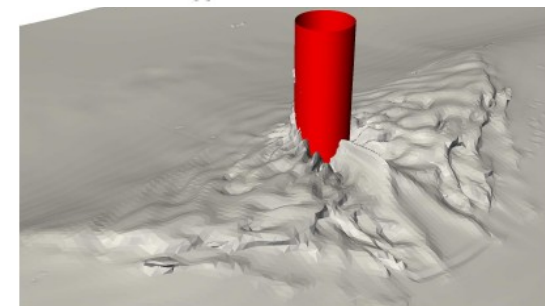
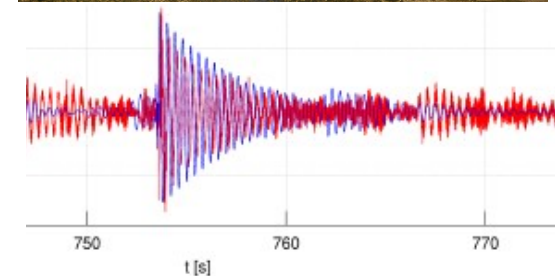


Ringling and impulsive excitation from steep and breaking waves

Results from the Wave Loads project

Henrik Bremose
DTU Wind Energy
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The Wave Loads project

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



Henrik Bredmose

Signe Schlør

Robert Mikkelsen

Stig Øye

Torben Juul Larsen

Taeseong Kim

Anders Melchior Hansen

Jesper Mariegaard

Flemming Schlütter

Jacob Tornfeldt Sørensen

Ole Svendstrup Petersen

Hans Fabricius Hansen

Anders Wedel Nielsen

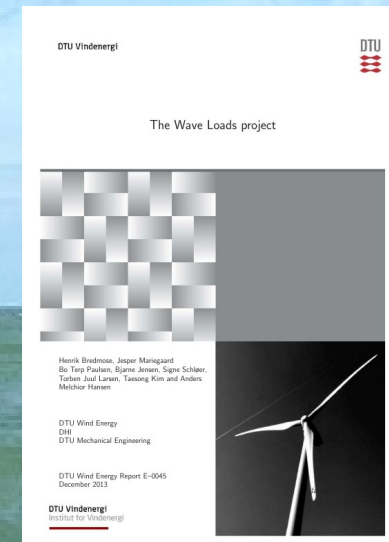
Bjarne Jensen

Iris Pernille Lohman

Xerxes Mandviwalla

Bo Terp Paulsen

Harry Bingham



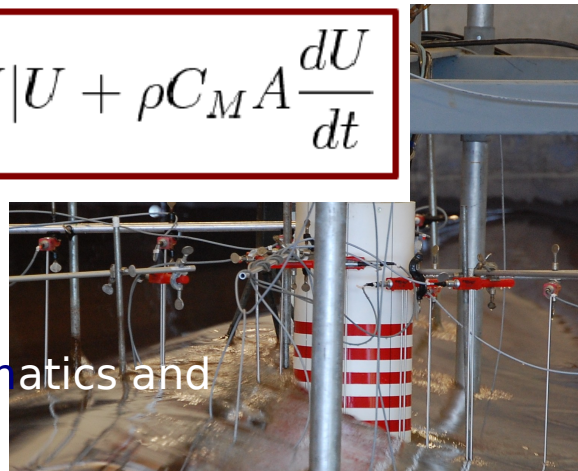
Hydrodynamic loads

Simplest: Linear wave kinematics and Morison equation

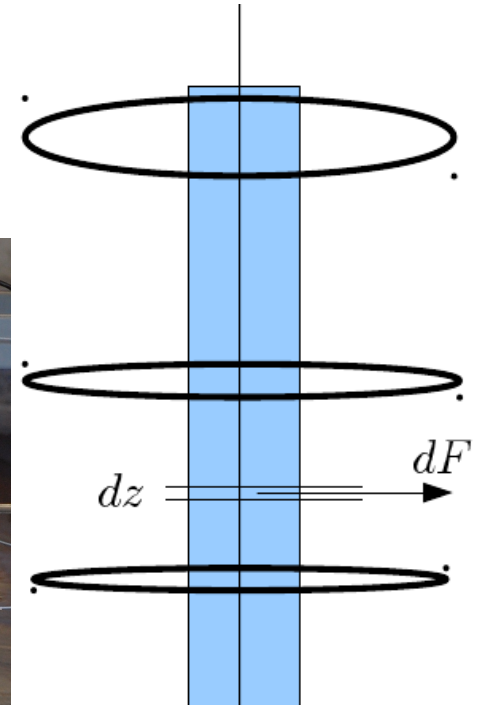
$$F = \frac{1}{2} \rho C_D D |U| U + \rho C_M A \frac{dU}{dt}$$

Better: Fully nonlinear wave kinematics and Morison-type force model

Advanced: CFD and coupled CFD



Zang and



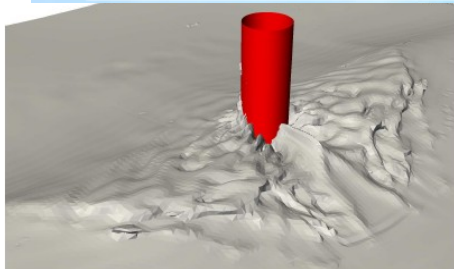
The Wave Loads project

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

Task A:

Boundary conditions for phase resolving wave models

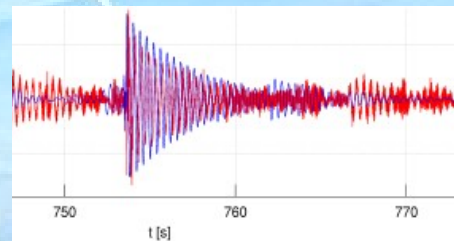
DHI



Task C:

Aero-elastic response to fully nonlinear wave forcing

DTU



Task B:

CFD methods for steep and breaking wave impacts

DTU, (DHI)



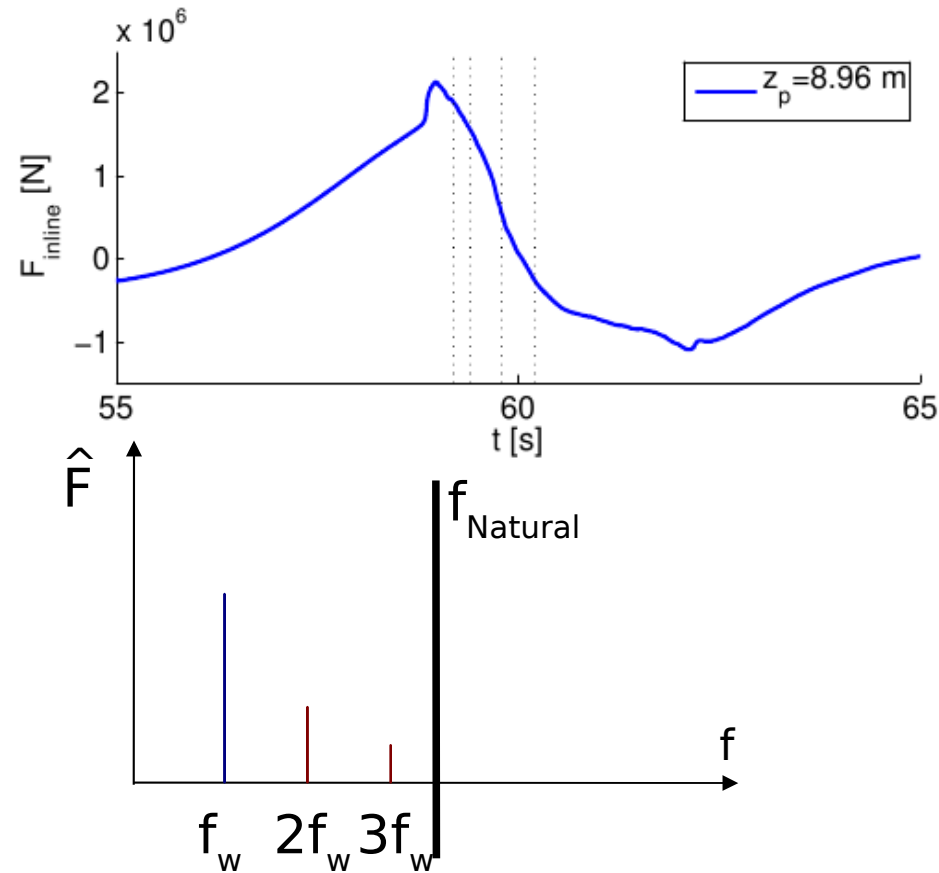
Task D:

Physical model tests

DHI

What is ringing?

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



Third-order inertia load theories:

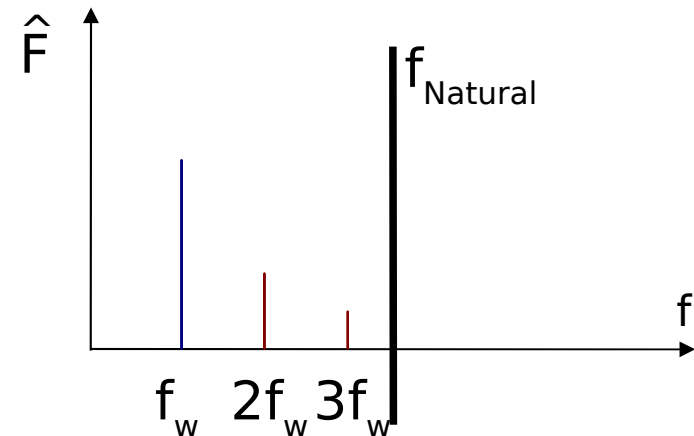
FNV (1995): regular waves deep water

Krokstad et al (1998): irregular waves

Malenica & Molin (1995): finite depth

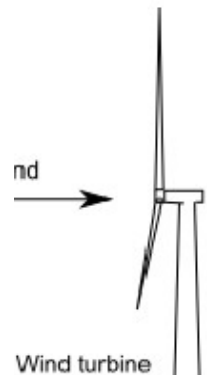
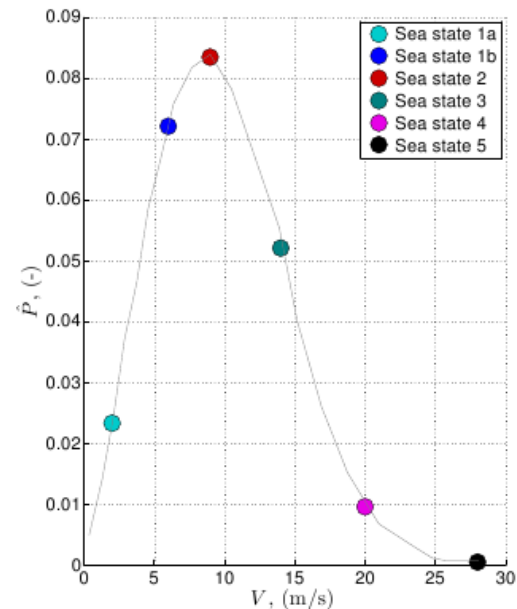
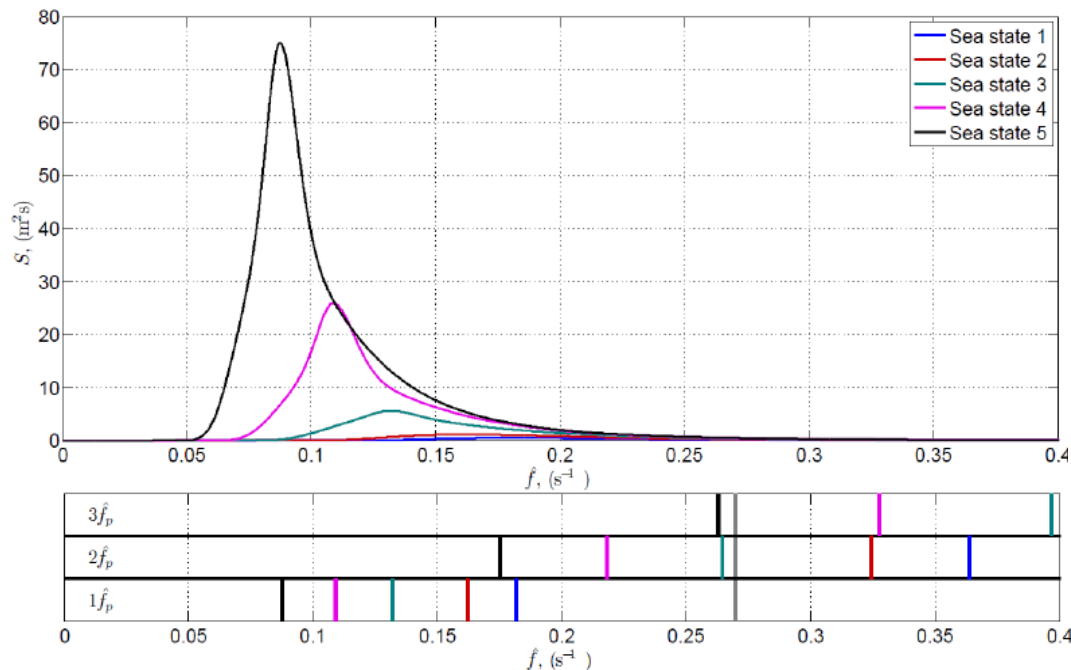
What is impulsive excitation?

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

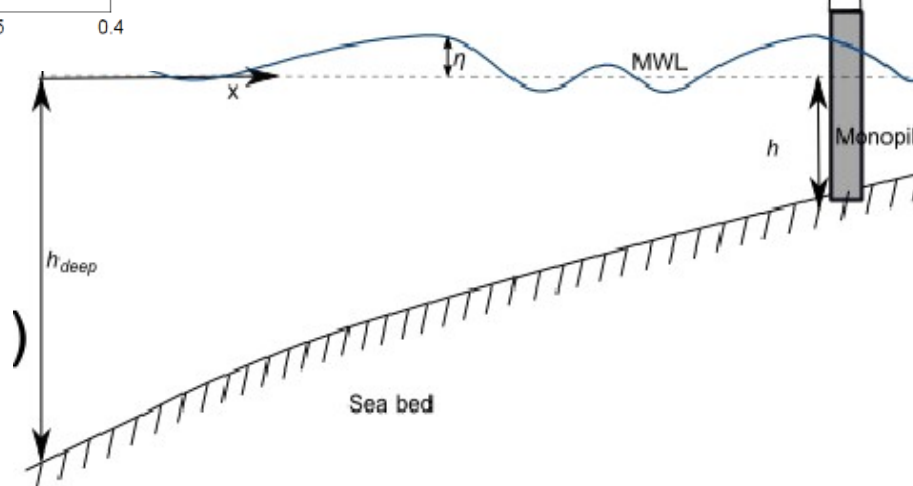


Study of nonlinear wave load effects

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



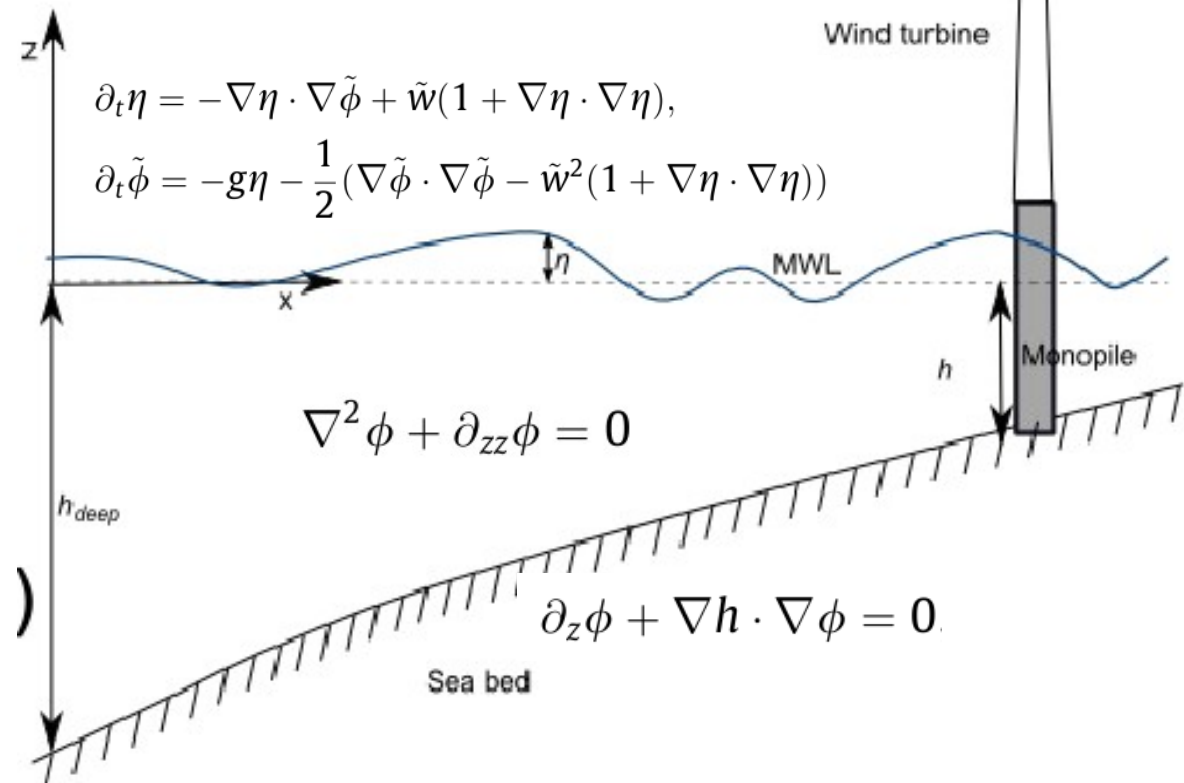
Signe Schl er (2013)



Kinematics from a fully nonlinear potential flow solver

'OceanWave3D', Engsig-Karup et al (2009)

Allan Engsig-Karup, Harry Bingham and Ole Lindberg



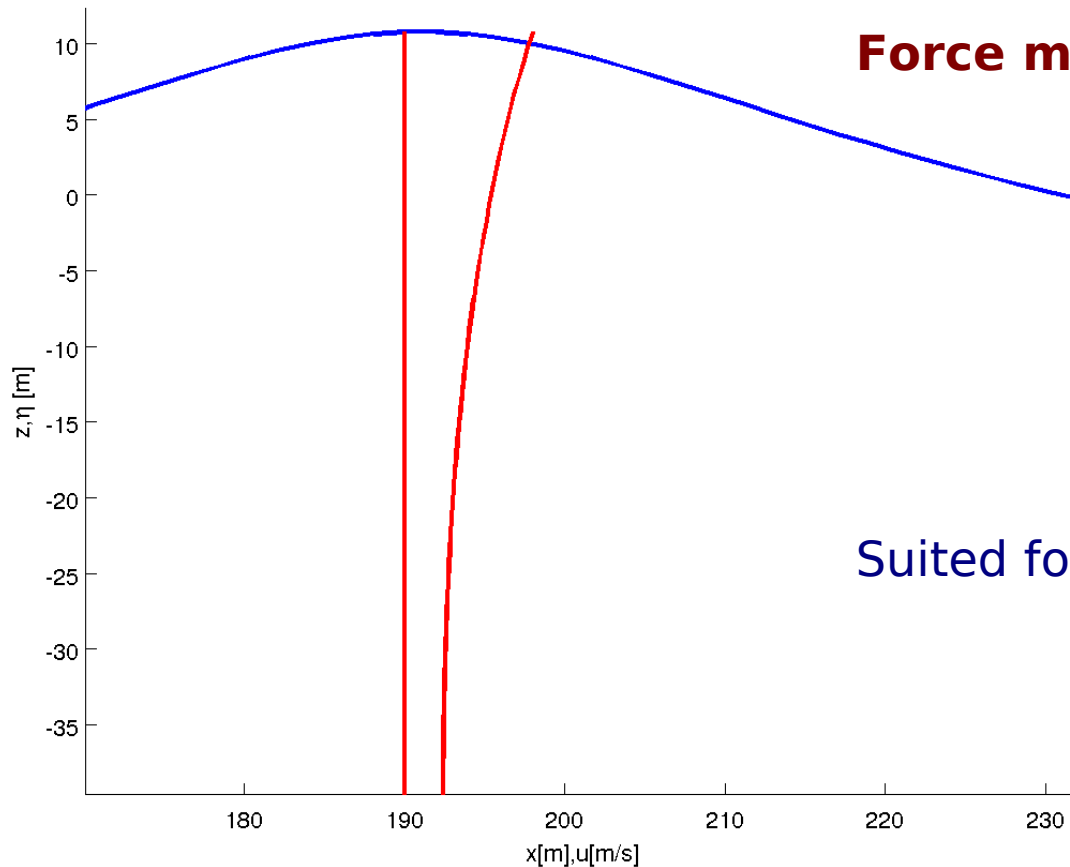
From kinematics to distributed force

Force model (Rainey 1989, 1995)

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

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

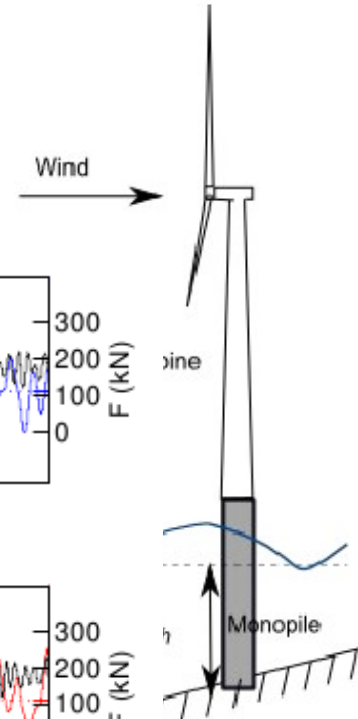
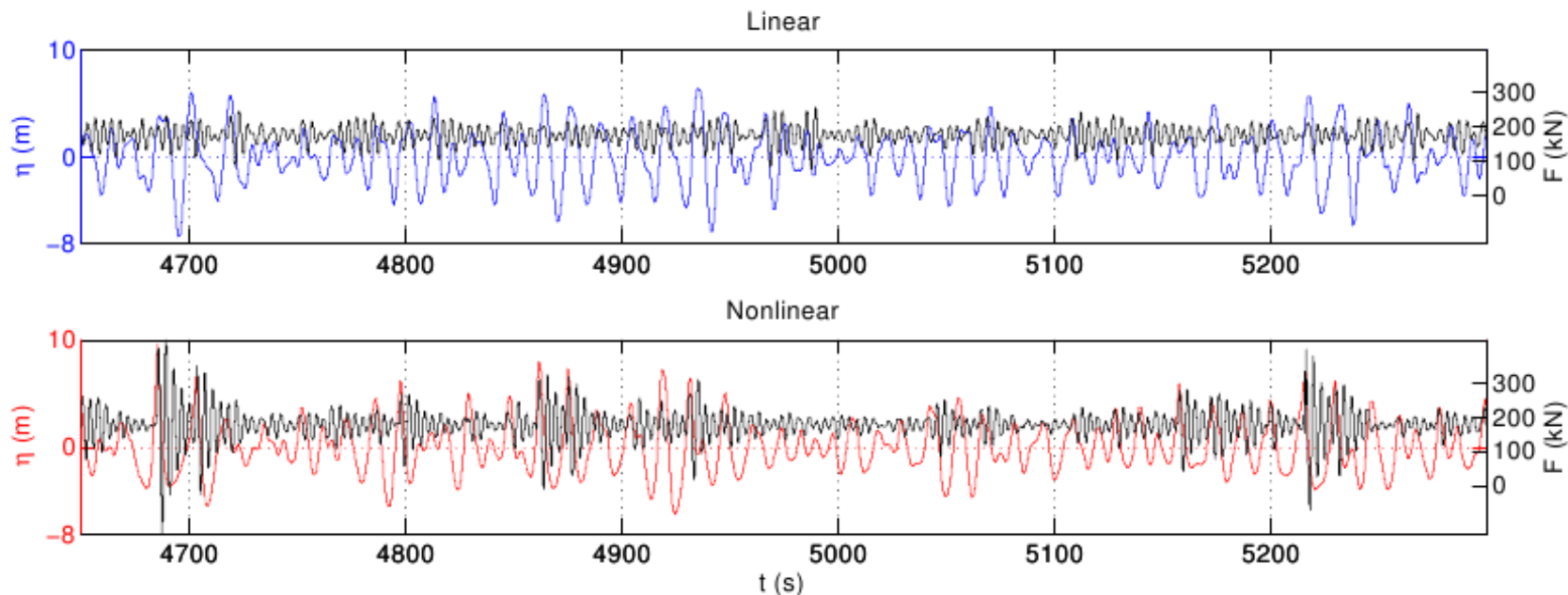
Suited for fully nonlinear kinematics



Response in bottom of tower

Fully nonlinear waves versus linear waves

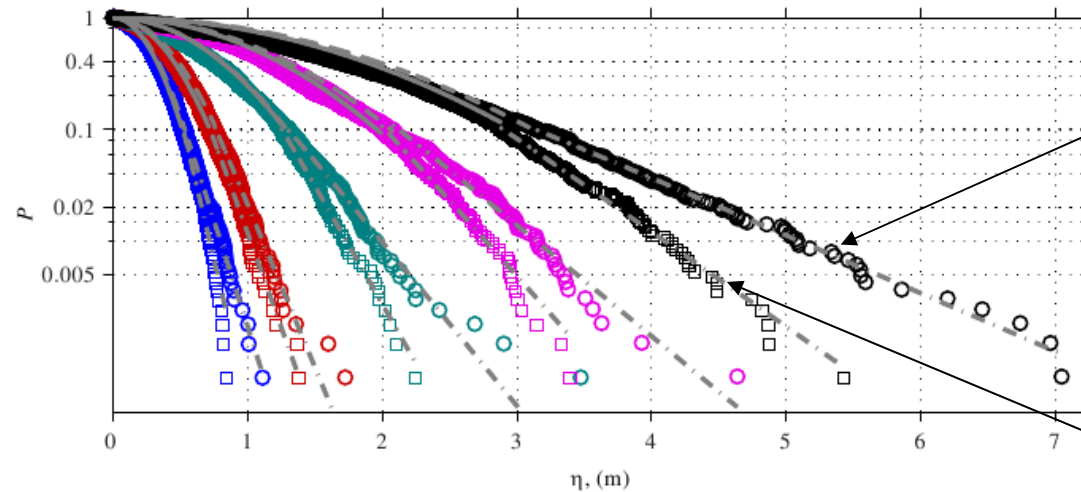
$$H_s = 9.4 \text{ m}, T_p = 14.2 \text{ s}, W = 5 \text{ m/s}$$



Schlører et al
(OMAE 2012)

Static load analysis, $h=30\text{m}$

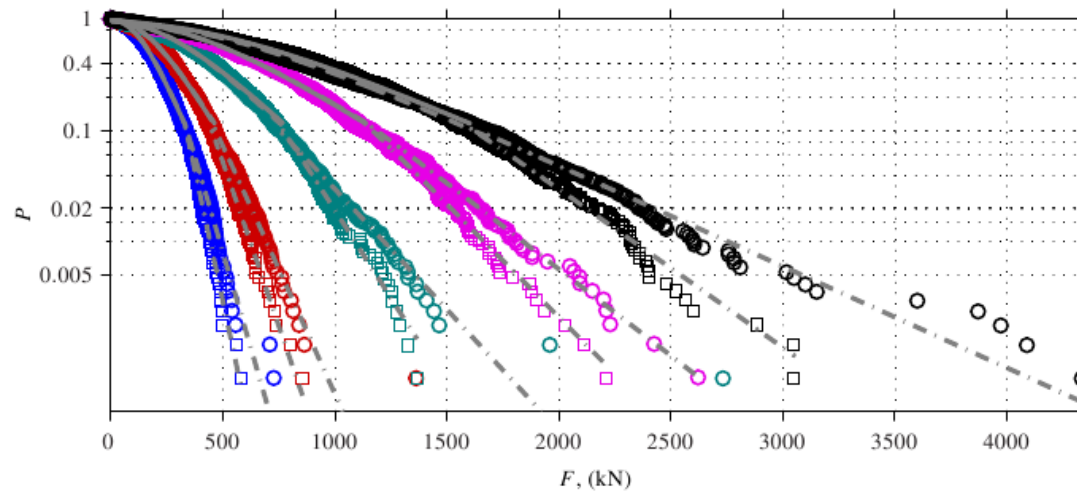
crest elevations



nonlinear

linear

force peaks
depth integrated
force



Results of aero-elastic computations

Tower response - largest sea state

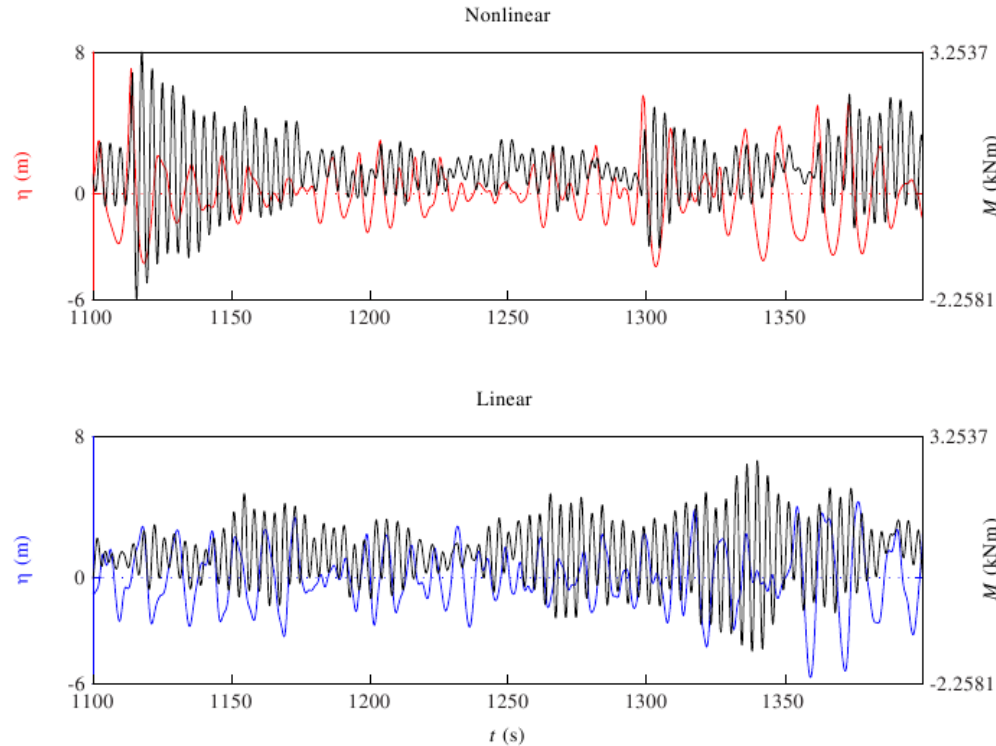


Figure 44: Nonlinear and linear surface elevation for the largest sea state and the corresponding moment in the bottom of the tower, $H_s = 6.76$ m, $T_p = 11.41$ s, $V = 28$ m/s and $I_t = 0.13$

Linear waves can also excite the tower

Results of aero-elastic computations

Monopile response - largest sea state

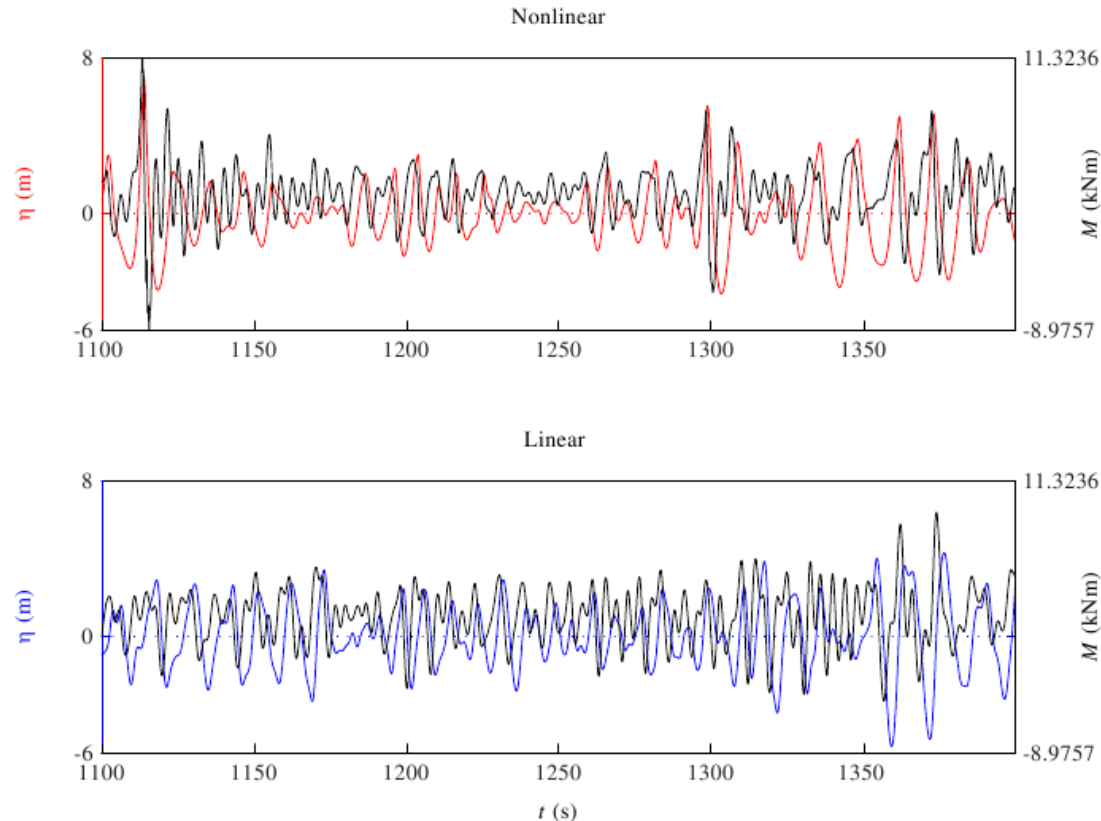


Figure 45: Nonlinear and linear surface elevation for the largest sea state and the corresponding moment in the bottom of the monopile, $H_s = 6.76$ m, $T_p = 11.41$ s, $V = 28$ m/s and $I_t = 0.13$

Vibrations less visible – occur on top of the wave loads

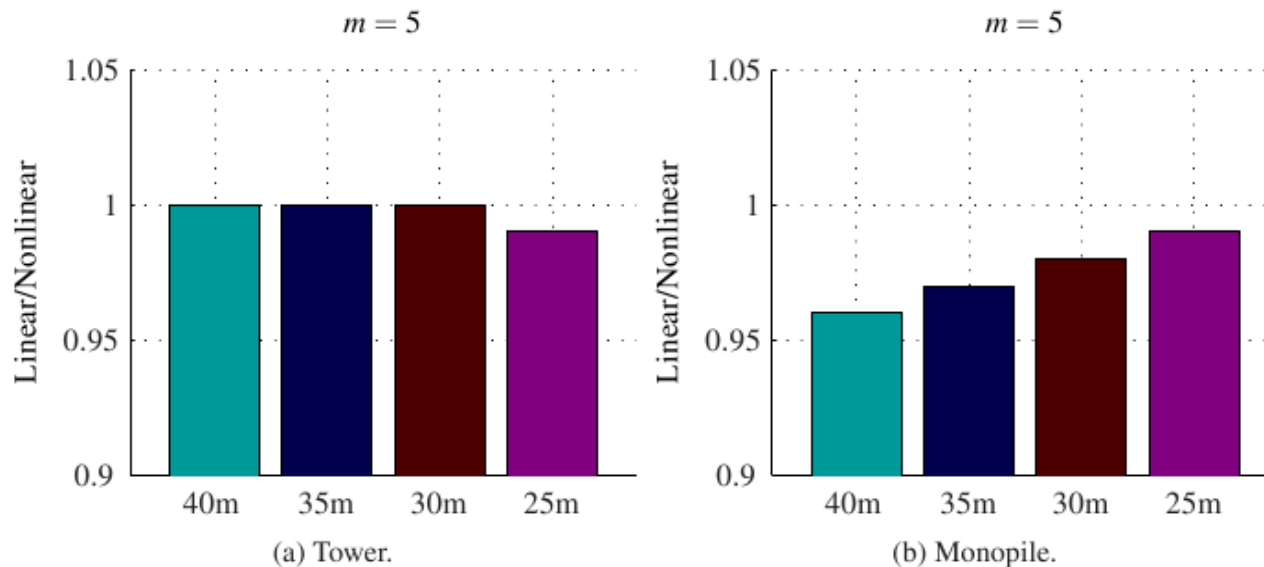
Quantify fatigue effect

Equivalent load

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

Accumulated equivalent load

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



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

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

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.

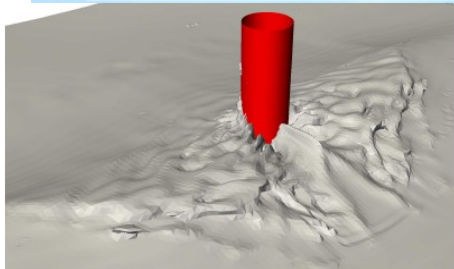
The Wave Loads project

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

Task A:

Boundary conditions for phase resolving wave models

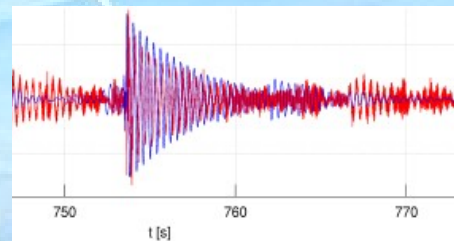
DHI



Task C:

Aero-elastic response to fully nonlinear wave forcing

DTU



Task B:

CFD methods for steep and breaking wave impacts

DTU, (DHI)



Task D:

Physical model tests

DHI

The OpenFOAM® CFD solver

Open source CFD toolbox

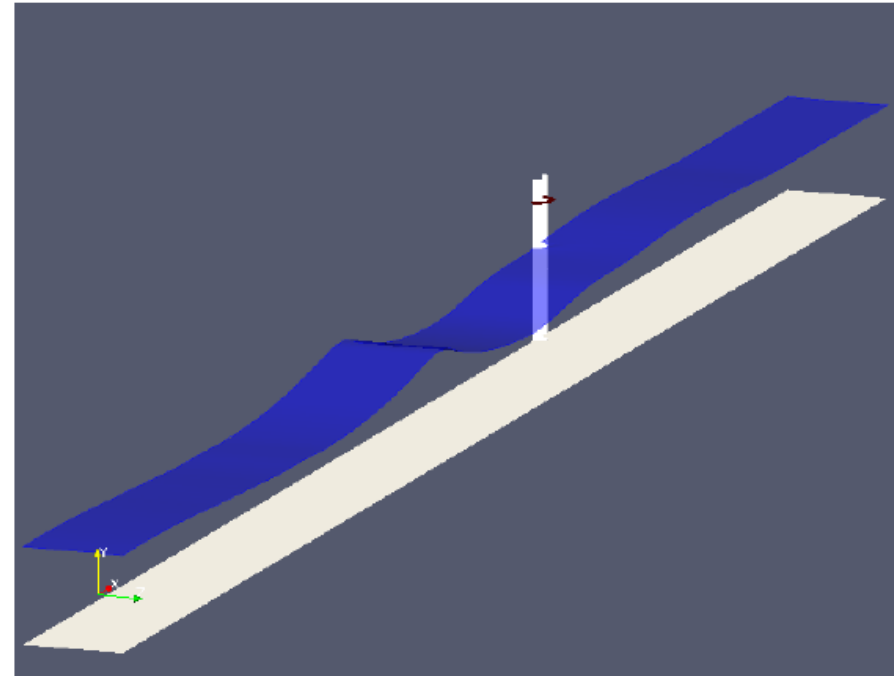
Vast attention during last 3 years

This study: interFoam solver

3D incompressible Navier-Stokes

two phases (water and air)

VOF treatment of free surface

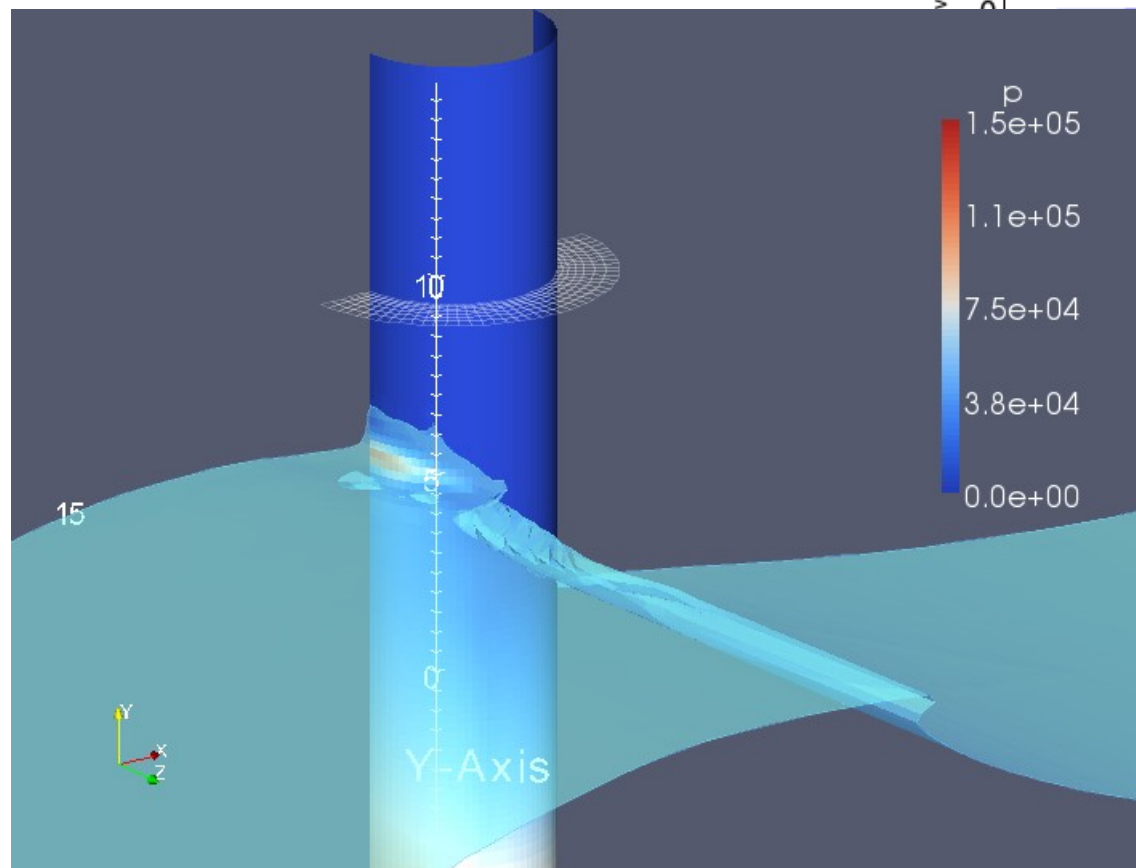


Waves2foam wave generation toolbox has been developed and validated

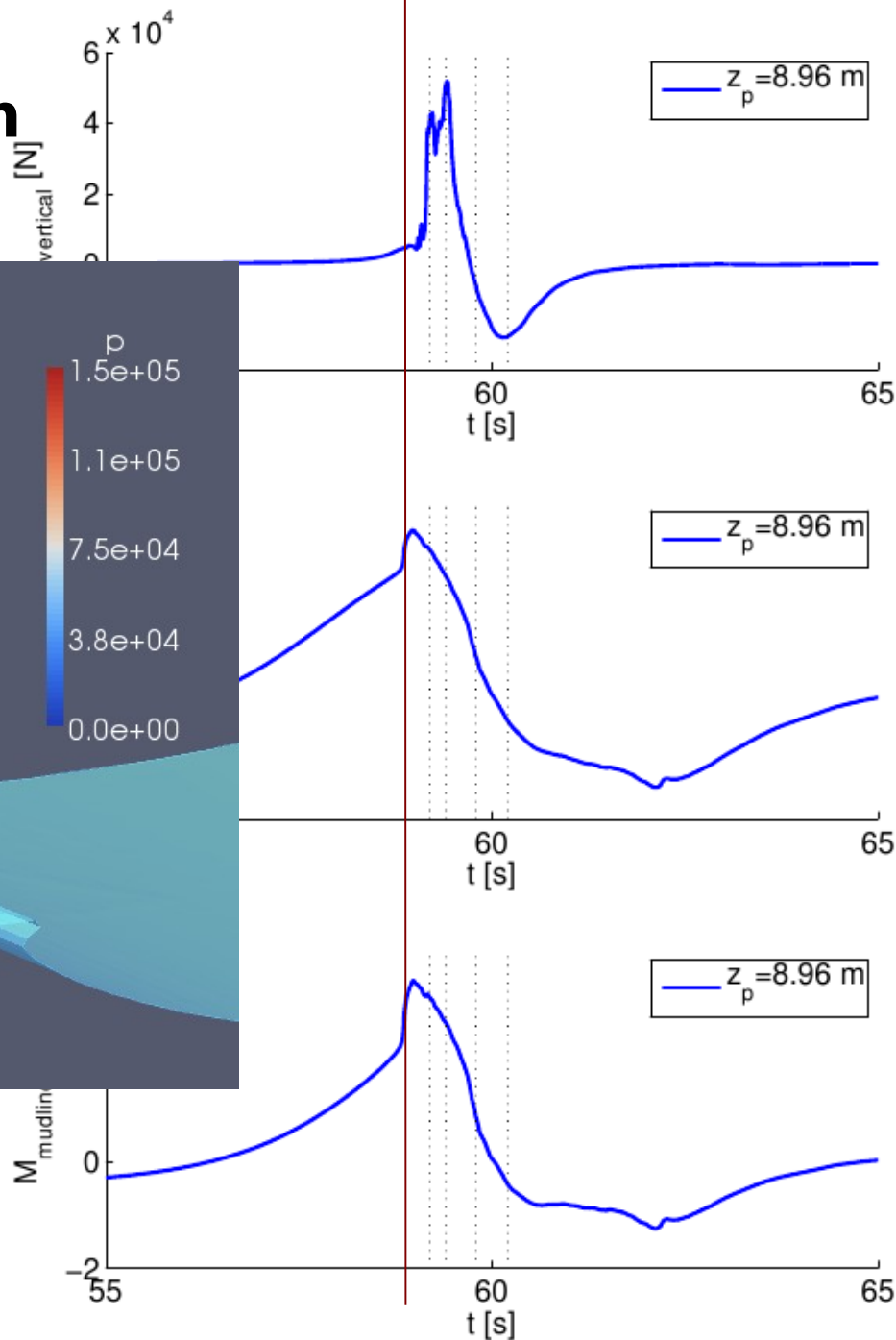
(Niels Gjør Jacobsen

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

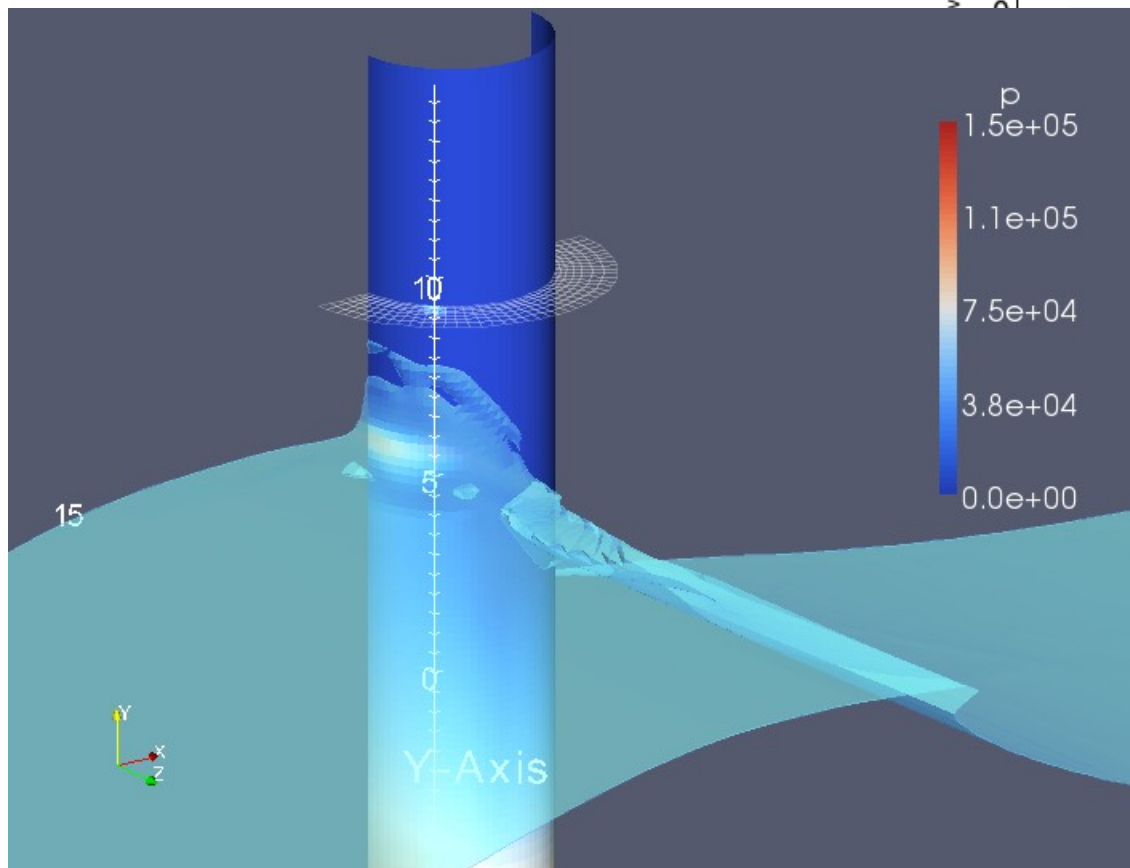
Platform height of 8.96m



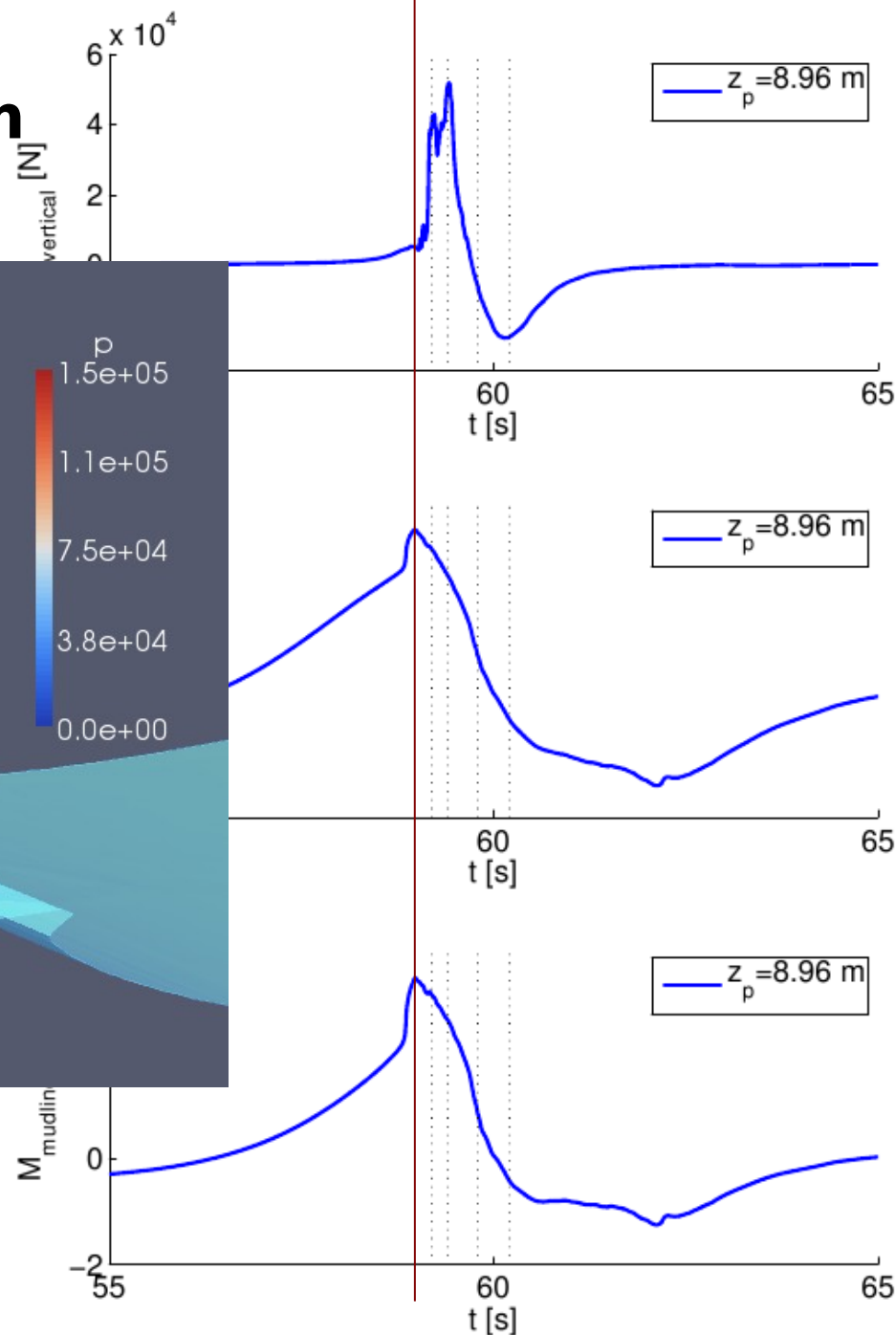
$t=59.0s$



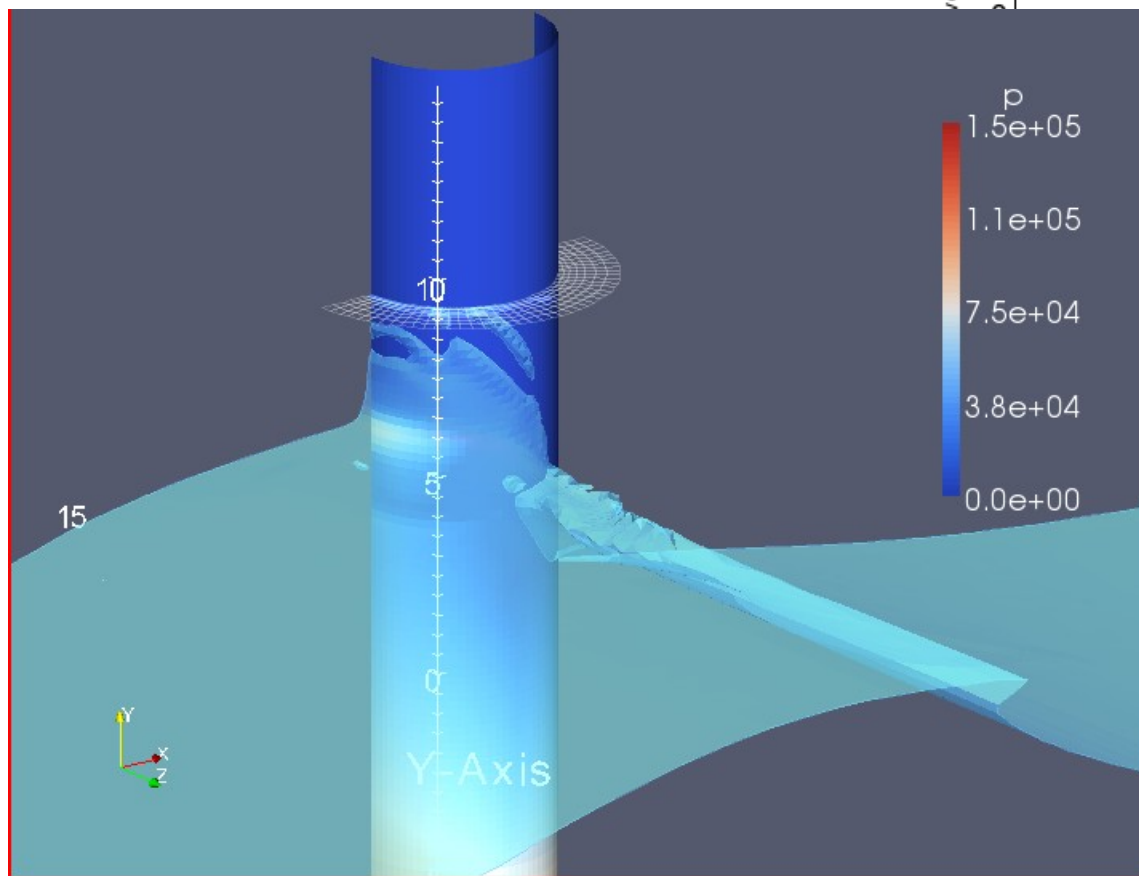
Platform height of 8.96m



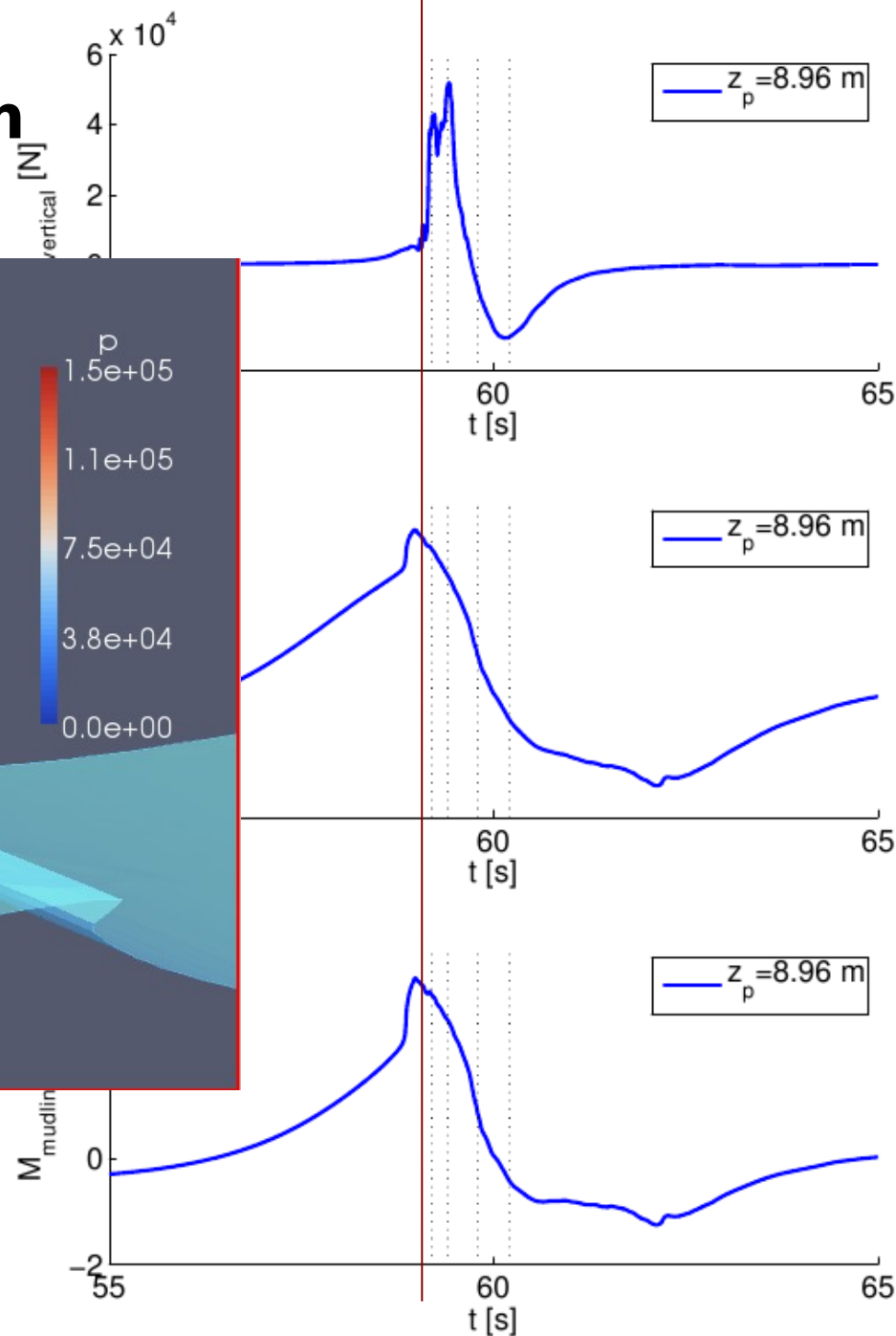
$t=59.1s$



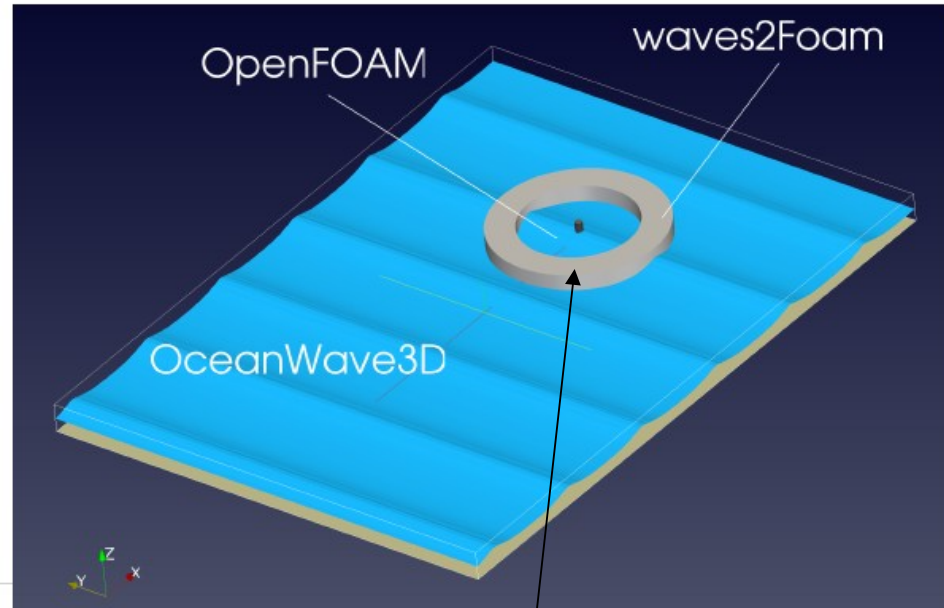
Platform height of 8.96m



$t=59.2s$



Development of a coupled solver

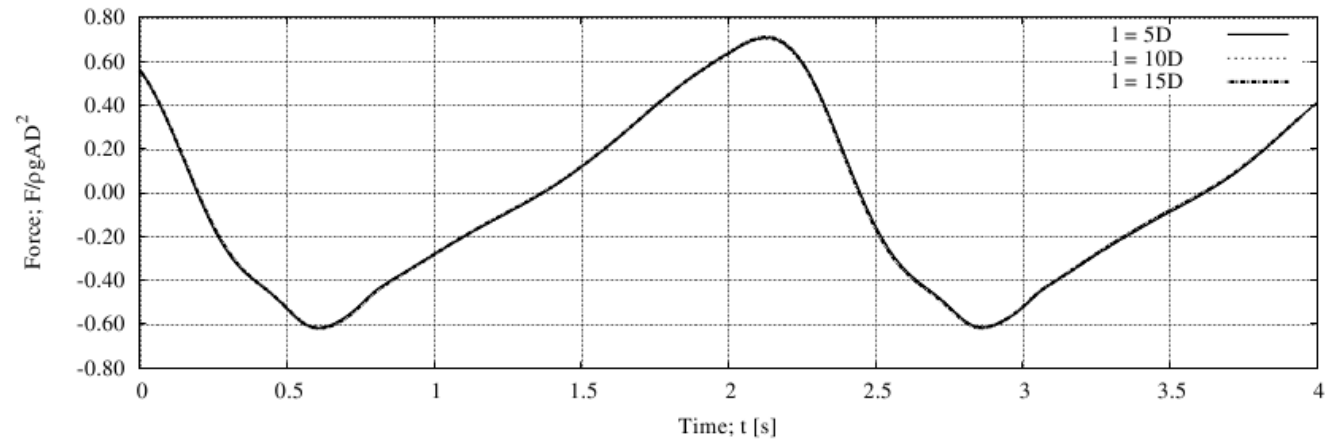
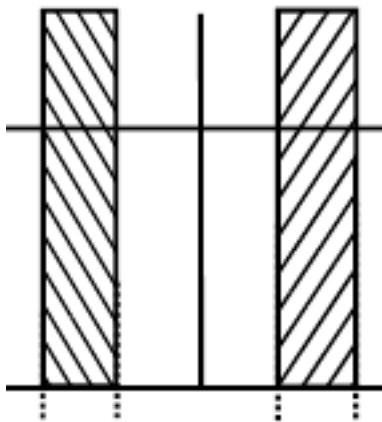


Compute outer flow field with potential flow wave model:
OceanWave3D (Engsig-Karup et al 2009)

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 $L/6$

Bo Terp Paulsen

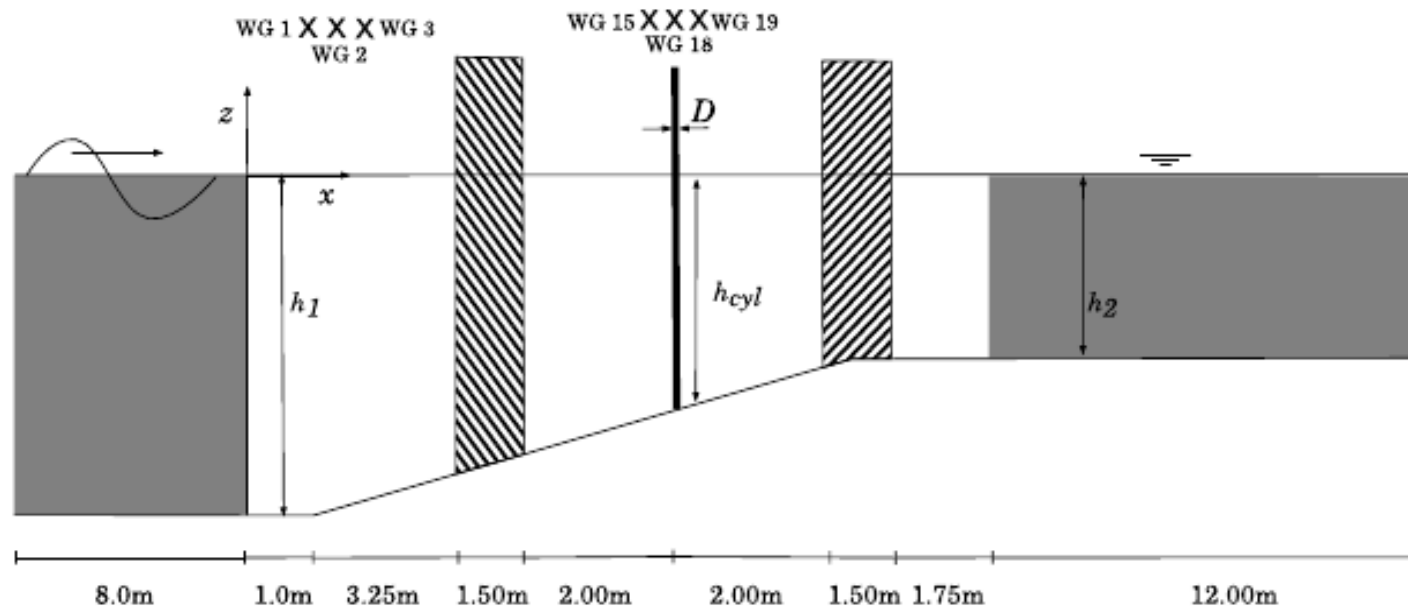
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Department of Wind Energy



DTU Mechanical Engineering
Department of Mechanical Engineering

Validation for irregular wave forcing on a slope

Experiment in the Wave Loads project. $H_s=8.3\text{m}$ (full scale). Scale 1:36



Bo Terp Paulsen

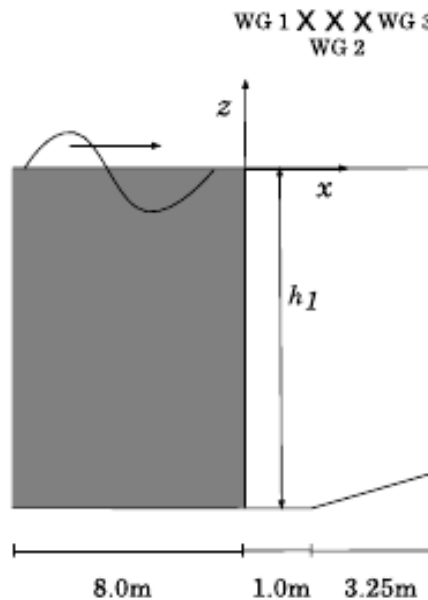
DTU Wind Energy
Department of Wind Energy



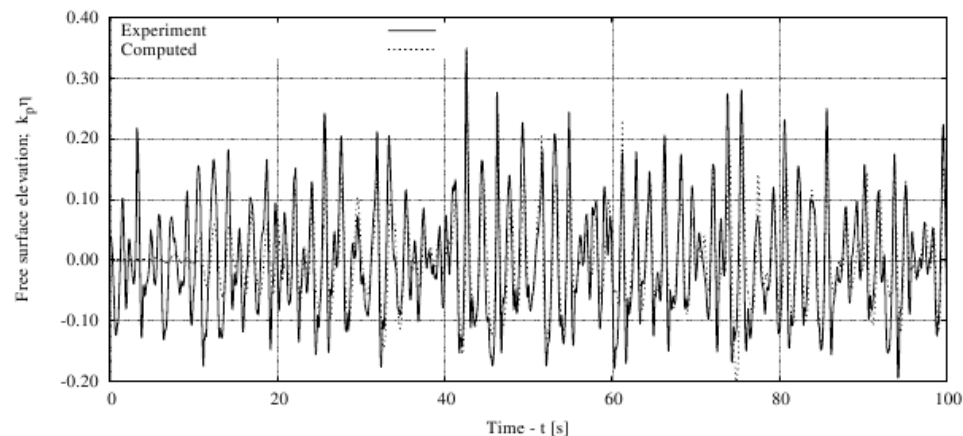
DTU Mechanical Engineering
Department of Mechanical Engineering

Validation for irregular wave forcing on a slope

Experiment in the Wave Loads project. $H_s=8.3\text{m}$ (full scale). Scale 1:36



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



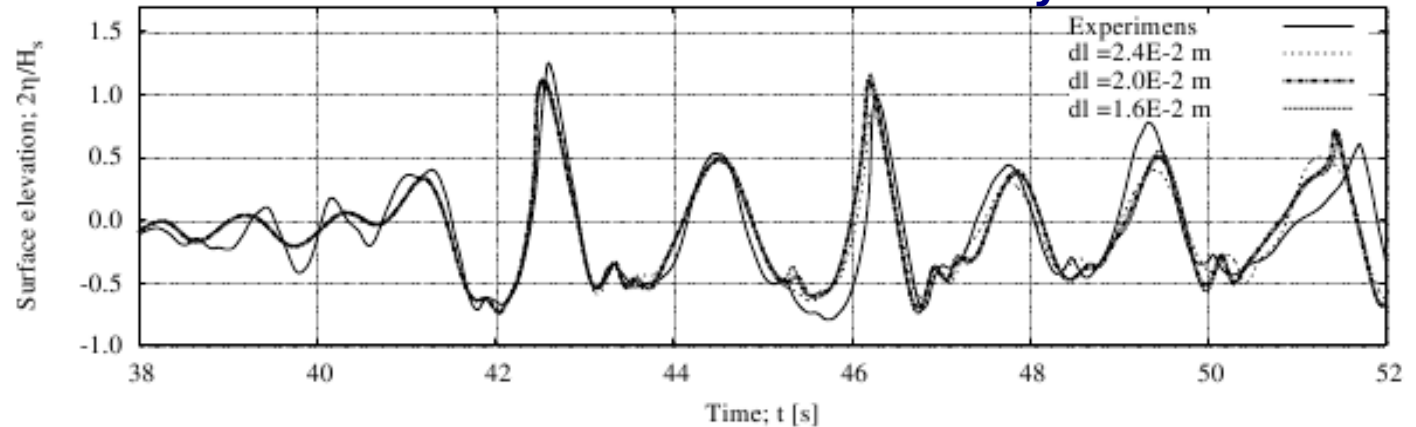
Bo Terp Paulsen

DTU Wind Energy
Department of Wind Energy

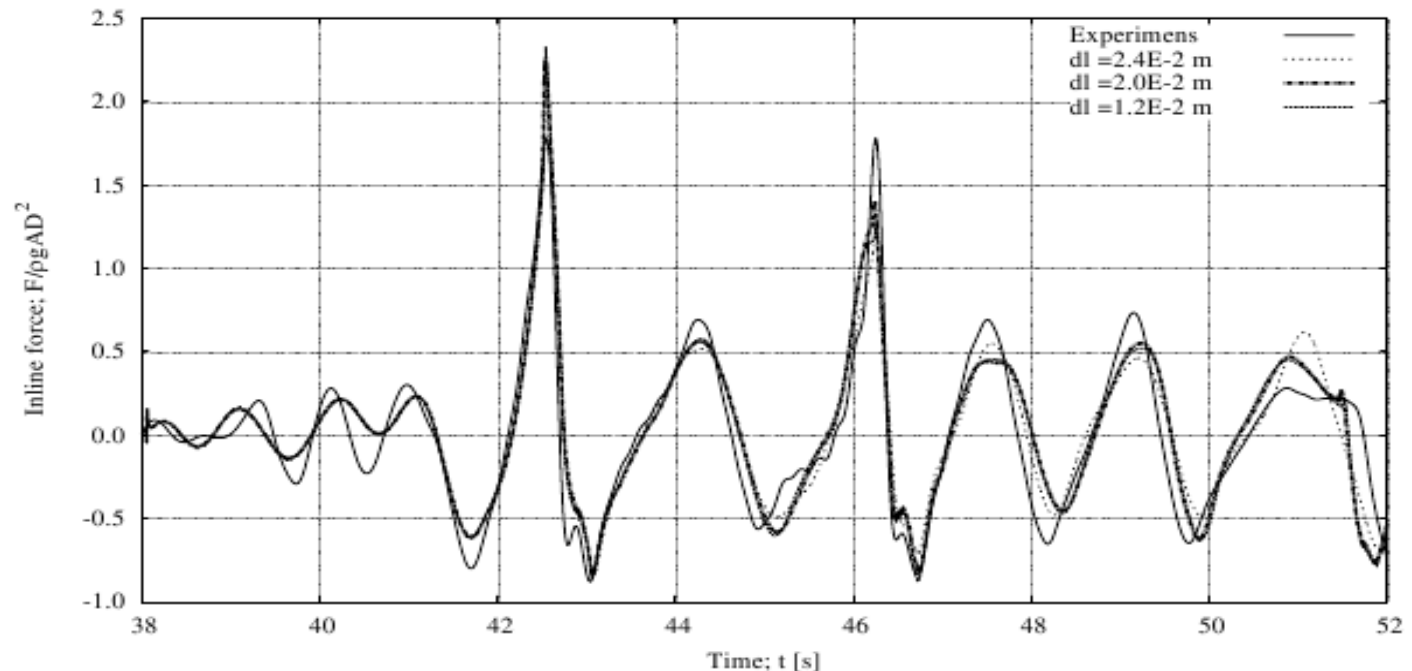
Validation for irregular wave forcing on a slope

Free surface elevation 0.25 cm in front of cylinder

Experiment

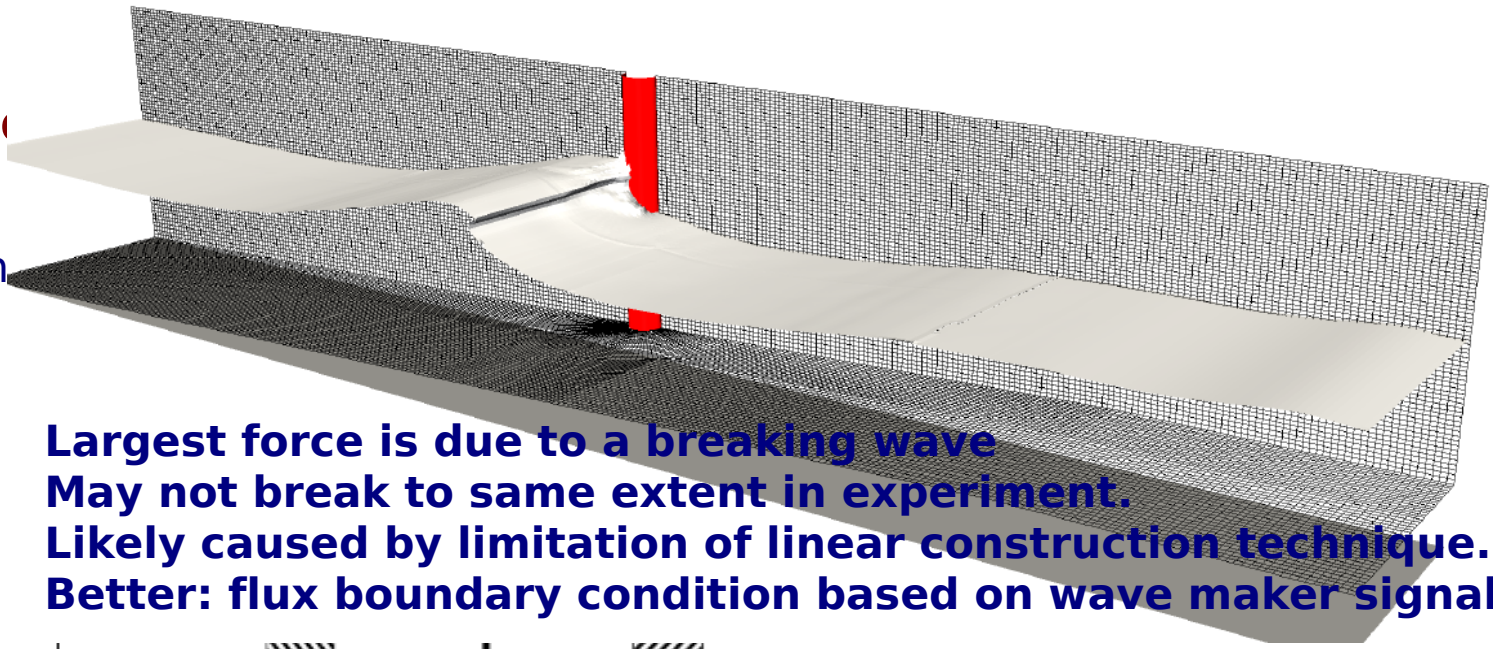


Inline force history



Validation

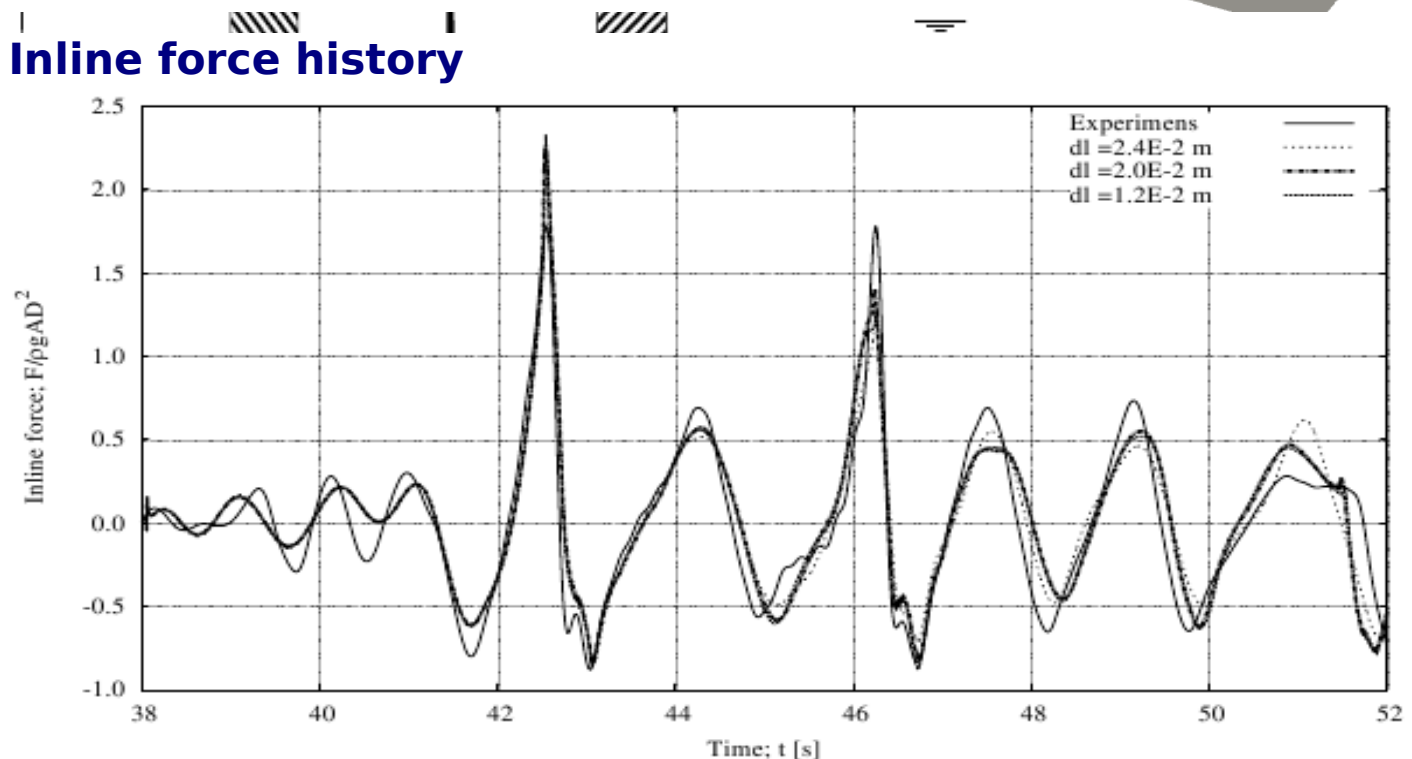
Experiment



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



Inline force history



Computation of multi-directional waves

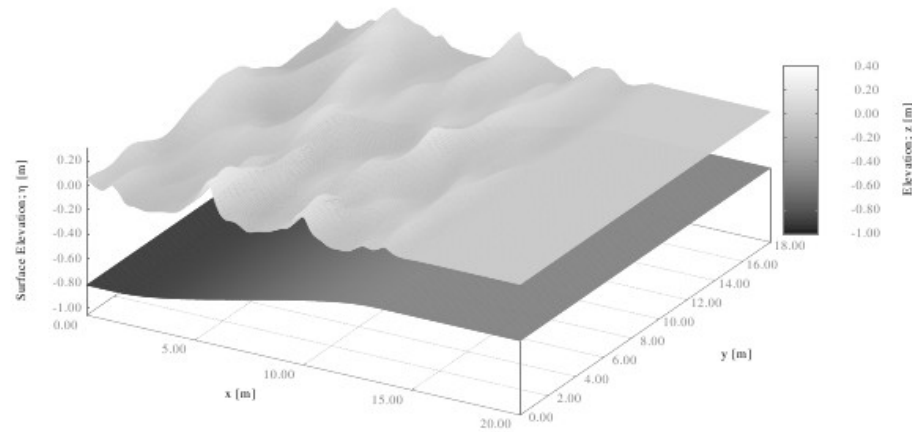
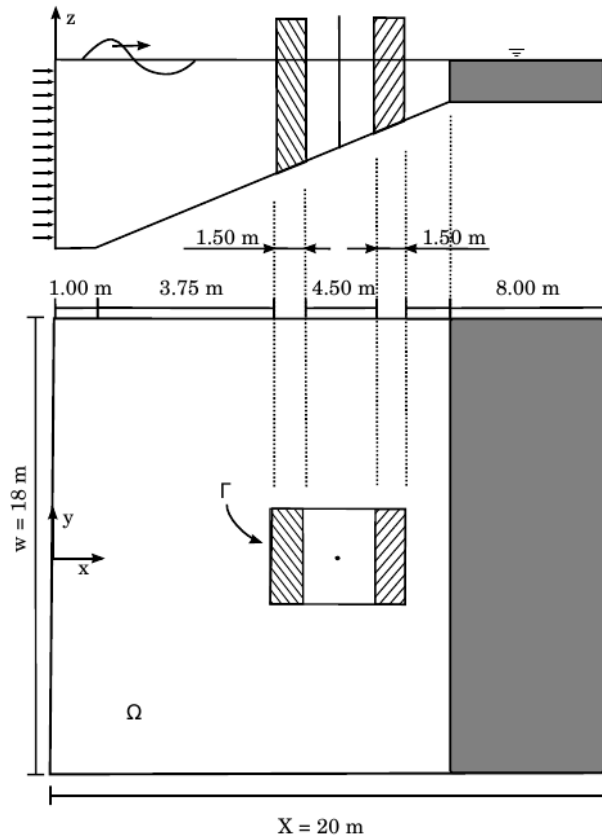


Figure 3.27: Snapshot of the free surface elevation computed by the potential flow solver at time $t = 15\text{ s}$.

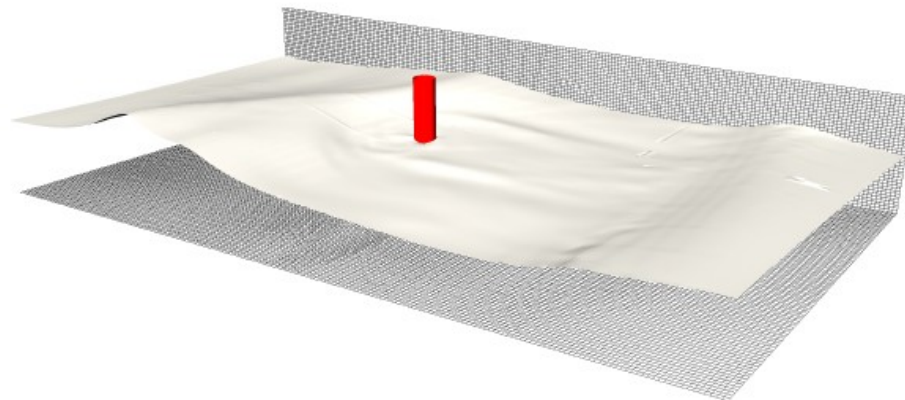
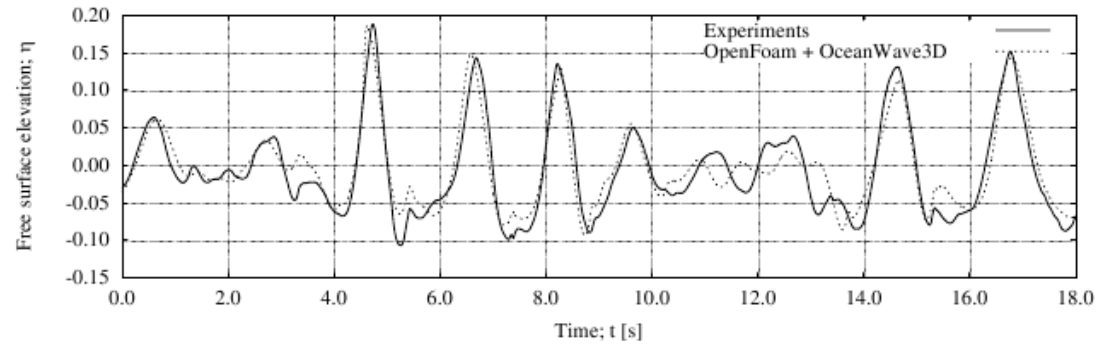
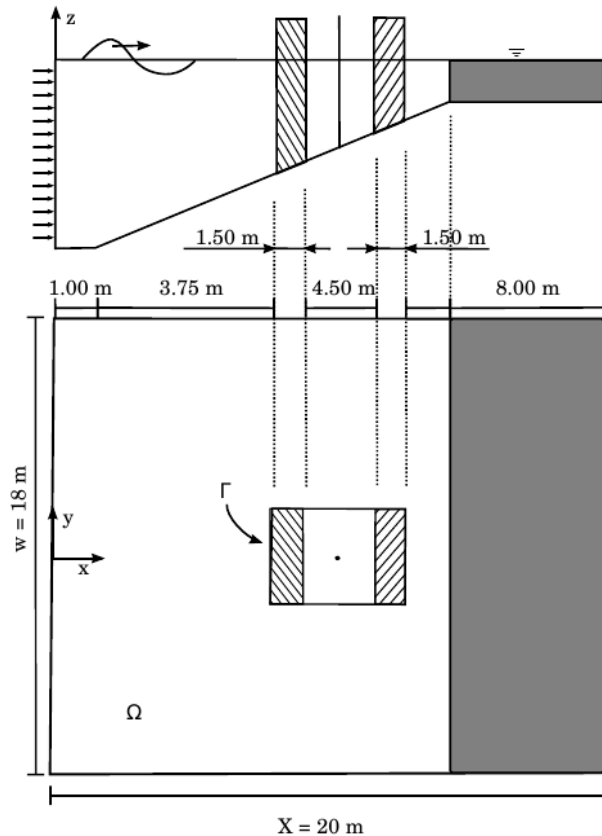
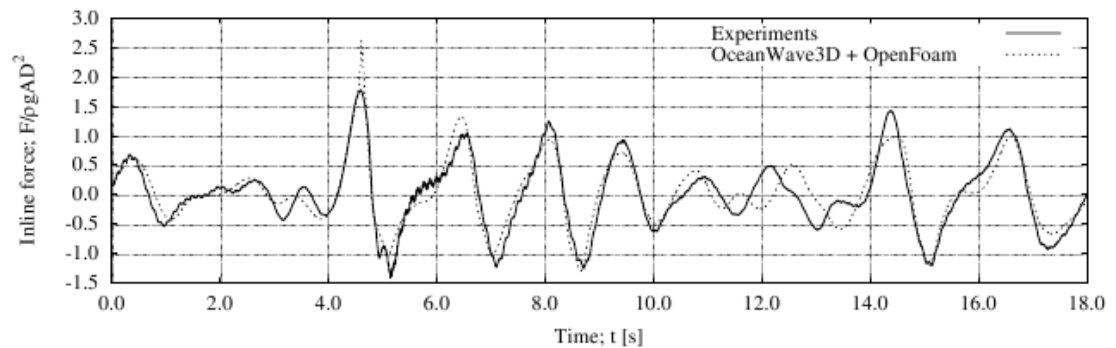


Figure 3.28: Snapshot of the free surface elevation computed by the Navier-Stokes solver at time $t = 15\text{ s}$.

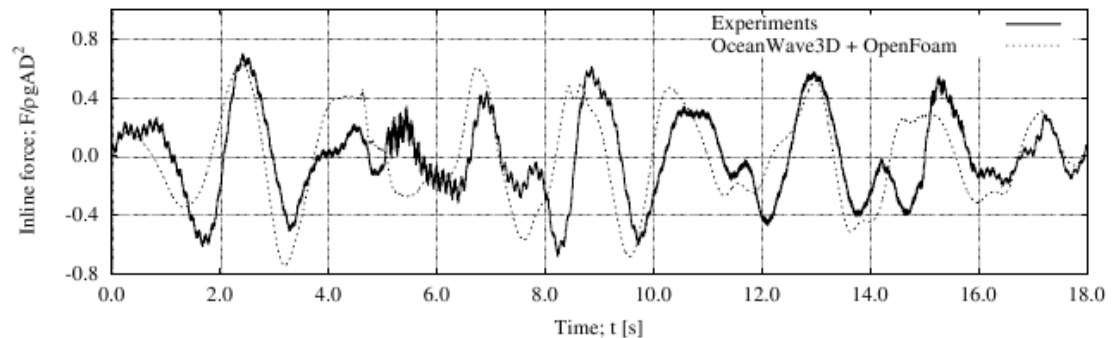
Computation of multi-directional waves



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

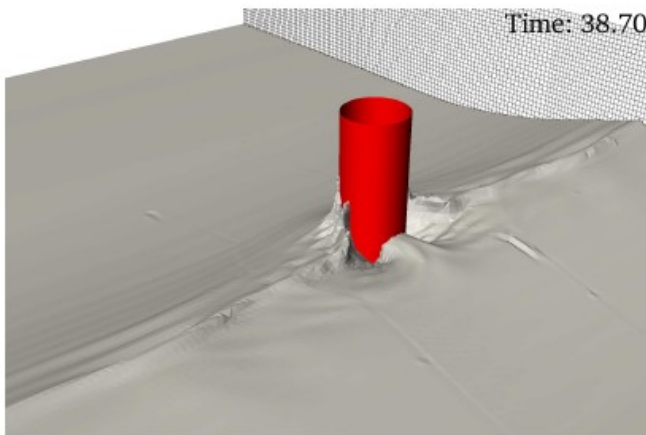


(a) Measured and computed inline force on the cylinder.

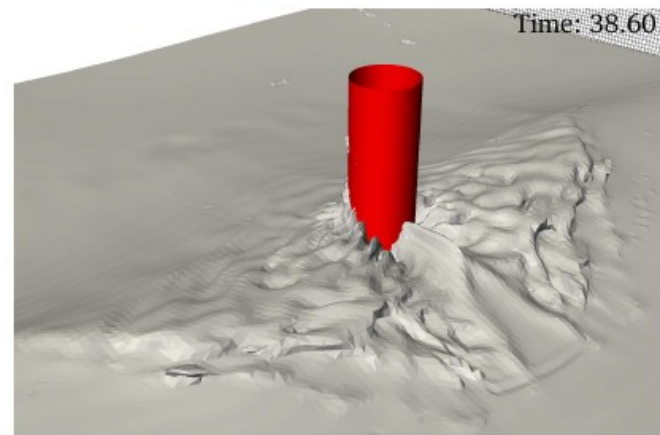


(b) Measured and computed force on the cylinder in the y -direction

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



(c) Unidirectional: The wave passage



(d) Bi-directional: The wave passage

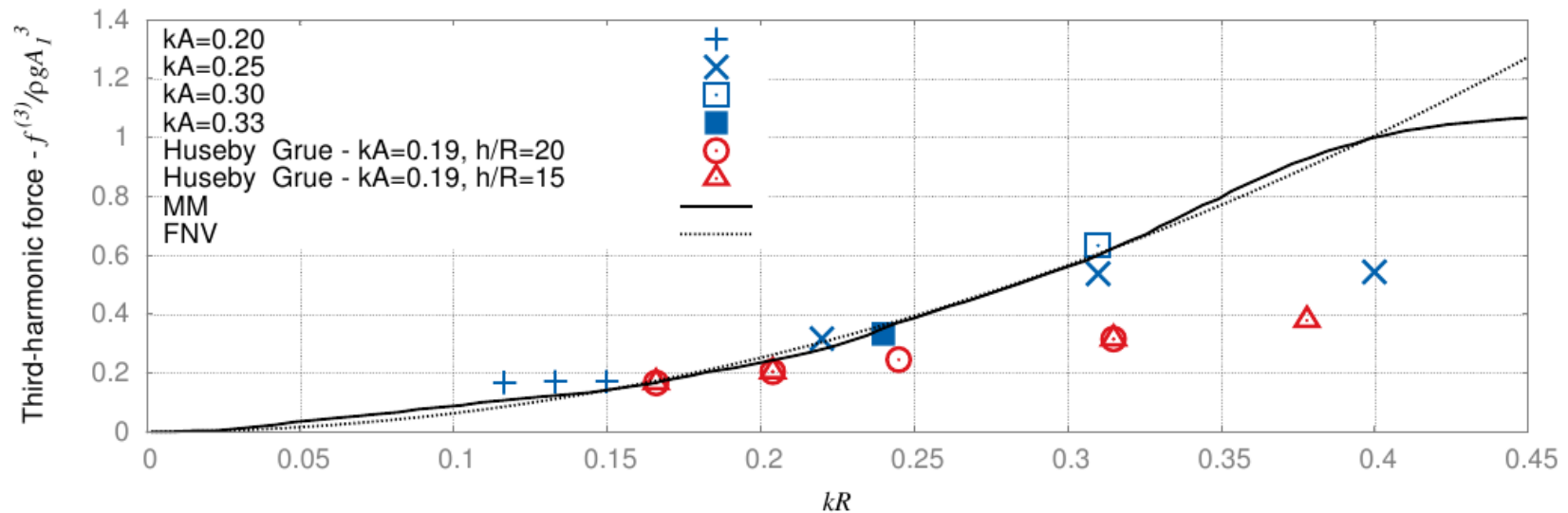
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Detailed study of regular wave forcing and higher-harmonic components



Third-harmonic force compared to FNV theory

Paulsen et al
IWWF 2012

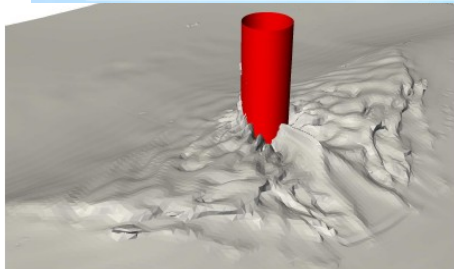
The Wave Loads project

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

Task A:

Boundary conditions for phase resolving wave models

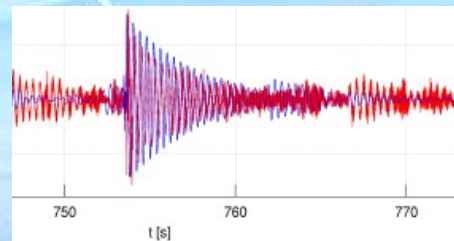
DHI



Task C:

Aero-elastic response to fully nonlinear wave forcing

DTU



Task B:

CFD methods for steep and breaking wave impacts

DTU, (DHI)



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

Target values
from NREL 5MW
reference WT

Pipe properties

	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	4.20·10 ¹⁰ Nm ²
ζ (estimated)	0.017	0.017
Density	0.64 kg/m	4.20·10 ³ kg/m
height	200 cm	160 m
m_1	1.786 kg	937·10 ³ kg
m_2	1.784 kg	936·10 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

tuning to get
1st and 2nd scaled
nat frequencies



Instrumentation

accelerometers

displacement
transducer

Wave gauges!



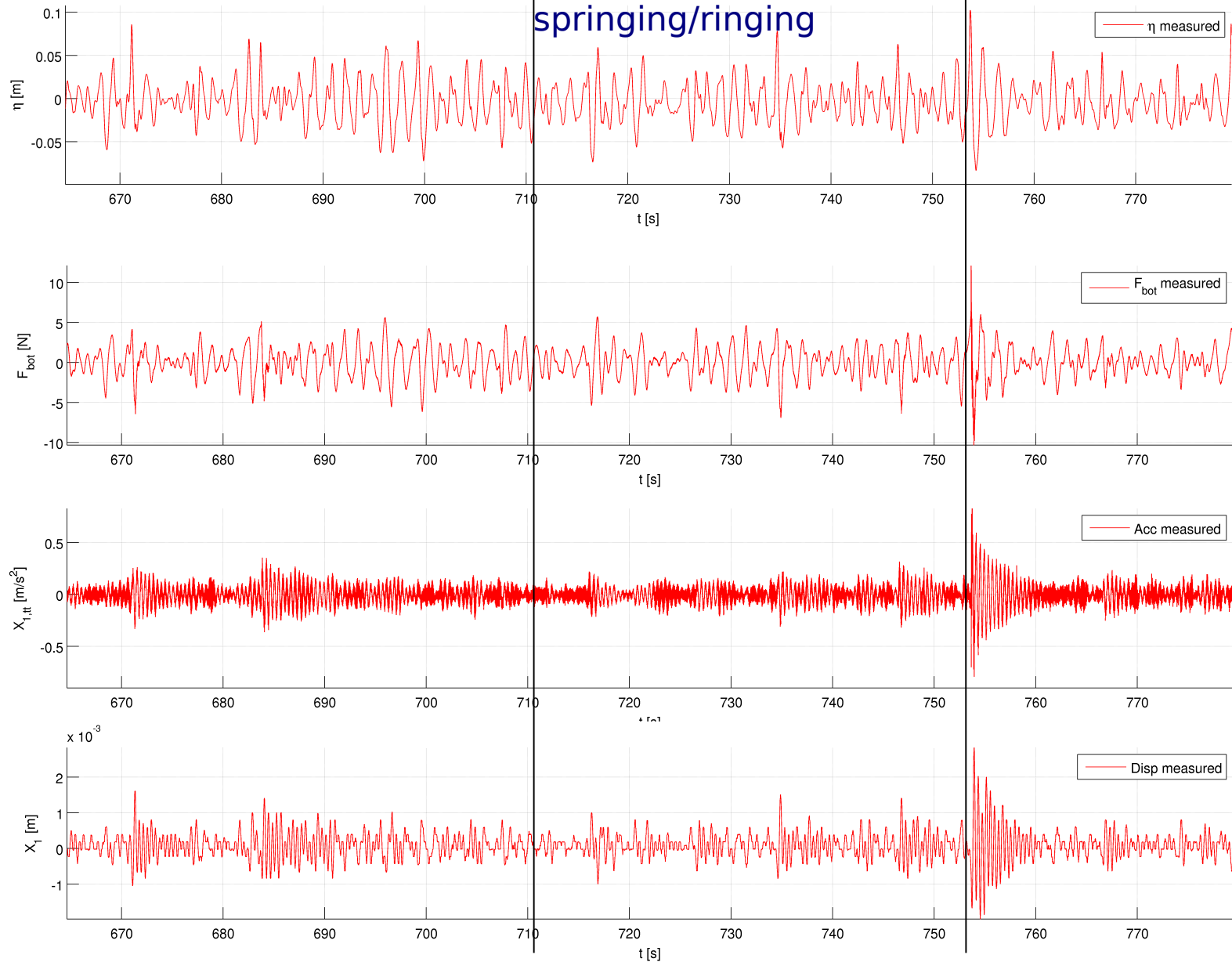
Example of measurement

$h=40.8\text{m}$; $H_s=8.3\text{m}$; $T_p=12.6\text{s}$

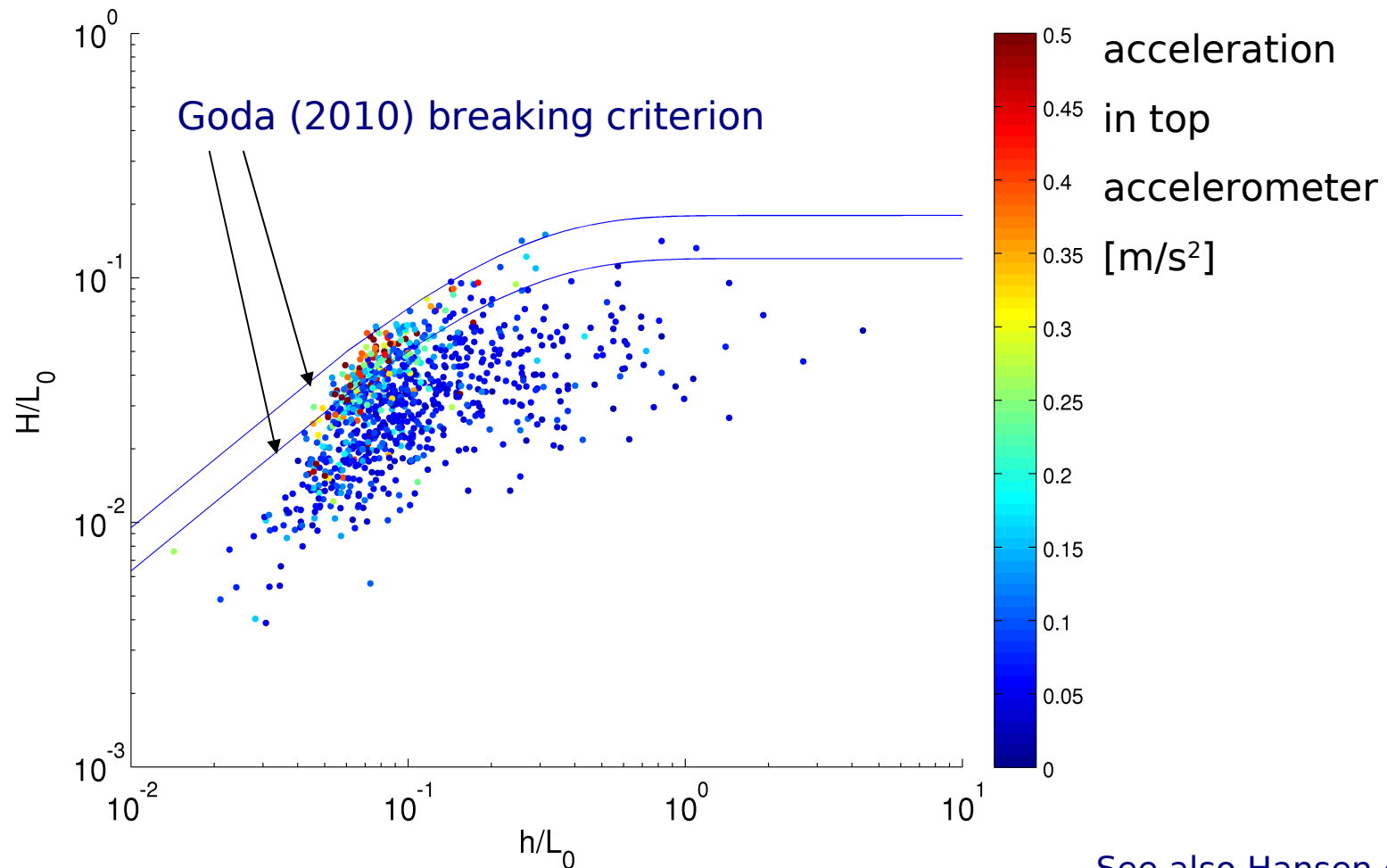
impulsive excitation



continuous forcing:
springing/ringing



Which waves give the largest accelerations?



See also Hansen et al
(OMAE 2012)

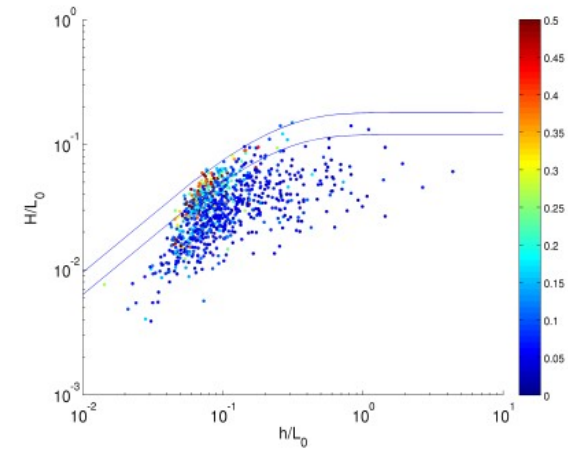
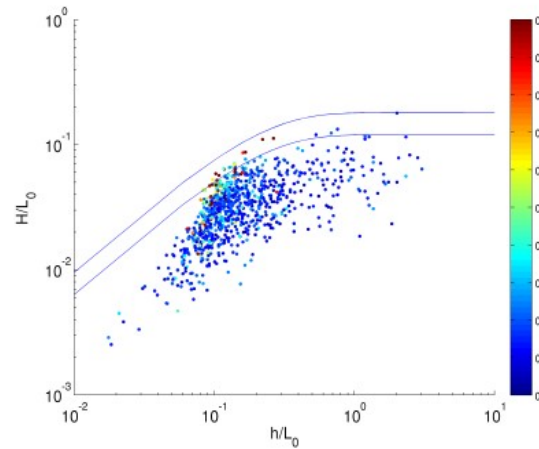
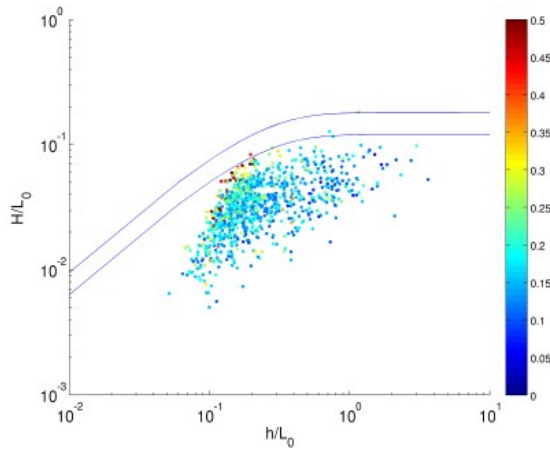
Which waves give the largest accelerations?

$h = 40.8 \text{ m}$

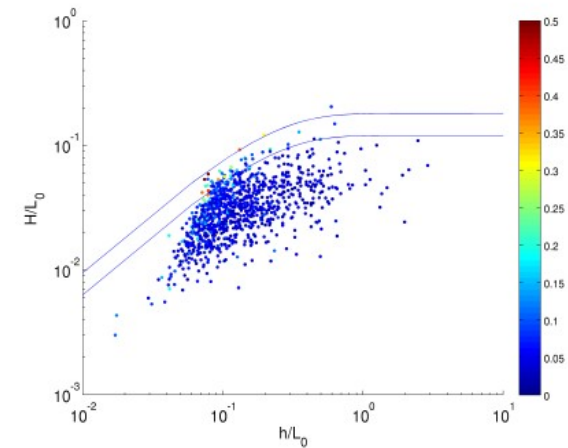
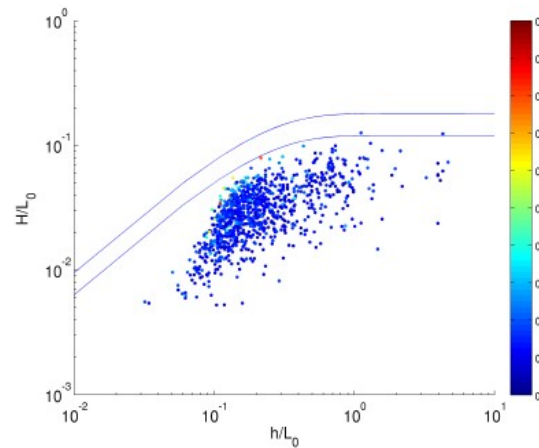
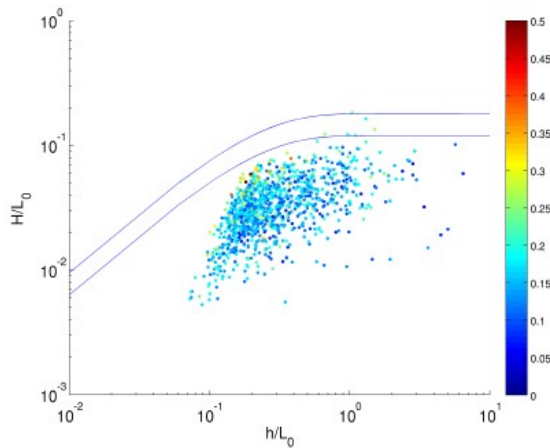
$h = 30.8 \text{ m}$

$h = 20.8 \text{ m}$

$H_s = 11 \text{ m}$



$H_s = 8.3 \text{ m}$



Deeper water: larger bulk accelerations. **DEPTH AND ARM**

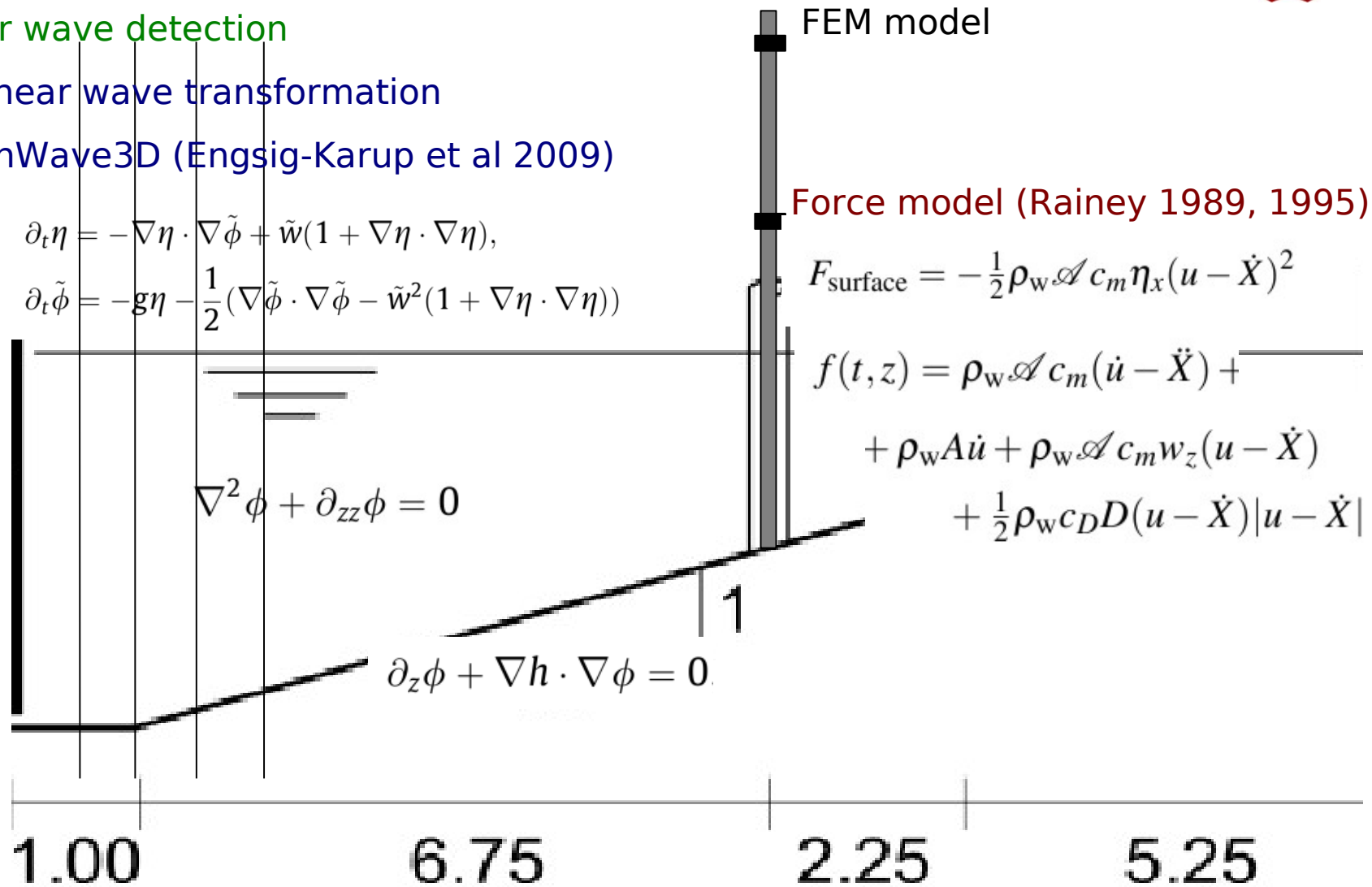
Shallow water: larger extreme accelerations. **NONLINEARITY AND BREAKING**

Numerical reproduction of experiments

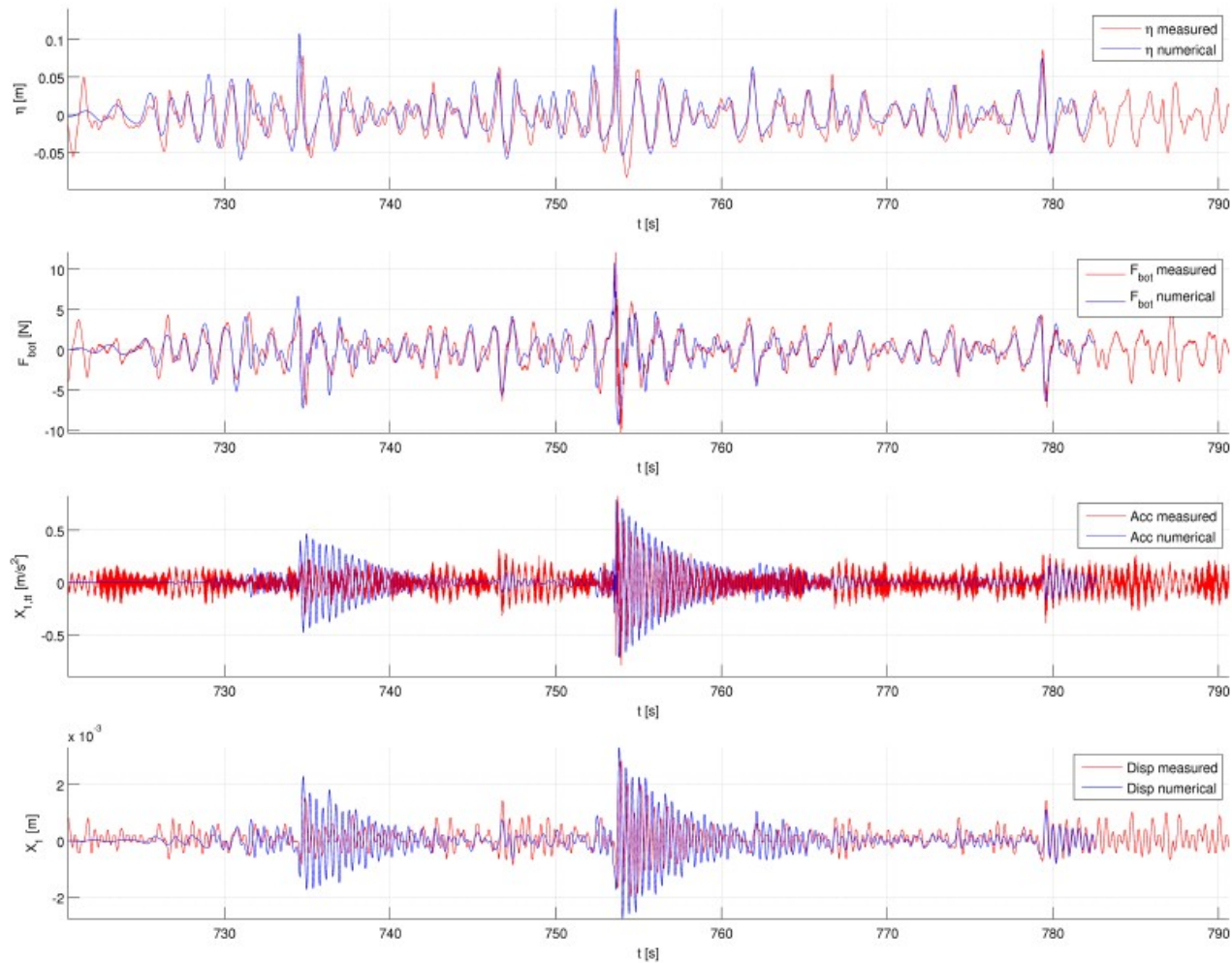
Linear wave detection

Nonlinear wave transformation

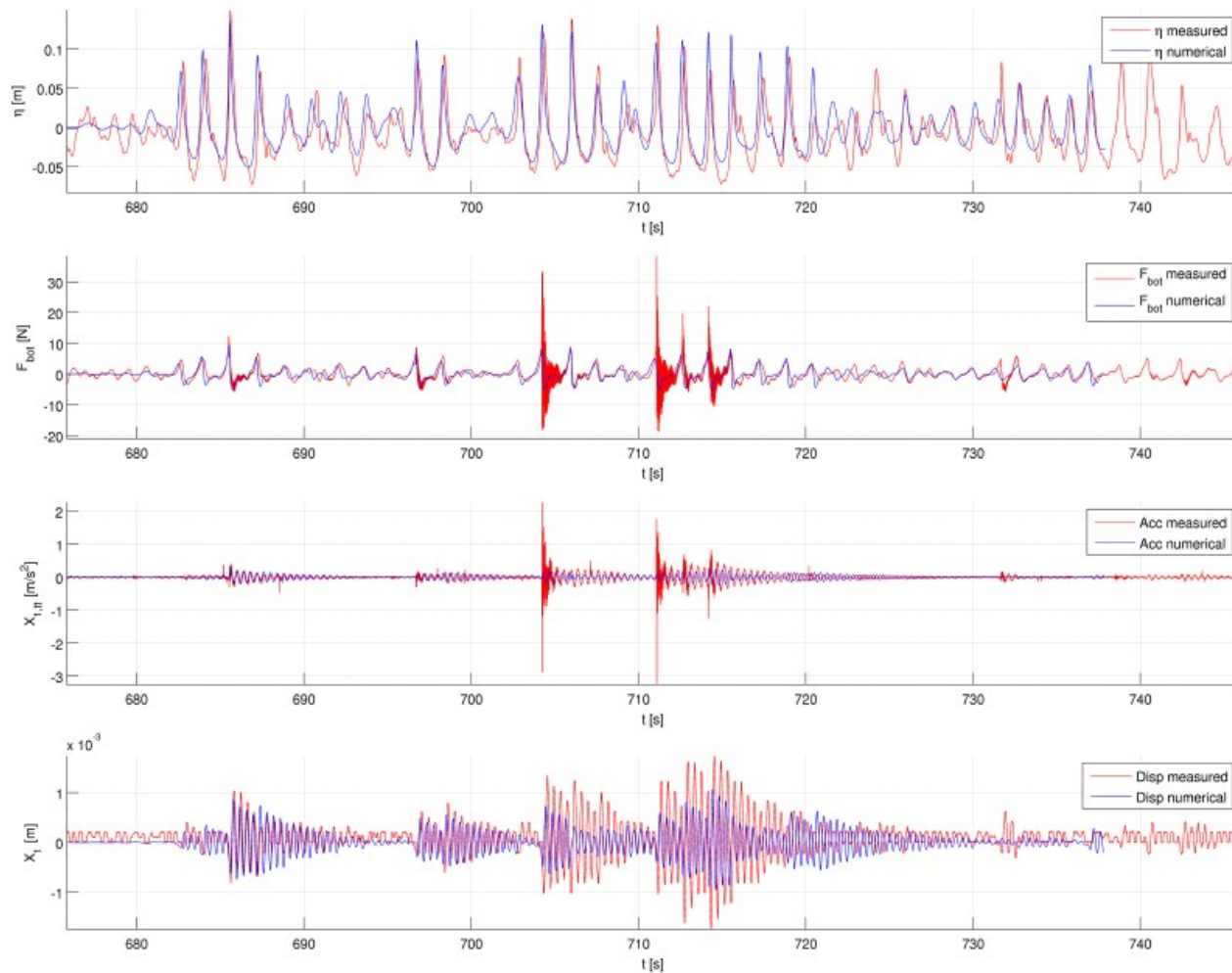
OceanWave3D (Engsig-Karup et al 2009)



Response, $h=40.8$ m



Response, $h=20.8$ m



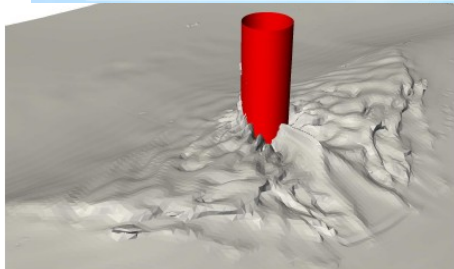
The Wave Loads project

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

Task A:

Boundary conditions for phase resolving wave models

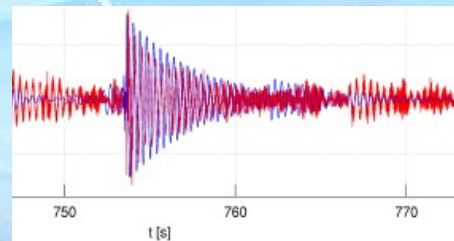
DHI



Task C:

Aero-elastic response to fully nonlinear wave forcing

DTU



Task B:

CFD methods for steep and breaking wave impacts

DTU, (DHI)



Task D:

Physical model tests

DHI