

$$\boxed{F = \frac{1}{2}\rho C_D D|U|U + \rho C_M A \frac{dU}{dt}}$$

Better: Fully nonlinear wave kinematics and

Morison-type force model

Advanced: CFD and coupled CFD



Zang ar

The Wave Loads project

ForskEL. DTU Wind Energy, DTU Mech. Engng., DHI. 2010-2013.

Task A:

Boundary conditions for phase resolving wave models

DHI

Task C:

Aero-elastic response to fully nonlinear wave forcing

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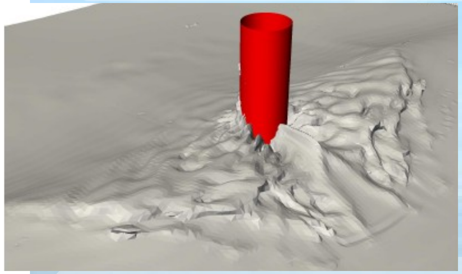

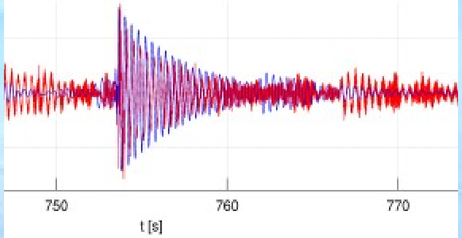

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Task B:

CFD methods for steep and breaking wave impacts

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Task D:

Physical model tests

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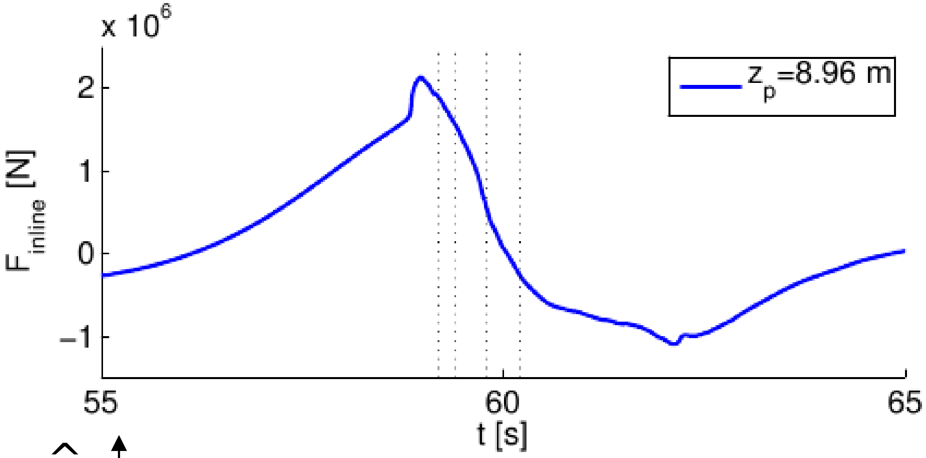
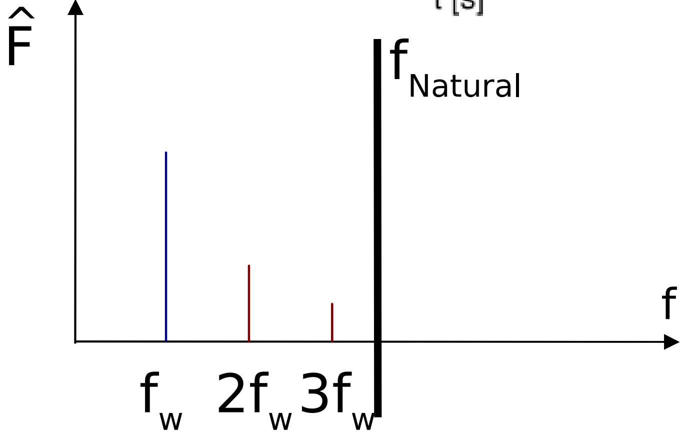
What is ringing?

Excitation of natural frequency by higher-harmonic forcing from nonlinear waves





Third-order inertia load theories:

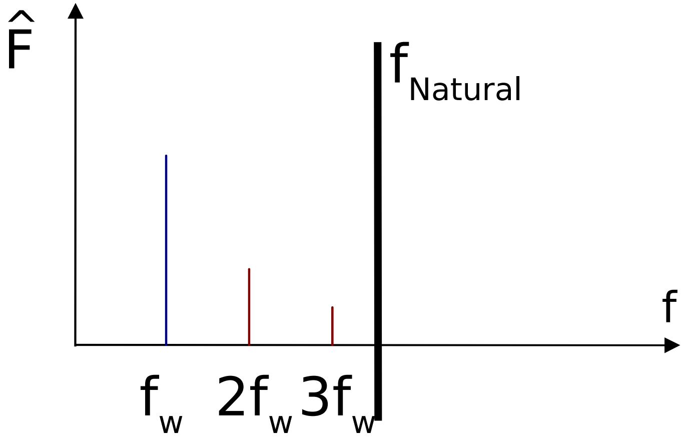
FNV (1995): regular waves deep water

Krokstad et al (1998): irregular waves

Malenica & Molin (1995): finite depth

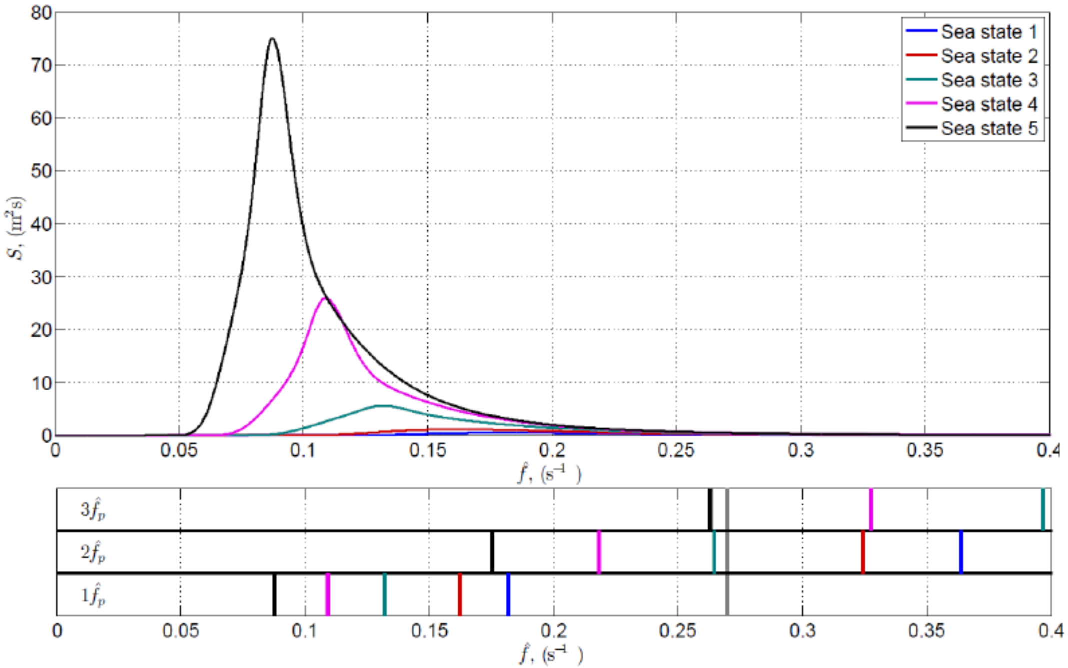
What is impulsive excitation?

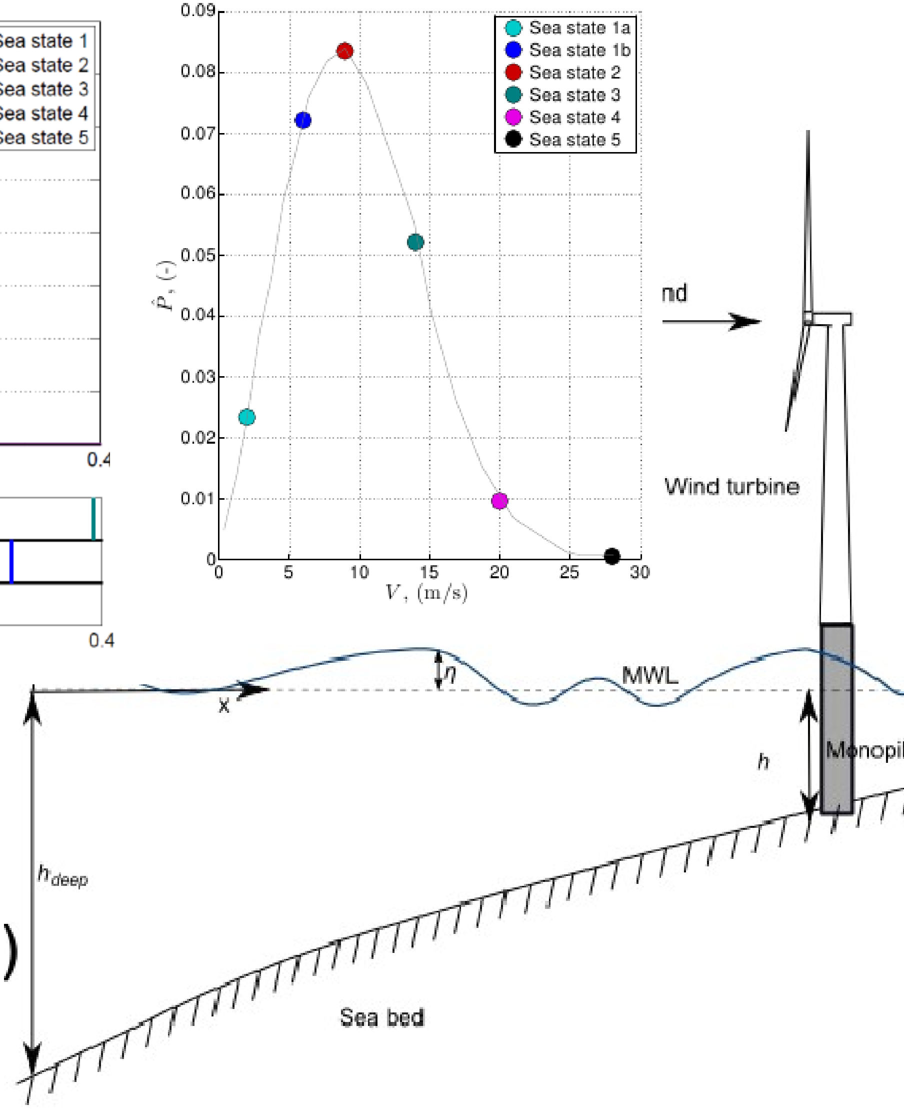
Sudden excitation of natural frequency by large and rapid force. Steep and breaking waves.



Study of nonlinear wave load effects

Response calculations with Flex5 aero-elastic model, NREL 5MW turbine





Signe Schløer (2013)

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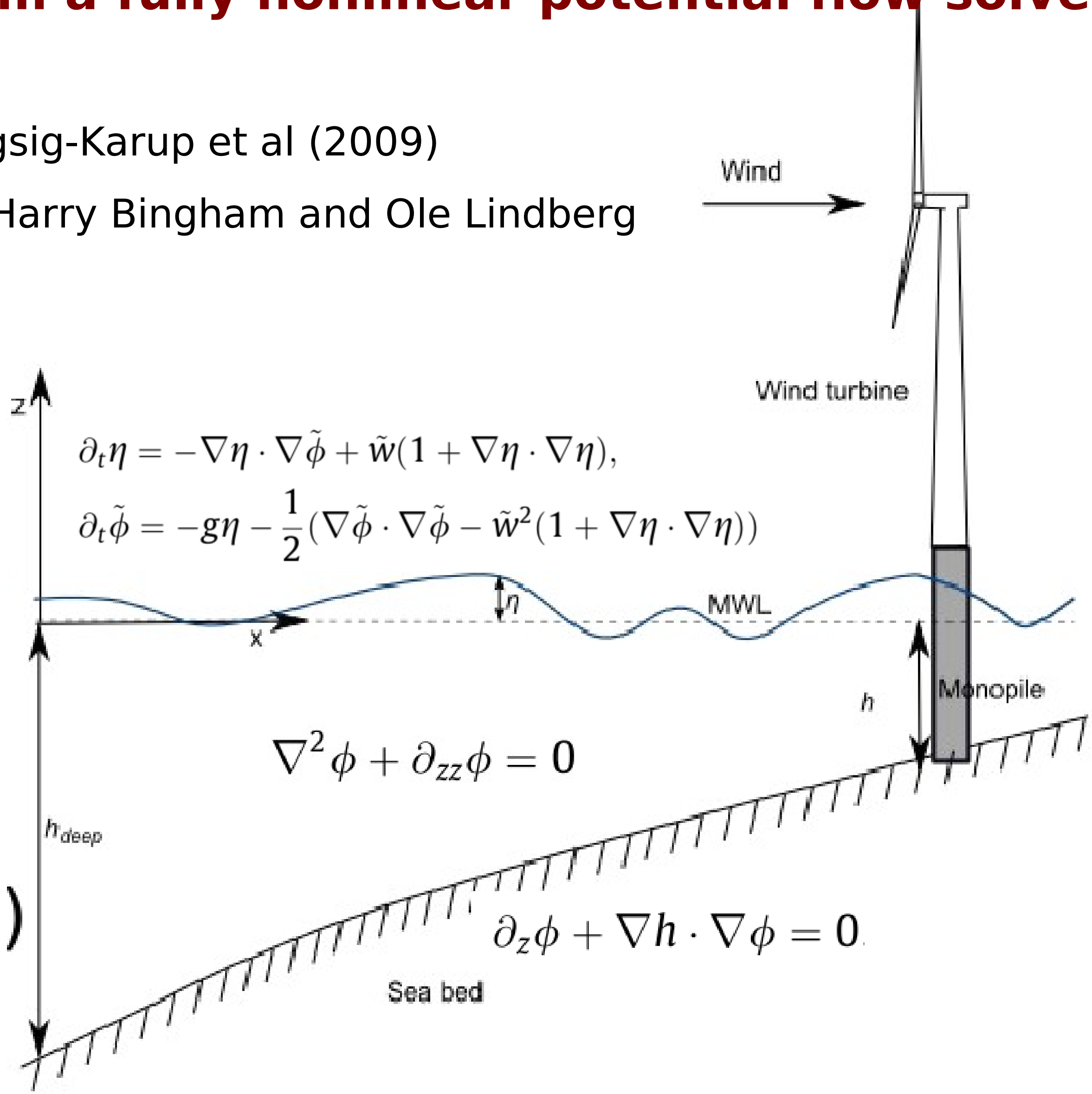
Kinematics from a fully nonlinear potential flow solver

‘OceanWave3D’, Engsig-Karup et al (2009)

Allan Engsig-Karup, Harry Bingham and Ole Lindberg



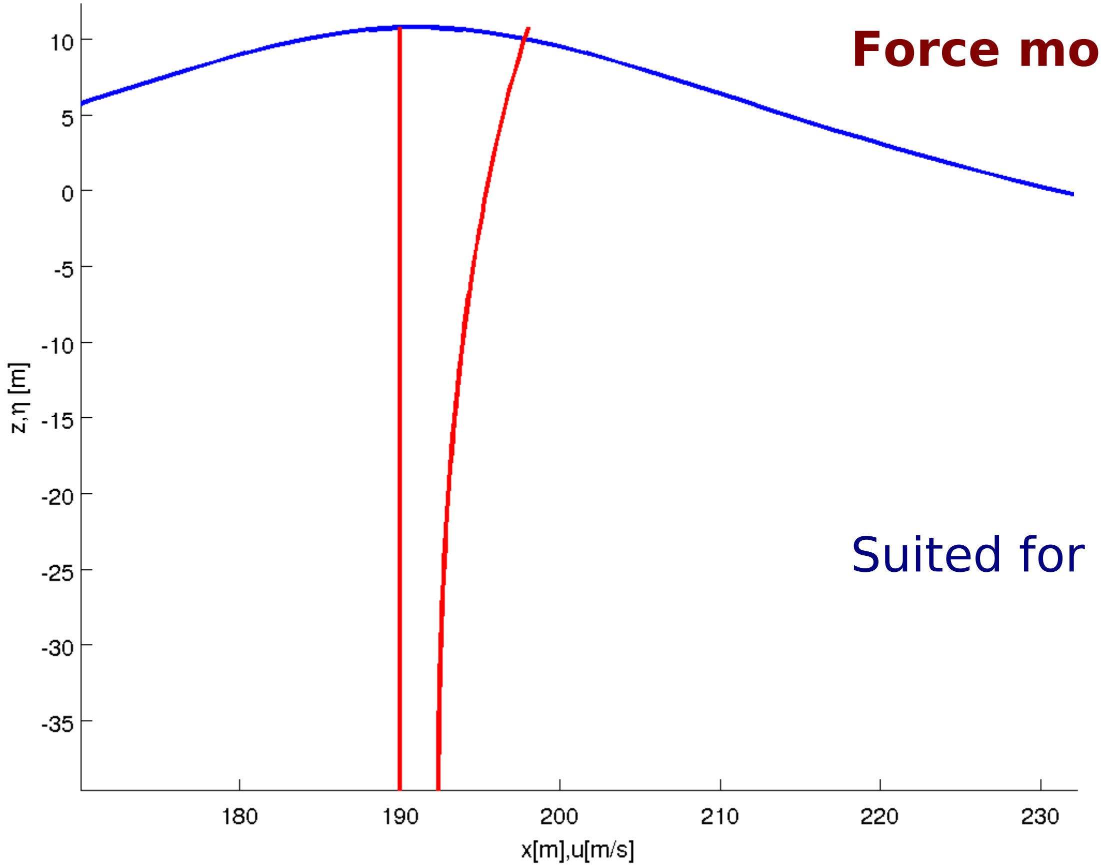
$$\partial_t \eta = -\nabla \eta \cdot \nabla \tilde{\phi} + \tilde{w}(1 + \nabla \eta \cdot \nabla \eta),$$

$$\partial_t \tilde{\phi} = -g\eta - \frac{1}{2}(\nabla \tilde{\phi} \cdot \nabla \tilde{\phi} - \tilde{w}^2(1 + \nabla \eta \cdot \nabla \eta))$$

$$\nabla^2 \phi + \partial_{zz} \phi = 0$$

$$\partial_z \phi + \nabla h \cdot \nabla \phi = 0$$

From kinematics to distributed force



Force model (Rainey 1989, 1995)

$$F_{\text{surface}} = -\tfrac{1}{2}\rho_{\mathrm{w}}\mathscr{A}\,c_m\eta_x(u-\dot{X})^2$$

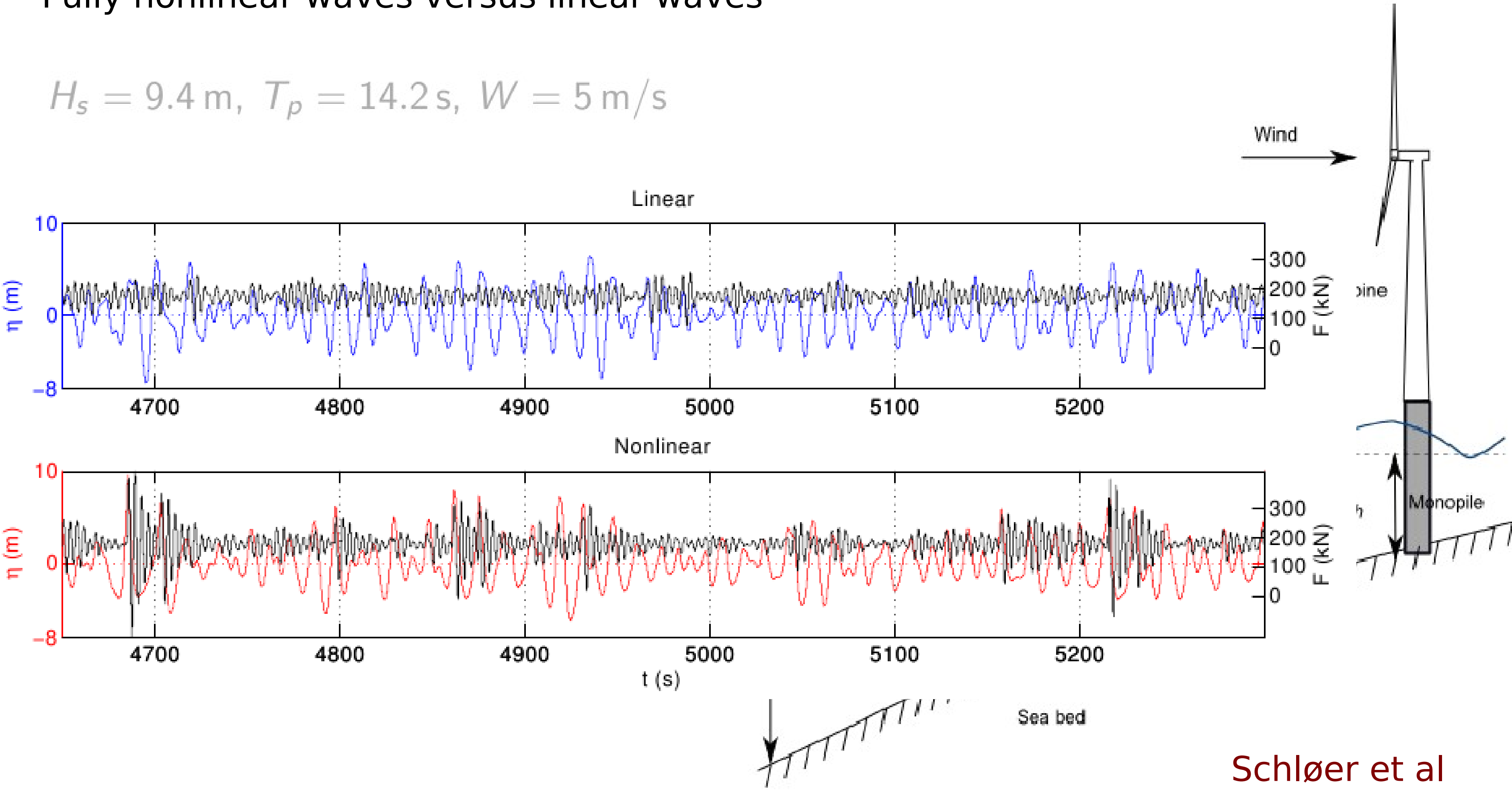
$$\begin{aligned}f(t,z) = {} & \rho_{\mathrm{w}}\mathscr{A}\,c_m(\dot{u}-\ddot{X})+\\ & +\rho_{\mathrm{w}}A\dot{u}+\rho_{\mathrm{w}}\mathscr{A}\,c_m w_z(u-\dot{X})\\ & +\tfrac{1}{2}\rho_{\mathrm{w}}c_D D(u-\dot{X})|u-\dot{X}|\end{aligned}$$

Suited for fully nonlinear kinematics

Response in bottom of tower

Fully nonlinear waves versus linear waves

$H_s = 9.4\,\mathrm{m},\ T_p = 14.2\,\mathrm{s},\ W = 5\,\mathrm{m/s}$



Schløer et al (OMAE 2012)

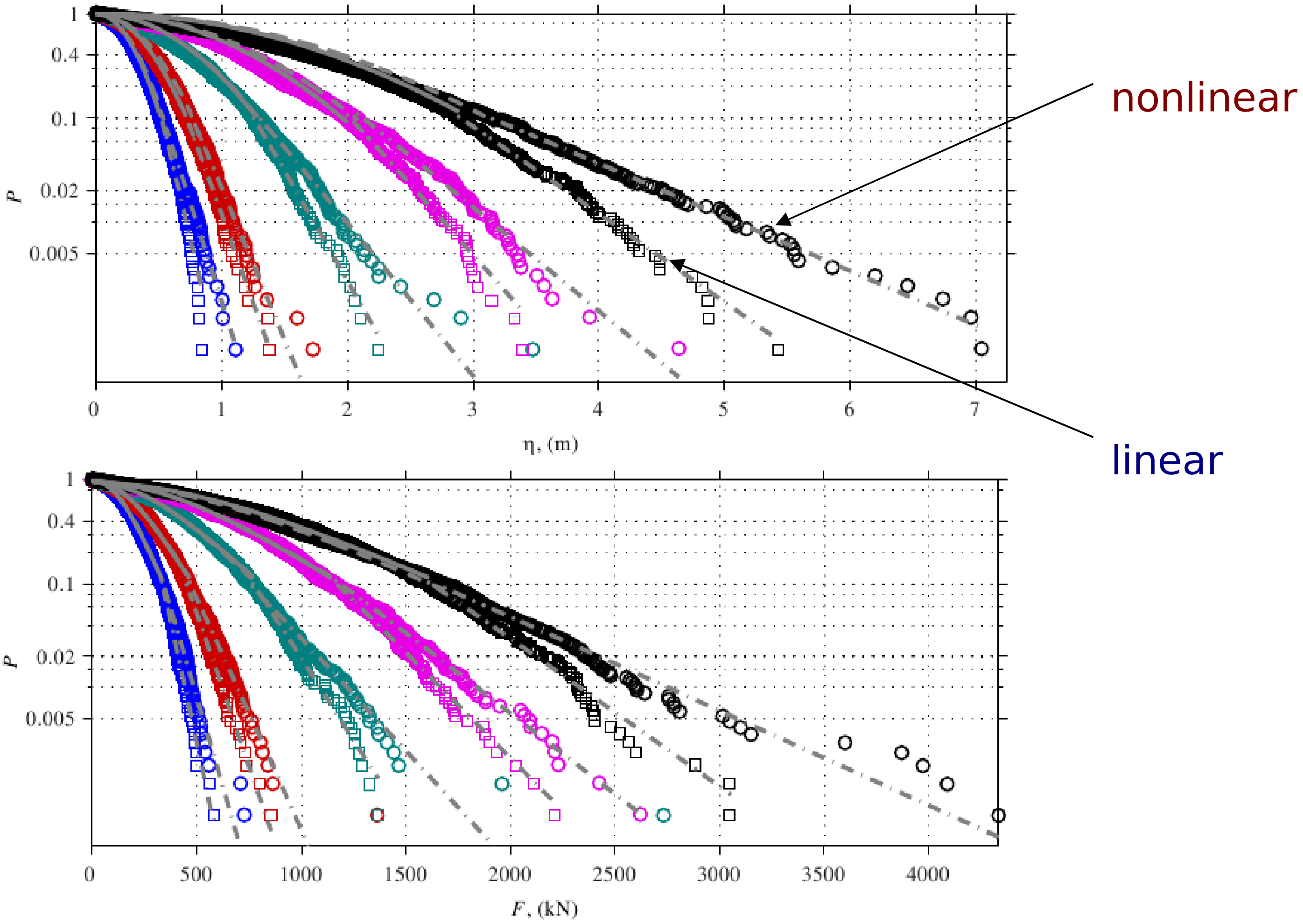
Static load analysis, h=30m

crest elevations

force peaks

depth integrated

force



Results of aero-elastic computations

Tower response – largest sea state

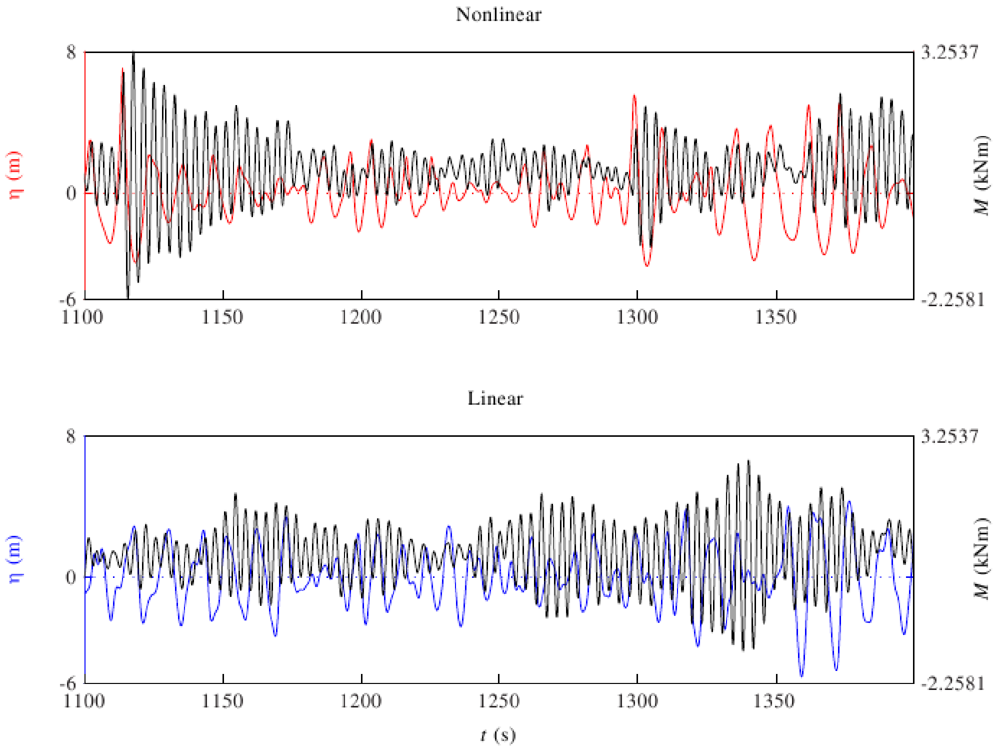


Figure 44: Nonlinear and linear surface elevation for the largest sea state and the corresponding moment in the bottom of the tower, $H_s = 6.76\,\mathrm{m}$, $T_p = 11.41\,\mathrm{s}$, $V = 28\,\mathrm{m/s}$ and $I_t = 0.13$

Linear waves can also excite the tower

Results of aero-elastic computations

Monopile response – largest sea state

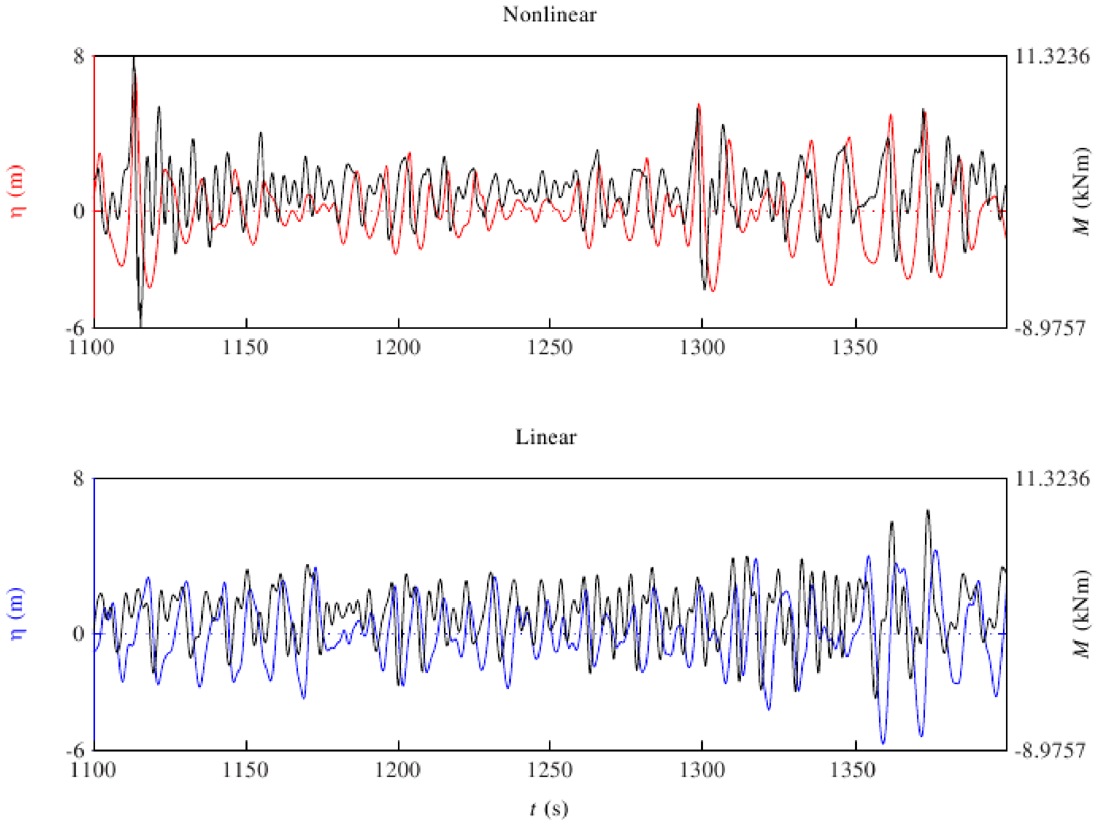


Figure 45: Nonlinear and linear surface elevation for the largest sea state and the corresponding moment in the bottom of the monopile, $H_s = 6.76\,\text{m}$, $T_p = 11.41\,\text{s}$, $V = 28\,\text{m/s}$ and $I_t = 0.13$

Vibrations less visible – occur on top of the wave loads

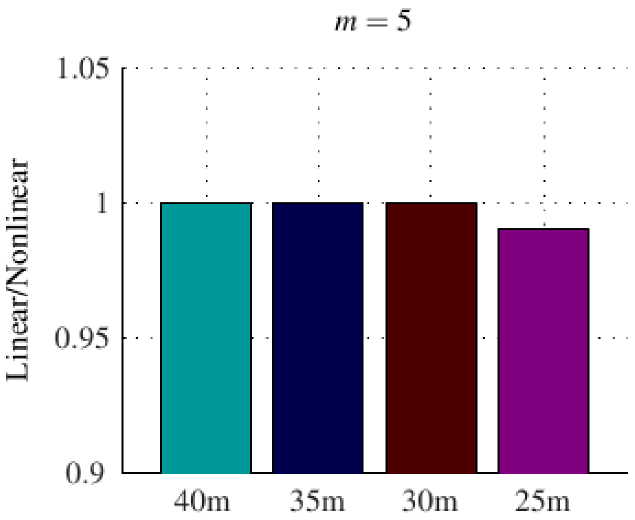
Quantify fatigue effect

Equivalent load

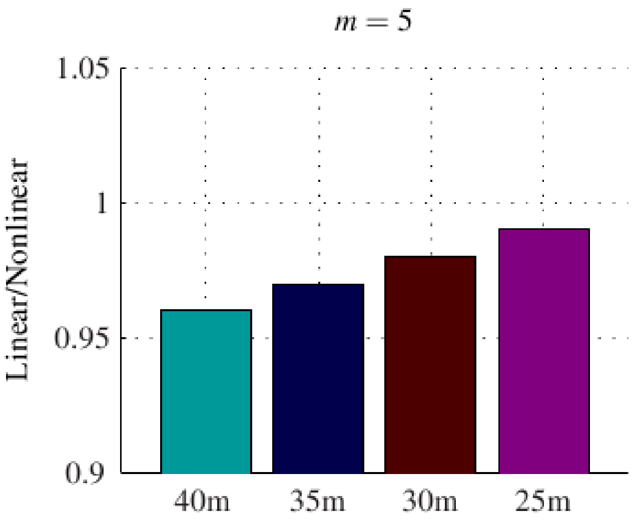
$$L_{eq} = \left(\sum_i \frac{N_{s,i}(S_i)^m}{N_{eq}}\right)^{\frac{1}{m}}$$

Accumulated equivalent load

$$L_{eq,acc} = \left(\sum_j L_{eq,j}^m \frac{T_j}{T}\right)^{\frac{1}{m}}$$



(a) Tower.



(b) Monopile.

Tower effect occur at 25m – wave nonlinearity is stronger for smaller depth

Monopile effect is largest at 40m, where it gives 4% larger equivalent loads.

Quantify fatigue effect

Equivalent load

$$L_{eq} = \left(\sum \frac{N_{s,i}(S_i)^m}{N}\right)^{\frac{1}{m}}$$

Accumulated equivalent load

$$L_{eq,acc} = \left(\sum_i L^m_{eq,j} \frac{T_j}{T}\right)^{\frac{1}{m}}$$

Conclusion of present study:

Wave nonlinearity not critical for *equivalent fatigue loads*.

But 4% in equivalent load corresponds to 18% in *fatigue damage*

More investigations with more sea states included needed

Inclusion of diffraction needed

Nonlinearity seems more important for ULS than for FLS

Hence ULS study is needed

Tower effect occur at 25m – wave nonlinearity is stronger for smaller depth

Monopile effect is largest at 40m, where it gives 4% larger equivalent loads.

The Wave Loads project

ForskEL. DTU Wind Energy, DTU Mech. Engng., DHI. 2010-2013.

Task A:

Boundary conditions for phase resolving wave models

DHI

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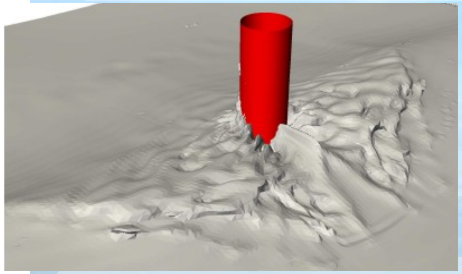

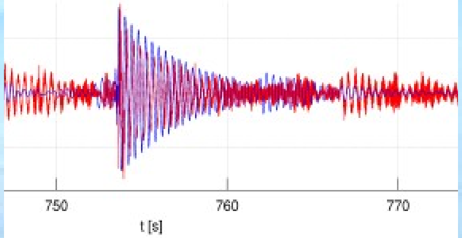

Task B:

CFD methods for steep and breaking wave impacts

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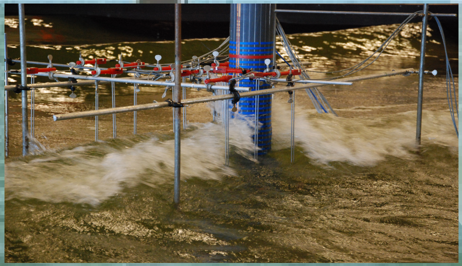

Task D:

Physical model tests

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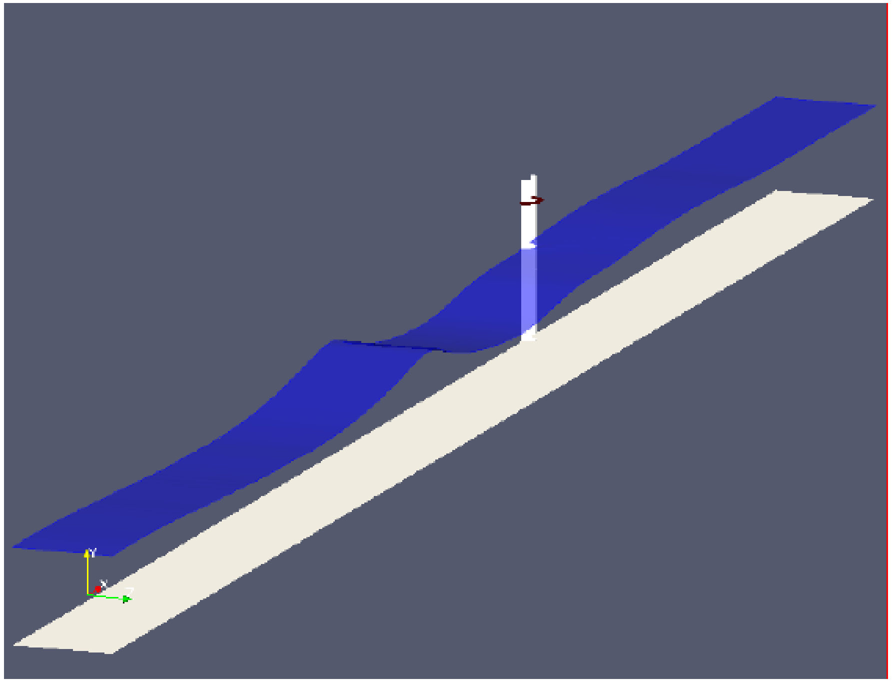
The OpenFOAM® CFD solver

Open source CFD toolbox

Vast attention during last 3 years



This study: interFoam solver

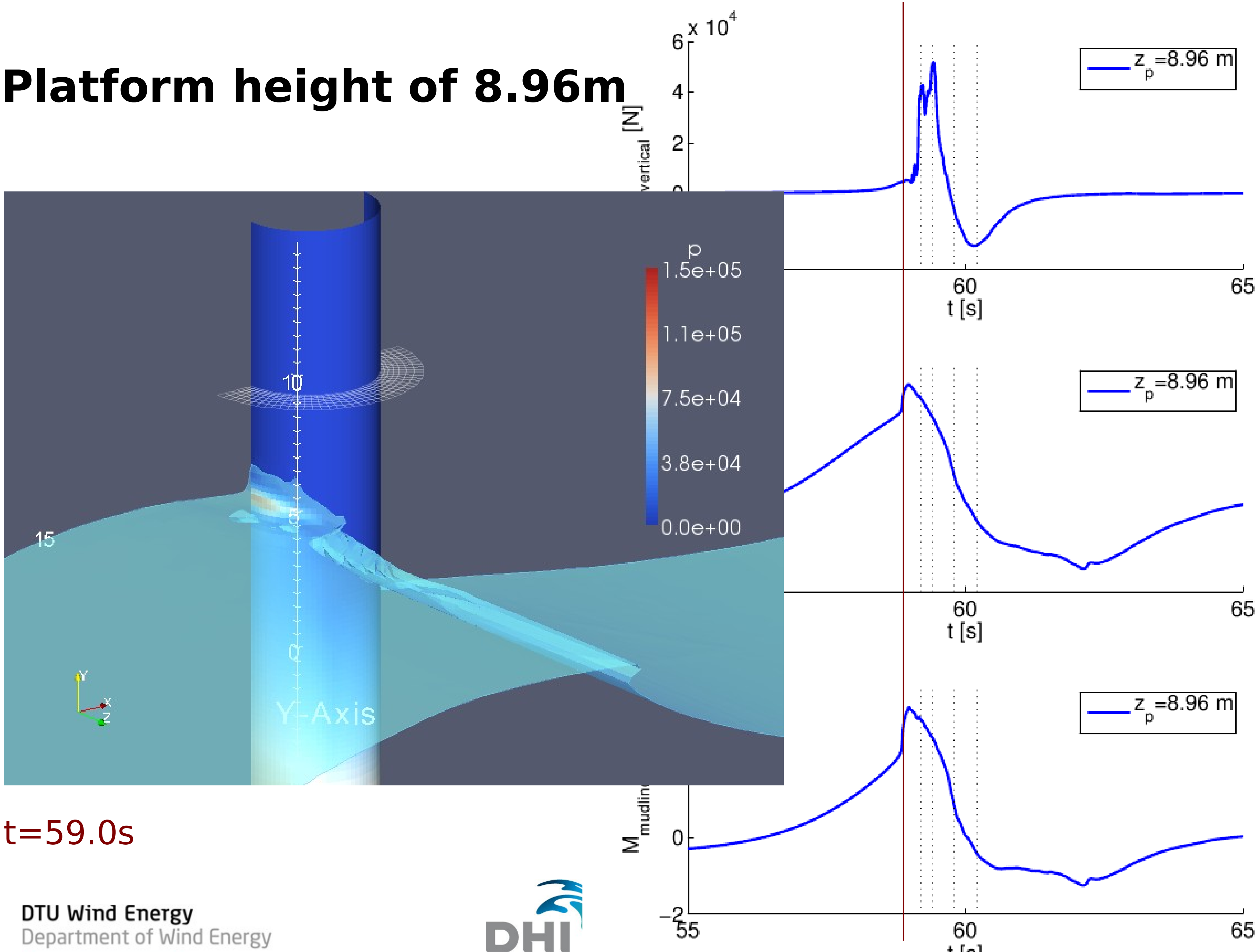
- 3D incompressible Navier-Stokes
- two phases (water and air)
- VOF treatment of free surface

Waves2foam wave generation toolbox has been developed and validated

(Niels Gjøl Jacobsen

PhD thesis 2011; Paper in Int. J. Num. Meth. Fluids)

Platform height of 8.96m



t=59.0s

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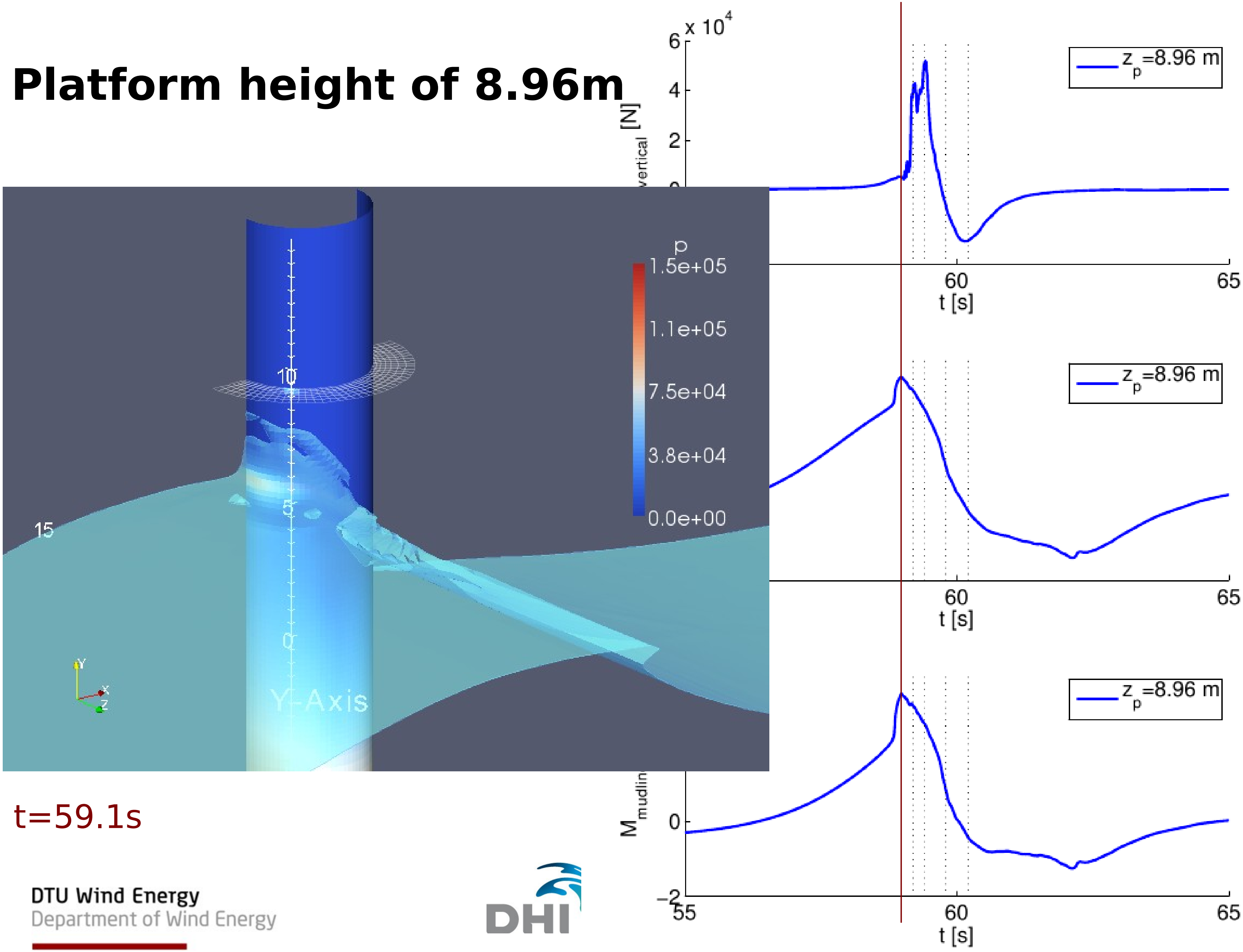
Platform height of 8.96m



t=59.1s

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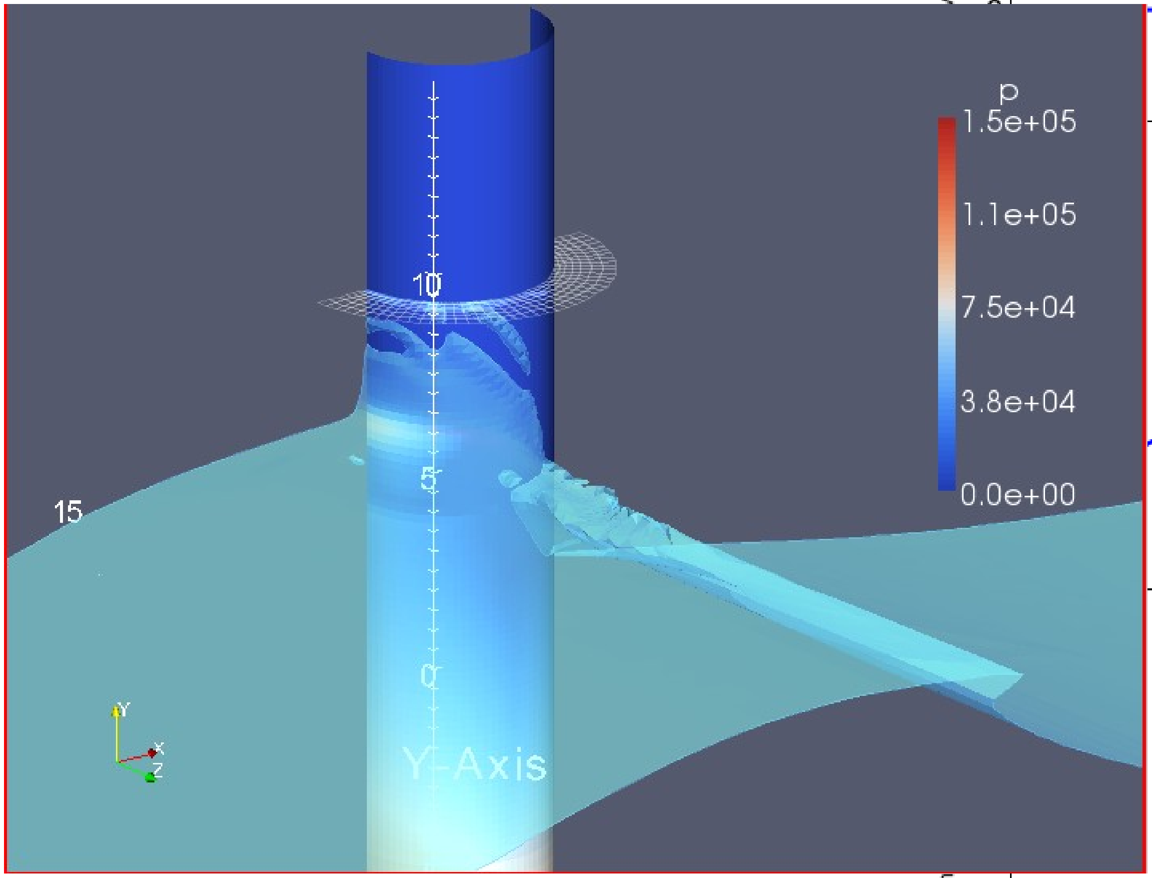
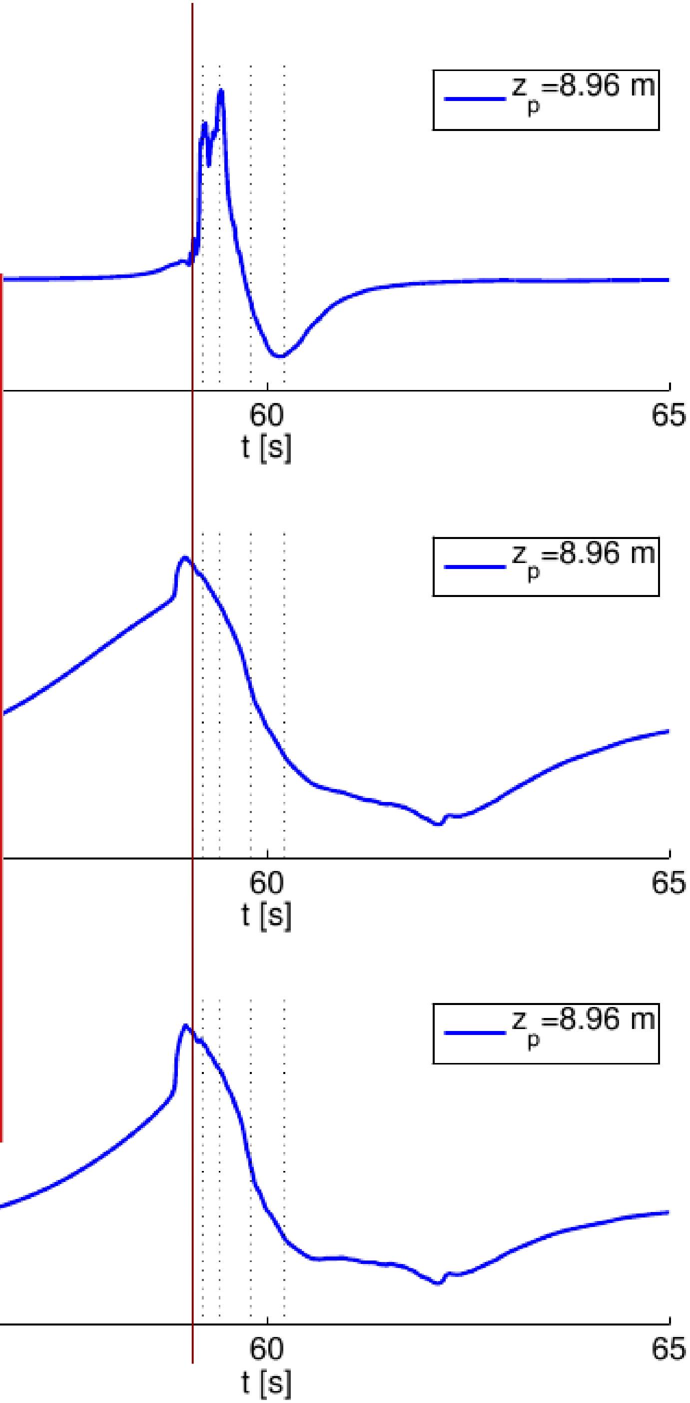
Platform height of 8.96m





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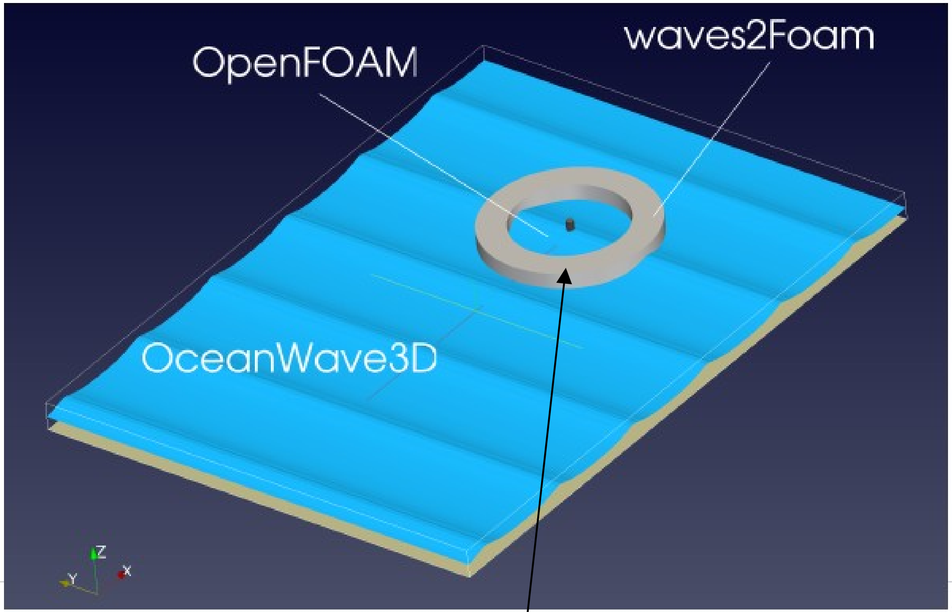
Development of a coupled solver

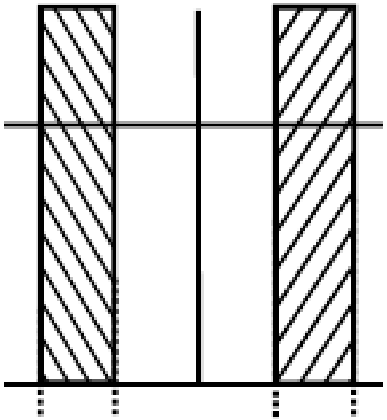


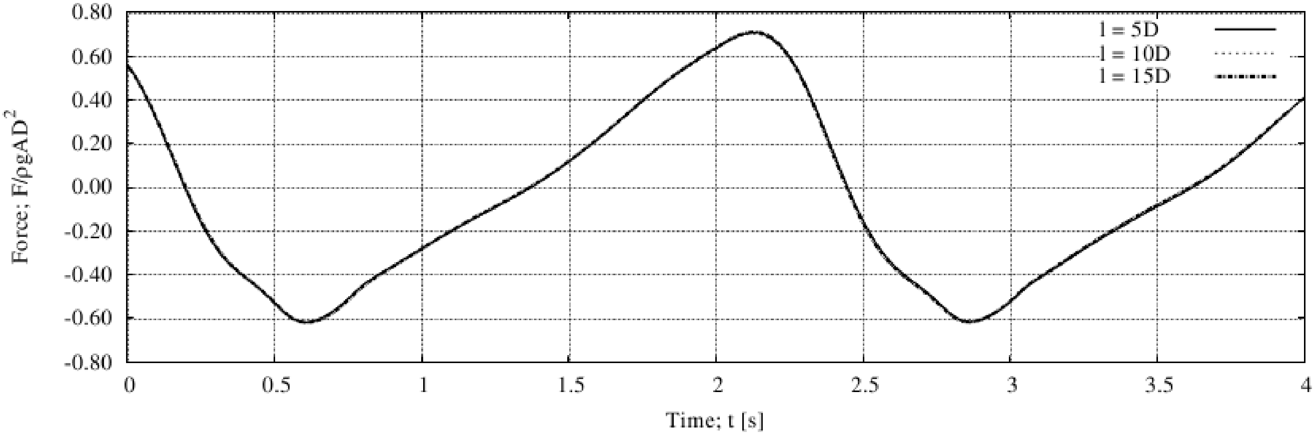
Compute outer flow field with potential flow wave model: OceanWave3D (Engsig-Karup et al 2009)

Compute inner field with wave-structure interaction with CFD-VOF model

Coupling zone

Slender body enables one-way coupling (transfer)





Incident waves enforced in relaxation zone

Diffracted waves damped in relaxation zone $\psi = \chi\psi_{\text{target}} + (1-\chi)\,\psi_{\text{com}}, \quad \psi \in \{\mathbf{u}_H, w, \alpha\}\,,$

D: cylinder diameter

l: distance to relaxation zone

kA=0.2; kR=0.1; kh=1

Distance can be as small as L/6

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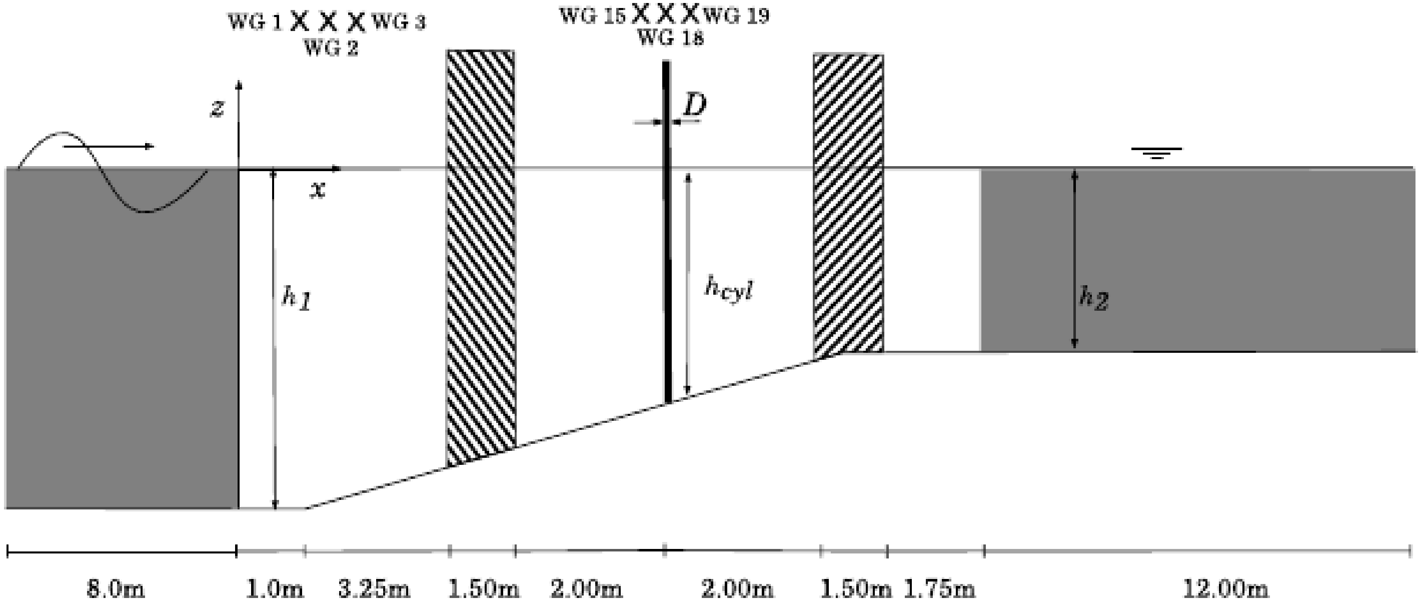
Validation for irregular wave forcing on a slope

Experiment in the Wave Loads project. Hs=8.3m (full scale). Scale 1:36



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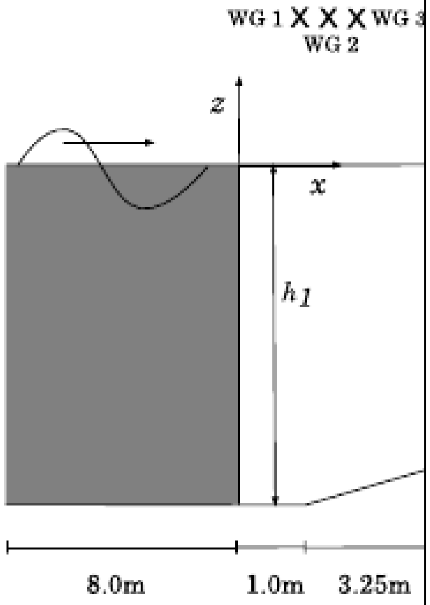
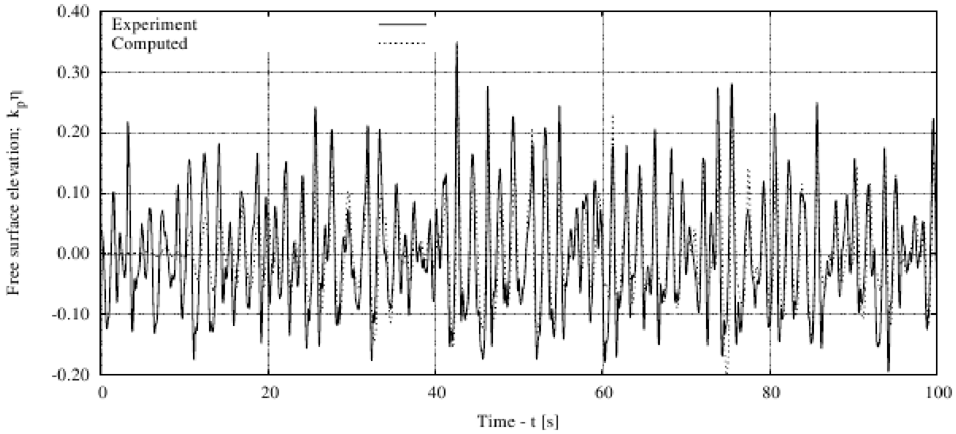
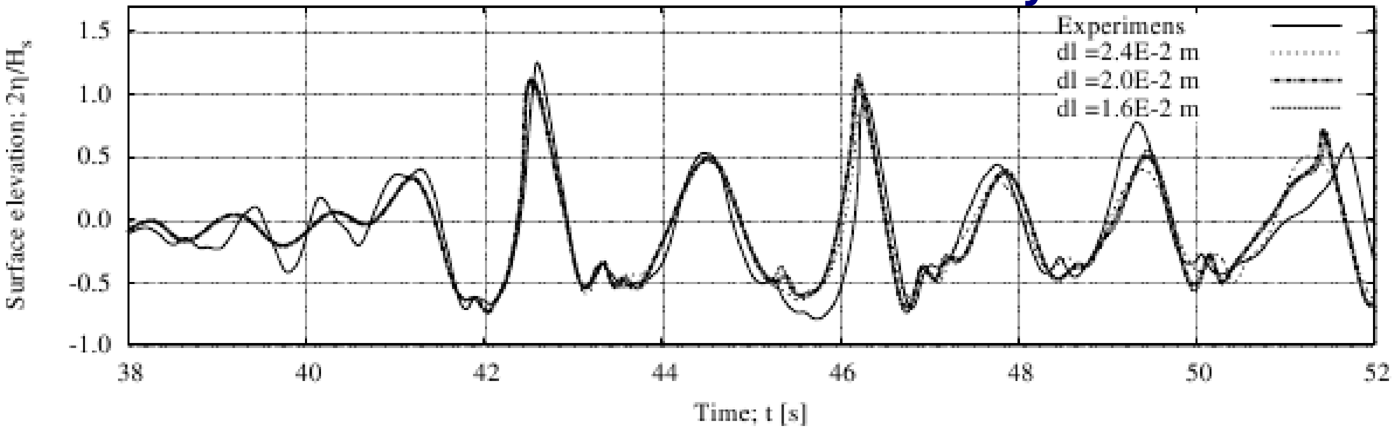


Reconstruct incident wave field by linear analysis of wave gauge measurements.
Total computed time series is 100s long.

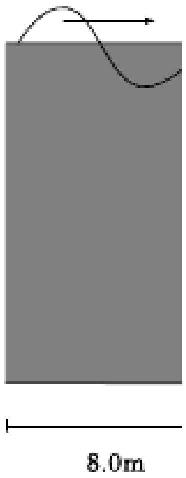


Validation for irregular wave forcing on a slope

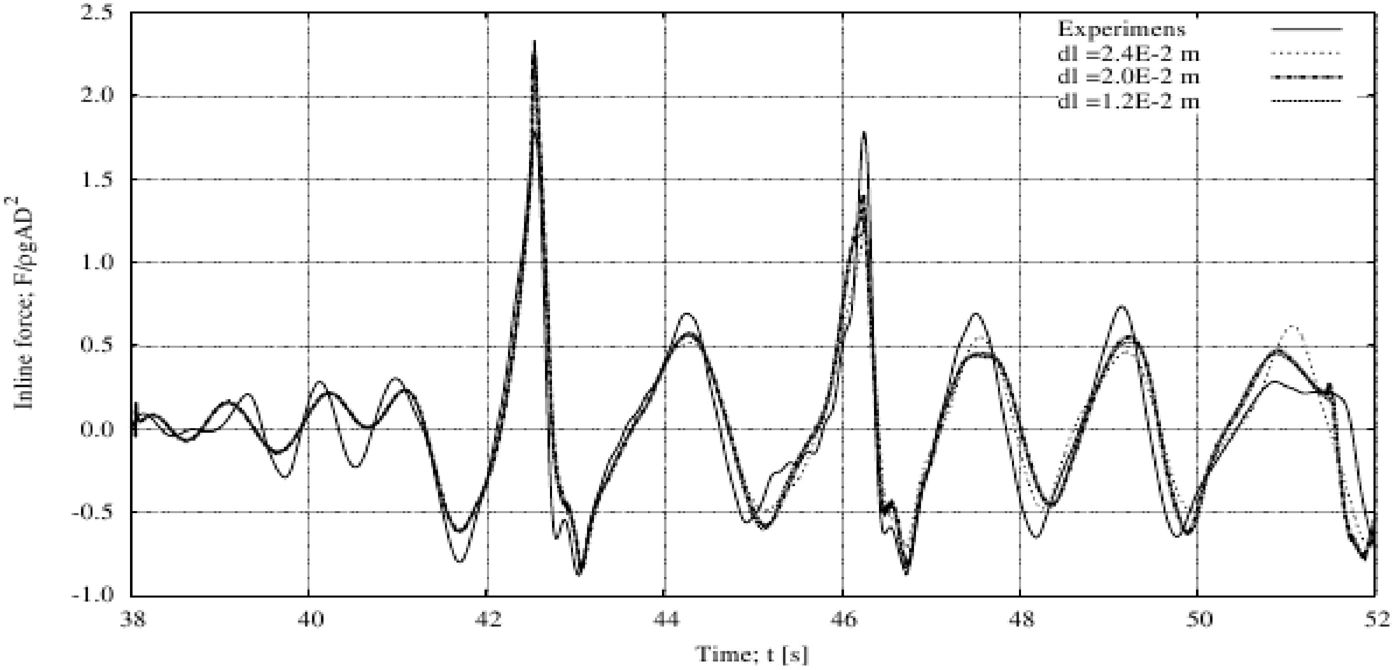
Free surface elevation 0.25 cm in front of cylinder



Experimen



Inline force history



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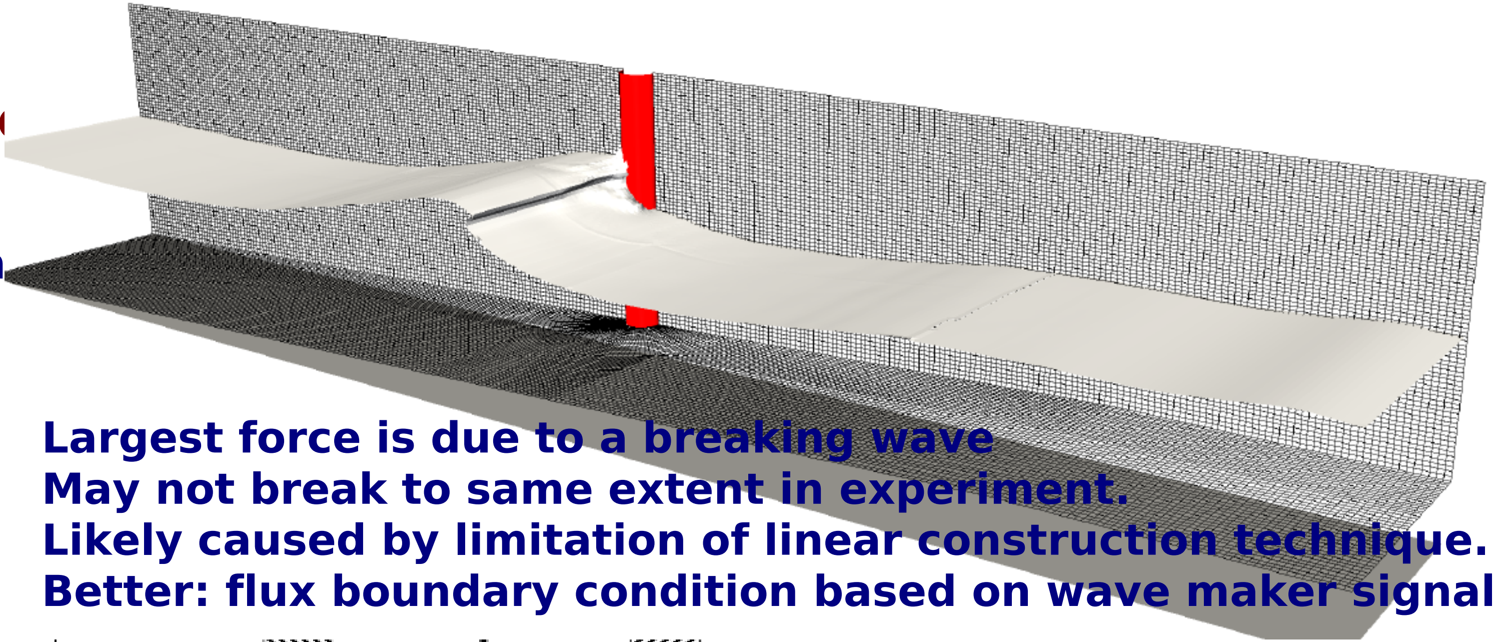
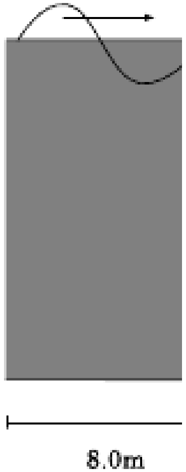
Validati

Experimen



Largest force is due to a breaking wave
May not break to same extent in experiment.
Likely caused by limitation of linear construction technique.
Better: flux boundary condition based on wave maker signal



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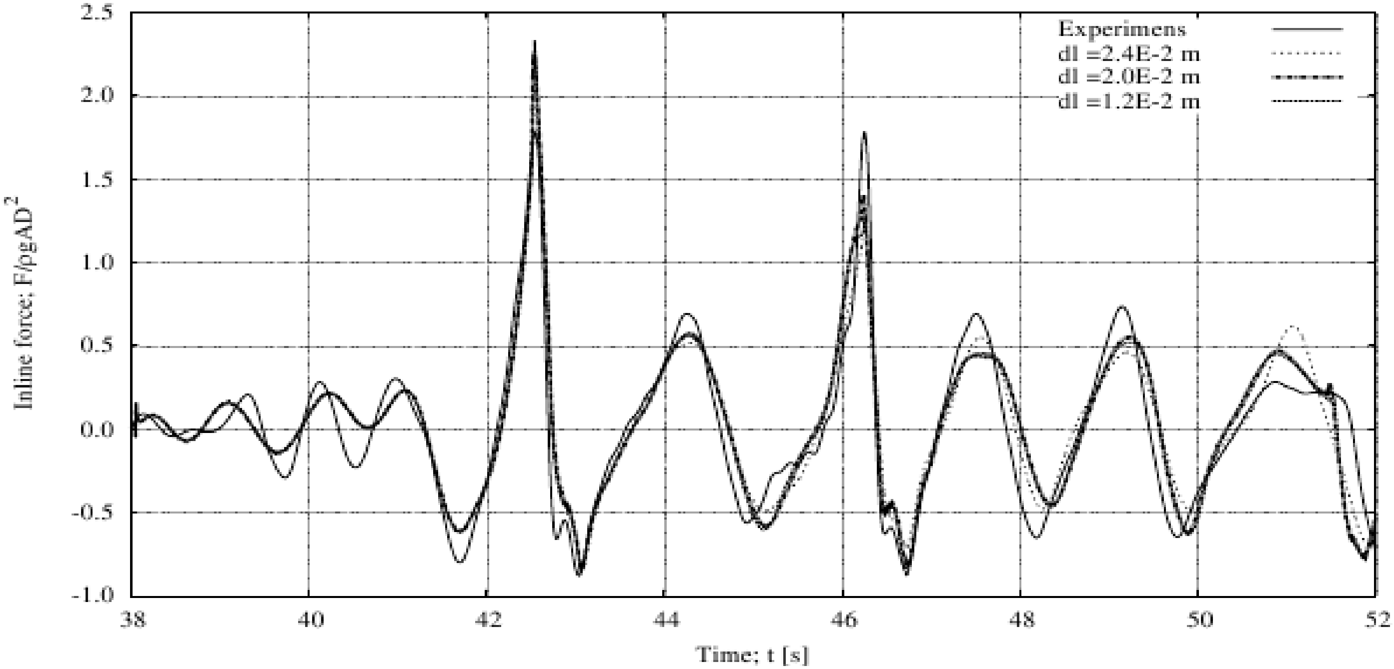

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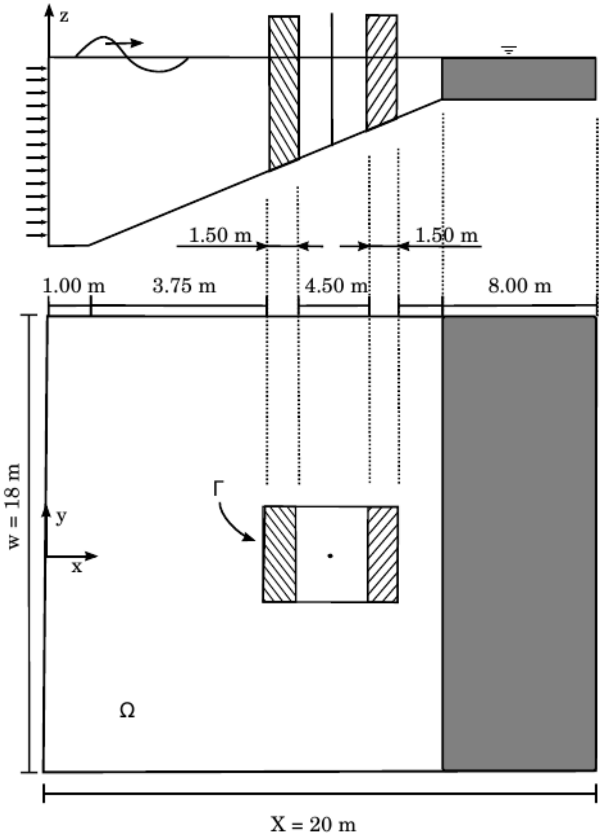
Computation of multi-directional waves



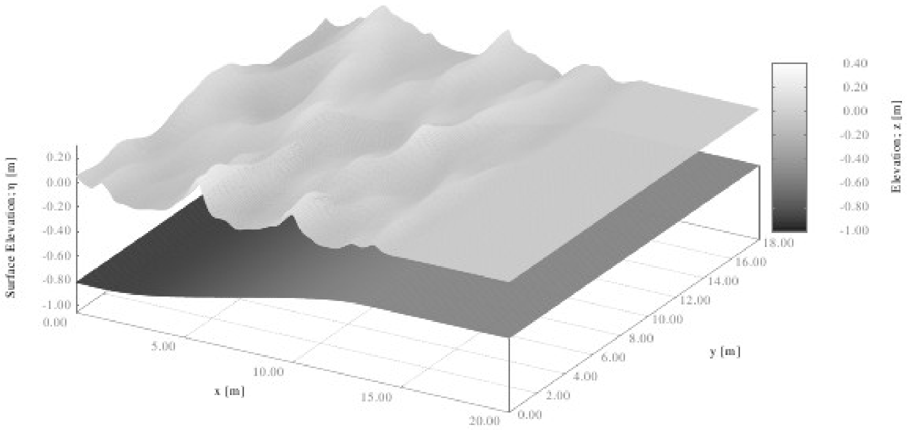


Figure 3.27: Snapshot of the free surface elevation computed by the potential flow solver at time $t = 15$ s.

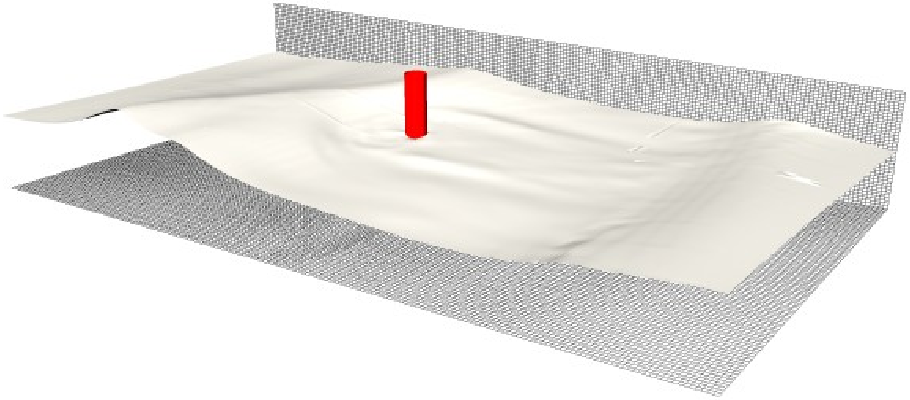
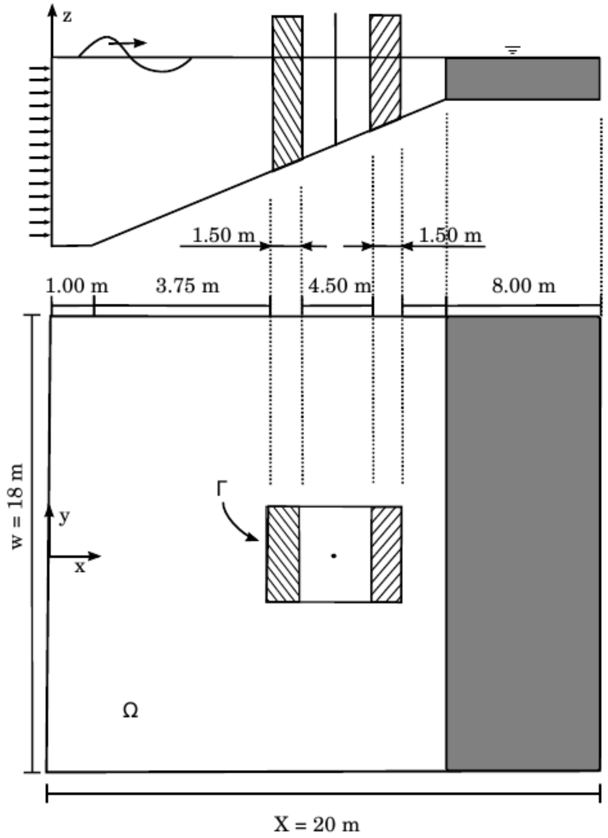
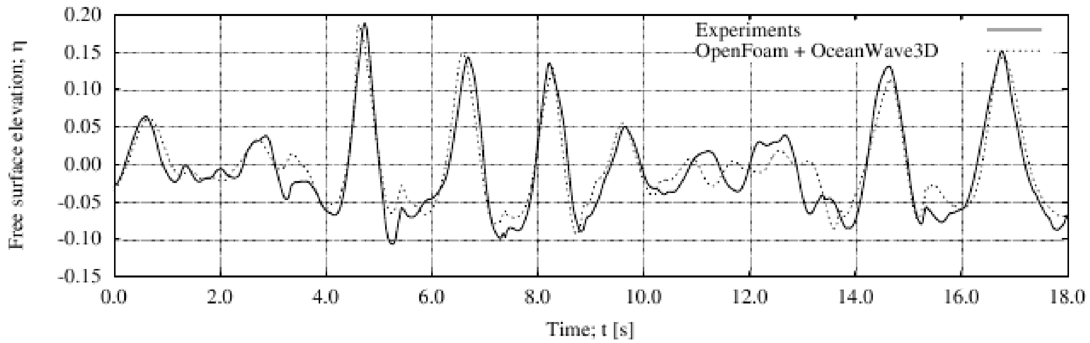


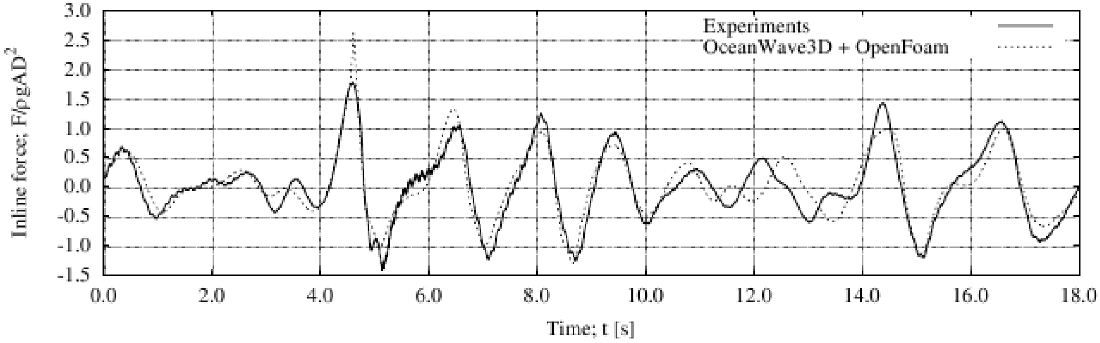
Figure 3.28: Snapshot of the free surface elevation computed by the Navier-Stokes solver at time $t = 15$ s.

Computation of multi-directional waves

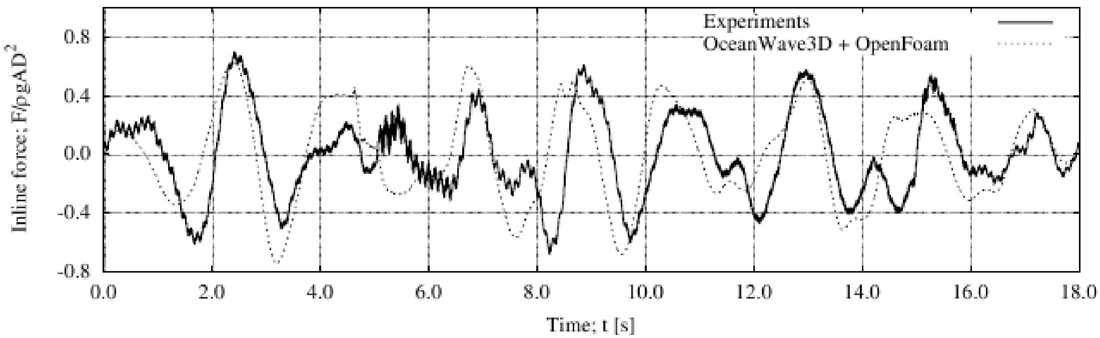




(a) Measured and computed free surface elevation at the location of wave gauge 15, $\{x; y\} = \{7.50; 0.00\}$.

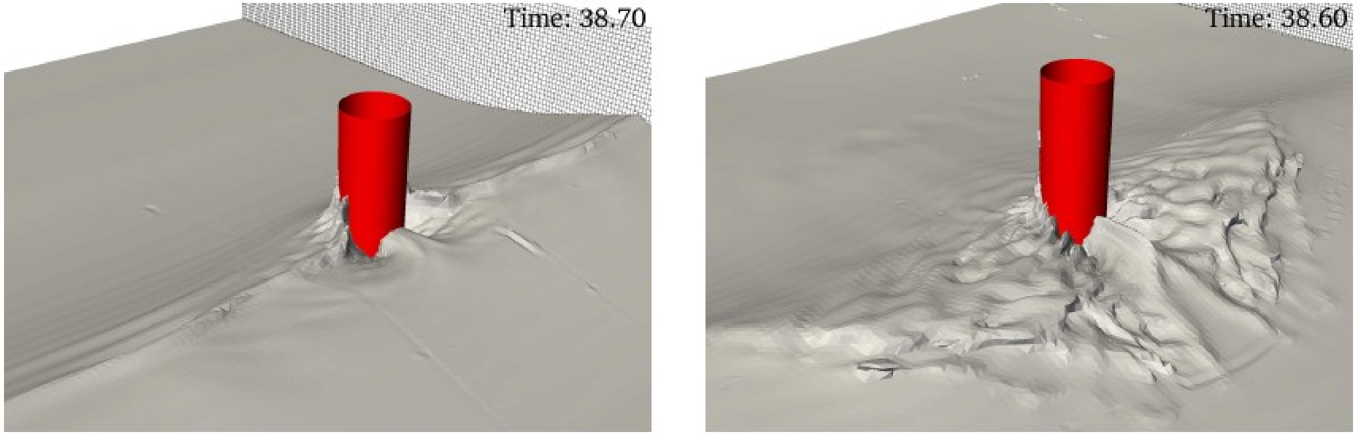


(a) Measured and computed inline force on the cylinder.



(b) Measured and computed force on the cylinder in the y-direction

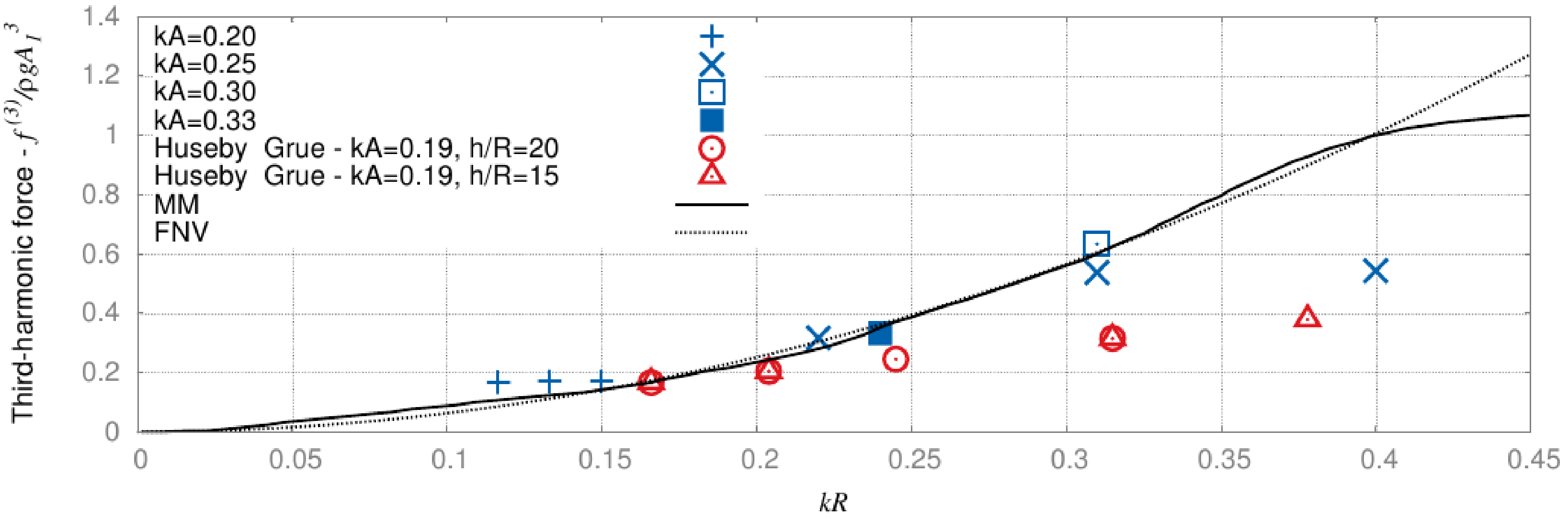
Detailed study on uni- and bi-directional wave group impacts



(c) Unidirectional: The wave passage

(d) Bi-directional: The wave passage

Detailed study of regular wave forcing and higher-harmonic components



Third-harmonic force compared to FNV theory

Paulsen et al
IWWWFB 2012

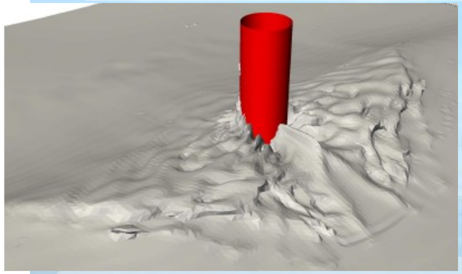
The Wave Loads project

ForskEL. DTU Wind Energy, DTU Mech. Engng., DHI. 2010-2013.

Task A:

Boundary conditions for phase resolving wave models

DHI



Task B:

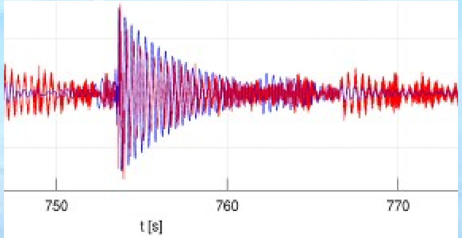
CFD methods for steep and breaking wave impacts

DTU, (DHI)

Task C:

Aero-elastic response to fully nonlinear wave forcing

DTU



Task D:

Physical model tests

DHI

Physical model test with a flexible cylinder at DHI

Bredmose et al OMAE 2013

Inspiration from de Ridder et al OMAE 2011

tuning to get

1st and 2nd scaled

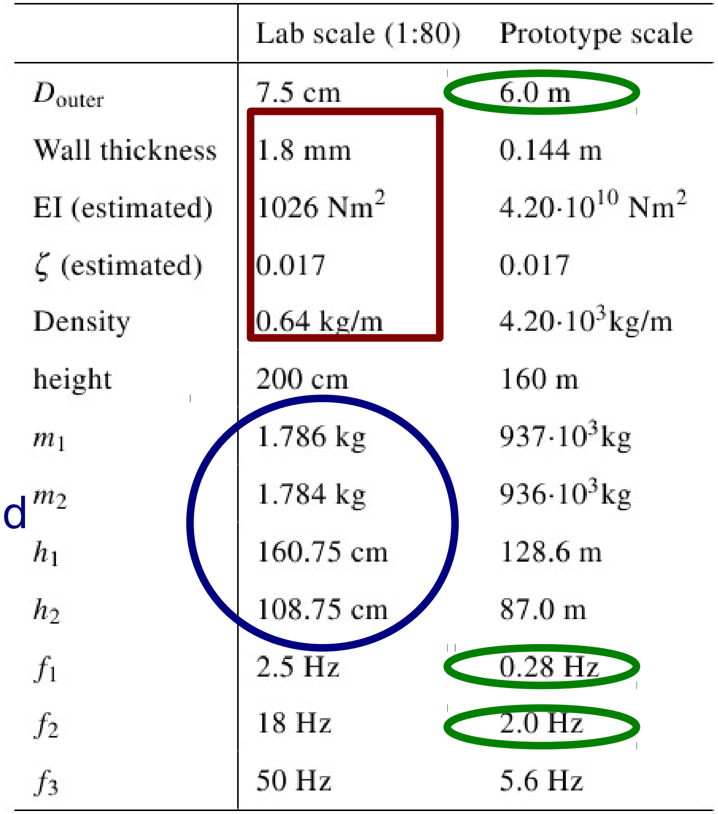
nat frequencies

Pipe properties

Target values

from NREL 5MW

reference WT



	Lab scale (1:80)	Prototype scale
D_{outer}	7.5 cm	6.0 m
Wall thickness	1.8 mm	0.144 m
EI (estimated)	1026 Nm^2	$4.20 \cdot 10^{10}$ Nm^2
ζ (estimated)	0.017	0.017
Density	0.64 kg/m	$4.20 \cdot 10^3$kg/m
height	200 cm	160 m
m_1	1.786 kg	$937 \cdot 10^3$kg
m_2	1.784 kg	$936 \cdot 10^3$kg
h_1	160.75 cm	128.6 m
h_2	108.75 cm	87.0 m
f_1	2.5 Hz	0.28 Hz
f_2	18 Hz	2.0 Hz
f_3	50 Hz	5.6 Hz

TABLE 1. Data for flexible pipe. Prototype values are indicated just for reference.

Instrumentation

accelerometers

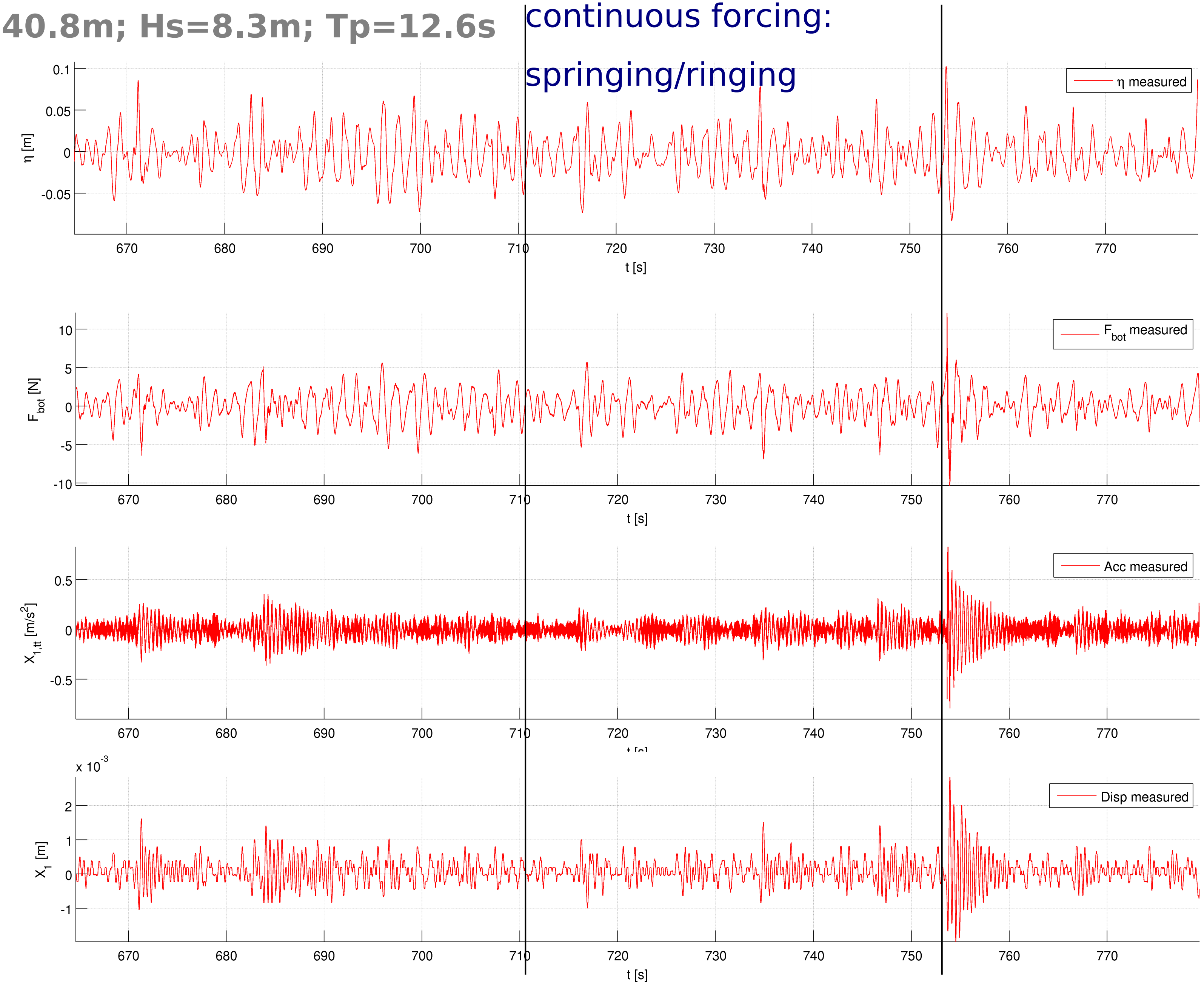
displacement

transducer

Wave gauges!

Example of measurement

h=40.8m; Hs=8.3m; Tp=12.6s

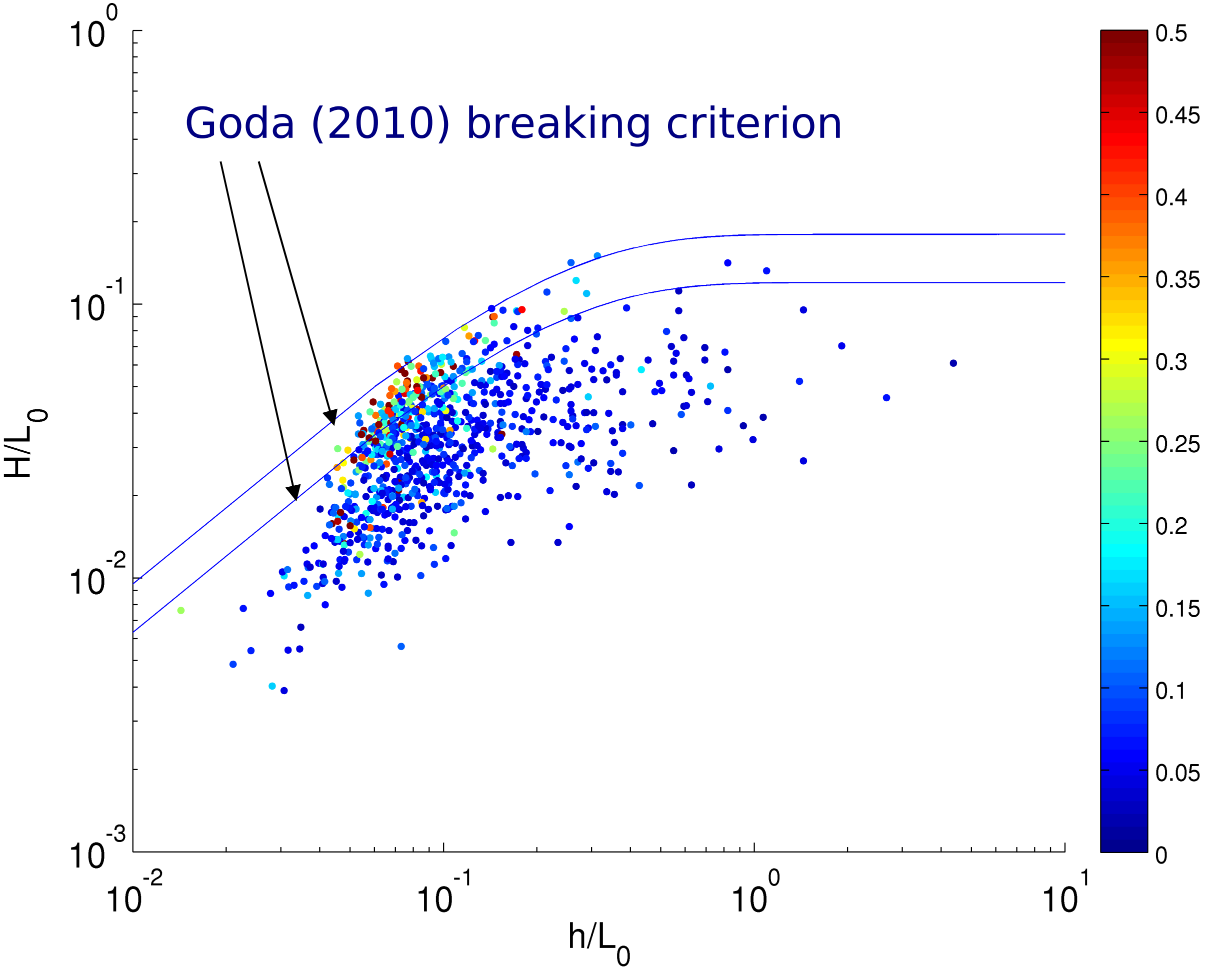


continuous forcing:

springing/ringing

impulsive excitation

Which waves give the largest accelerations?



acceleration

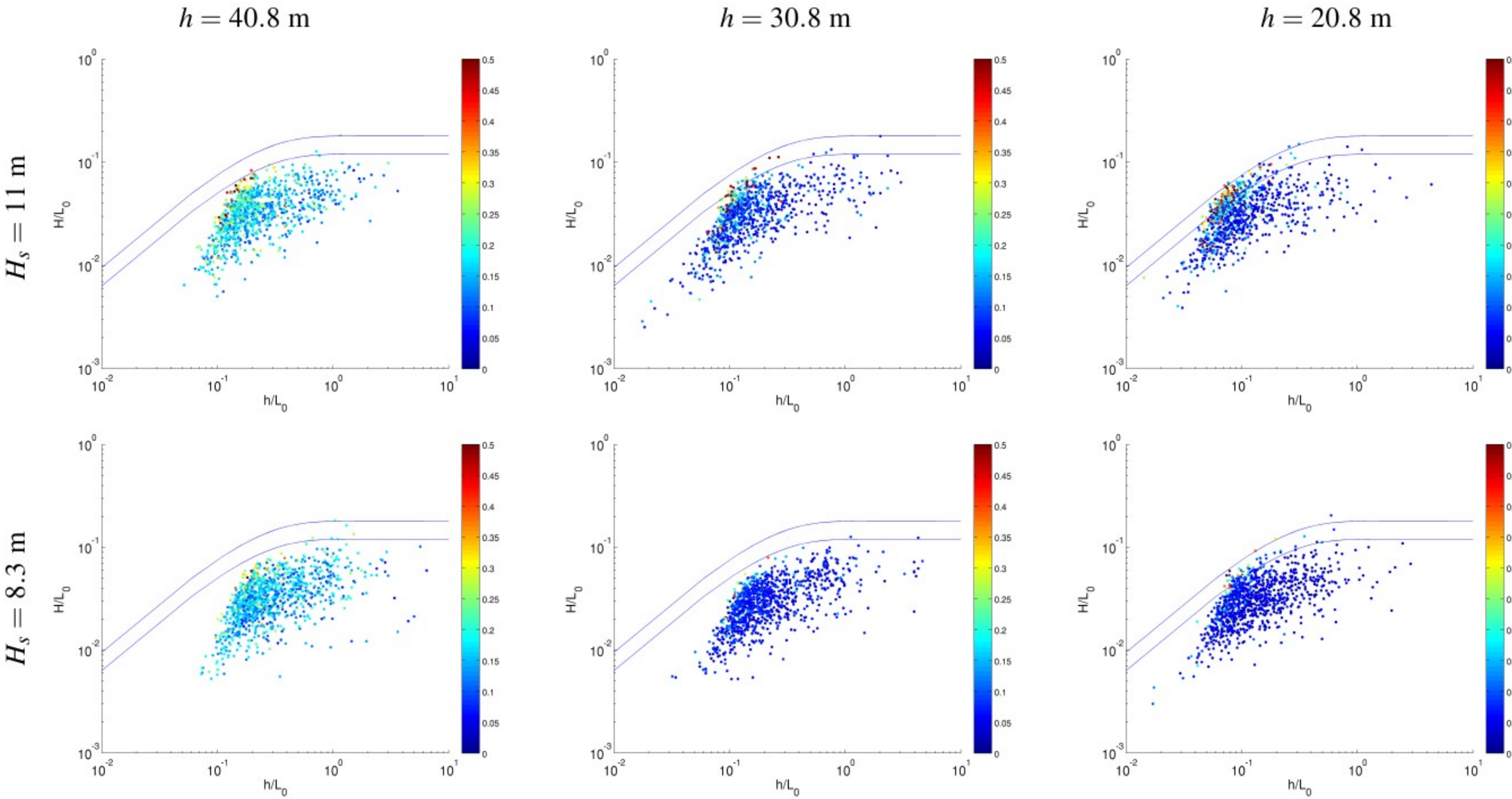
in top

accelerometer

[m/s^2]

See also Hansen et al (OMAE 2012)

Which waves give the largest accelerations?



Deeper water: larger bulk accelerations. DEPTH AND ARM

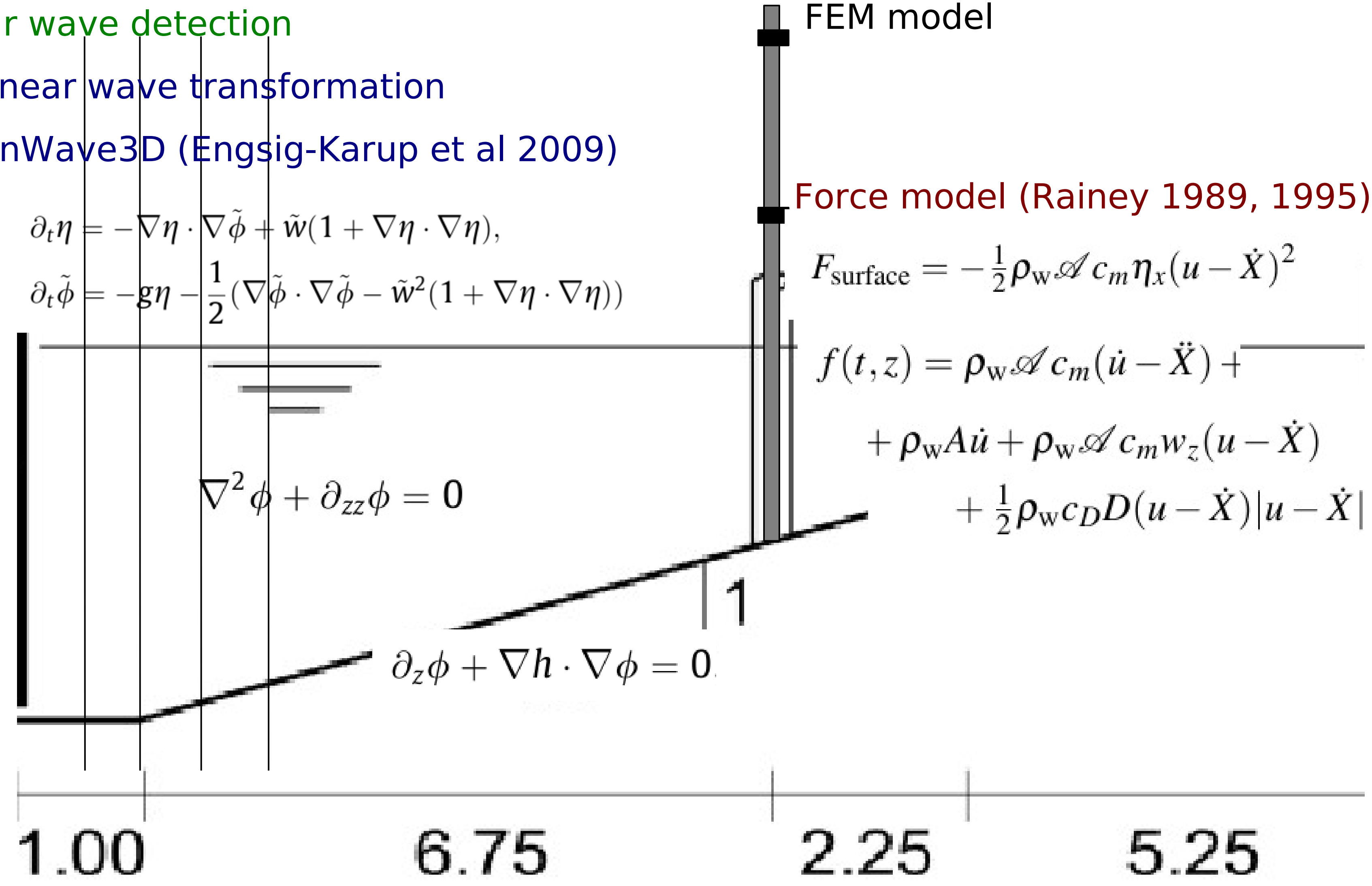
Shallow water: larger extreme accelerations. NONLINEARITY AND BREAKING

Numerical reproduction of experiments

Linear wave detection

Nonlinear wave transformation

OceanWave3D (Engsig-Karup et al 2009)



Force model (Rainey 1989, 1995)

$$\partial_t \eta = -\nabla\eta \cdot \nabla\tilde{\phi} + \tilde{w}(1 + \nabla\eta \cdot \nabla\eta),$$

$$\partial_t \tilde{\phi} = -g\eta - \frac{1}{2}(\nabla\tilde{\phi} \cdot \nabla\tilde{\phi} - \tilde{w}^2(1 + \nabla\eta \cdot \nabla\eta))$$

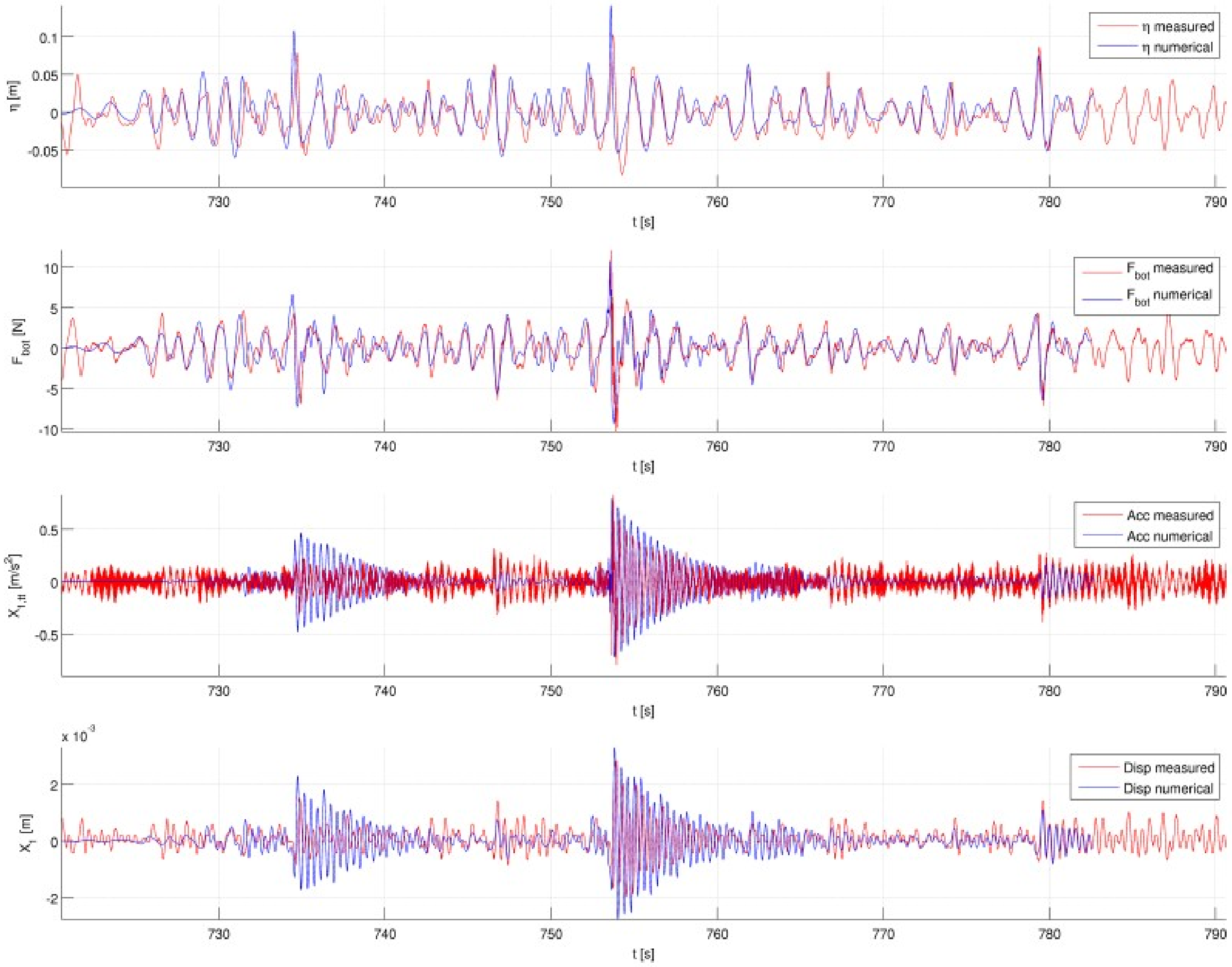
$$\nabla^2\phi + \partial_{zz}\phi = 0$$

$$\partial_z\phi + \nabla h \cdot \nabla\phi = 0$$

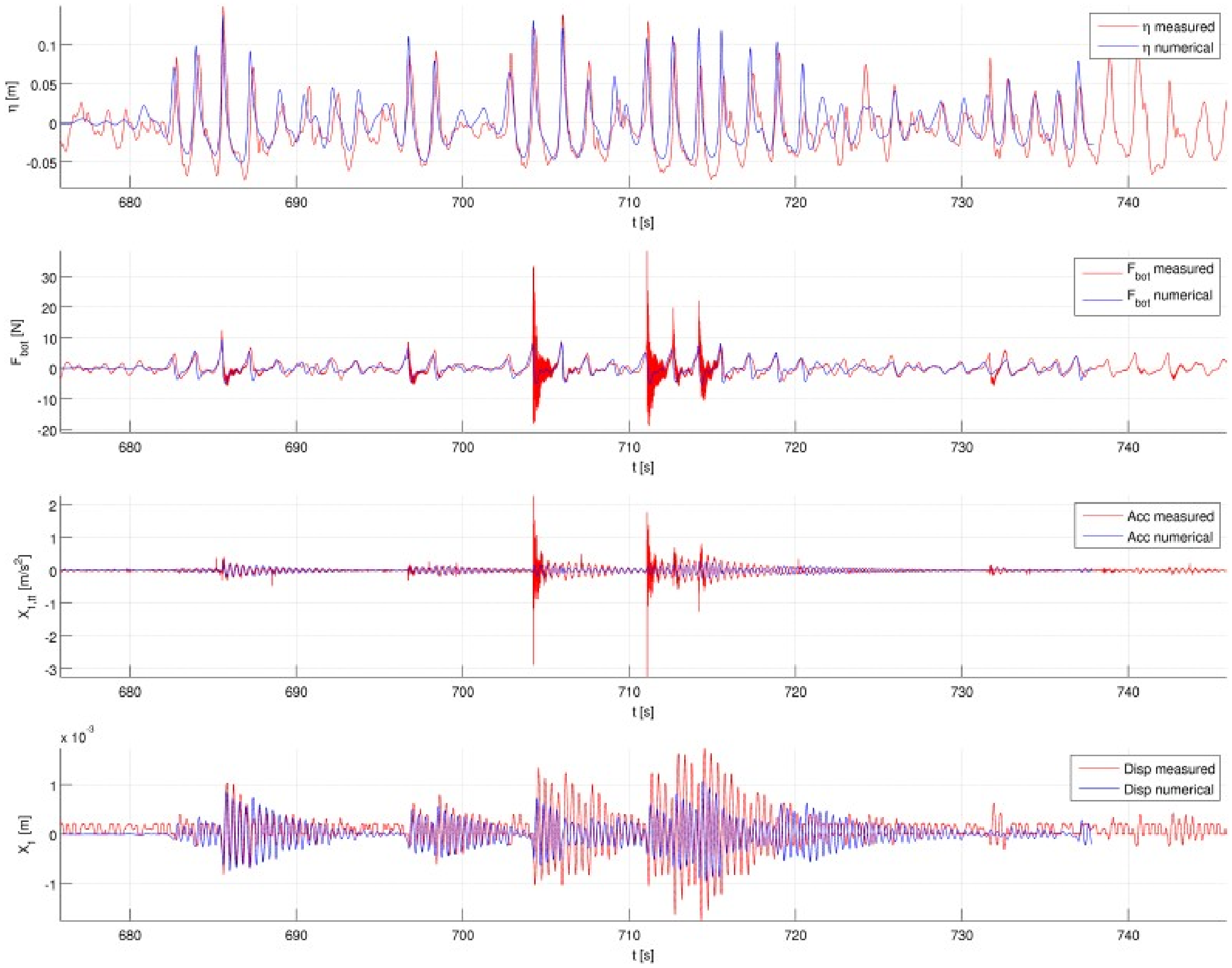
$$F_{\text{surface}} = -\tfrac{1}{2}\rho_w \mathscr{A} c_m \eta_x (u - \dot{X})^2$$

$$f(t,z) = \rho_w \mathscr{A} c_m (\dot{u} - \ddot{X}) + {} + \rho_w A\dot{u} + \rho_w \mathscr{A} c_m w_z (u - \dot{X}) + \tfrac{1}{2}\rho_w c_D D (u - \dot{X})|u - \dot{X}|$$

Response, h=40.8 m



Response, h=20.8 m



The Wave Loads project

ForskEL. DTU Wind Energy, DTU Mech. Engng., DHI. 2010-2013.

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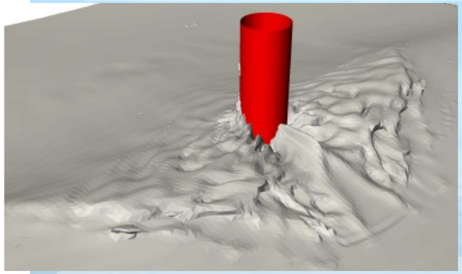
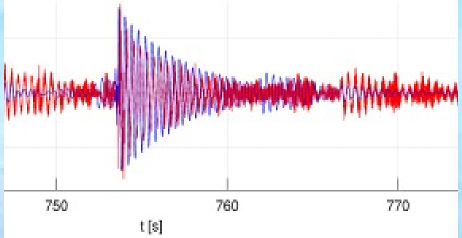


Task C:

Aero-elastic response to fully nonlinear wave forcing

DTU

Statkraft



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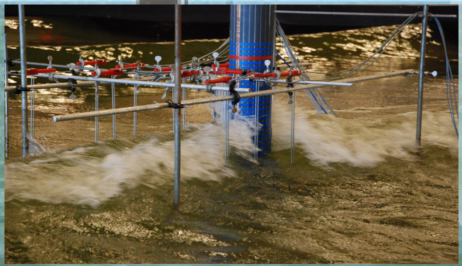

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