Danish Wind Industry Annual Event 26-27 March 2014

# The Wave Loads project
# Key results and future trends

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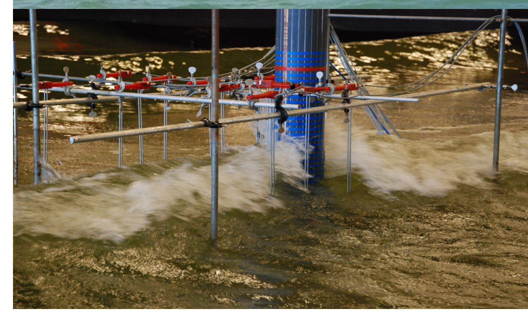

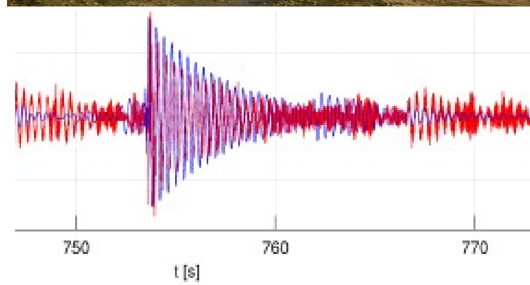


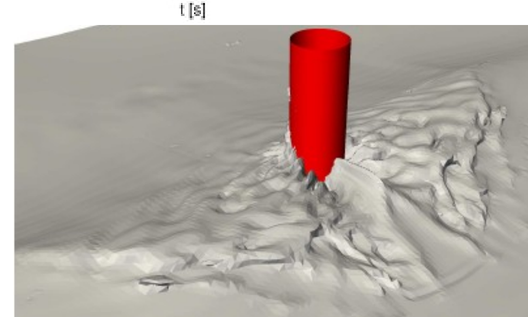

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# The Wave Loads project

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Bjarne Jensen
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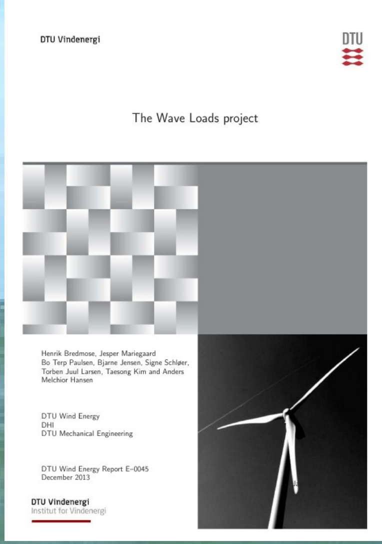
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The Wave Loads project

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DTU Wind Energy Report E-0045
December 2013

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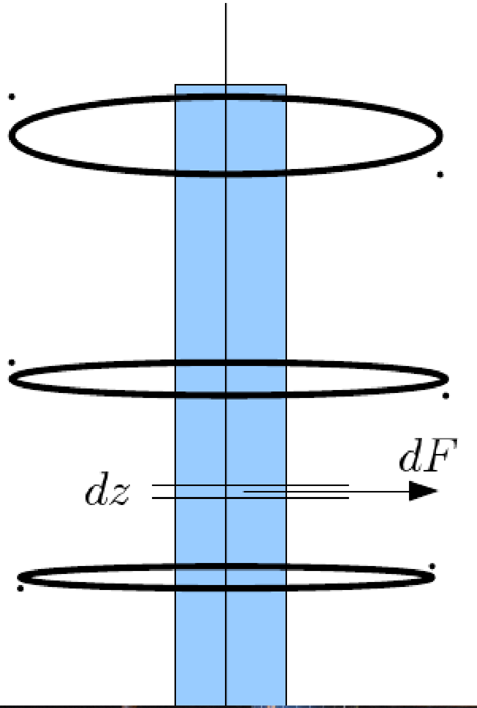
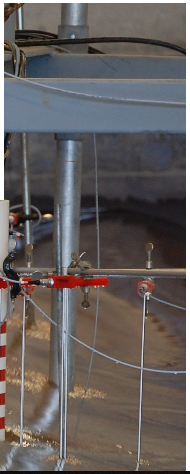
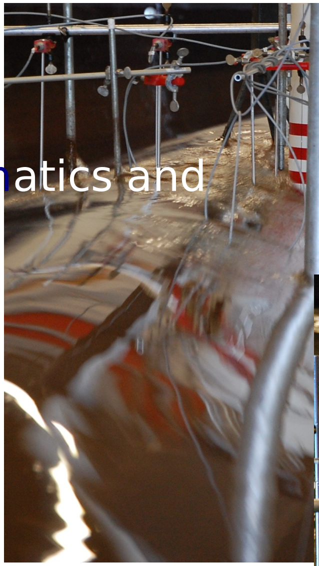
# Hydrodynamic loads

Simplest: Linear wave kinematics and Morison equation

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



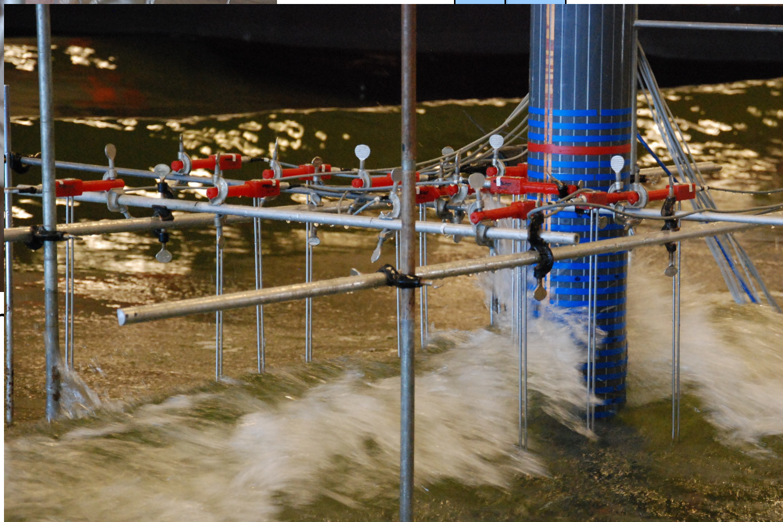


Better: Fully nonlinear wave kinematics and

Morison-type force model

Advanced: CFD and coupled CFD

Zang ar



# What is ringing?

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

J. Grue, M. Huseby / Applied Ocean Research 24 (2002) 203–214

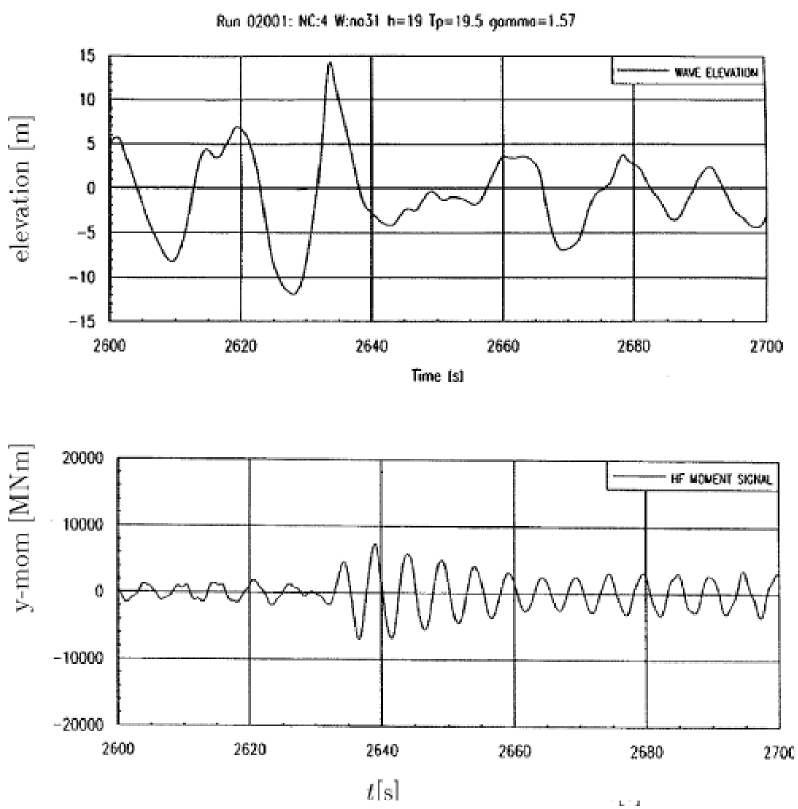
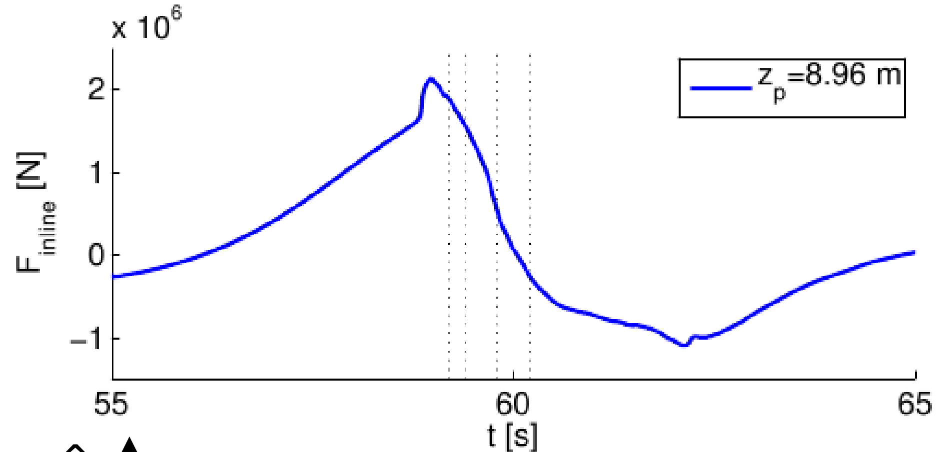
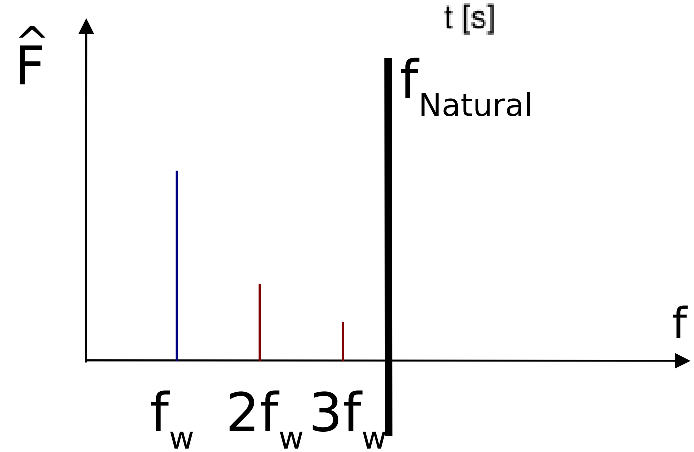



Fig. 8. Resonant build-up of vibrations in model tests [3, Fig. 3.3]. Bending moment of the Draugen GBS (lower). $(k\eta_m, kR) = (0.22, 0.13)$. Wave elevation (upper). Reproduced with kind permission by Shell.




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?

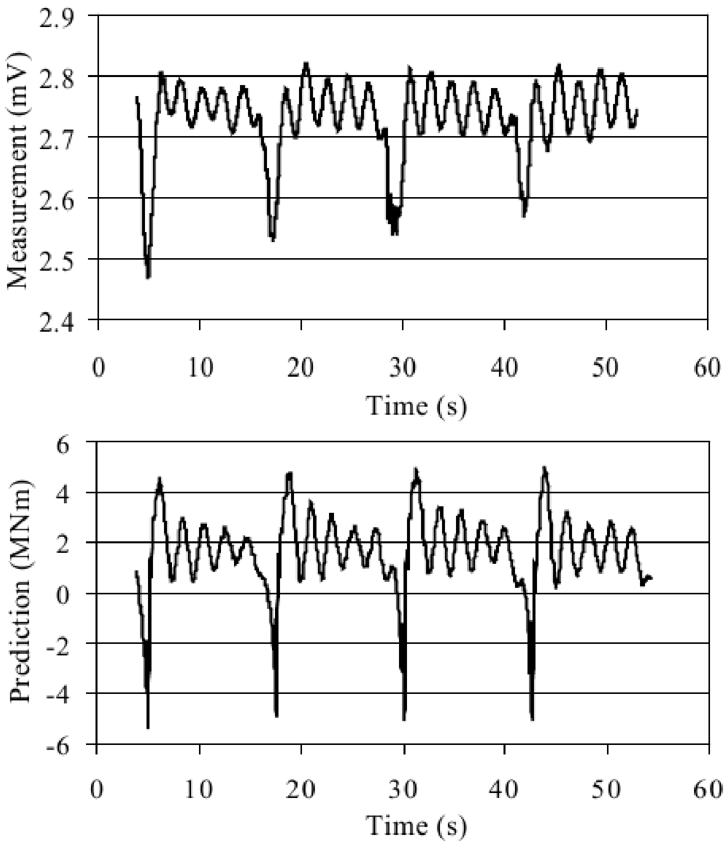
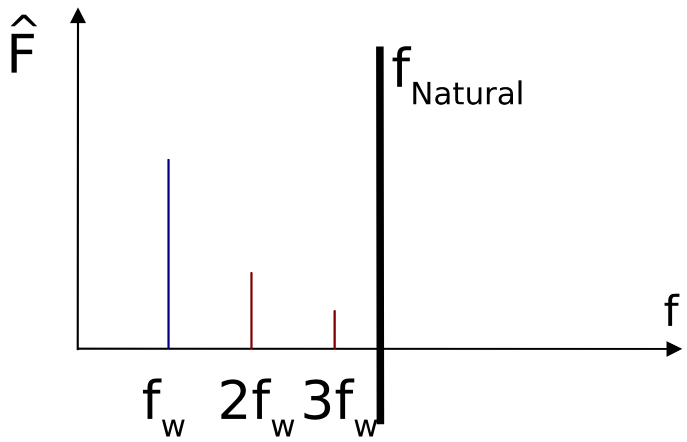



**Figure 12:** Measured and predicted breaking wave loads

From Camp et al (2002; 2003)

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



# The Wave Loads project

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**Task A**:

Boundary conditions for phase resolving wave models

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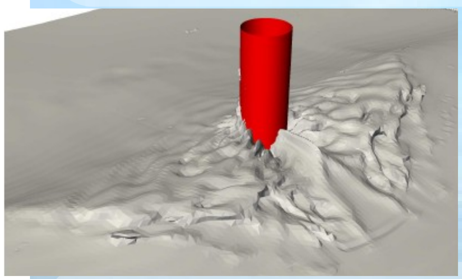
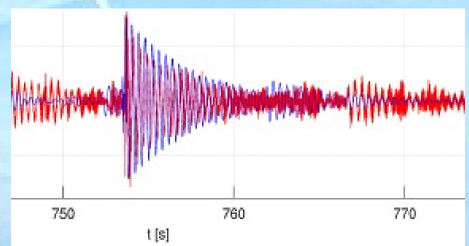


**Task C**:

Aero-elastic response to fully nonlinear wave forcing

DTU

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**Task B**:

CFD methods for steep and breaking wave impacts

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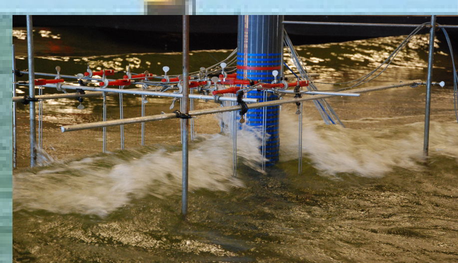
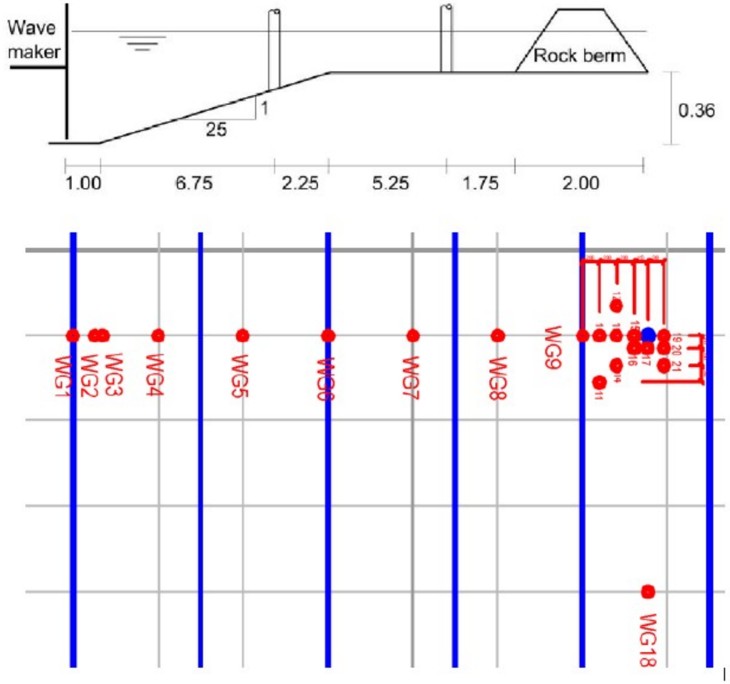


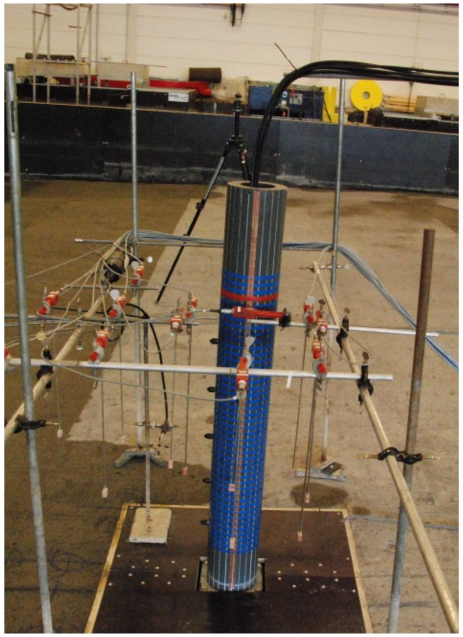
**Task D**:

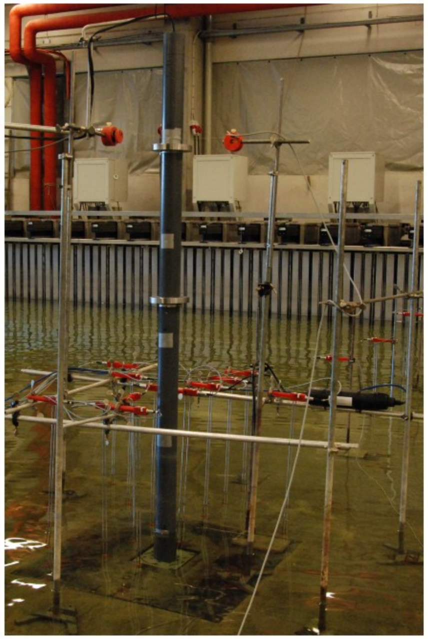
Physical model tests

DHI

# Physical tests at DHI

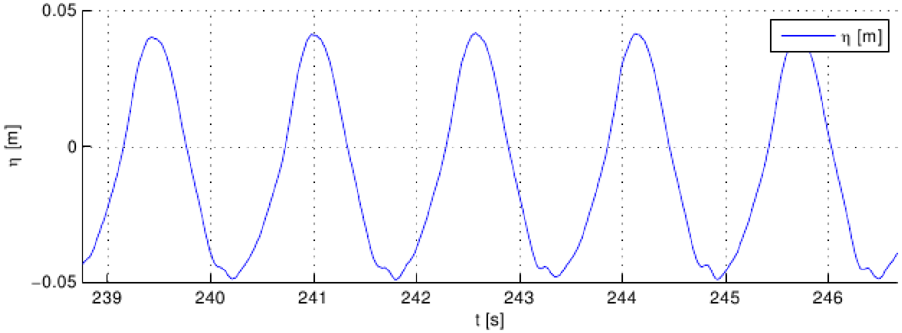


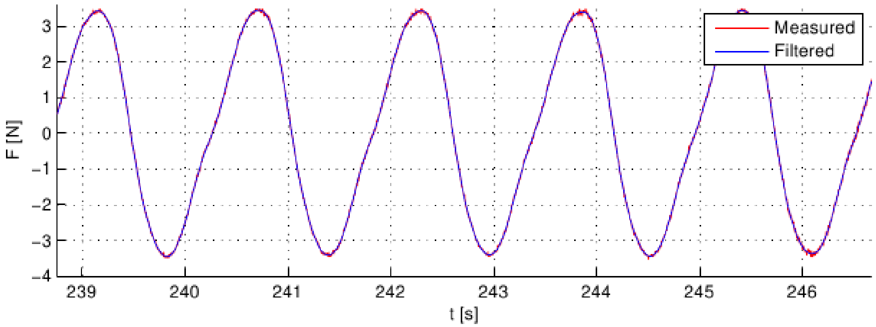





# 2D regular waves

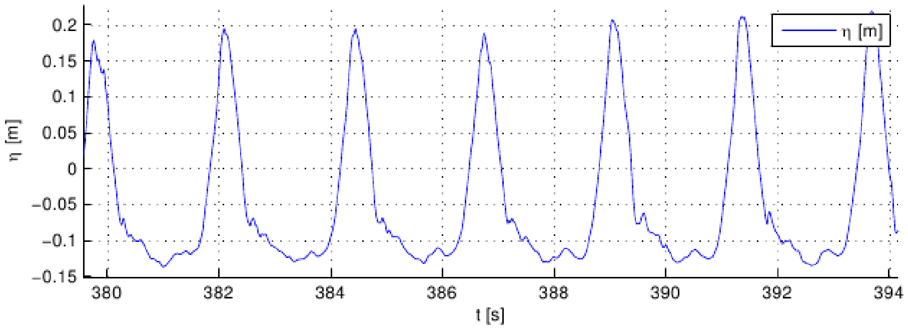
## Weakly nonlinear

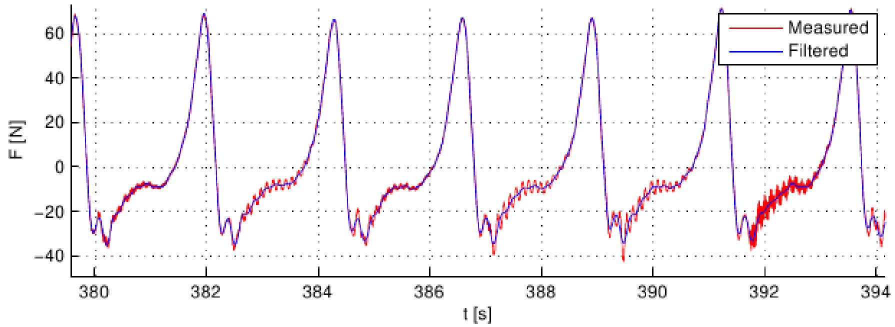



1:80; h=40.8m; H=8m; T=14s (at full scale)

## Strongly nonlinear

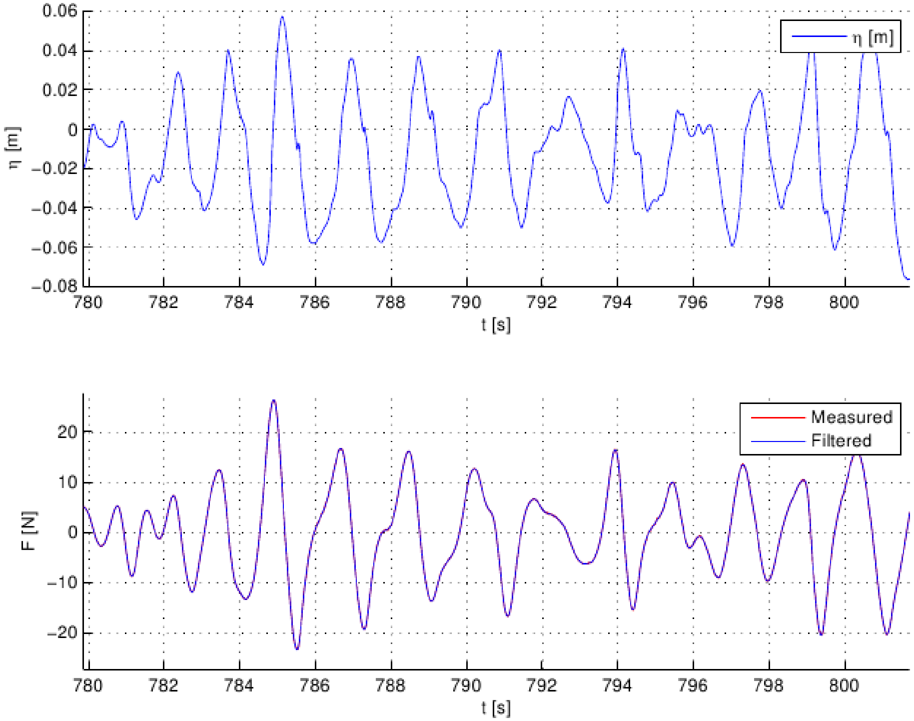



1:36.6; h=17.2m; H=11m; T=14s (at full scale)

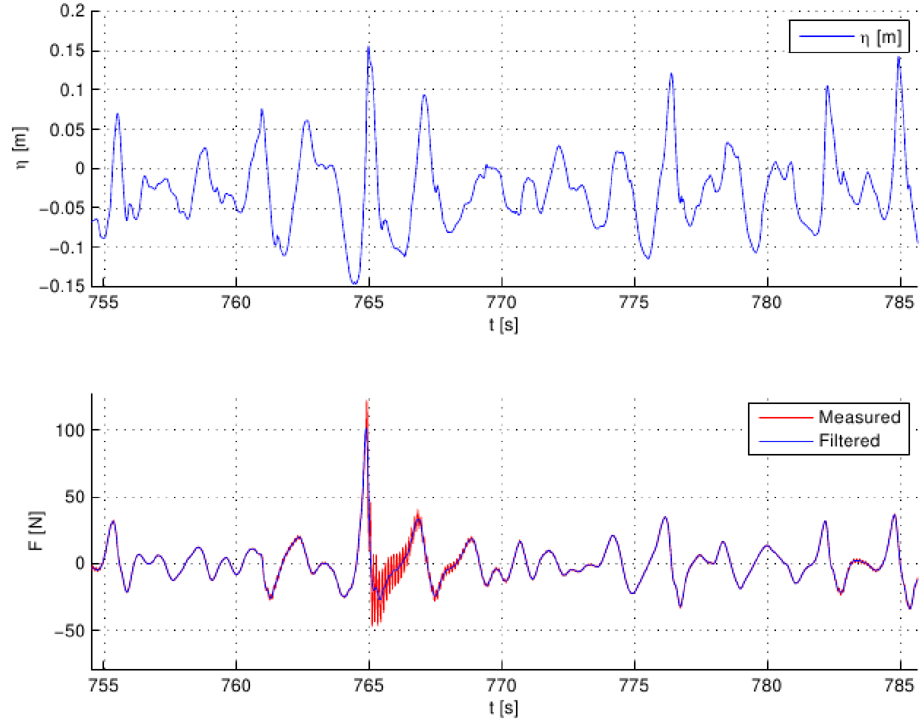
# 3D irregular waves

## Weakly nonlinear




1:36.6; h=17.2m; Hs=4.3m; Tp=10.2s (at full scale)

## nonlinear




1:36.6; h=17.2m; H=8.3m; T=12.6s (at full scale)

# 3D irregular waves

Weakly nonlinear


1:36.6; h=17.2m; Hs=4.3m; Tp=10.2s (at full scale)

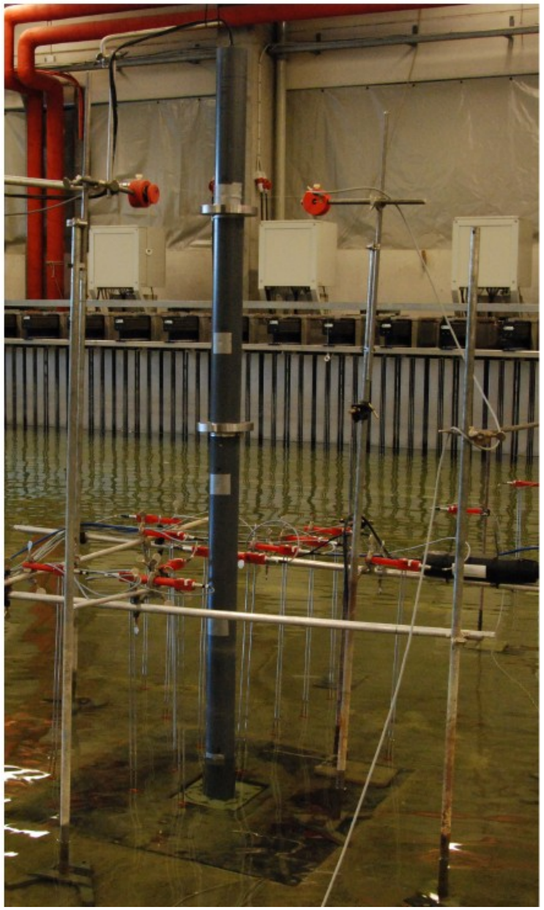
1:36.6; h=17.2m; H=8.3m; T=12.6s (at full scale)

# Tests with a flexible cylinder

Bredmose et al OMAE 2013

Inspiration from de Ridder et al OMAE 2011

Target values from NREL 5MW reference WT



Pipe properties

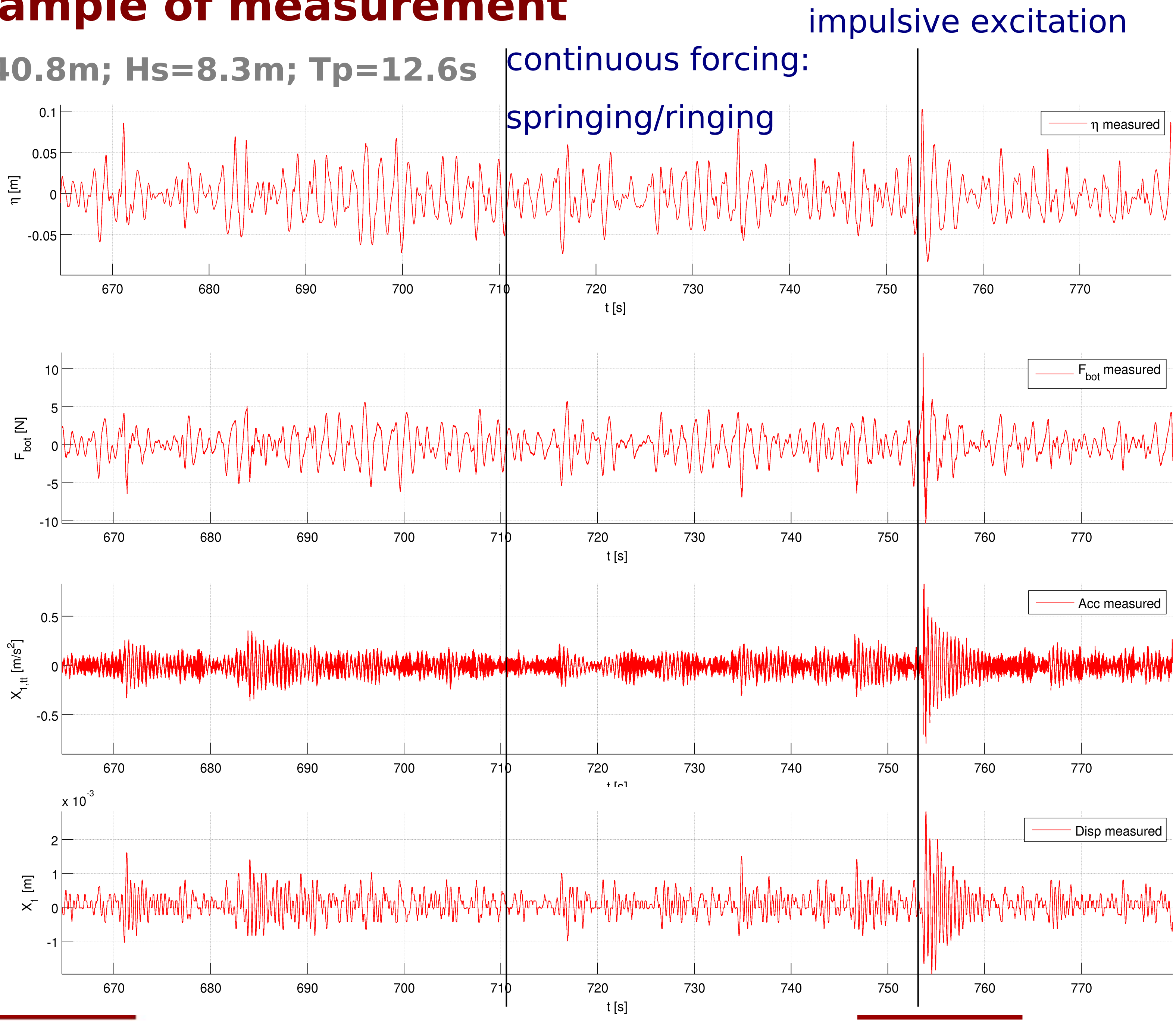
tuning to get 1st and 2nd scaled nat frequencies

| | Lab scale (1:80) | Prototype scale |
|---|---|---|
| $D_{\text{outer}}$ | 7.5 cm | 6.0 m |
| Wall thickness | 1.8 mm | 0.144 m |
| EI (estimated) | 1026 Nm$^2$ | 4.20·10$^{10}$ Nm$^2$ |
| $\zeta$ (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 |

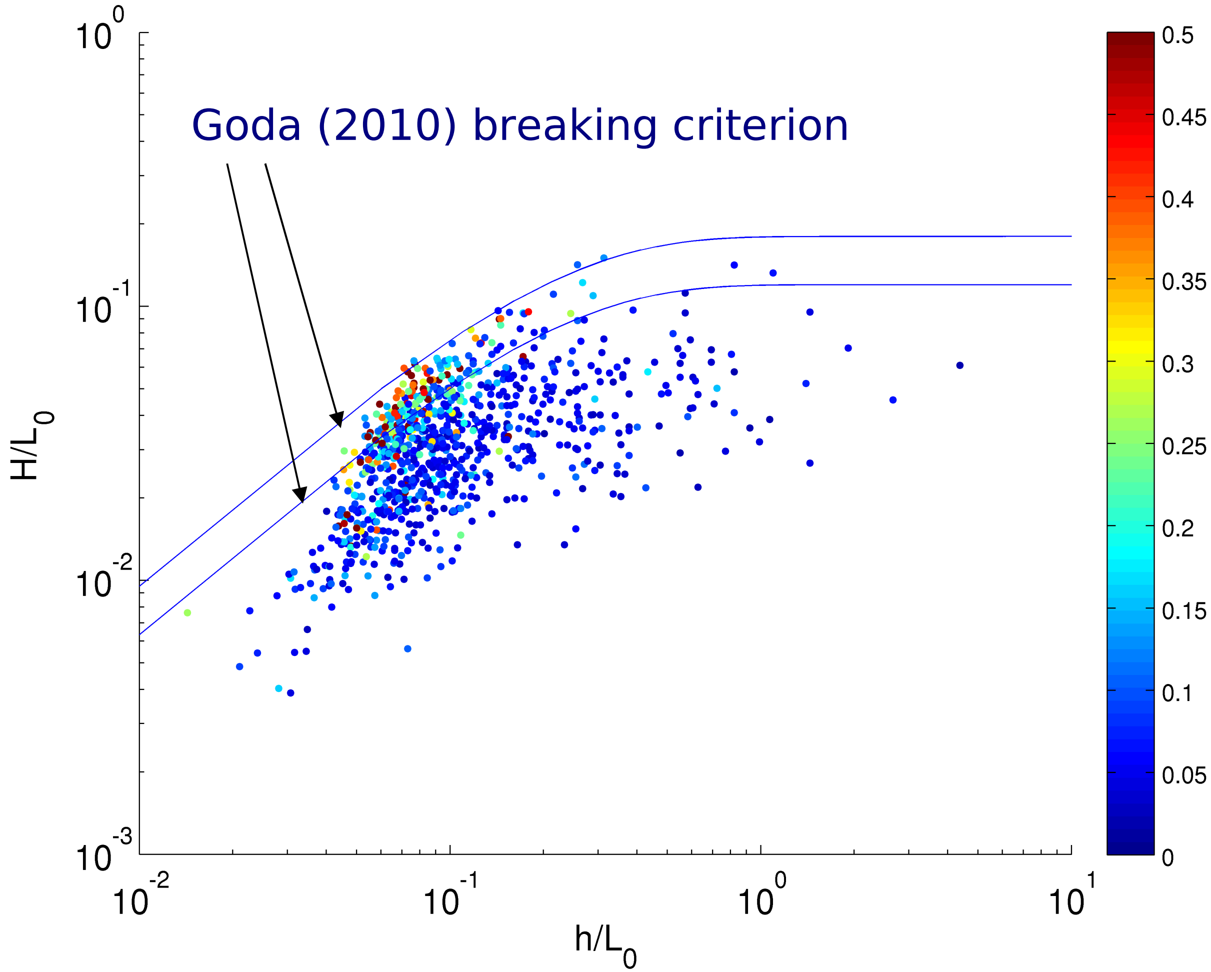
**TABLE 1.** Data for flexible pipe. Prototype values are indicated just for reference.

# Example of measurement

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



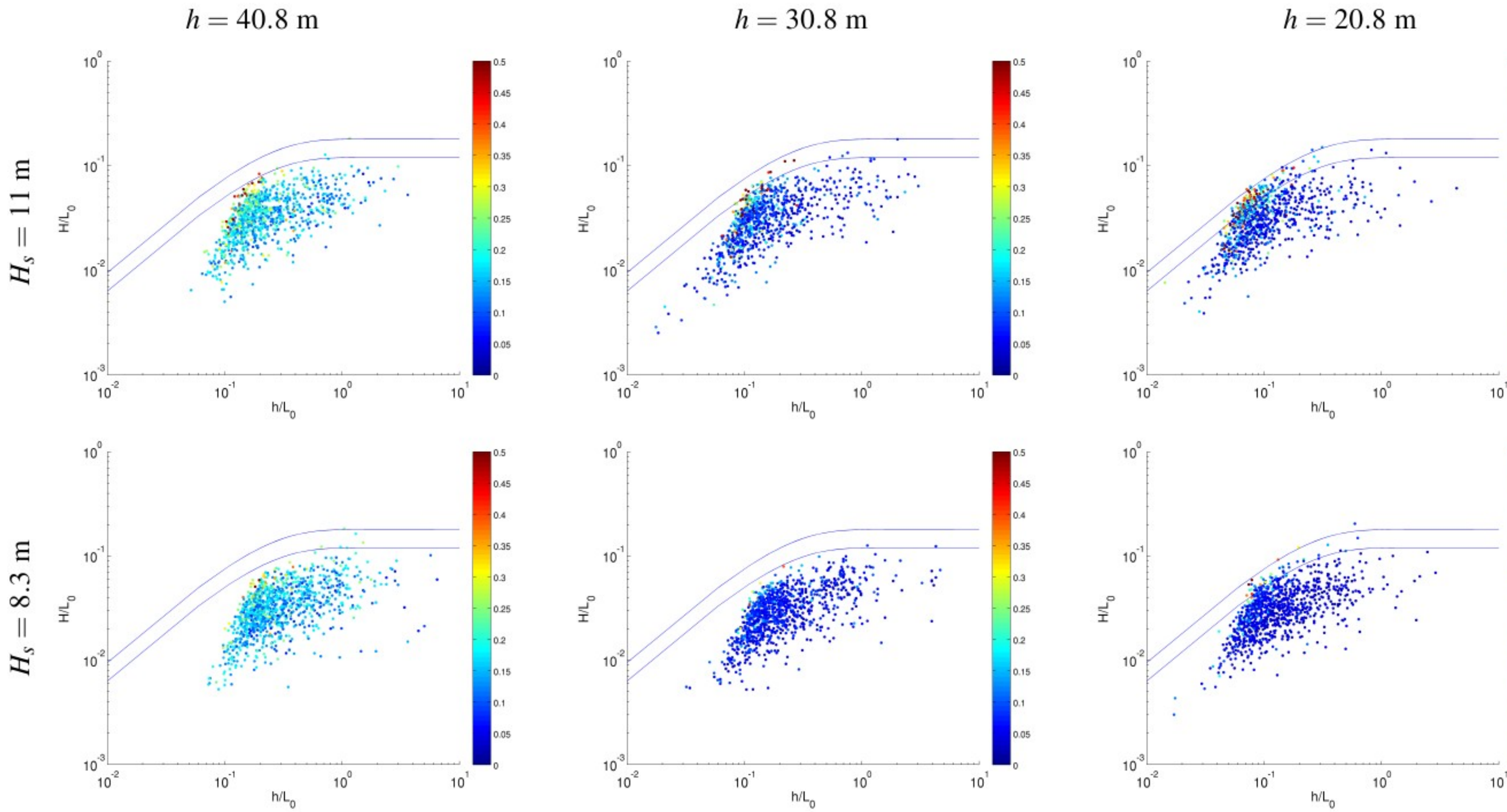
# Which waves give the largest accelerations?




acceleration in top accelerometer [m/s²]

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

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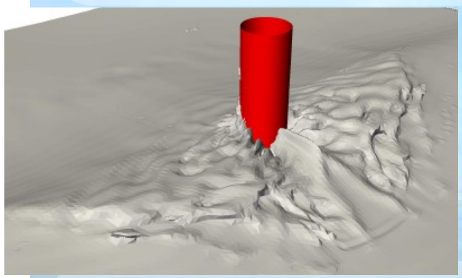
DHI



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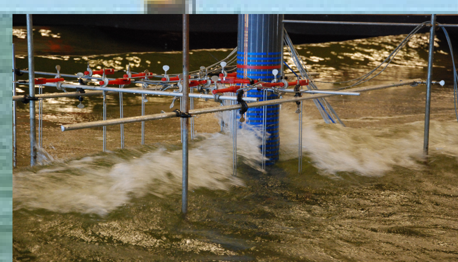
CFD methods for steep and breaking wave impacts

DTU, (DHI)



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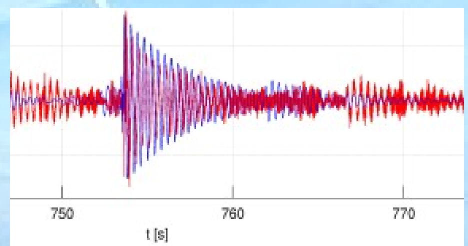
Aero-elastic response to fully nonlinear wave forcing

DTU

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**Task D**:

Physical model tests

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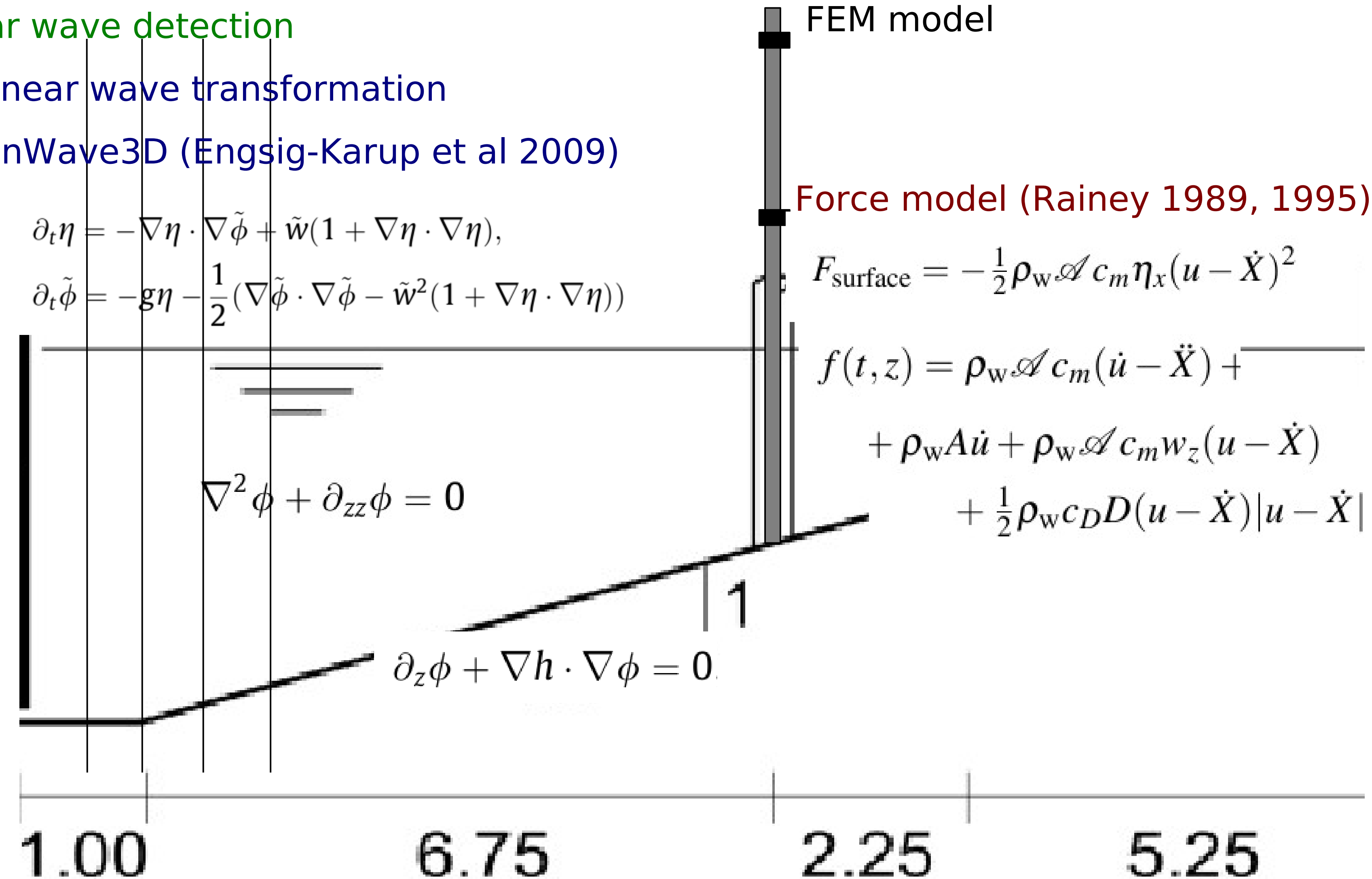
# Numerical reproduction of experiments

Linear wave detection

Nonlinear wave transformation

OceanWave3D (Engsig-Karup et al 2009)




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

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

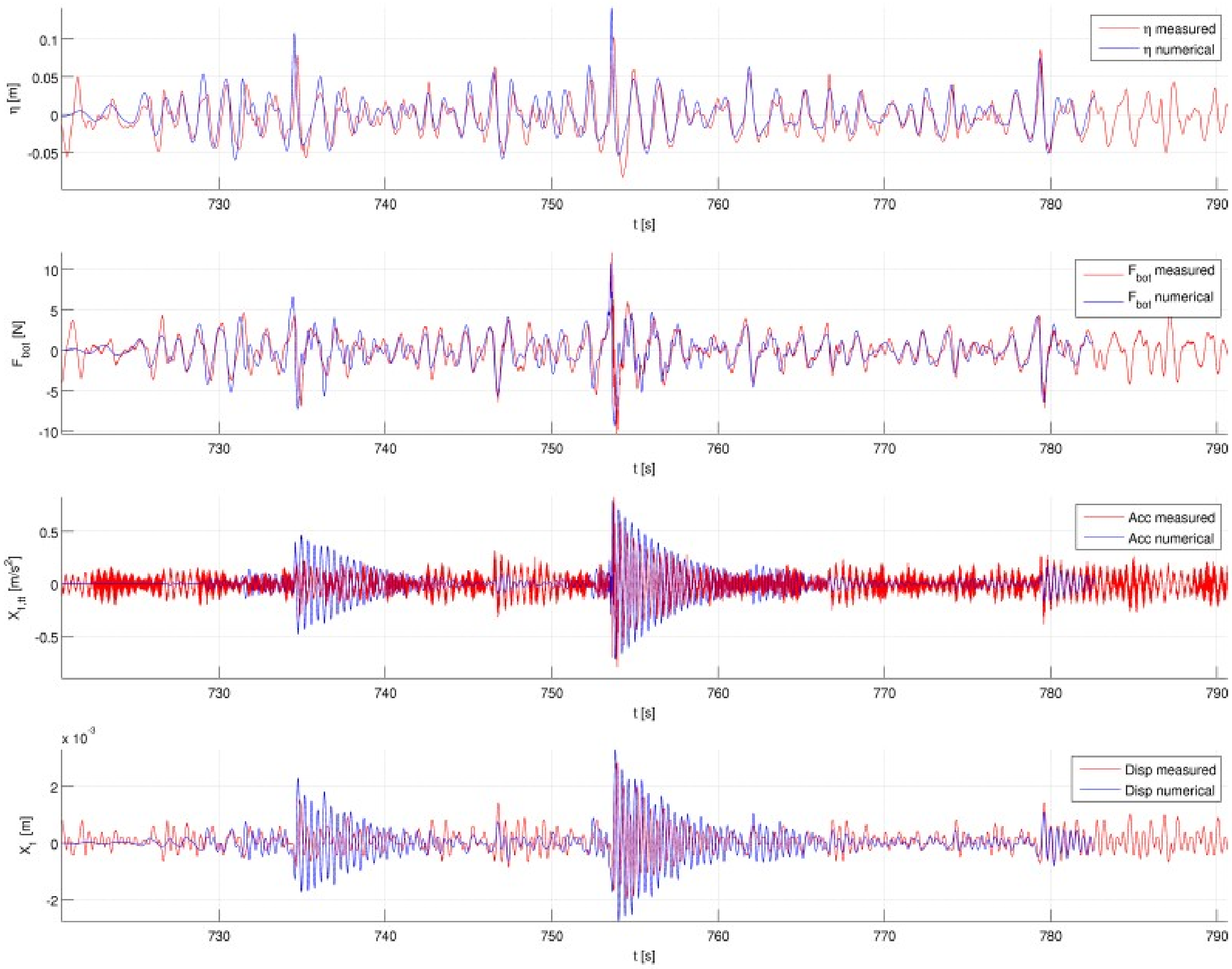
$$\nabla^2\phi + \partial_{zz}\phi = 0$$

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

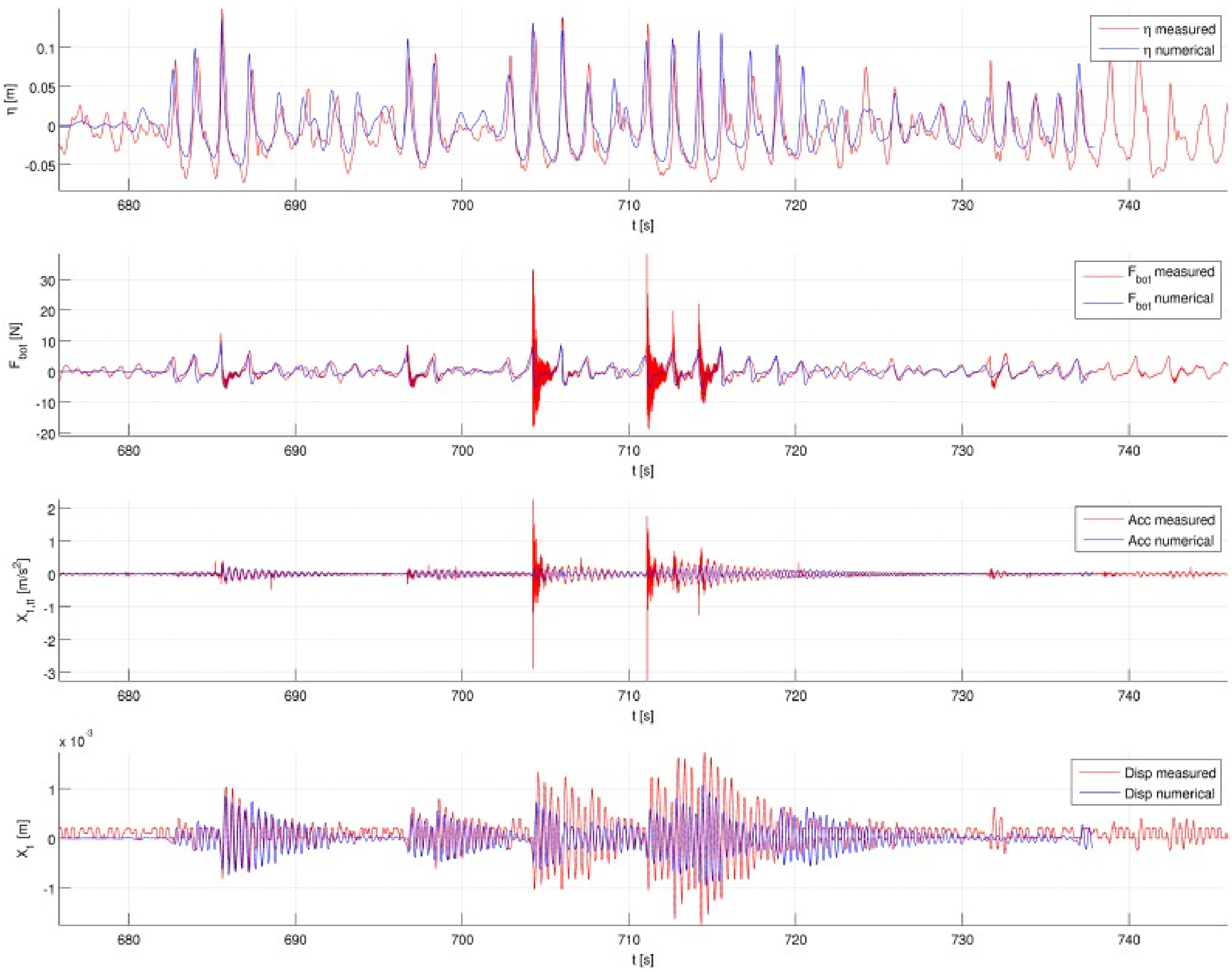
$$F_{\text{surface}} = -\tfrac{1}{2}\rho_{\text{w}}\mathscr{A}c_m\eta_x(u-\dot{X})^2$$

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

# Response, h=40.8 m



# Response, h=20.8 m

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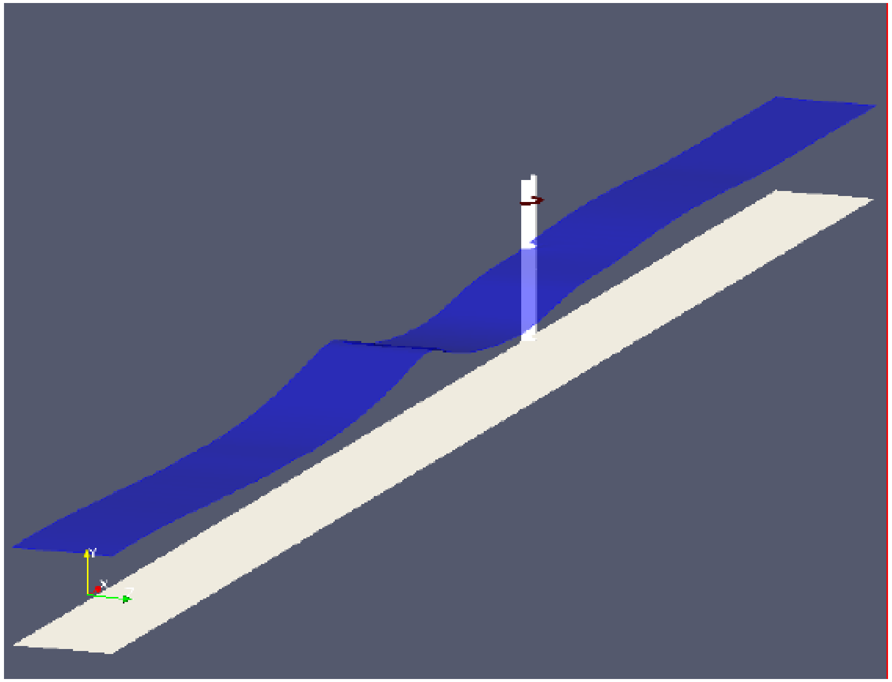
# The OpenFOAM® CFD solver

Open source CFD toolbox

Vast attention during last 3 years



This study: interFoam solver

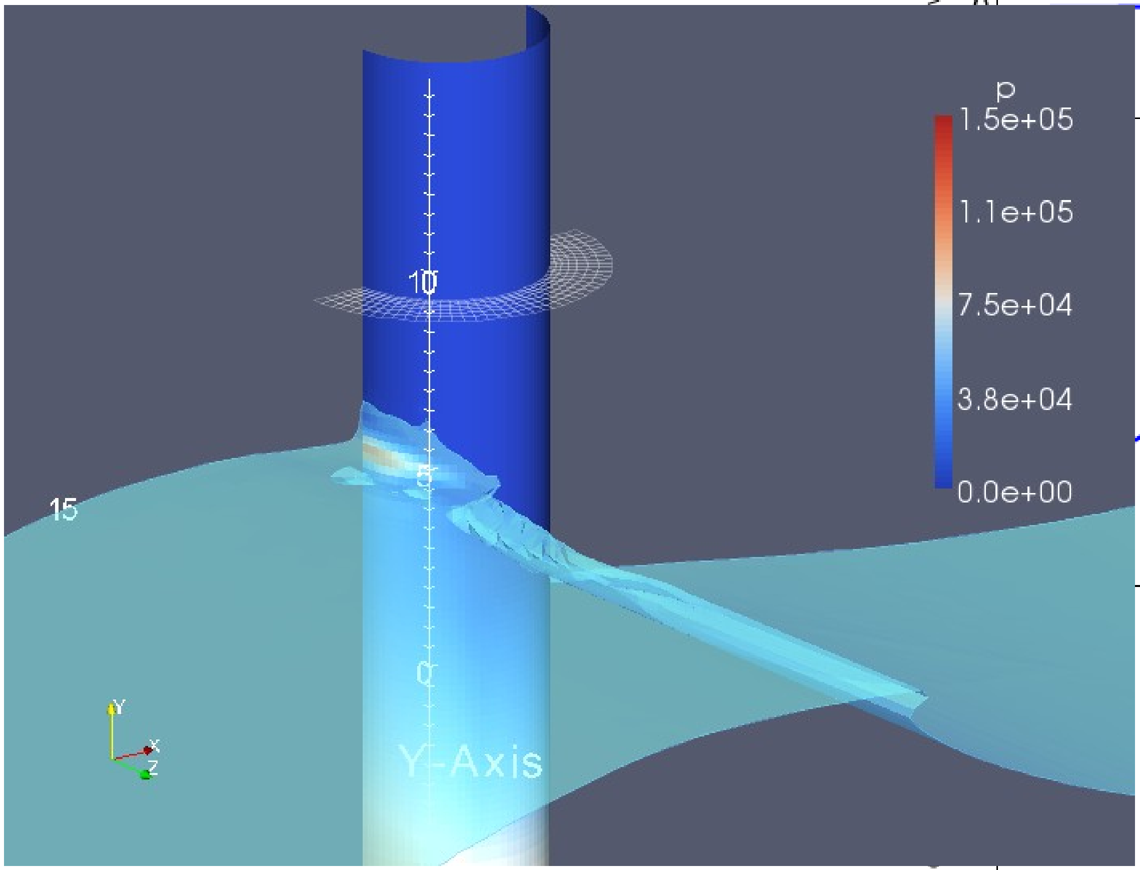
- 3D incompressible Navier-Stokes
- two phases (water and air)
- VOF treatment of free surface

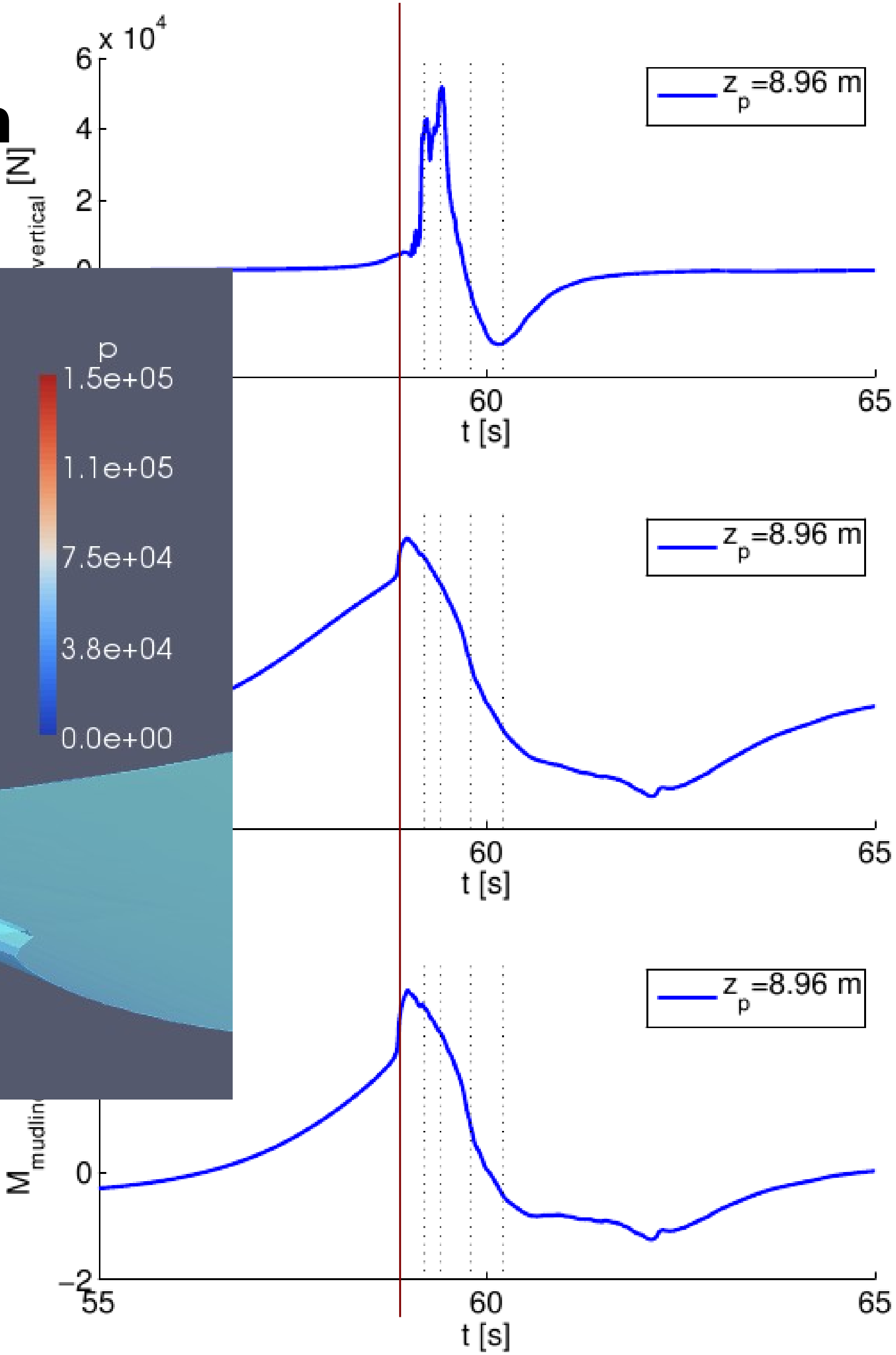
Waves2foam wave generation toolbox has been developed and validated

(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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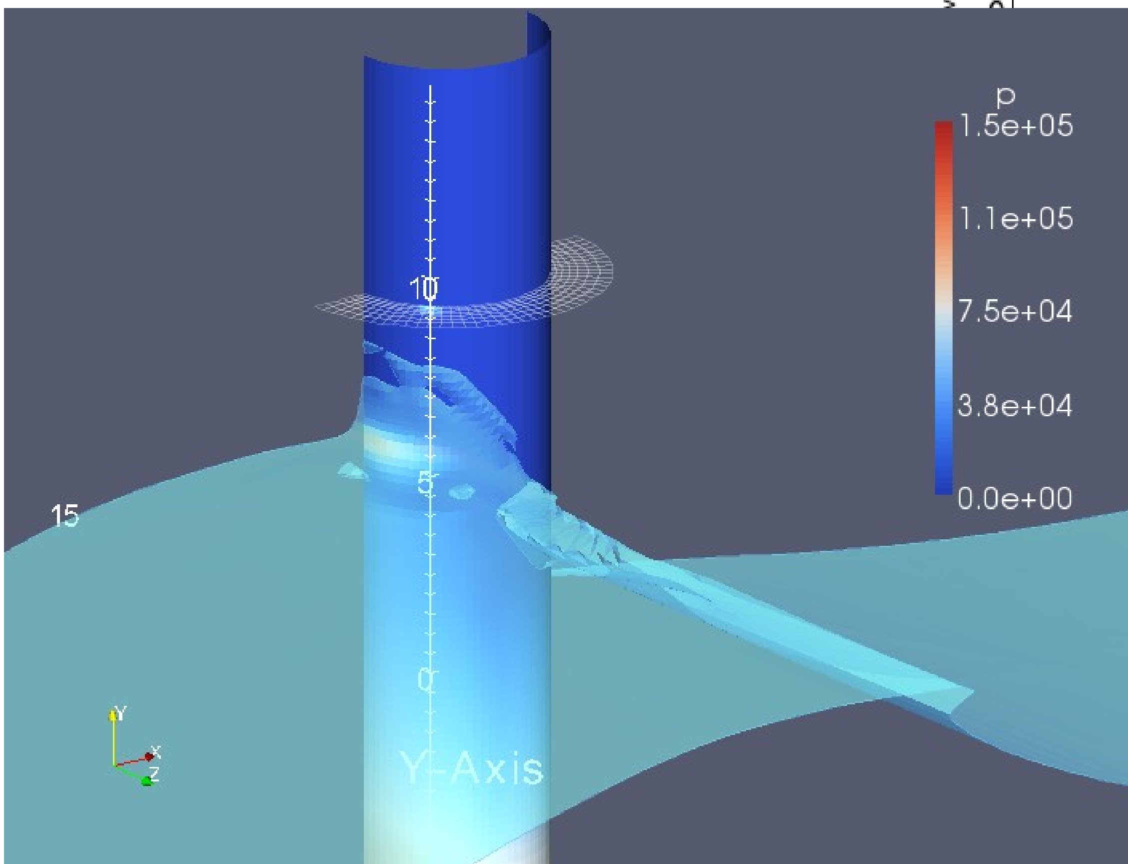
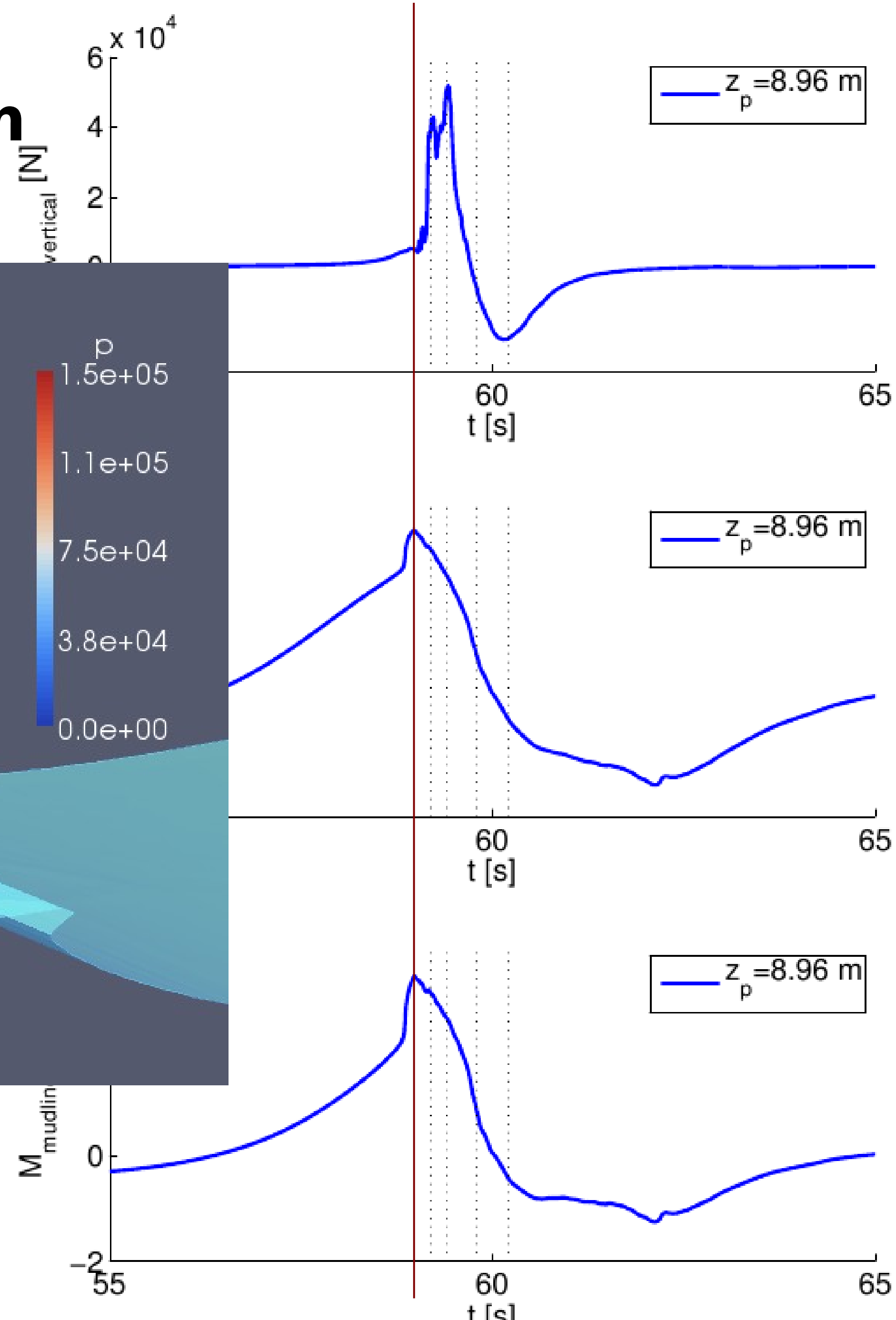
# Platform height of 8.96m




t=59.1s

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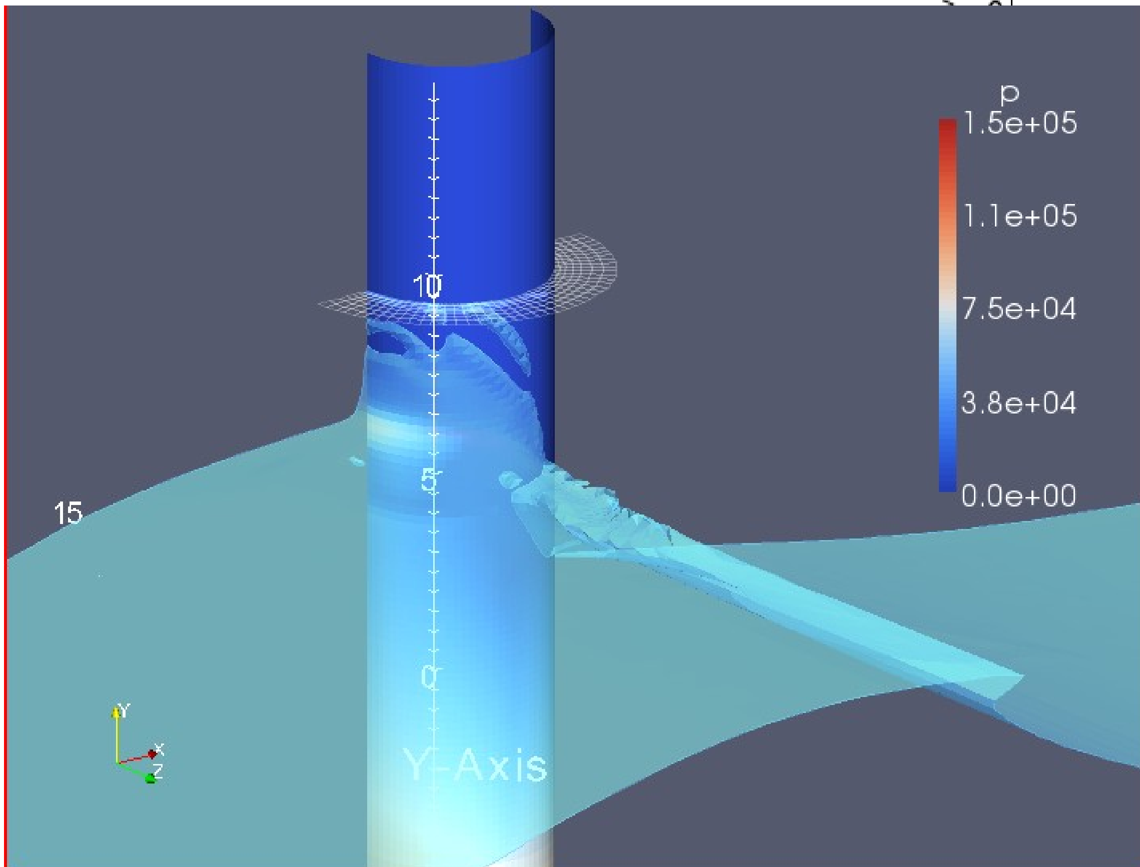
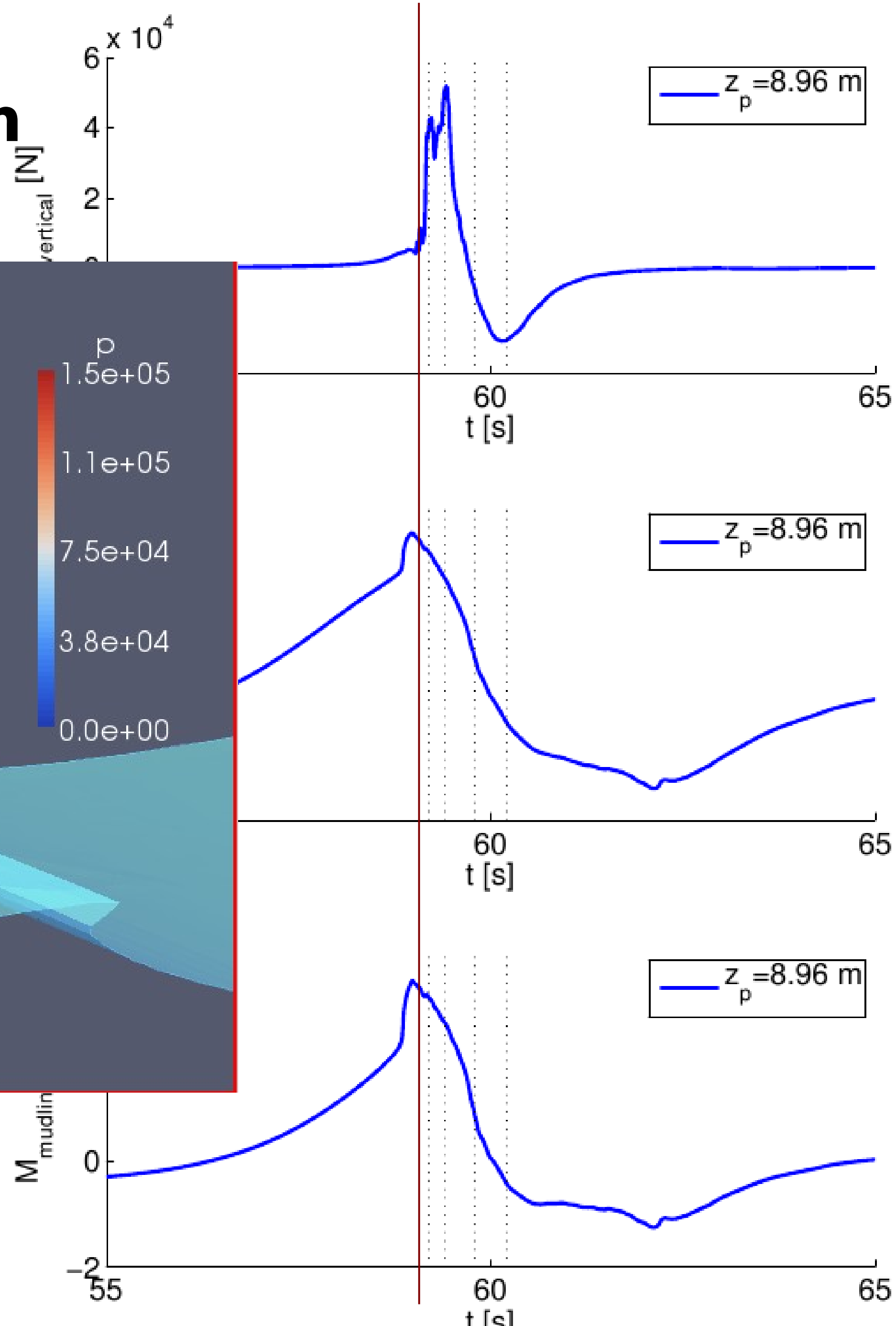
# Platform height of 8.96m

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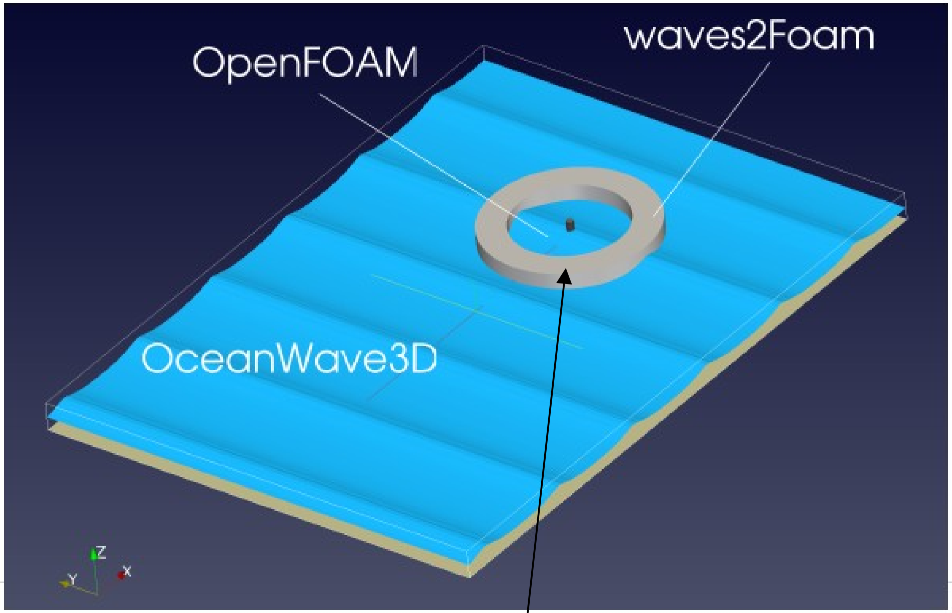
# Development of a coupled solver

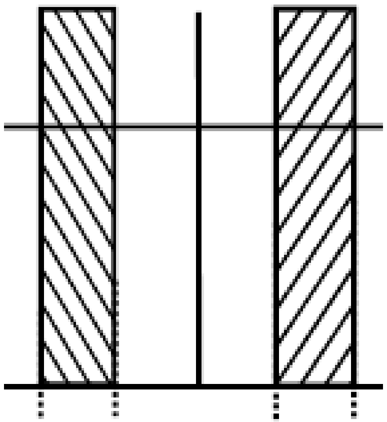


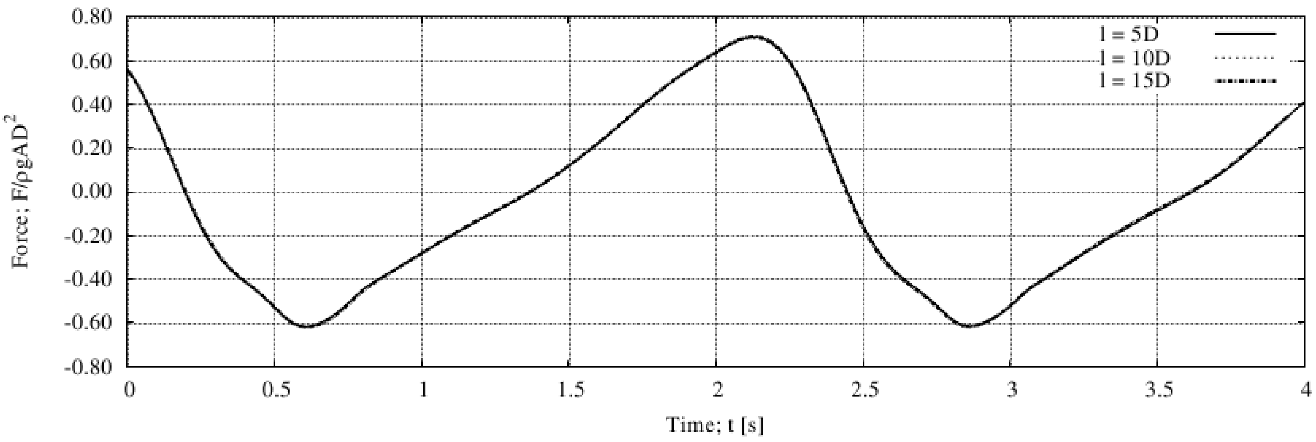

Compute outer flow field with potential flow wave model: OceanWave3D (Engsig-Karup et al 2009)

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

$$\psi = \chi\psi_{\text{target}} + (1-\chi)\,\psi_{\text{com}}, \qquad \psi \in \{\mathbf{u}_H, w, \alpha\},$$

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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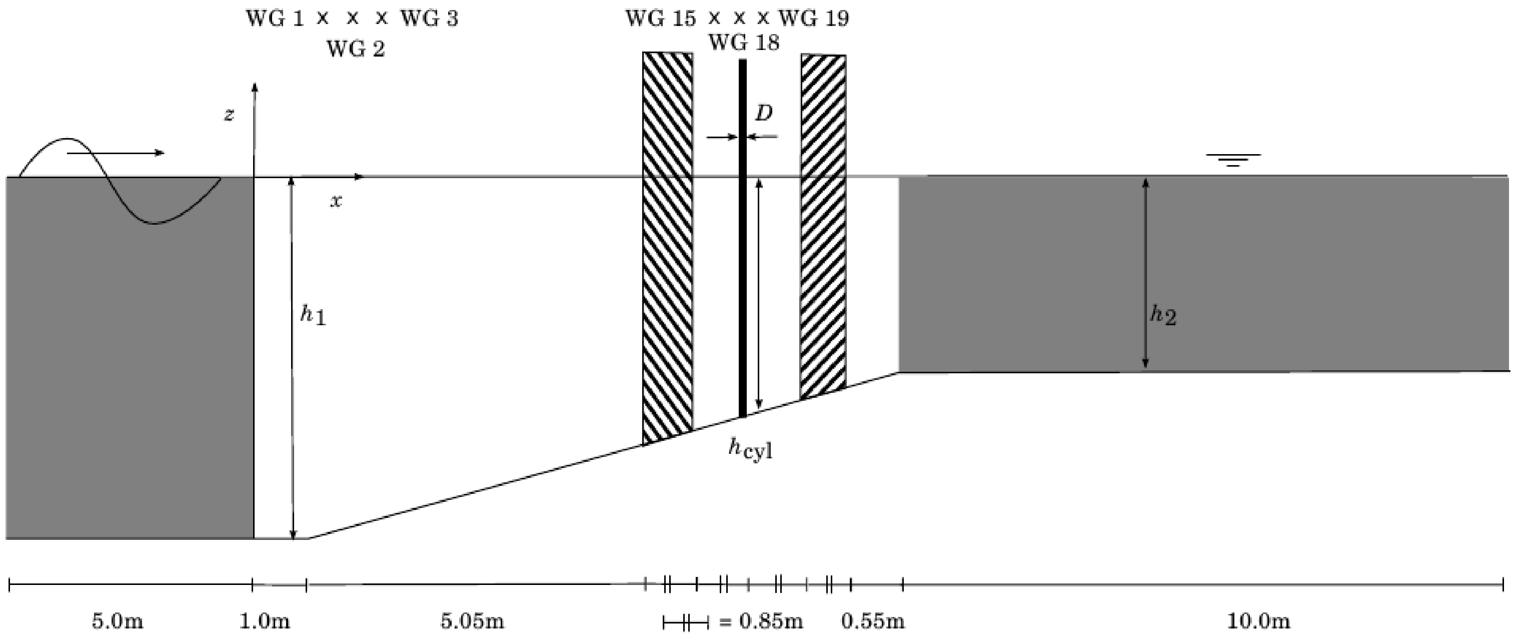
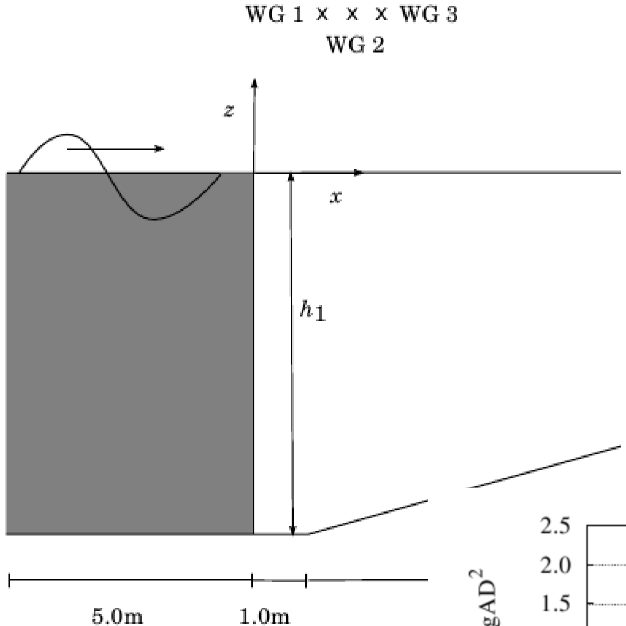
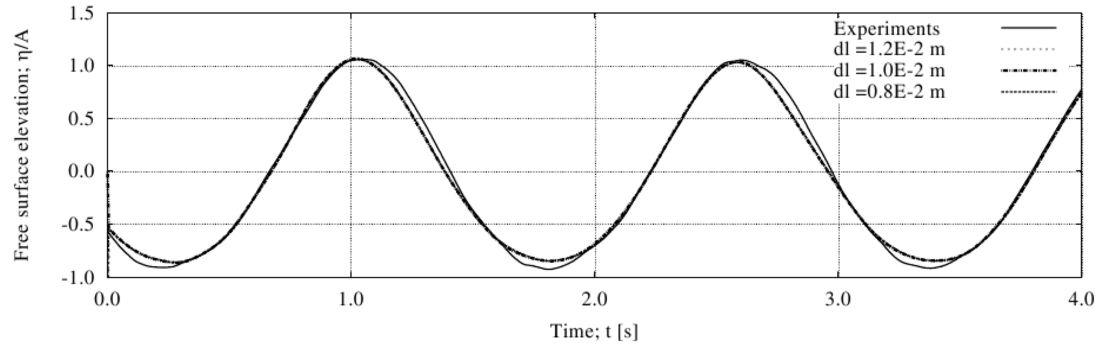
# Regular waves on a slope

1:80, h=40.8m, H=7.67m

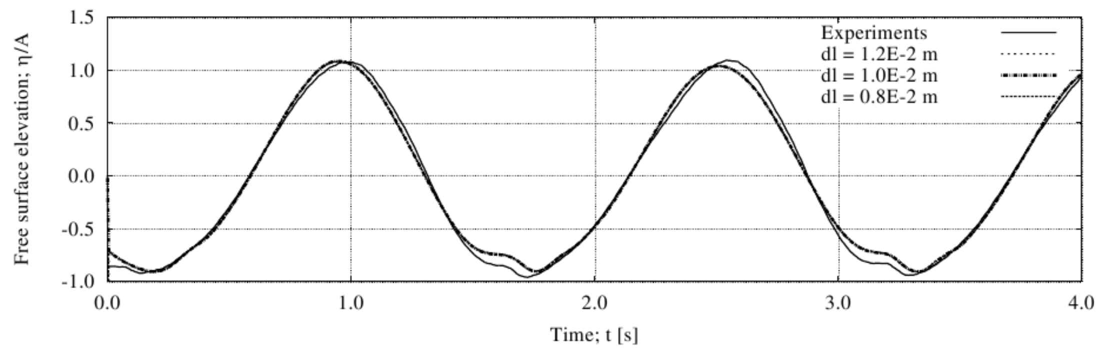


# Regular waves on a slope

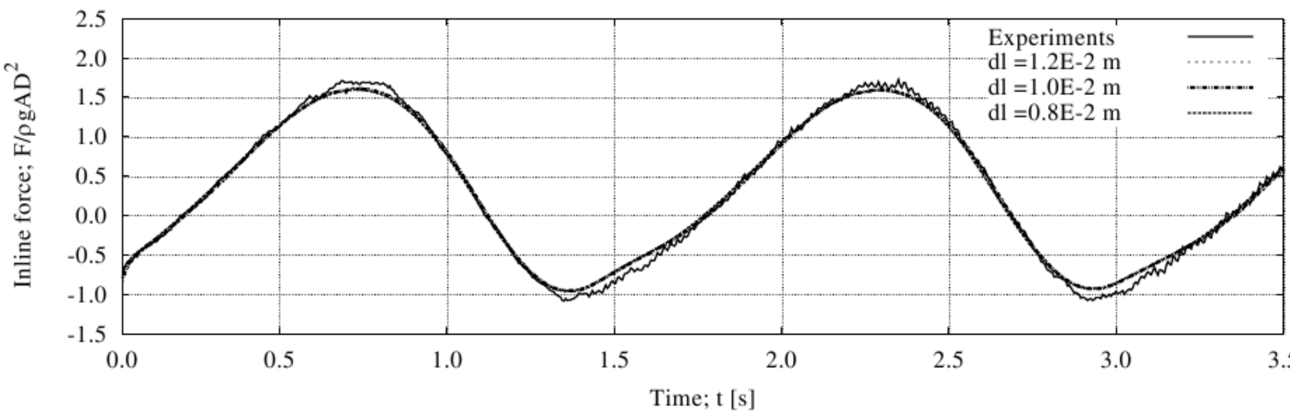



(a) Measured and computed free surface elevation at the location of wave gauge 18, positioned at $\{x;y\} = \{7.75;-1.00\}$ m.



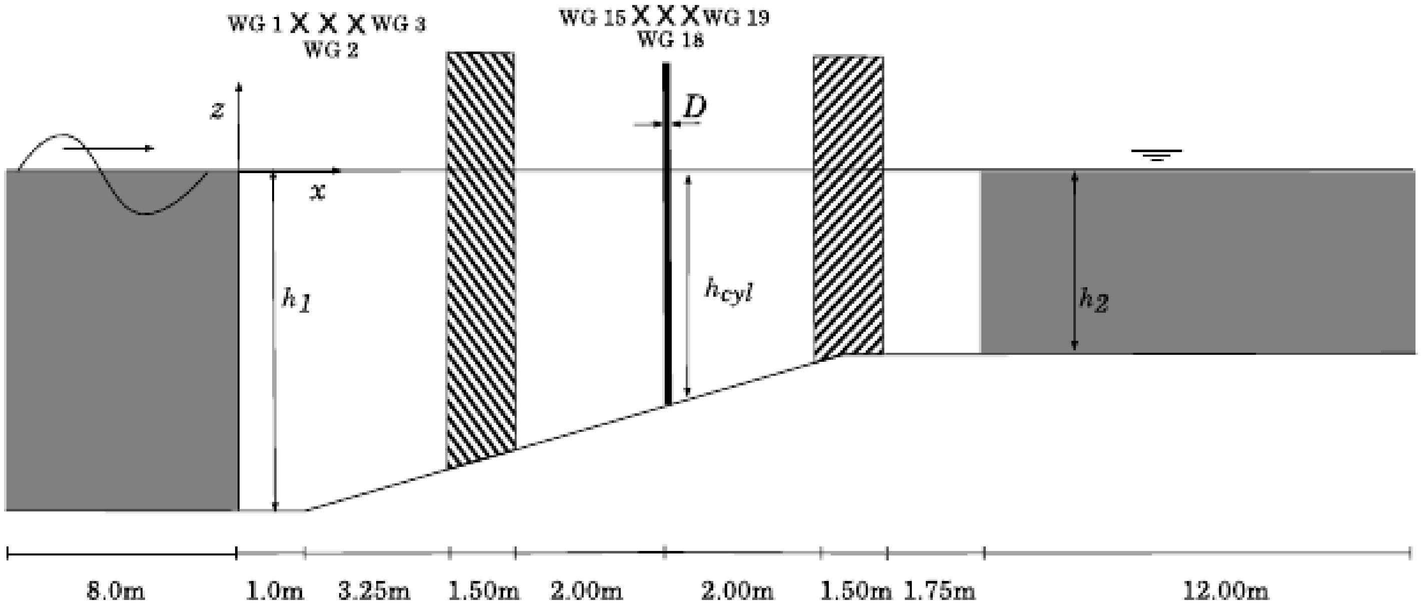

(b) Measured and computed free surface elevation at the location of wave gauge 15, positioned 15 cm= $2D$ upstream of the cylinder at $\{x;y\} = \{7.50;0.00\}$ m.




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

# 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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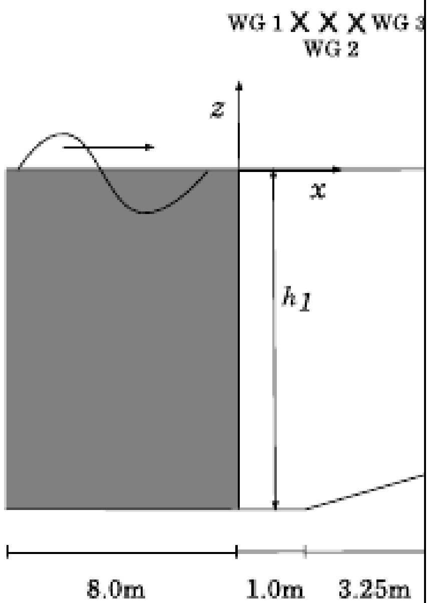
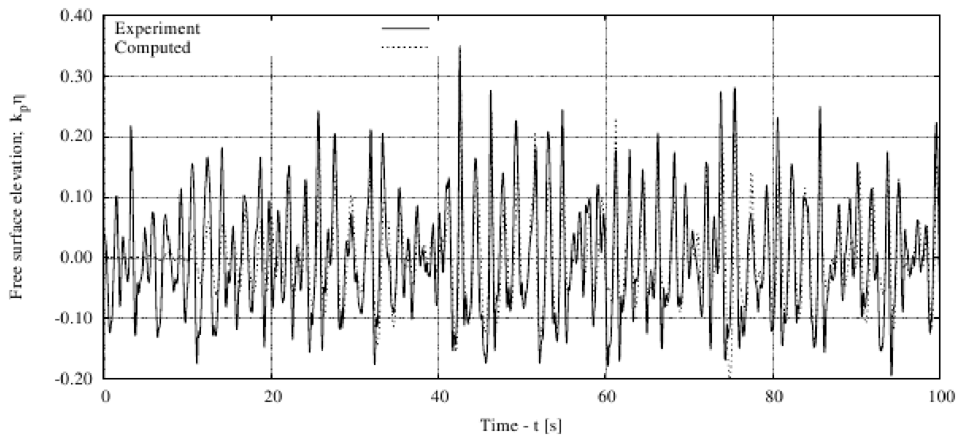



Reconstruct incident wave field by linear analysis of wave gauge measurements.
Total computed time series is 100s long.





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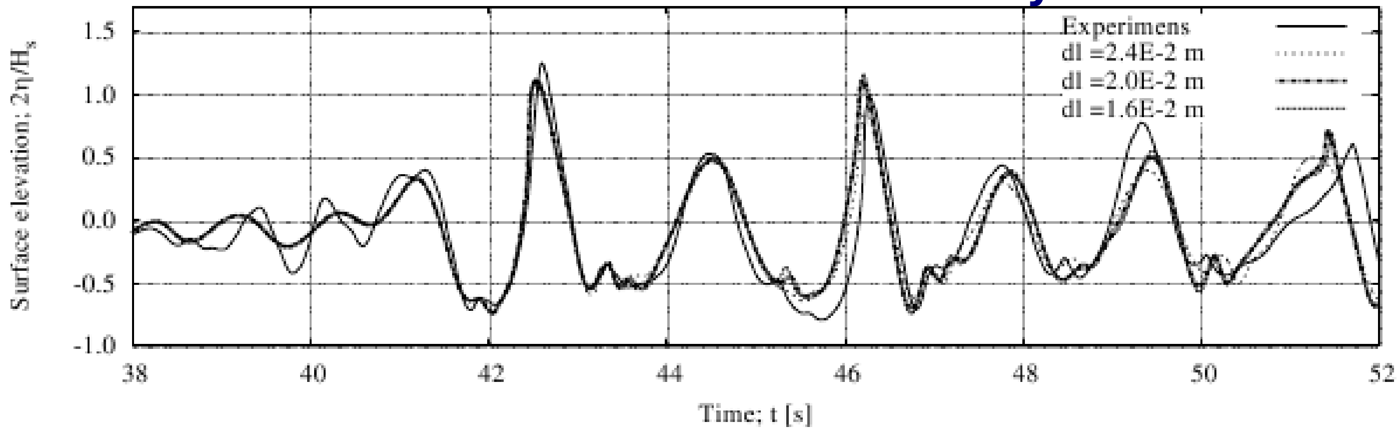
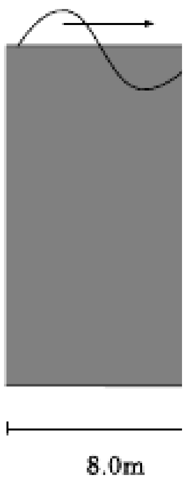
# Validation for irregular wave forcing on a slope

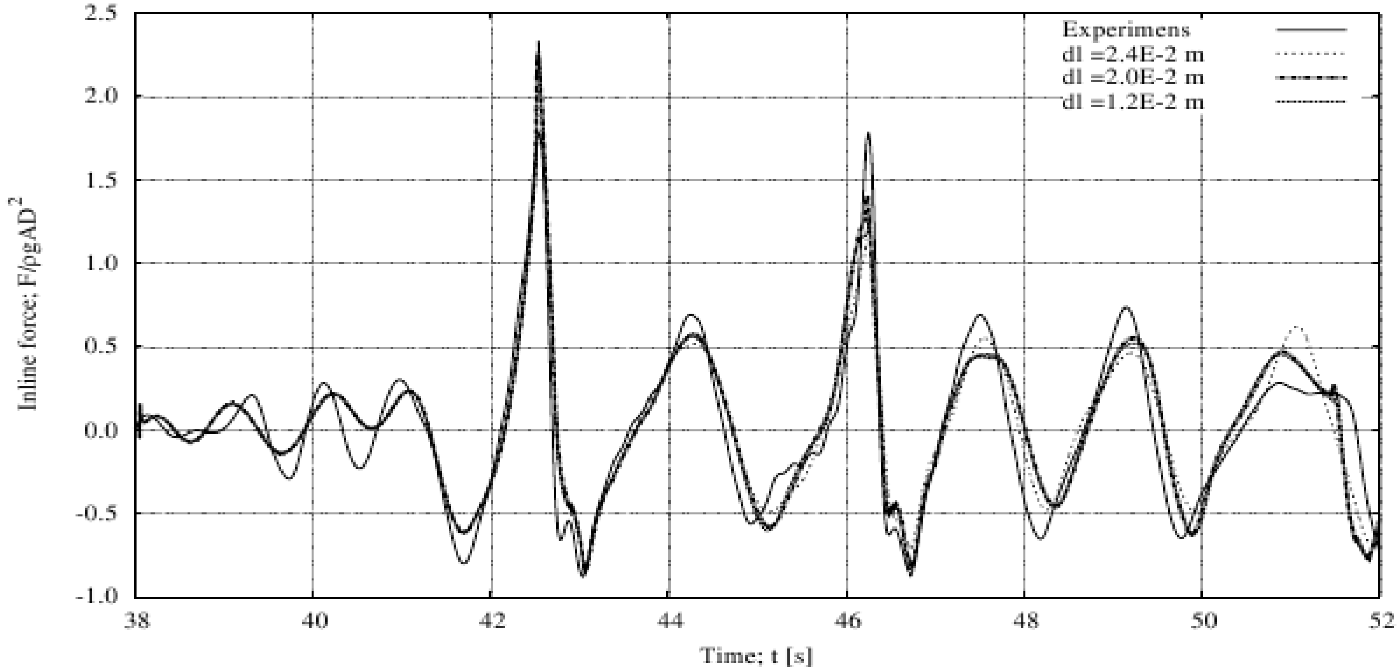
Experimen

## Free surface elevation 0.25 cm in front of cylinder




## Inline force history

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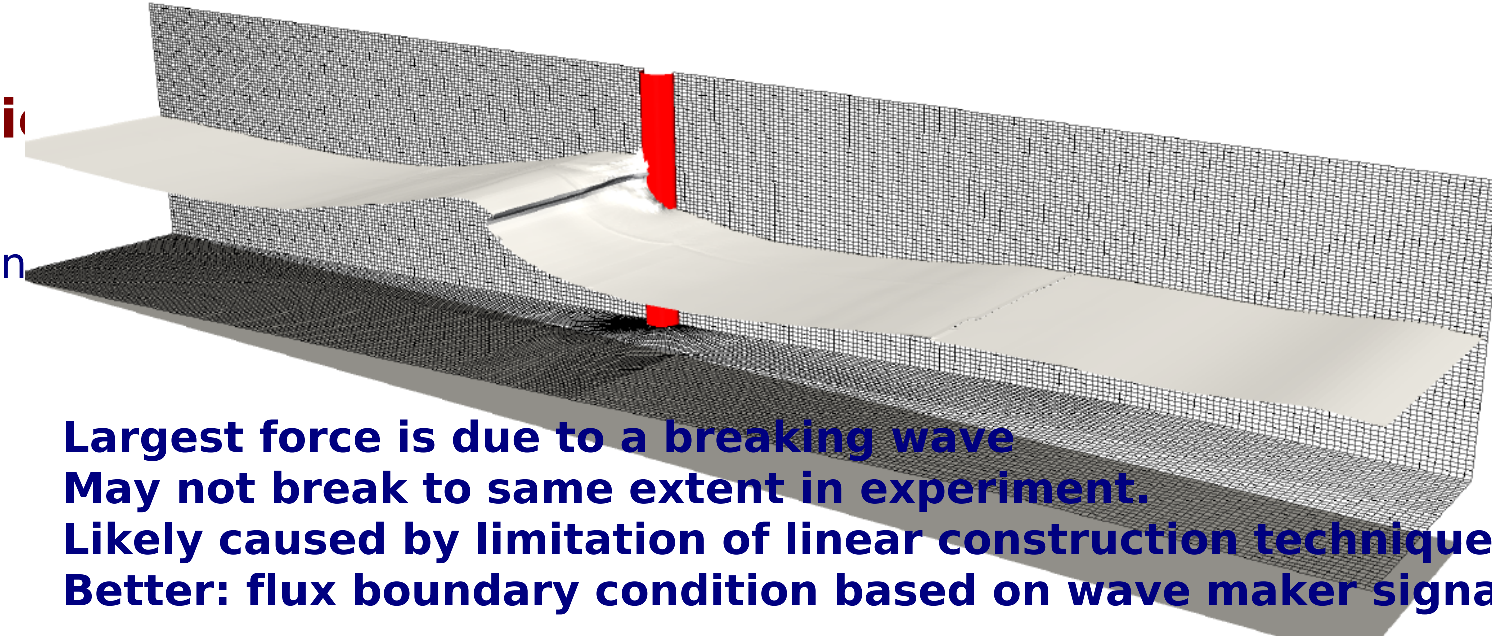
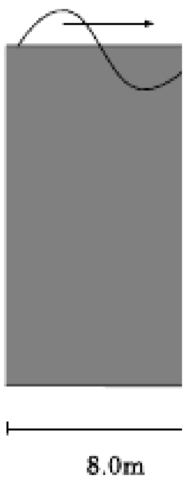
# Validati

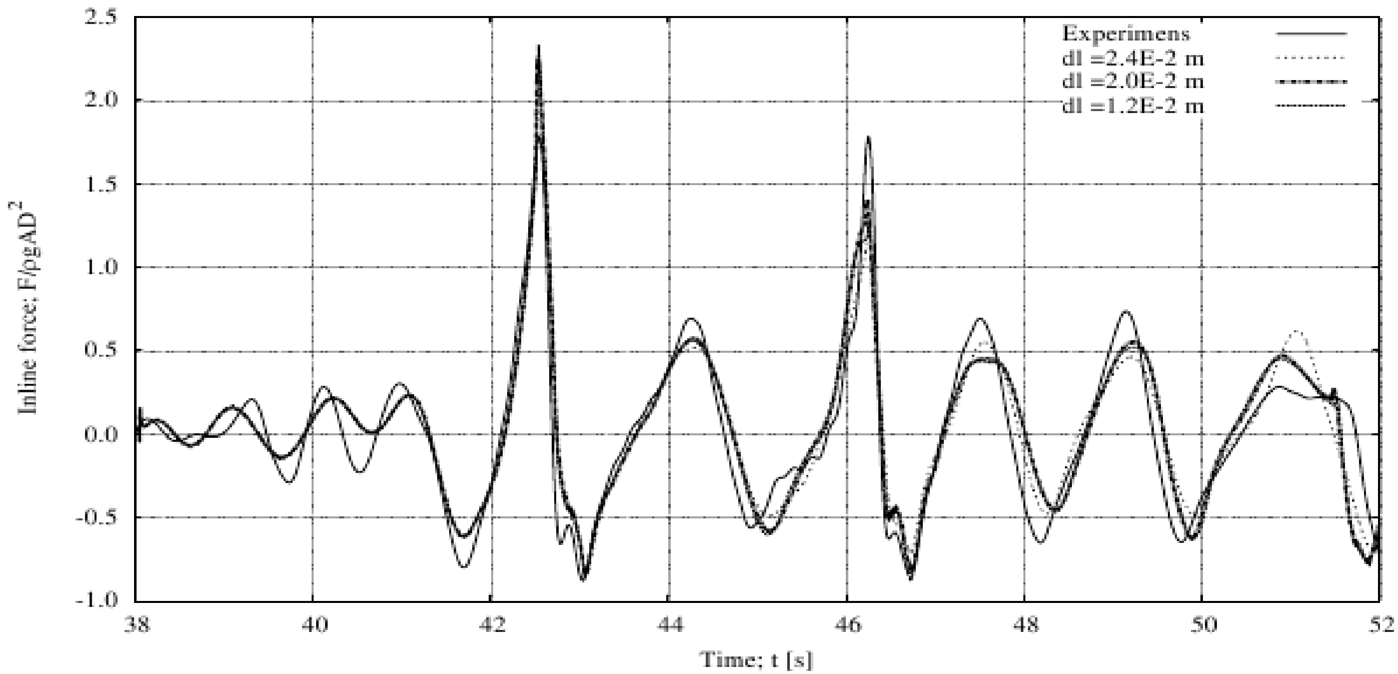
Experimen



**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**




**Inline force history**





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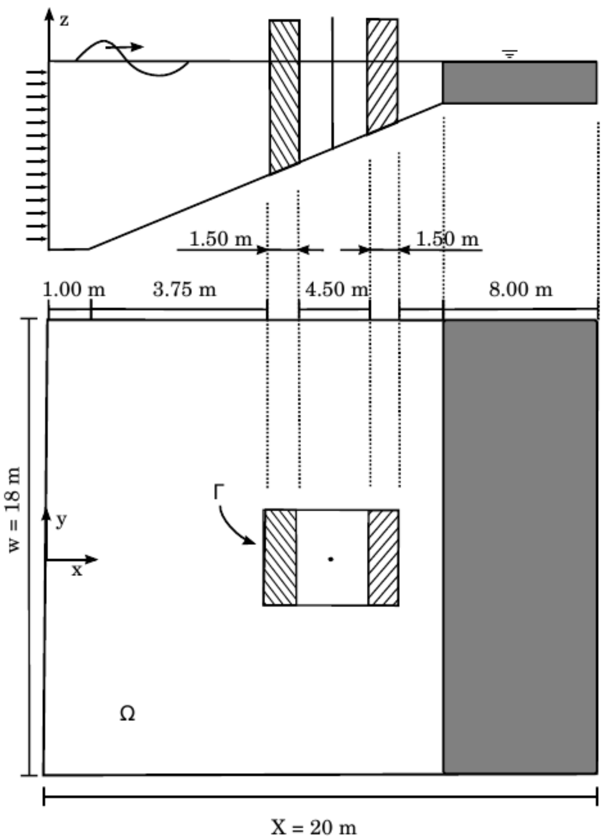
# Computation of multi-directional waves



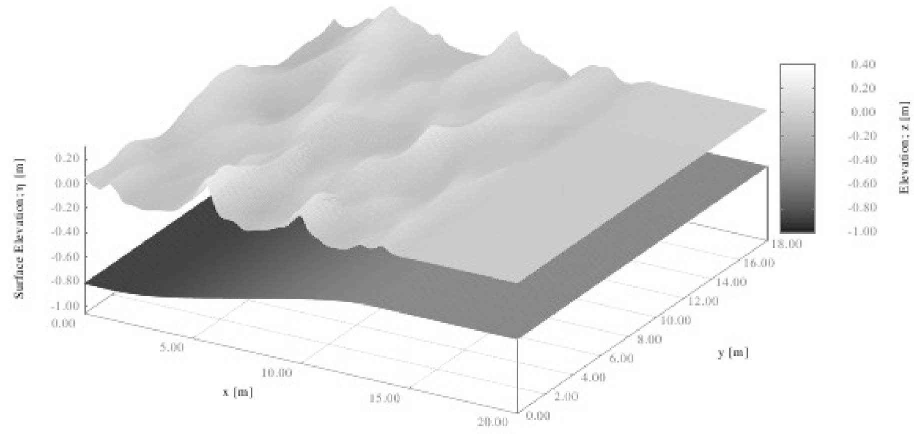




**Figure 3.27:** Snapshot of the free surface elevation computed by the potential flow solver at time $t = 15$ s.

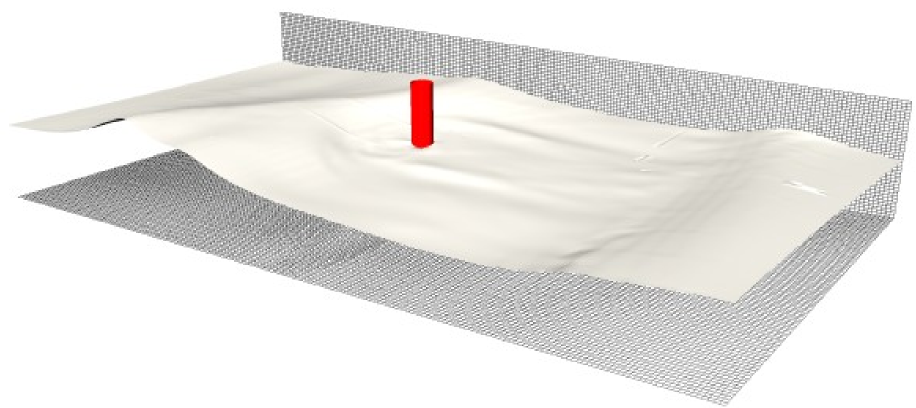
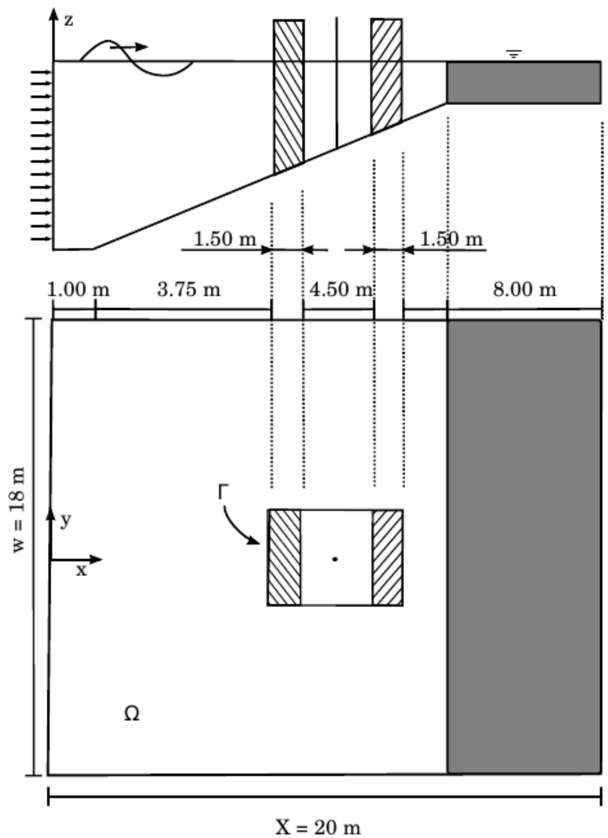
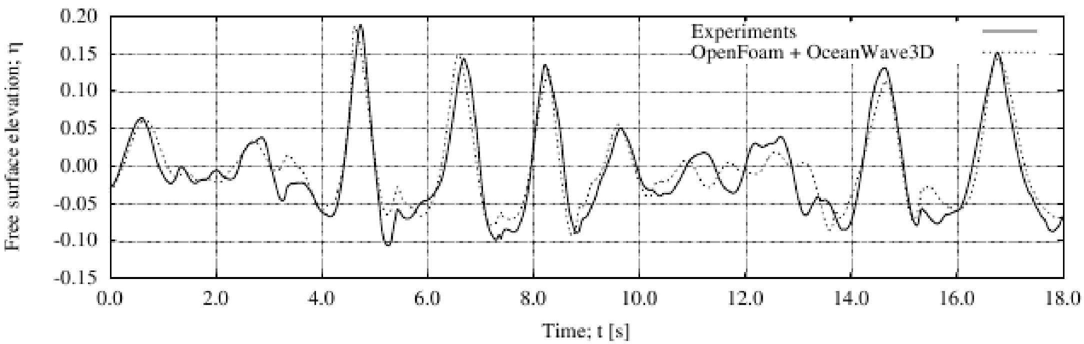


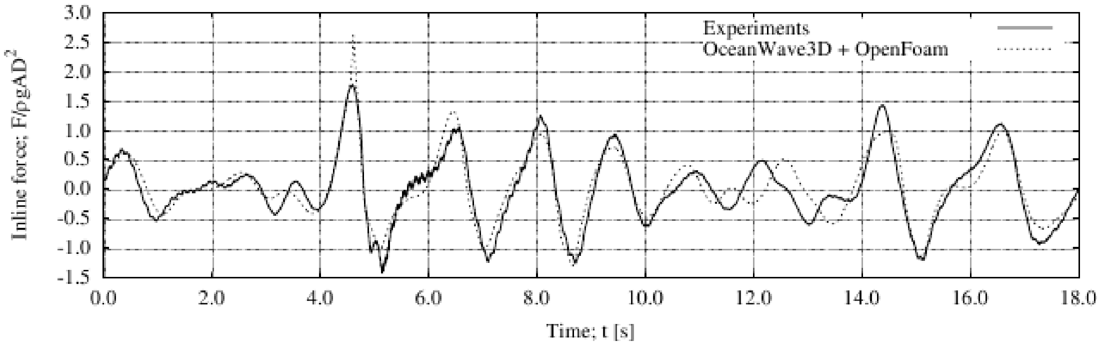
**Figure 3.28:** Snapshot of the free surface elevation computed by the Navier-Stokes solver at time $t = 15$ s.

# Computation of multi-directional waves

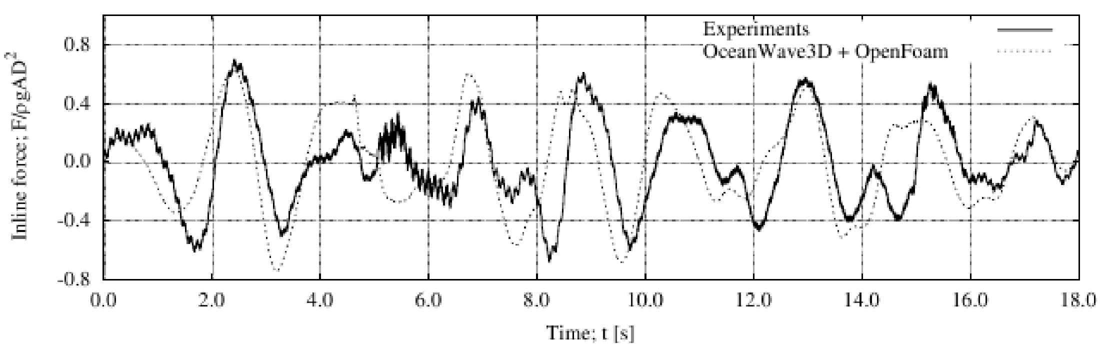



**(a)** Measured and computed free surface elevation at the location of wave gauge 15, $\{x; y\} = \{7.50; 0.00\}$.

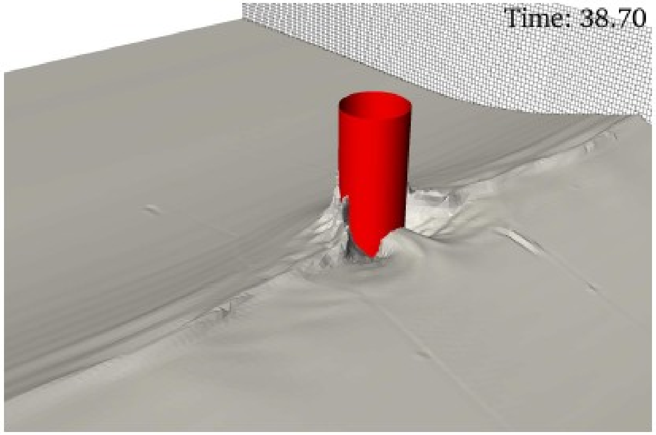



**(a)** Measured and computed inline force on the cylinder.

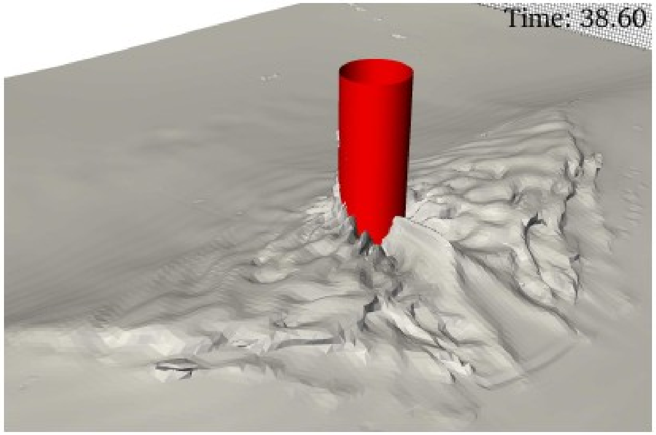



**(b)** Measured and computed force on the cylinder in the $y$-direction

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




(c) Unidirectional: The wave passage




(d) Bi-directional: The wave passage

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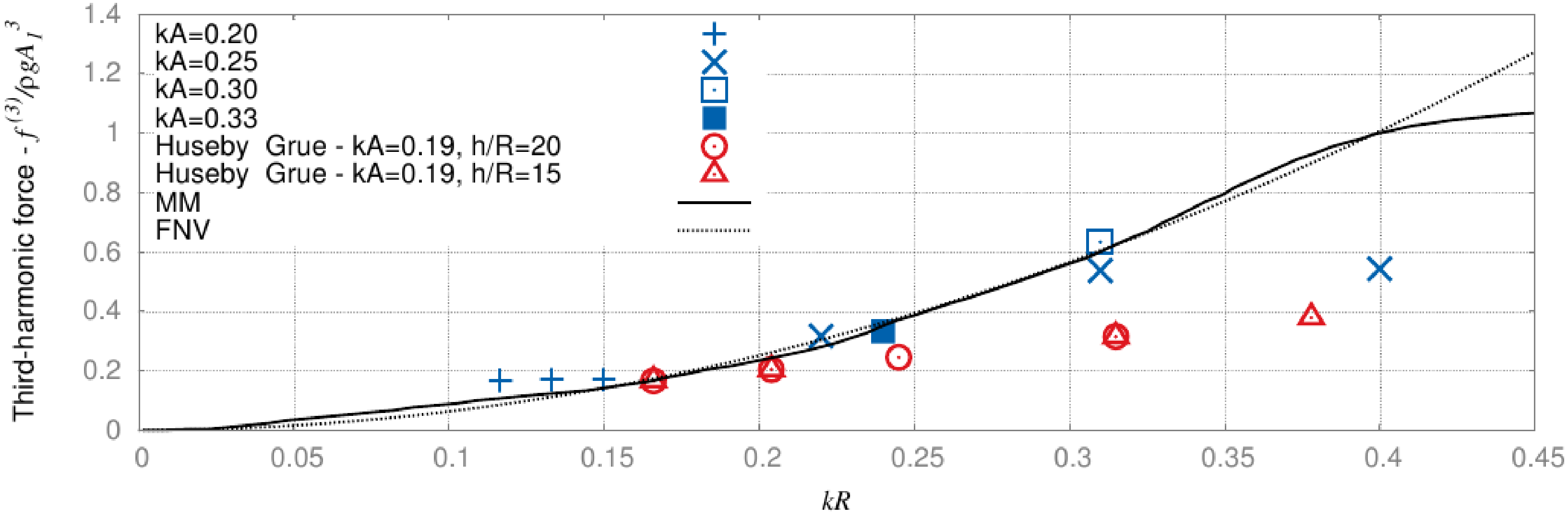
# Detailed study of regular wave forcing and higher-harmonic components




## Third-harmonic force compared to FNV theory

Paulsen et al
IWWWFB 2012

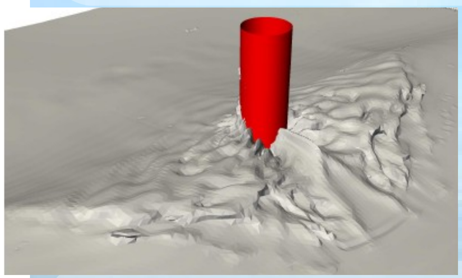
# The Wave Loads project

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

**Task A**:

Boundary conditions for phase resolving wave models

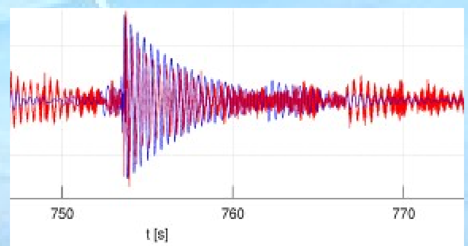
DHI



**Task C**:

Aero-elastic response to fully nonlinear wave forcing

DTU

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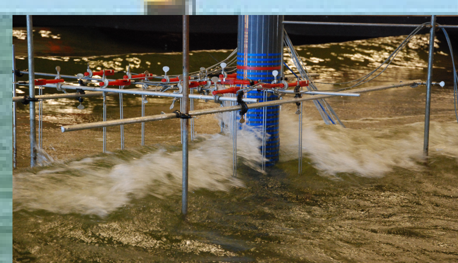
**Task B**:

CFD methods for steep and breaking wave impacts

DTU, (DHI)



**Task D**:

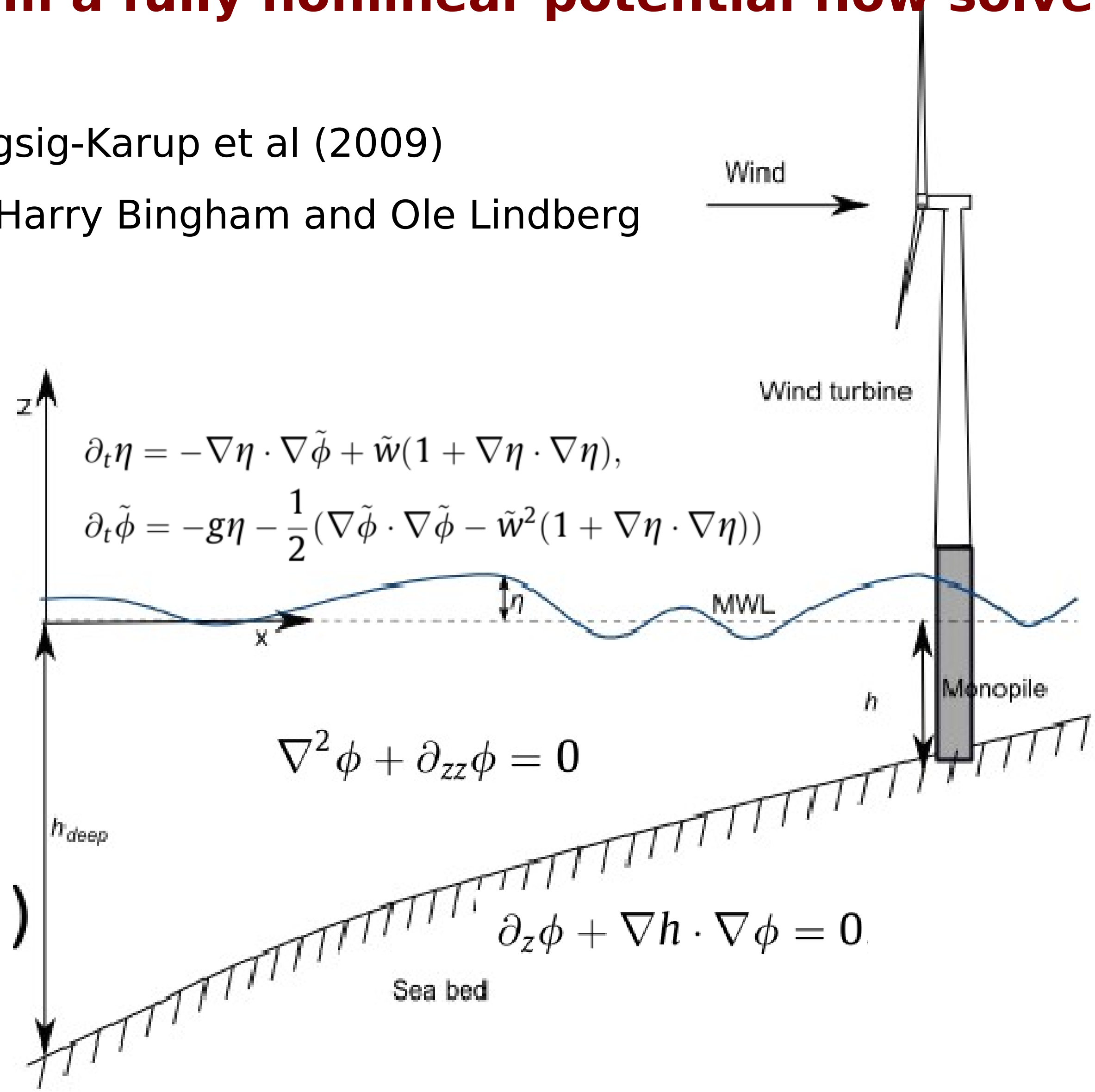
Physical model tests

DHI

# Kinematics from a fully nonlinear potential flow solver

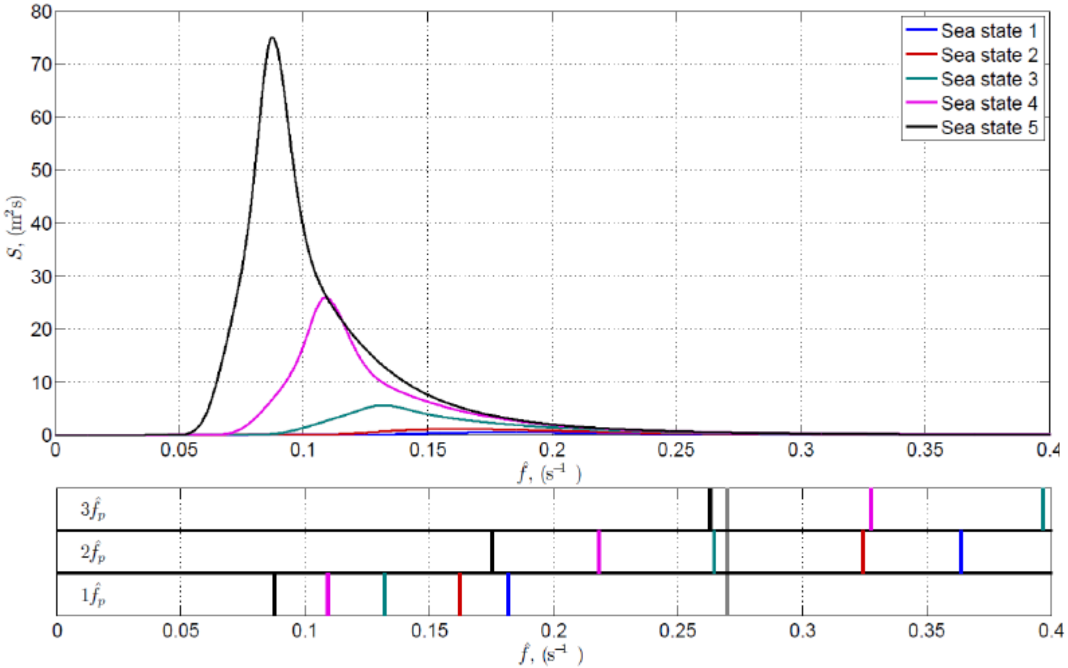
'OceanWave3D', Engsig-Karup et al (2009)

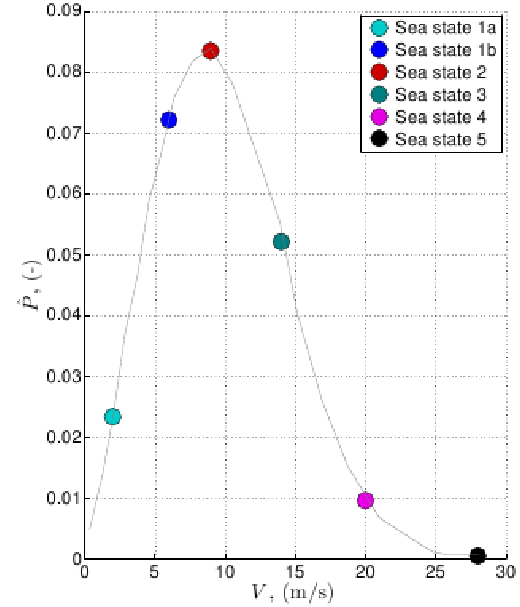
Allan Engsig-Karup, Harry Bingham and Ole Lindberg

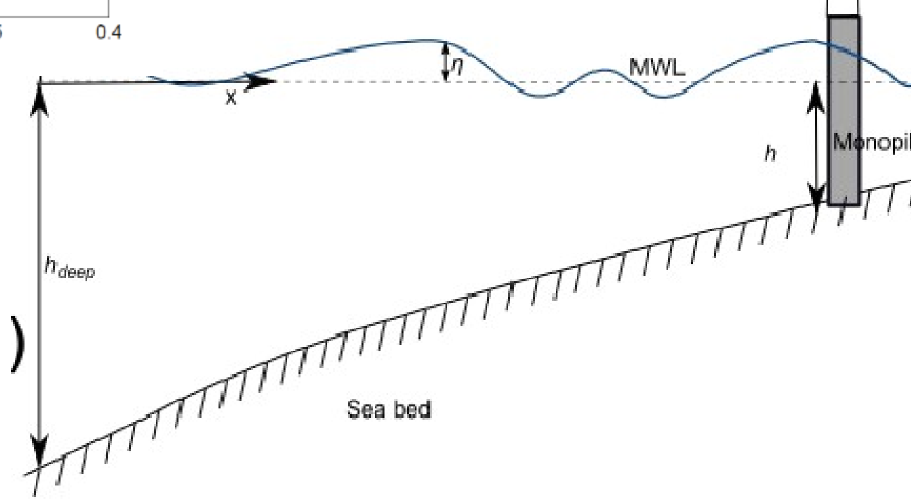


# Study of nonlinear wave load effects

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




Signe Schløer (2013)

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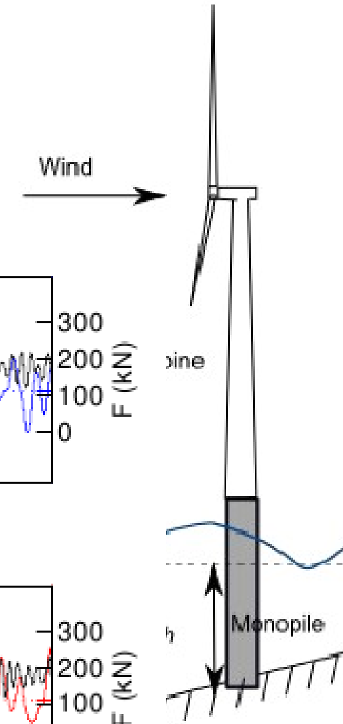
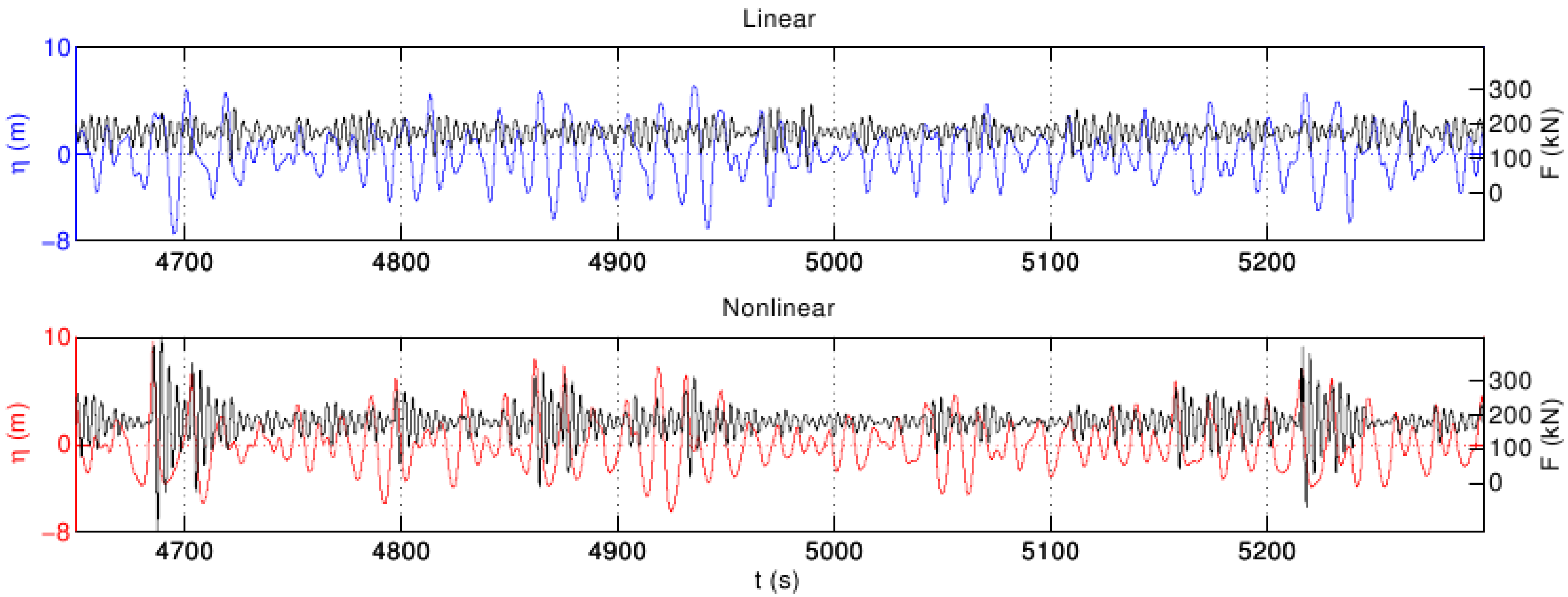
# Response in bottom of tower

Fully nonlinear waves versus linear waves

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

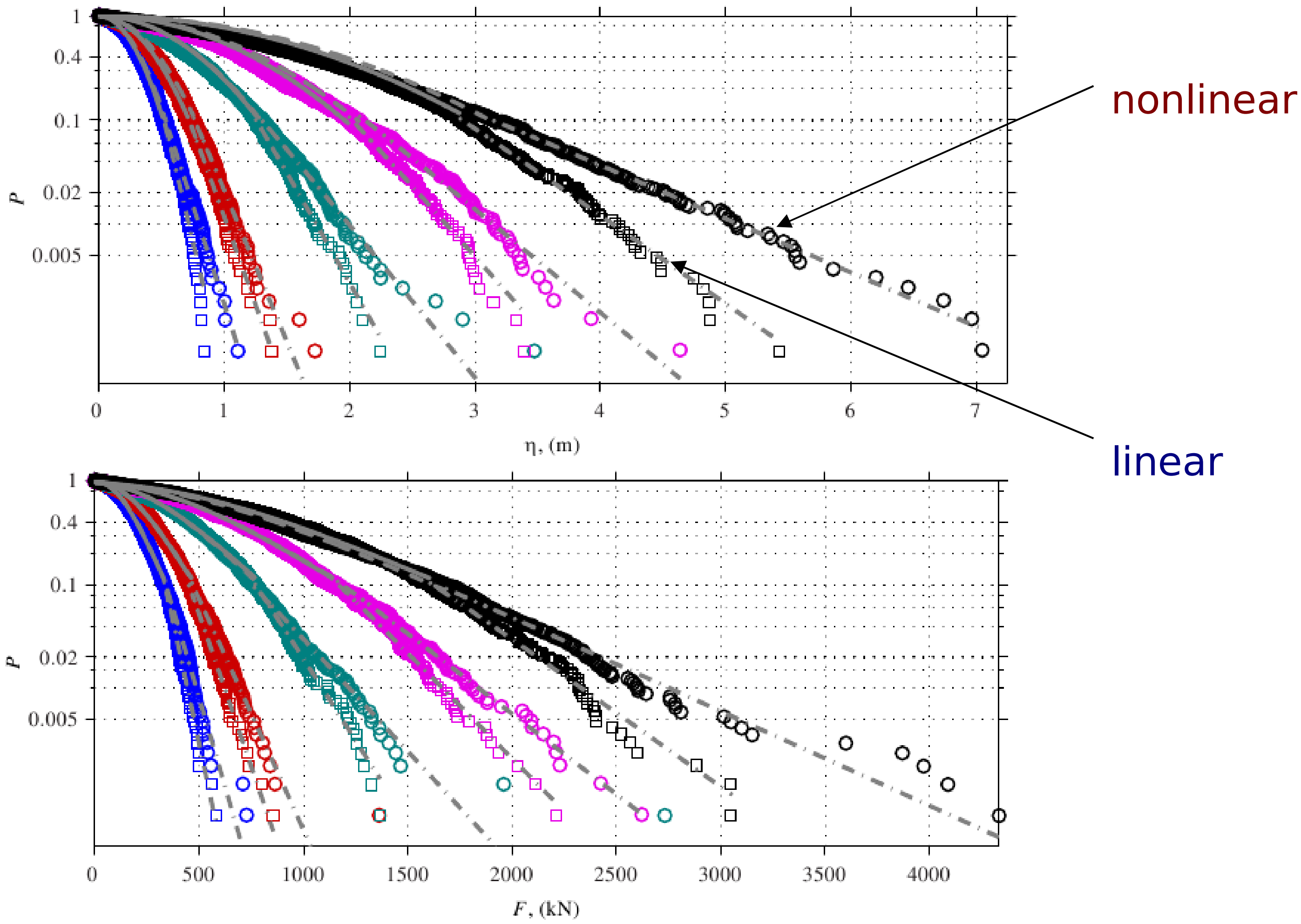




Schløer et al
(OMAE 2012)

# Static load analysis, h=30m




crest elevations

force peaks

depth integrated

force

# Results of aero-elastic computations

# Tower response – largest sea state

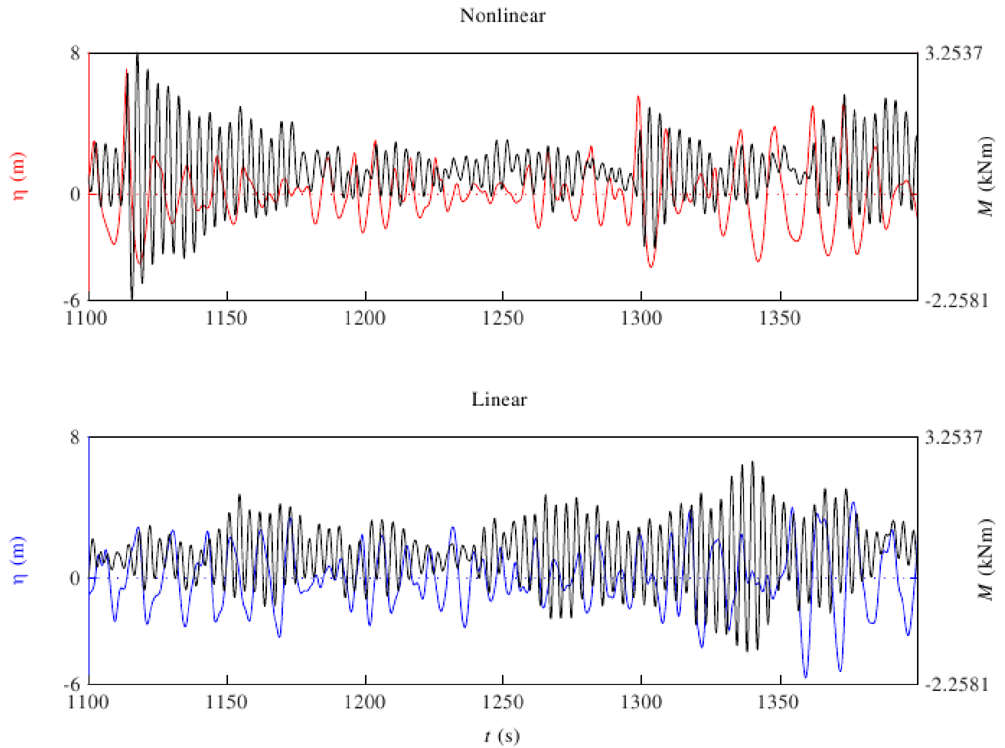



*Figure 44*: Nonlinear and linear surface elevation for the largest sea state and the corresponding moment in the bottom of the tower, $H_s = 6.76\,\mathrm{m}$, $T_p = 11.41\,\mathrm{s}$, $V = 28\,\mathrm{m/s}$ and $I_t = 0.13$

Linear waves can also excite the tower

# Results of aero-elastic computations

# Monopile response – largest sea state

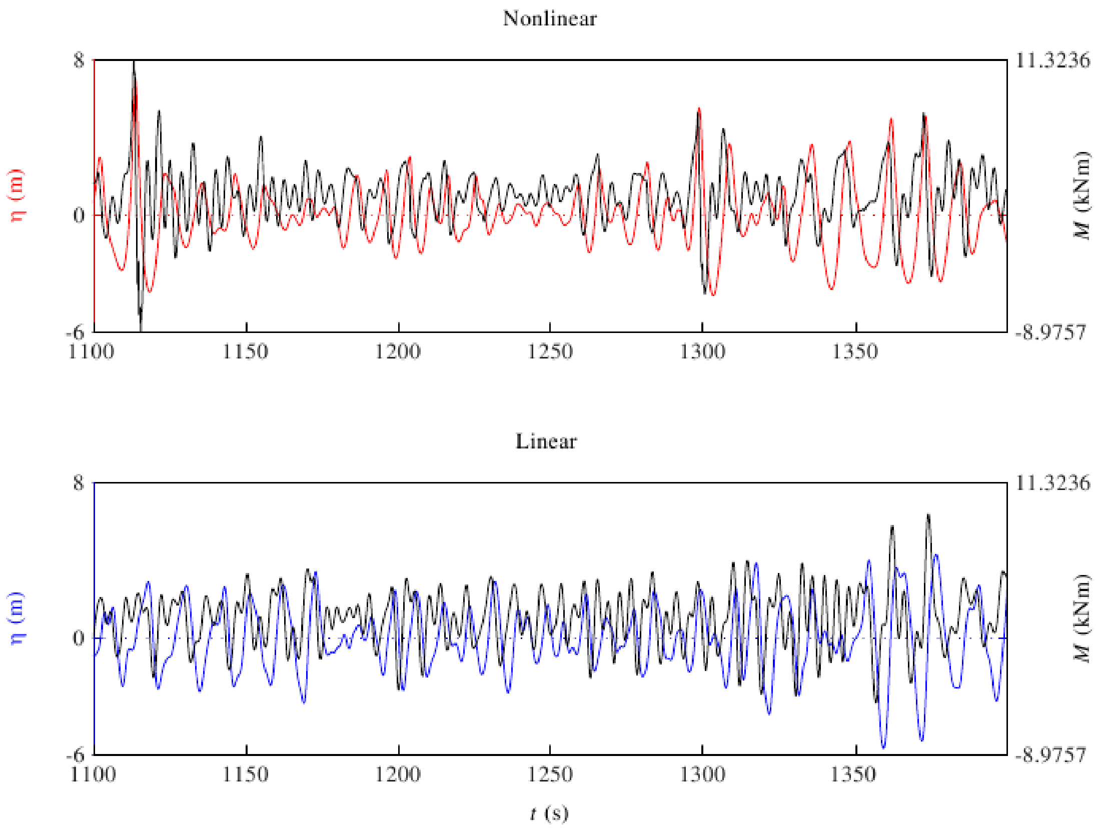



*Figure 45*: Nonlinear and linear surface elevation for the largest sea state and the corresponding moment in the bottom of the monopile, $H_s = 6.76\,\mathrm{m}$, $T_p = 11.41\,\mathrm{s}$, $V = 28\,\mathrm{m/s}$ and $I_t = 0.13$

Vibrations less visible – occur on top of the wave loads

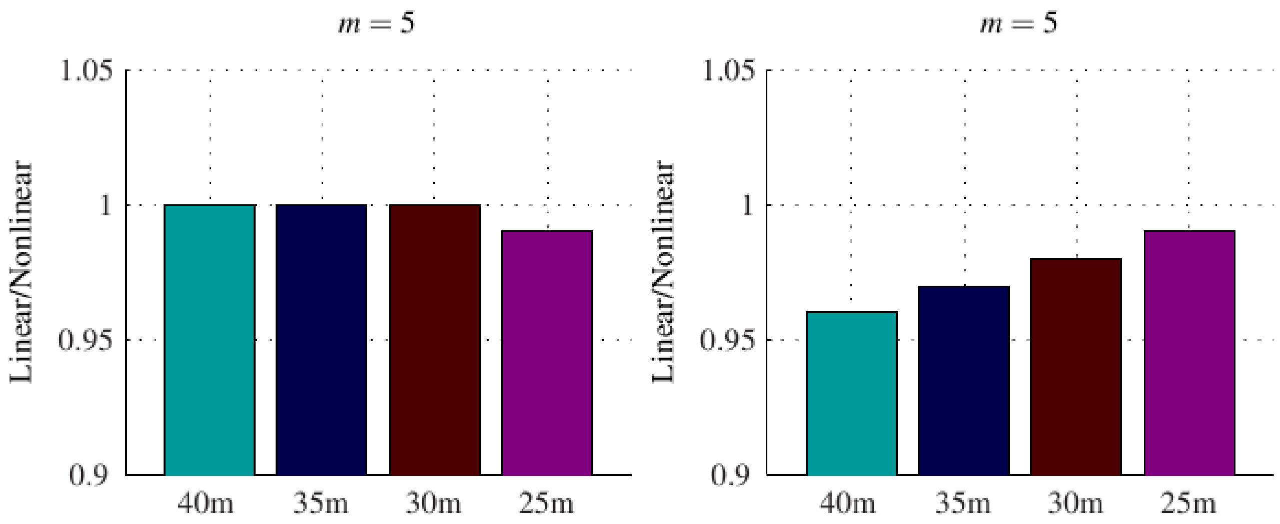
# Quantify fatigue effect

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

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

Accumulated equivalent load

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

Conclusion of present study:

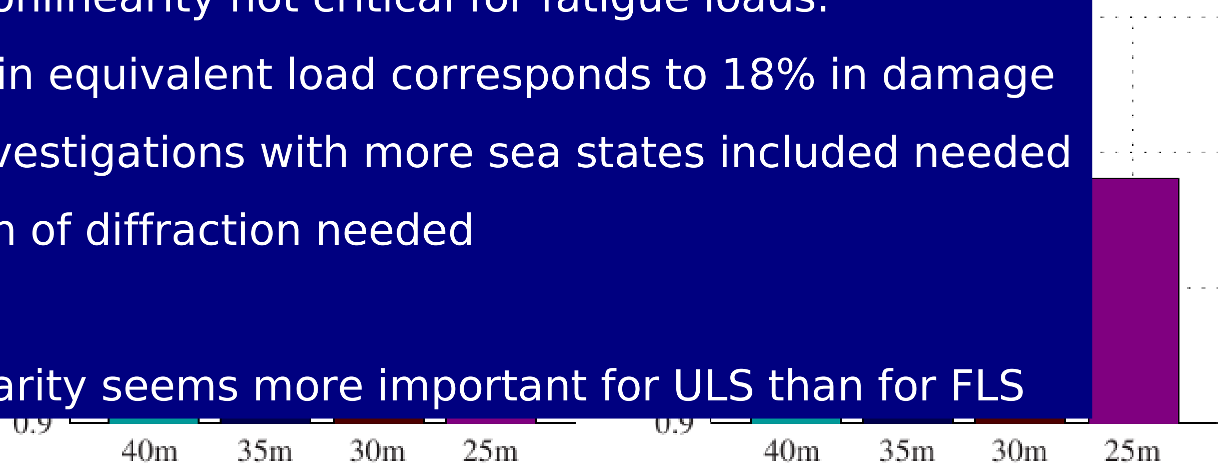
Wave nonlinearity not critical for fatigue loads.

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

More investigations with more sea states included needed

Inclusion of diffraction needed

Nonlinearity seems more important for ULS than for FLS




(a) Tower. (b) Monopile.

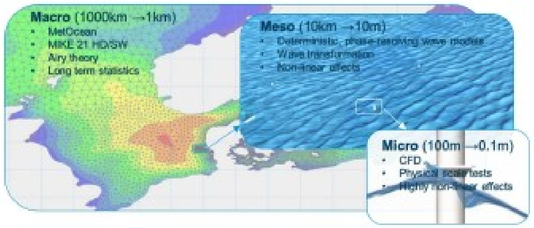
Tower effect occur at 25m – wave nonlinearity is stronger for smaller depth

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

# More results...

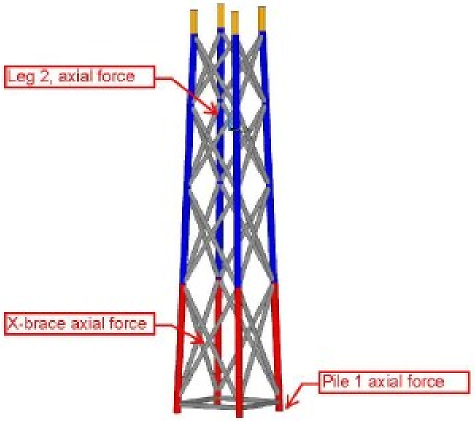
Second-order transfer functions for Mike21 Boussinesq model

Soil model for monopiles with frictional effect

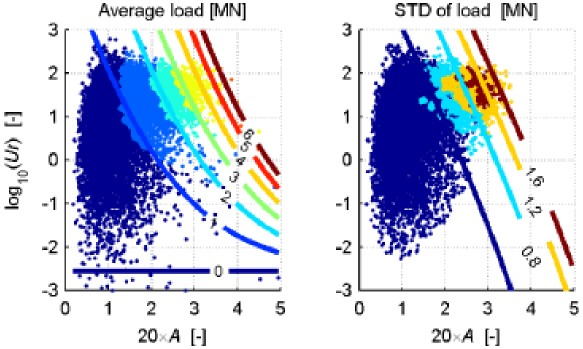



Misaligment study

Superelement for jackets




Probabilistic model for wave impact loads



# The Wave Loads project

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

**Task A**:

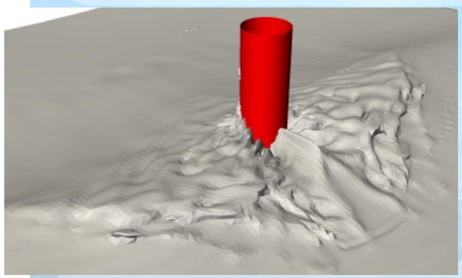
Boundary conditions for phase resolving wave models

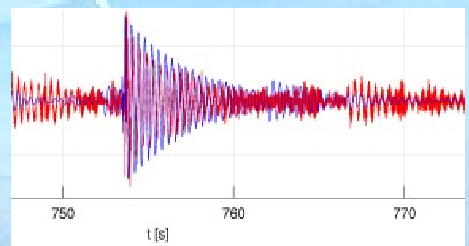
DHI

**Task C**:

Aero-elastic response to fully nonlinear wave forcing

DTU



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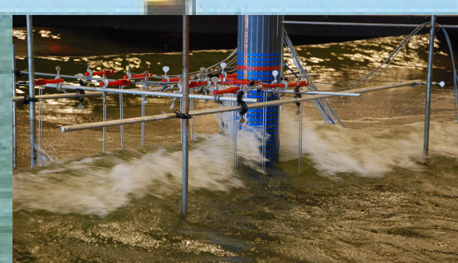
**Task B**:

CFD methods for steep and breaking wave impacts

DTU, (DHI)



**Task D**:

Physical model tests

DHI

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# The Wave Loads project

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**Task A**:

Boundary
phase reso
models

- 3D generation
- Generation at varying depth

- ULS study
- Diffraction
- Wave breaking
- Validated force model
- Uncertainty quantification

nse
wave

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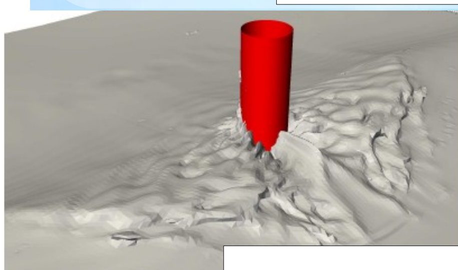

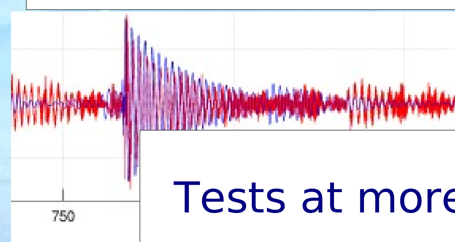


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**Task B**:

CFD me
and bre
impacts

- Viscous boundary layer
- Breaking wave loads
- Improved surface modelling

- Tests at more slopes
- Detailed force/kinematics measurements
- 3D tests
- Secondary structures

DHI