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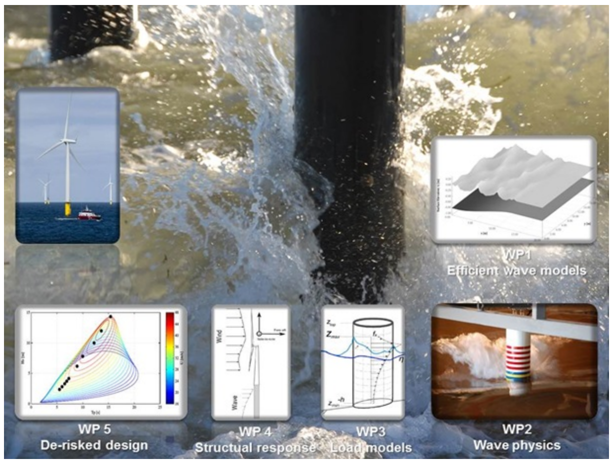
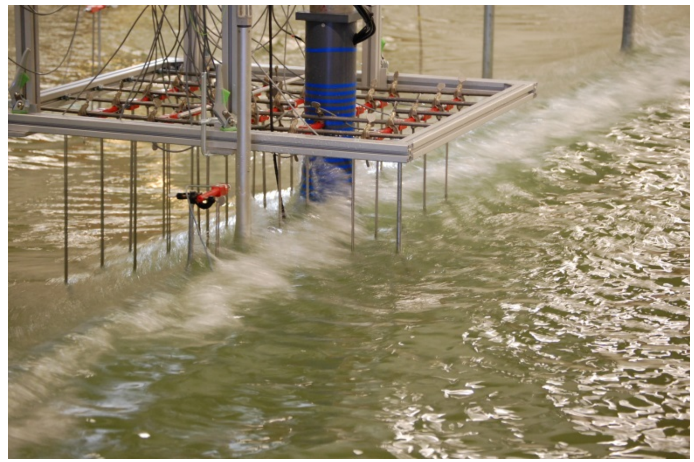
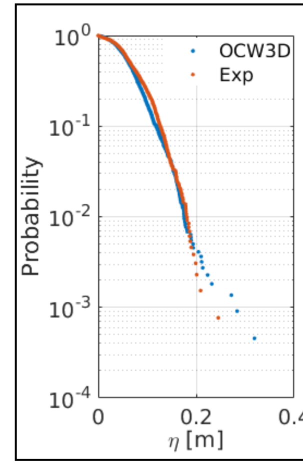
DeRisk
Accurate prediction of ULS wave loads



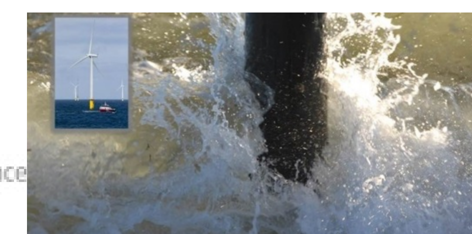




Outlook and first results

Henrik Bredmose et al
DTU

DHI
UNIVERSITY OF OXFORD
University of Stavanger
DONG energy
Statkraft
Statoil



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13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

DeRisk — Accurate prediction of ULS wave loads. Outlook and first results

H. Bredmose[a,*], M. Dixen[d], A. Ghadirian[a], T. J. Larsen[a], S. Schlöer[a], S.J. Andersen[a], S. Wang[a], H.B. Bingham[b], O. Lindberg[b], E.D. Christensen[b], M.H. Vested[b], S. Carstensen[b], A.P. Engsig-Karup[c], O.S. Petersen[d], H.F. Hansen[d], J.S. Mariegaard[d], P.H. Taylor[e], T.A.A. Adcock[e], C. Obhrai[f], O.T. Gudmestad[f], N.J. Tarp-Johansen[g], C.P. Meyer[g], J.R. Krokstad[h], L. Suja-Thauvin[h], T.D Hanson[i]

[a] DTU Wind Energy, Nils Koppels Allé Building 403, DK-2800 Kgs. Lyngby, Denmark
[b] DTU Mechanical Engineering, DK-2800 Kgs. Lyngby, Denmark
[c] DTU Department of Applied Mathematics and Computer Science, DK-2800 Kgs. Lyngby, Denmark
[d] DHI, Agern Allé 5, DK-2970 Hørsholm, Denmark
[e] University of Oxford, Wellington Square, Oxford, OX1 2JD, United Kingdom
[f] University of Stavanger, 4036 Stavanger, Norway
[g] DONG Energy A/S, Kraftværksvej 53, DK-7000 Fredericia, Denmark
[h] Statkraft AS, P.O Box 200 Lilleaker, NO-0216 Oslo, Norway
[i] Statoil ASA, Box 7200, NO-5020 Bergen, Norway

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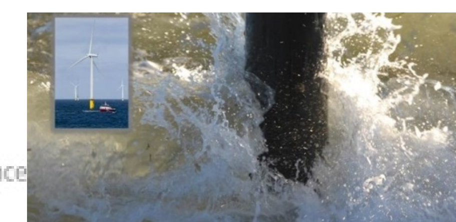

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4 years (2015-2019)

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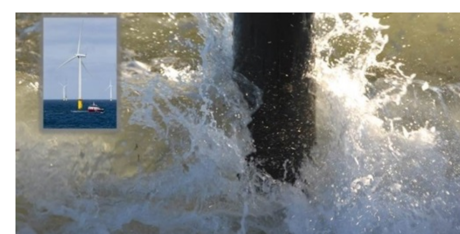

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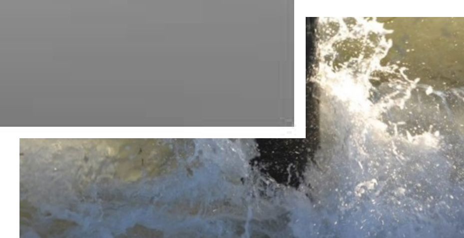
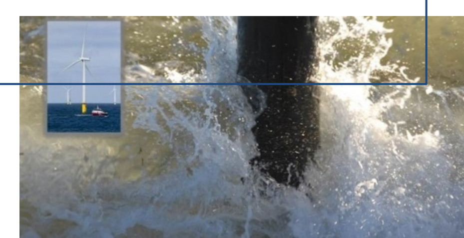
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

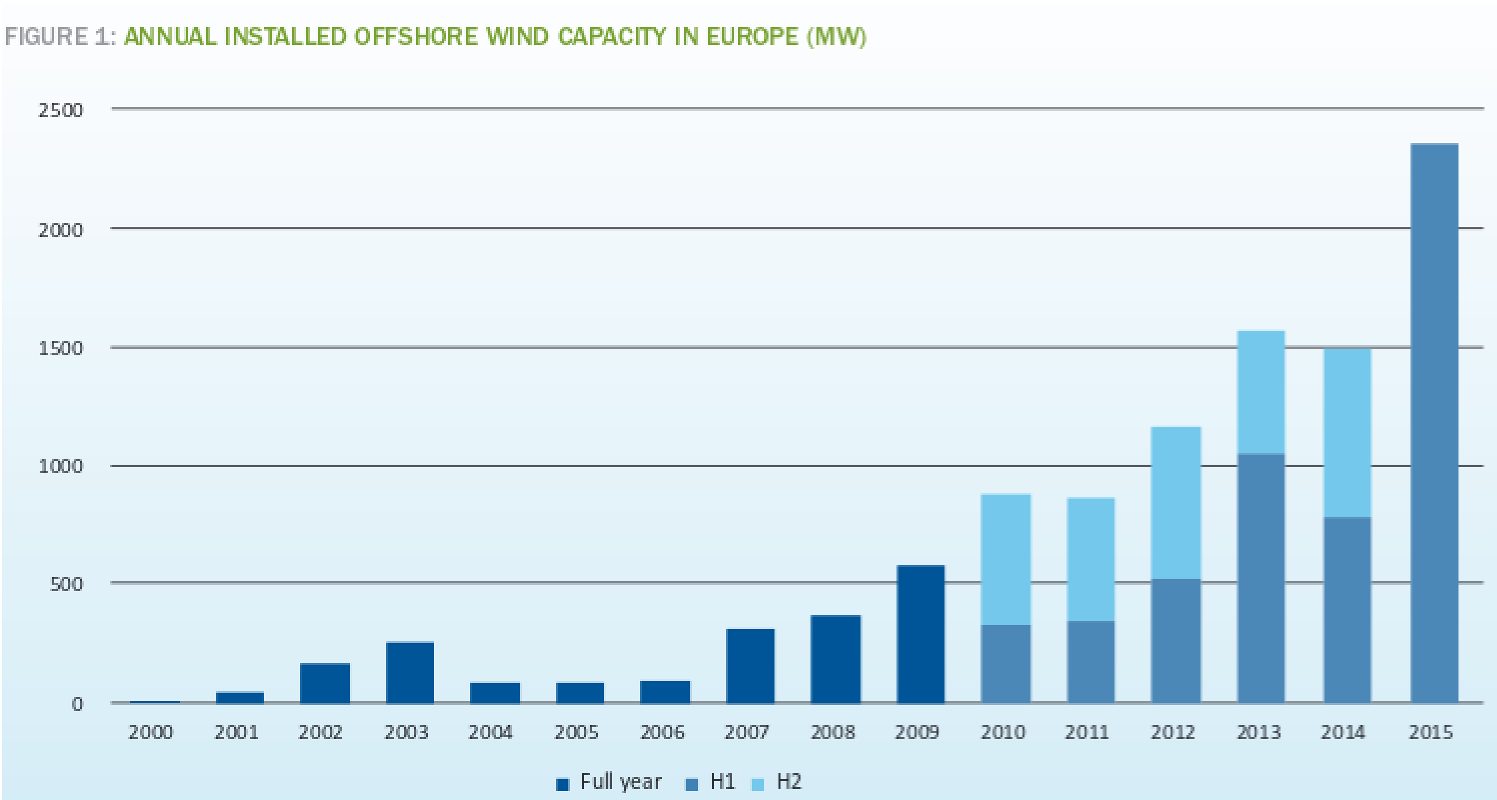


Outline

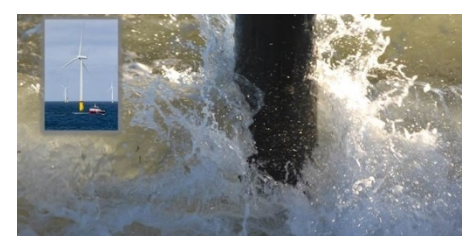
- Background
- Opportunities
- Elements of DeRisk
- First results



Offshore wind energy



Source: EWEA

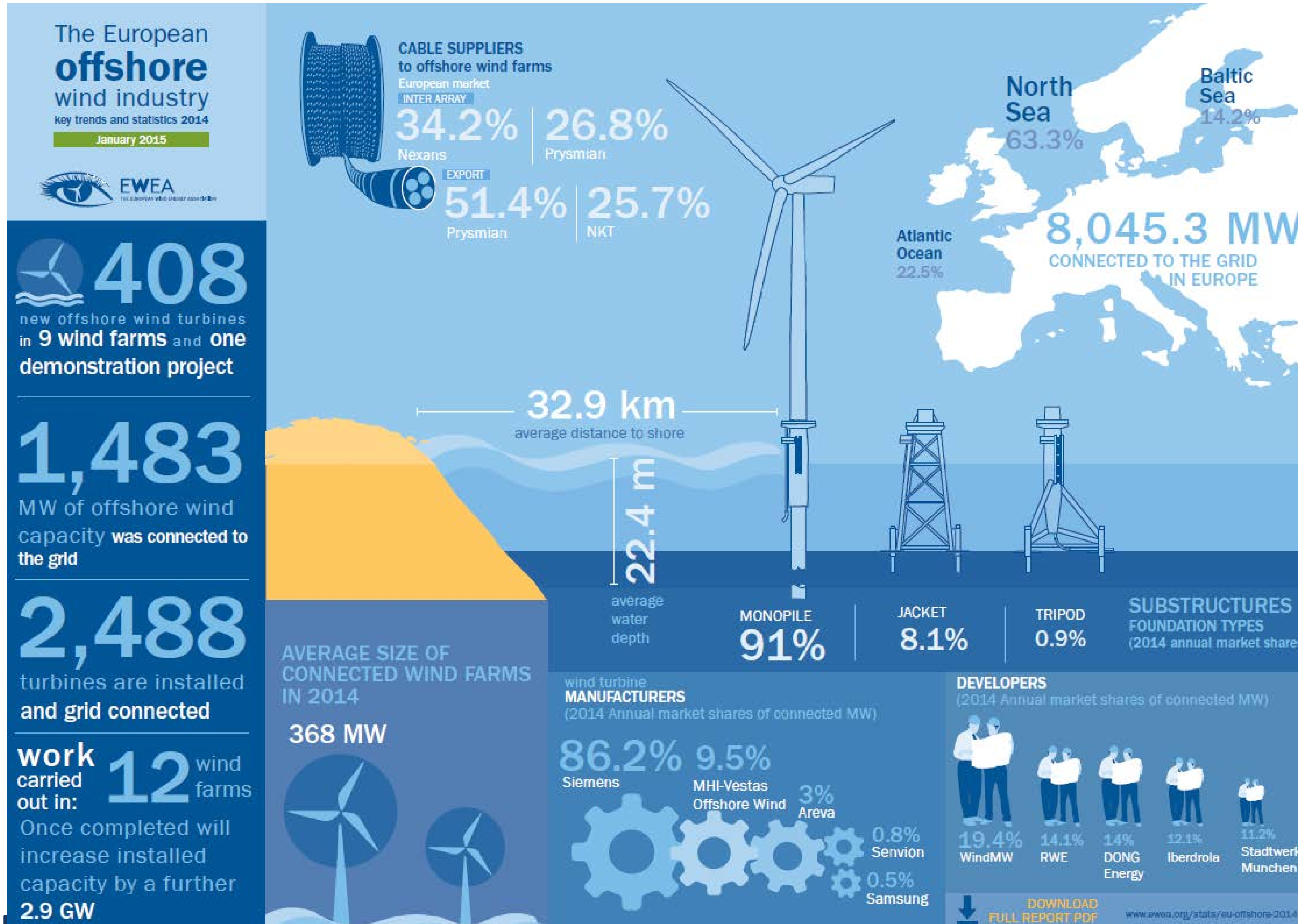


DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

Graphics from www.ewea.com

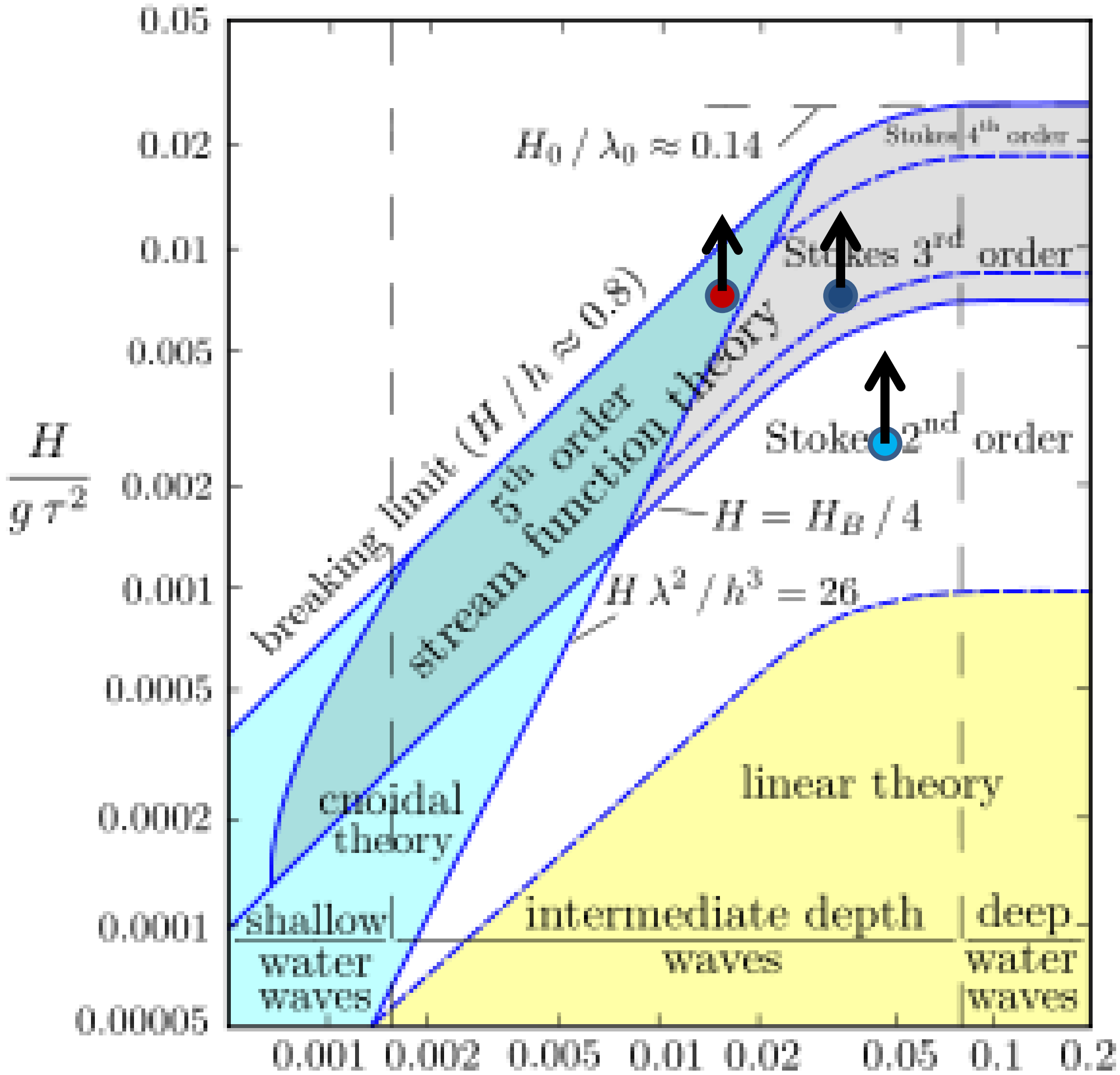
Offshore wind energy

Innovation Fund Denmark
RESEARCH, TECHNOLOGY & GROWTH



Graphics from www.ewea.com

How deep do we go?



At h=22m depth

Operational

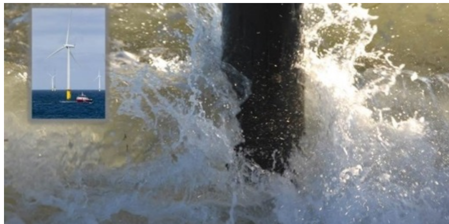
Hs=1m; Tp=6s

Hs=6m; Tp=9.5s

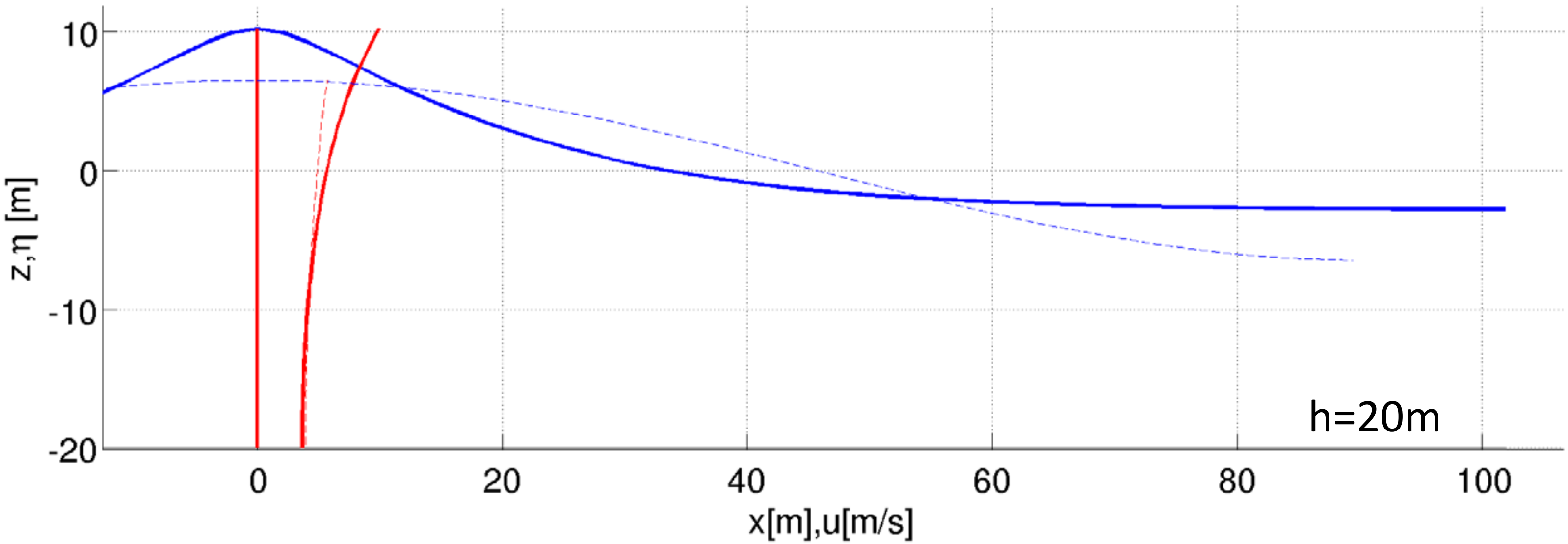
ULS

Hs=9.5; Tp=12s

1.86 x Hs



Stream function theory waves



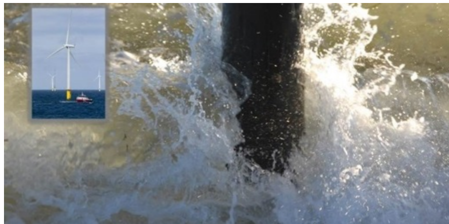
Fully nonlinear

Easily computed (e.g. Fenton 1988)

Can be embedded into background state

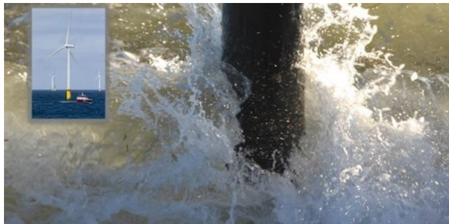
But: flat bed theory; periodic; 2D

What about wave transformation, transient group nature, current, 3D effects?



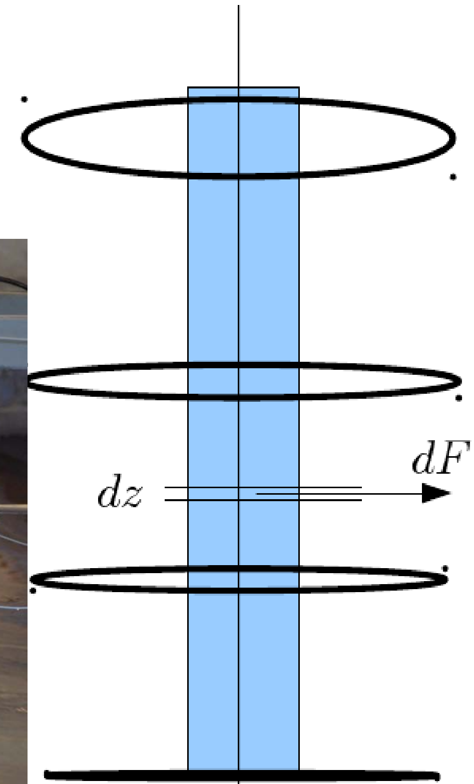
Opportunities

Can we improve the design methods?



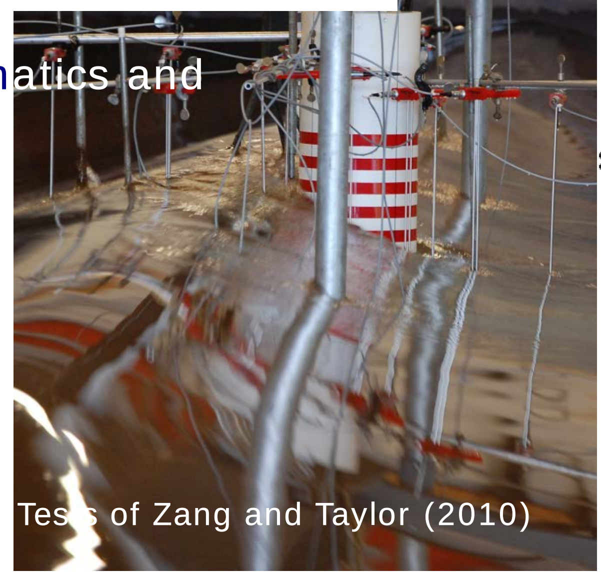
Hydrodynamic loads

Simplest: Linear wave kinematics and Morison equation



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

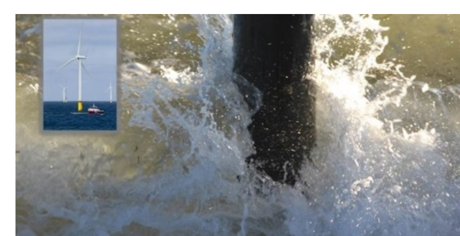
Better: Fully nonlinear wave kinematics and Morison-type force model



Tests of Zang and Taylor (2010)

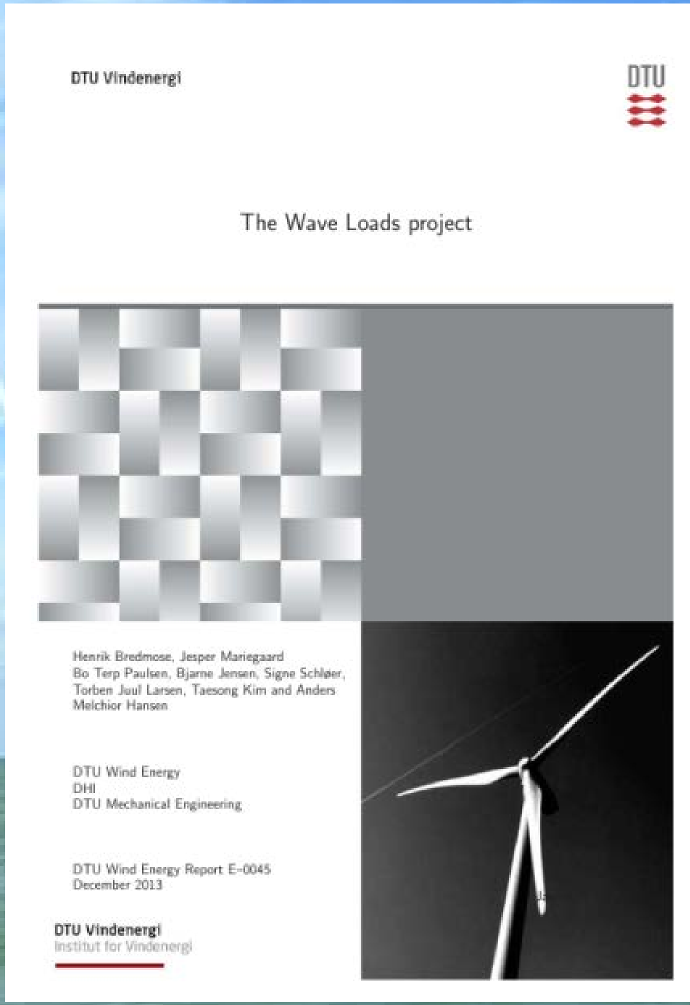
Advanced: CFD and coupled CFD

DeRisk – De-risking of ULS wave loads on offshore wind turbine structures



The Wave Loads project

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

The Wave Loads project

Henrik Bredmose, Jesper Mariegaard
Bo Terp Paulsen, Bjarne Jensen, Signe Schløer,
Torben Juul Larsen, Taesong Kim and Anders
Melchior Hansen

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DTU Mechanical Engineering

DTU Wind Energy Report E-0045
December 2013

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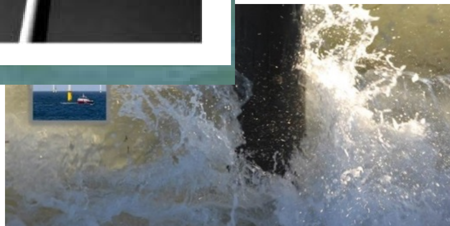
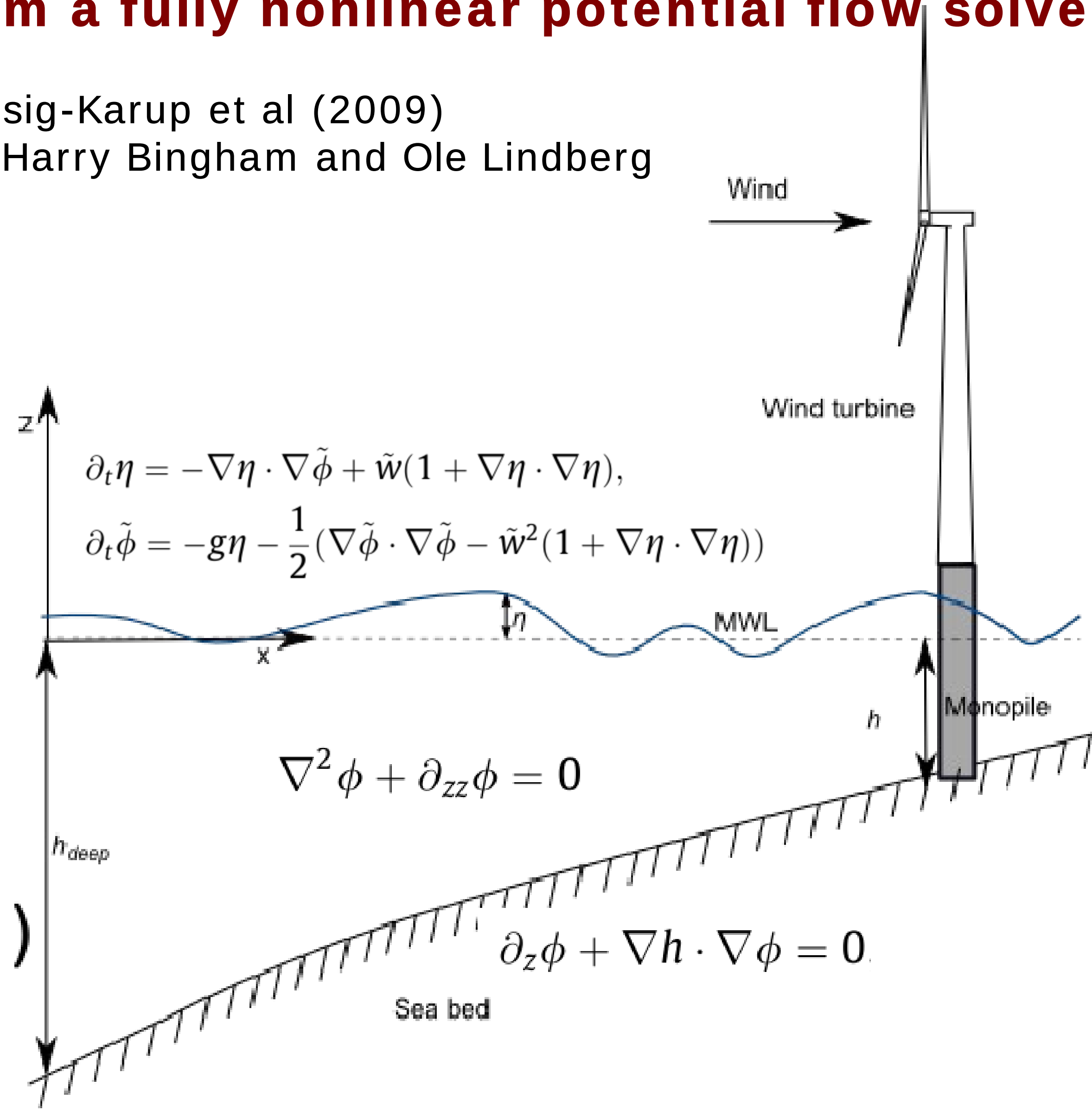
Institut for Vindenergi



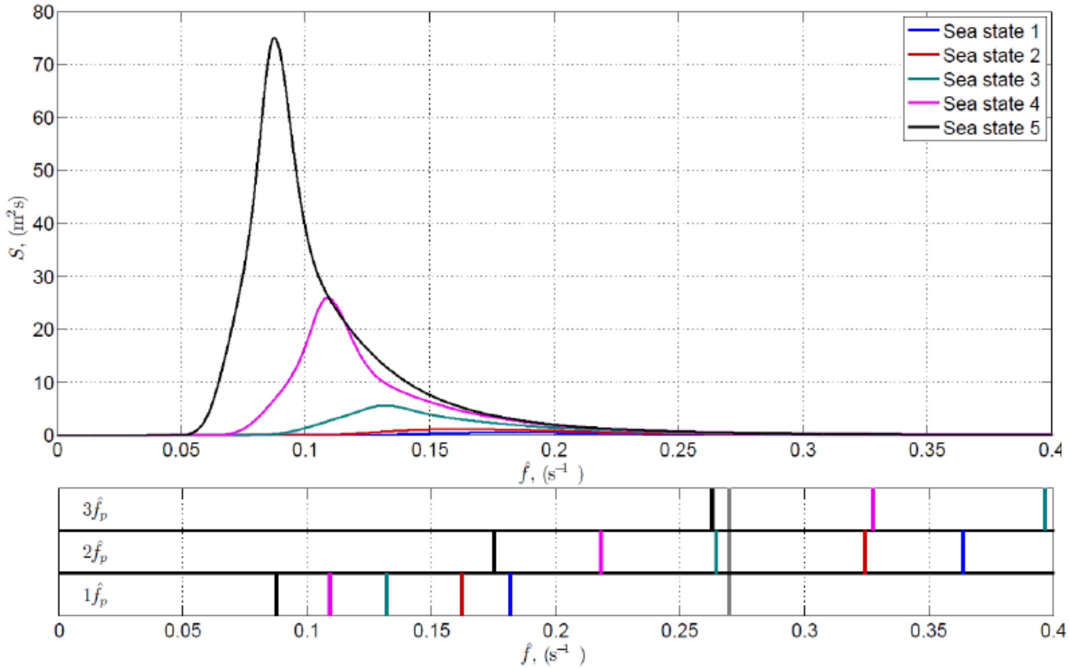
Kinematics from a fully nonlinear potential flow solver

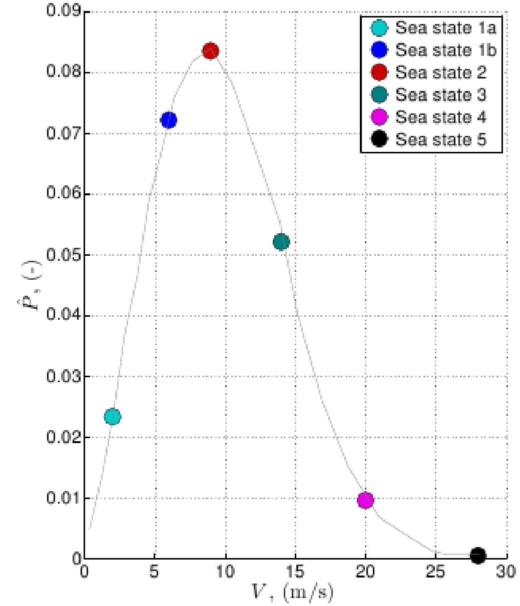
‘OceanWave3D’, Engsig-Karup et al (2009)
Allan Engsig-Karup, Harry Bingham and Ole Lindberg

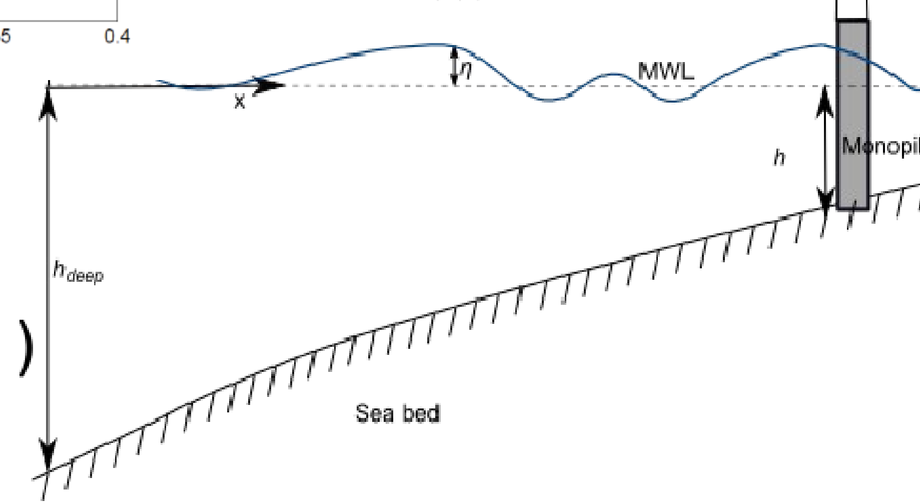


Study of nonlinear wave load effects

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





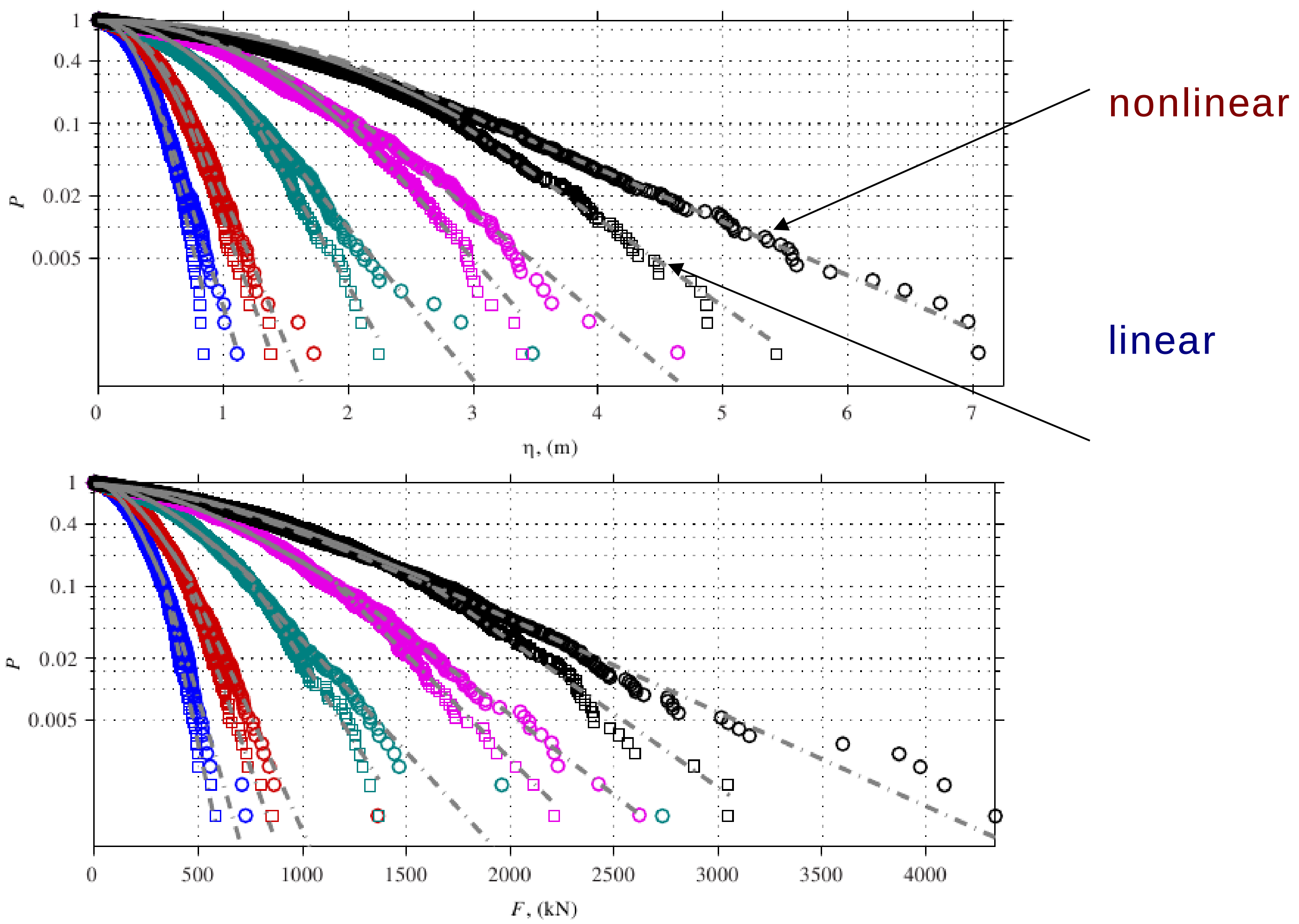


Signe Schløer (2013)

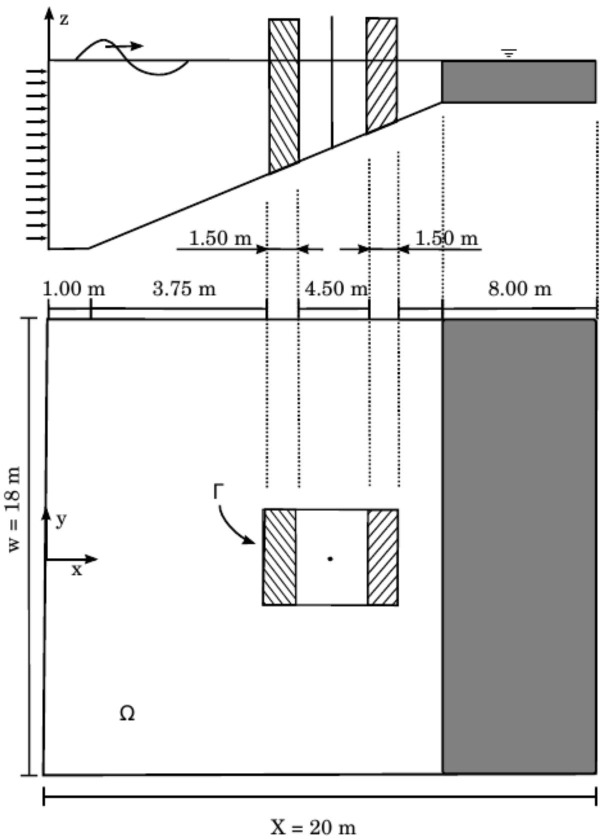
Static load analysis, h=30m

crest elevations

force peaks
depth integrated
force



CFD for multi-directional waves Coupled solver



Bo Terp Paulsen
Paulsen, Bredmose & Bingham (2014)

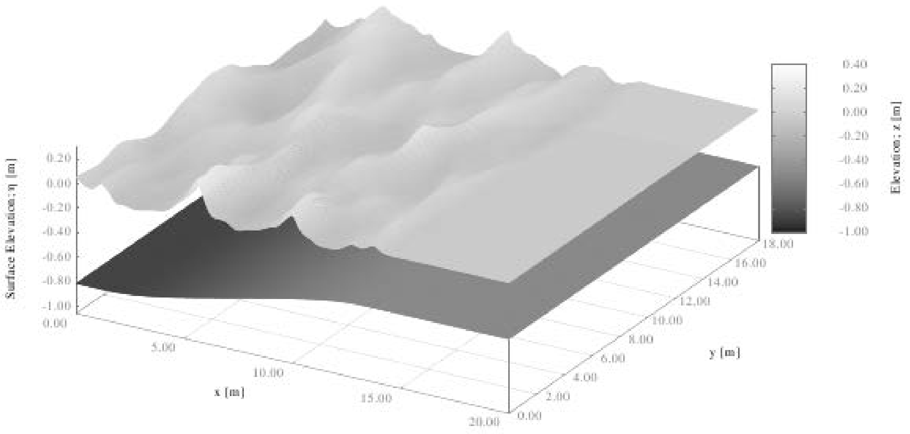


Figure 3.27: Snapshot of the free surface elevation computed by the potential flow solver at time $t = 15$ s.

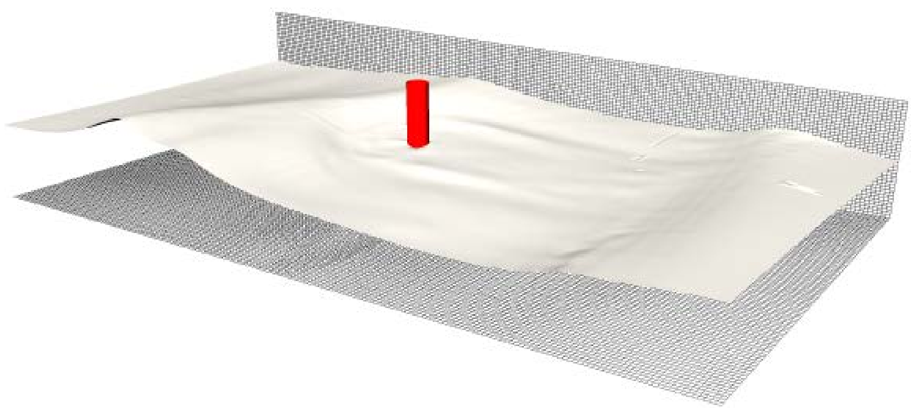


Figure 3.28: Snapshot of the free surface elevation computed by the Navier-Stokes solver at time $t = 15$ s.

Study of regular steep wave forcing of circular cylinders

J. Fluid Mech. (2014), *vol.* 755, *pp.* 1–34.
doi:10.1017/jfm.2014.386

Forcing of a bottom-mounted circular cylinder by steep regular water waves at finite depth

Bo T. Paulsen[1,2,†], **H. Bredmose**[3], **H. B. Bingham**[1] and **N. G. Jacobsen**[1,2]

[1]Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, 2800, Denmark

[2]Deltares, Rotterdamseweg 185, 2629HD Delft, The Netherlands

[3]Department of Wind Energy, Technical University of Denmark, Kgs. Lyngby, 2800, Denmark

(Received 22 March 2013; revised 13 June 2014; accepted 28 June 2014; first published online 14 August 2014)

Forcing by steep regular water waves on a vertical circular cylinder at finite depth was investigated numerically by solving the two-phase incompressible Navier–Stokes equations. Consistently with potential flow theory, boundary layer effects were neglected at the sea bed and at the cylinder surface, but the strong nonlinear motion of the free surface was included. The numerical model was verified and validated by grid convergence and by comparison to relevant experimental measurements. First-order convergence towards an analytical solution was demonstrated and an excellent agreement with the experimental data was found. Time-domain computations of the normalized inline force history on the cylinder were analysed as a function

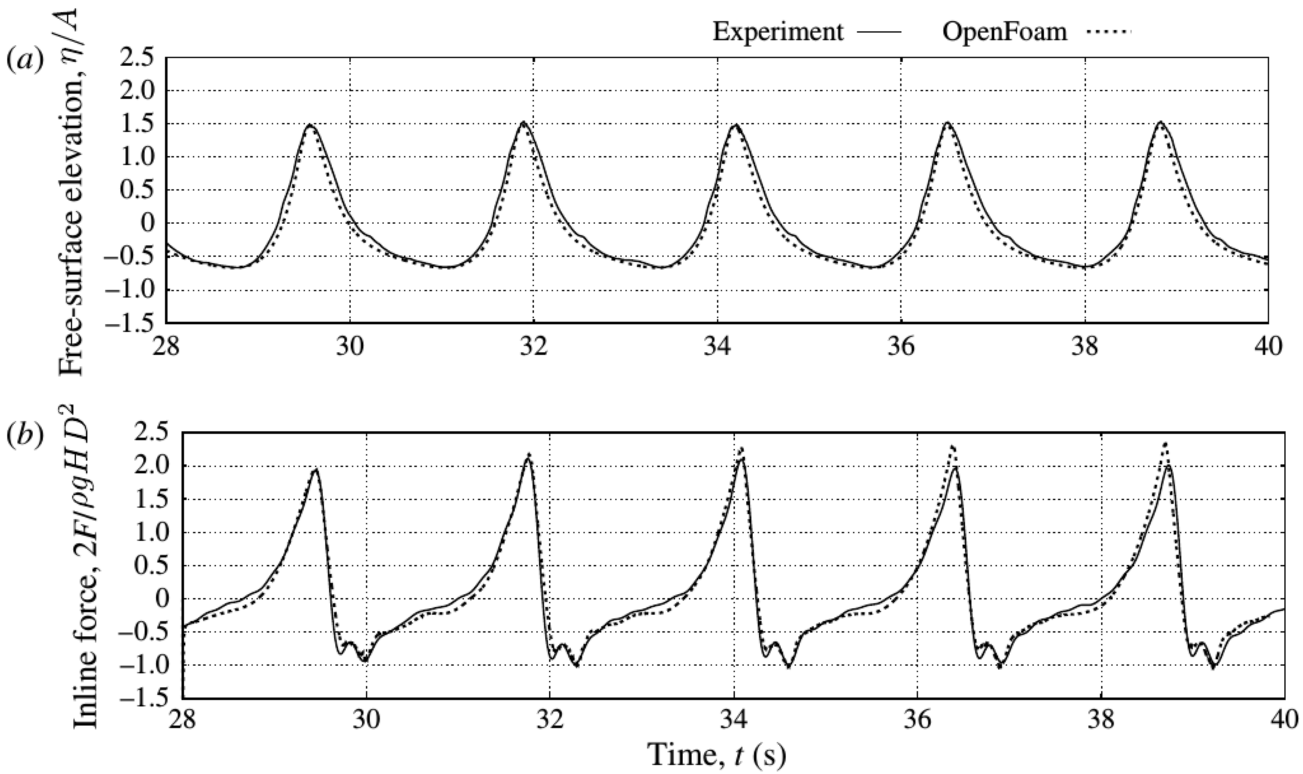
Validation for propagation of nonlinear waves

Force validation

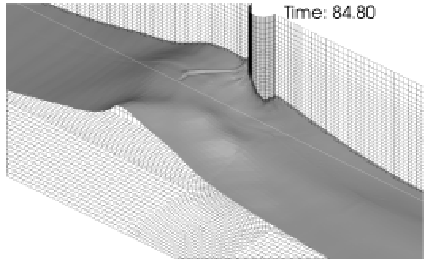
Parameter study

The flow of the secondary load cycle

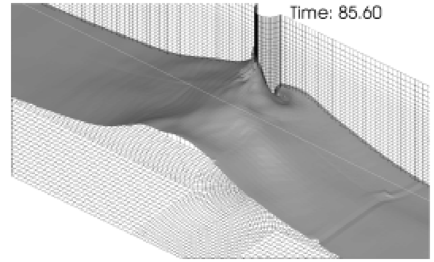
How about the forces? II



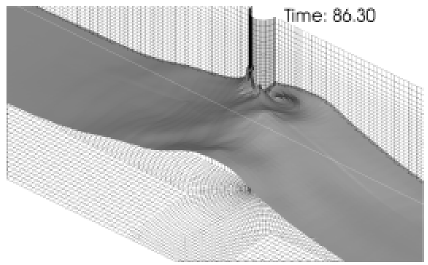
Comparison to experiments of Wave Loads project (DTU-DHI)



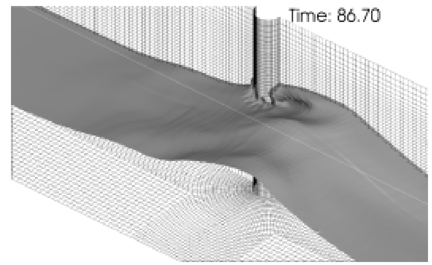
(a) The free surface at the time of the wave impact.



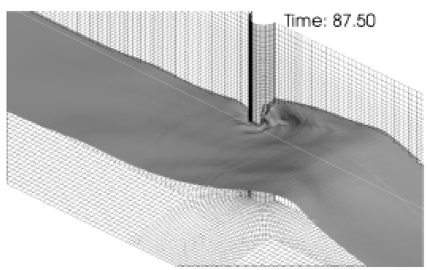
(b) The free surface when the front of the locally diffracted wave hits the symmetry plane.



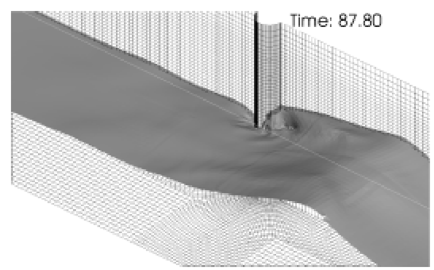
(c) The free surface at the time of maximum wave run-up at the downstream side of the cylinder.



(d) The free surface at the beginning of the secondary load cycle.



(e) The free surface during the secondary load cycle.

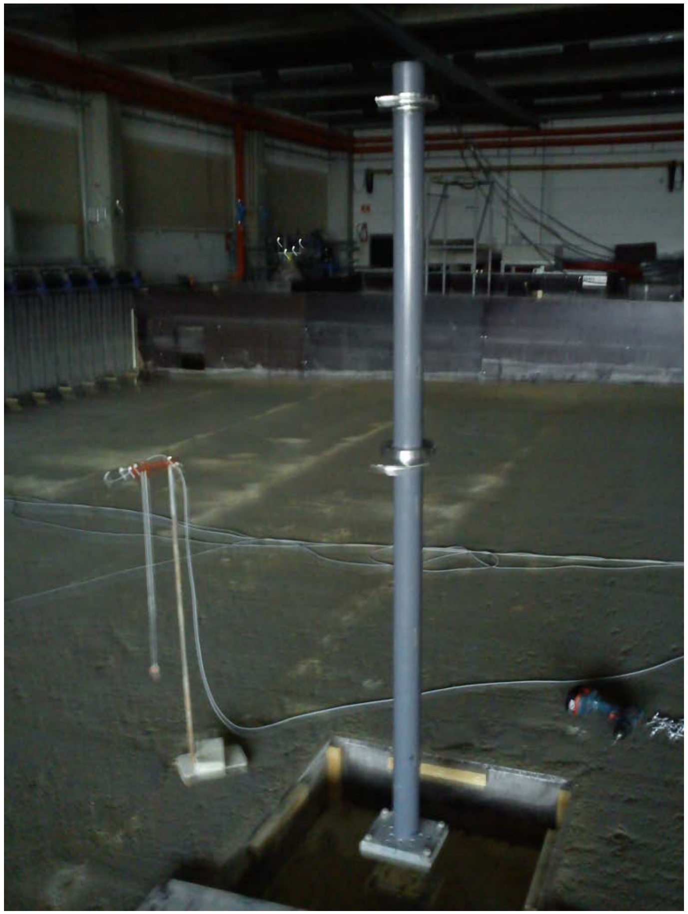


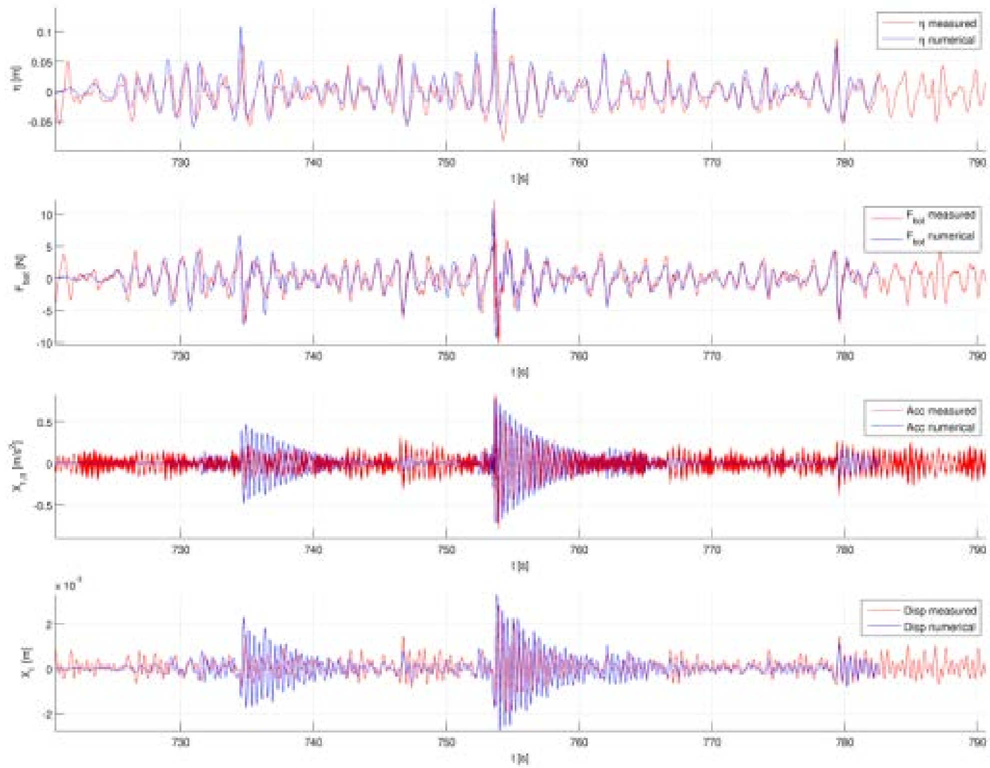
(f) The free surface at the end of the secondary load cycle.

Figure 12: Snapshots of the free surface for a regular wave with $H/H_{\max} = 0.8$, $kh = 0.67$ and $kR = 0.10$.

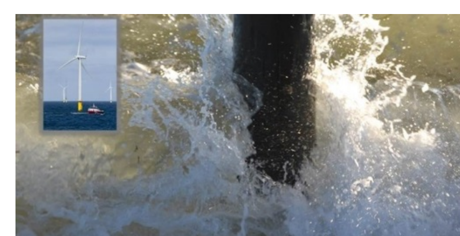
Physical model test with a flexible cylinder at DHI

Bredmose et al OMAE 2013
Inspiration from de Ridder et al OMAE 2011
Data used in OC5 (Robertson et al yesterday)





DeRisk – De-risking of ULS wave loads on offshore wind turbine structures



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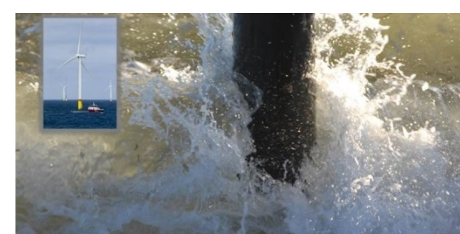
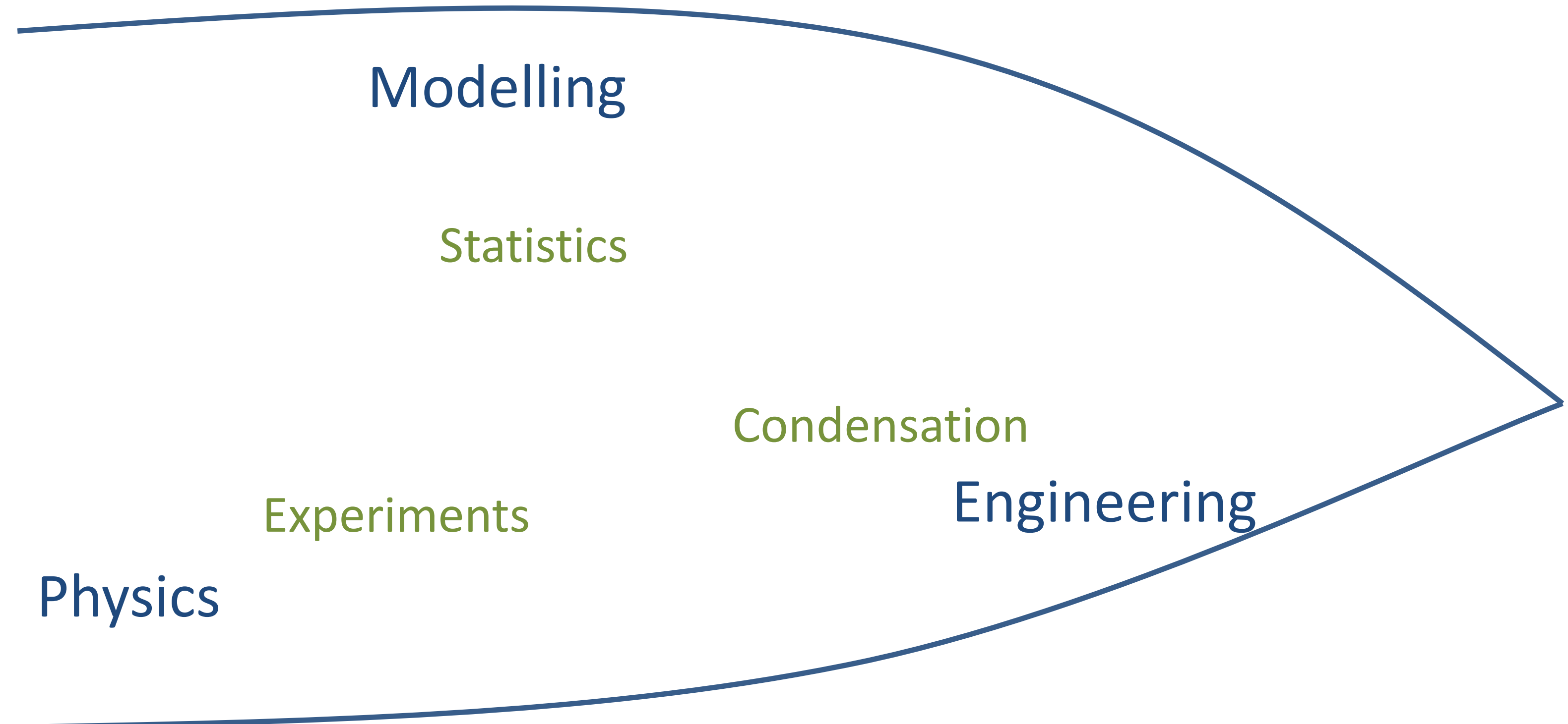
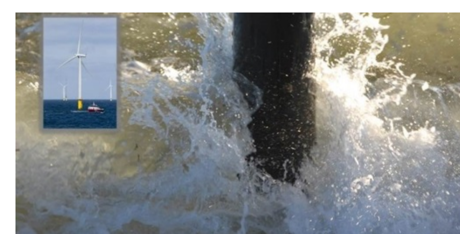


Mission

Bring tools for realistic ULS wave loads into engineering!

Apply to reduce risk and uncertainty. Thereby reduce LCOE.





Elements of DeRisk

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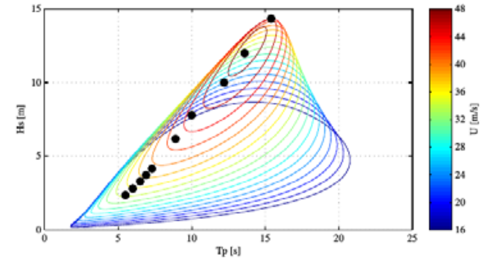
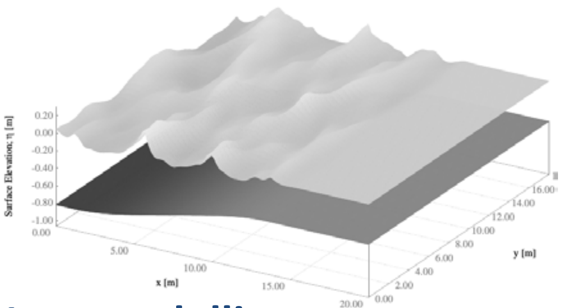
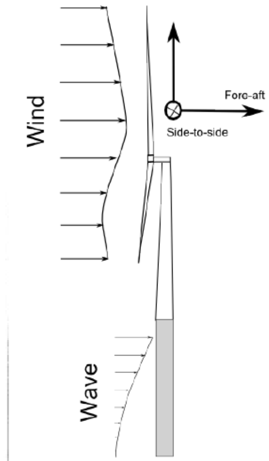


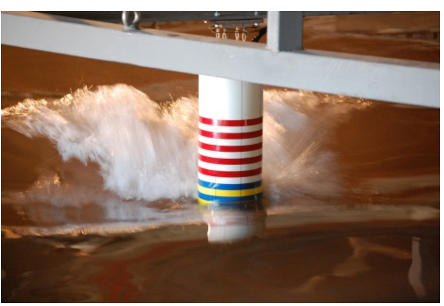
Design



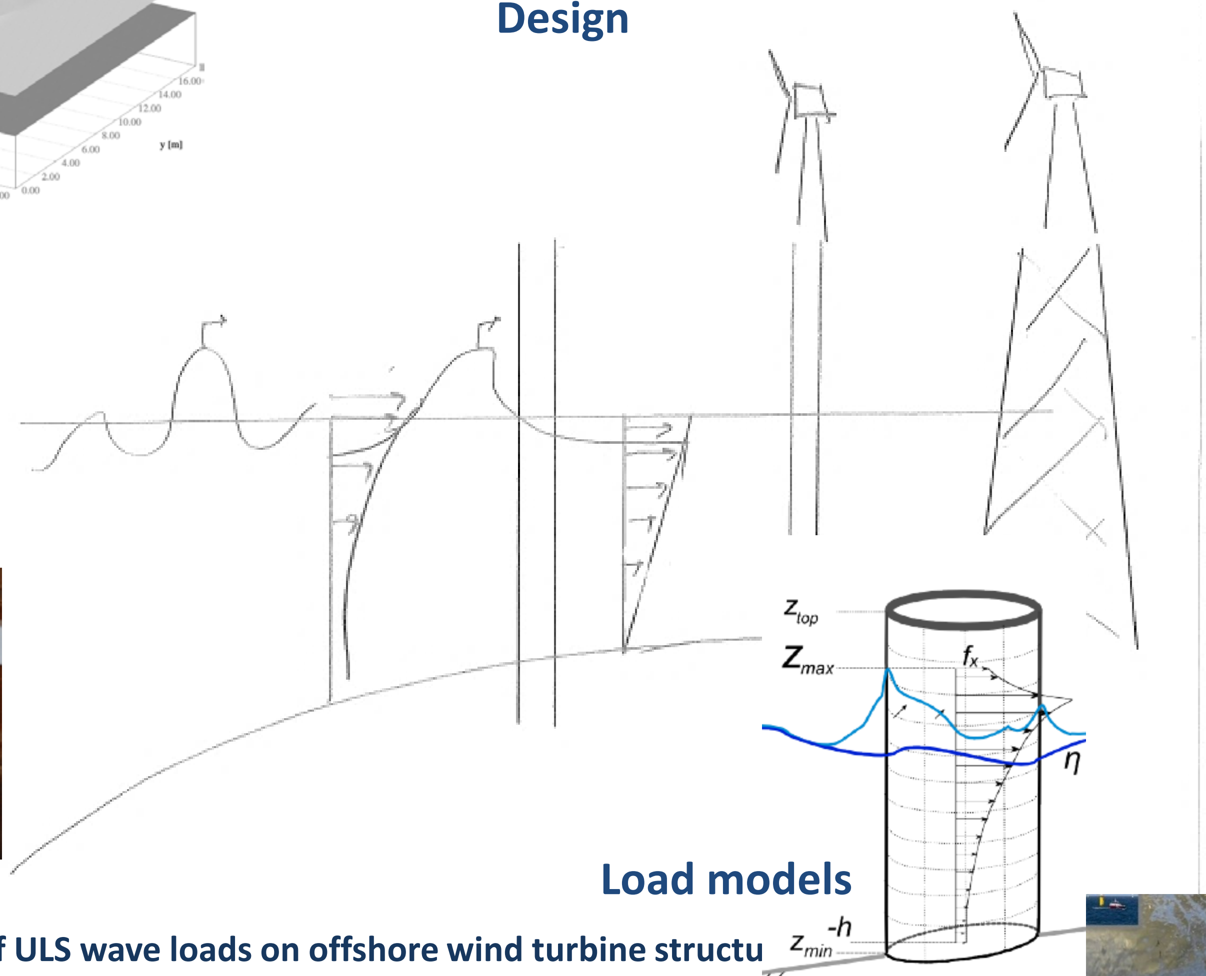
Wave modelling



Structural response



Wave physics



Load models

DeRisk – De-risking of ULS wave loads on offshore wind turbine structu

Efficient wave models

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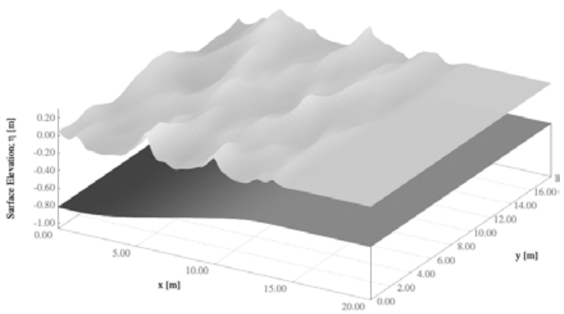
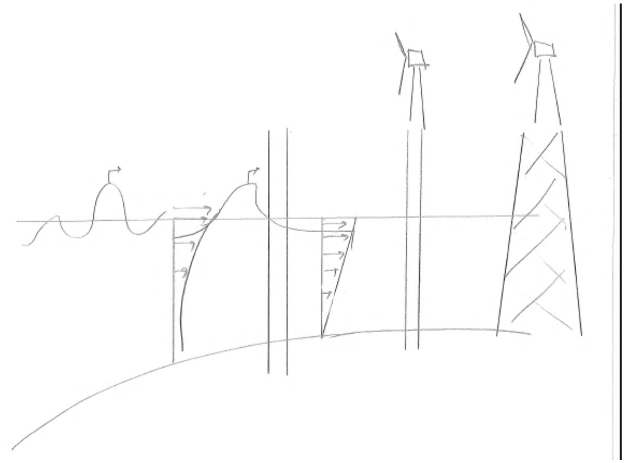
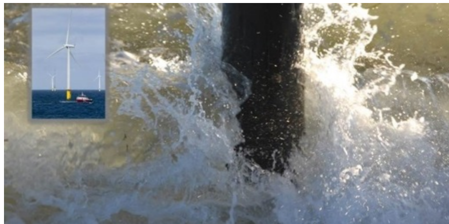




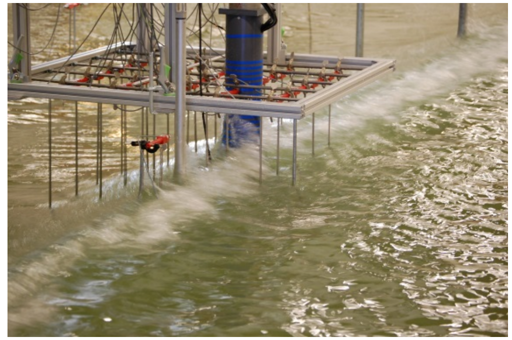
- Operational GPU wave model with wave generation.
- Improved breaking.
- Kinematics library for use by the other work packages.
- Proof of concept for DHI wave model for flows with vorticity.

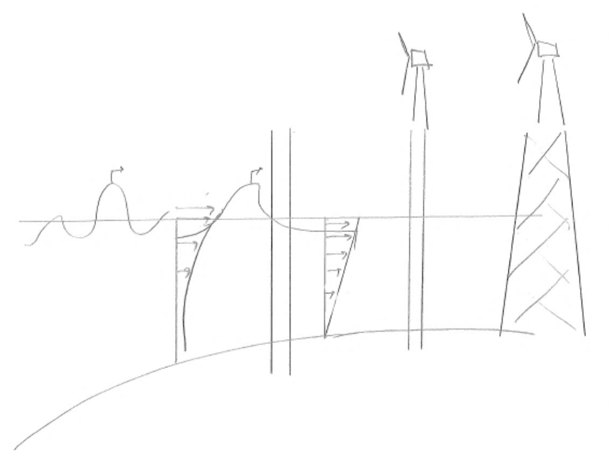
WP leader: Harry Bingham, DTU Mechanical Engineering.

Partners: DTU Mechanical Engineering, DTU Compute and DHI.



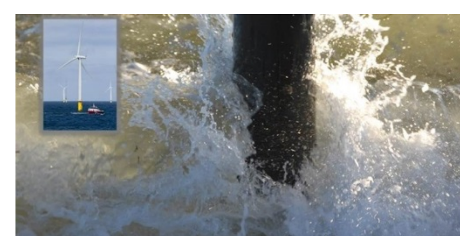
Wave physics



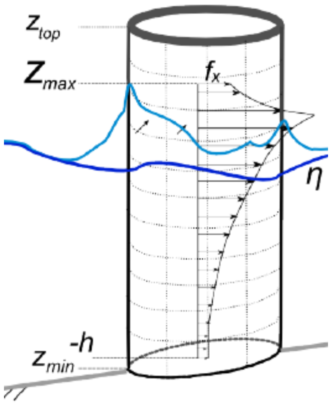


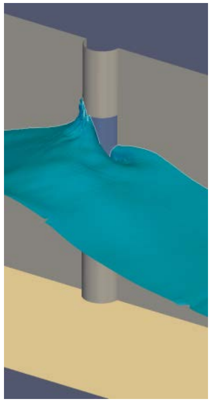
- Experiments with steep/breaking wave impacts
- Derivation of a slope reduction factor for extreme loads.
- Quantification of current effect on loads.
- Kinematics and corresponding forces
- Mathematical uncertainty quantification for wave kinematics and loads.
- Numerical study of 3D wave formation and effects on crest height distribution and load distribution.

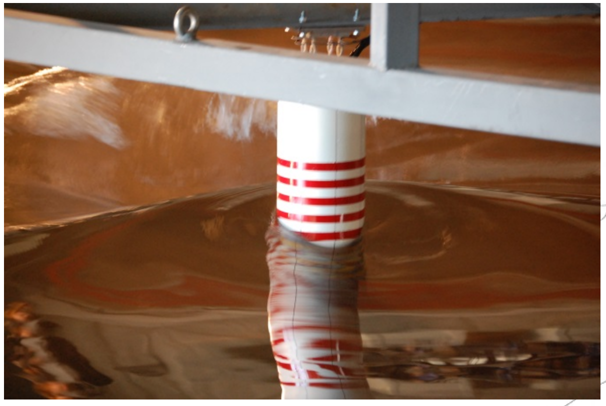
WP leader: Henrik Bredmose, DTU Wind Energy.
Partners: DTU Wind Energy, DTU Mechanical Engineering, DTU Compute, DHI and University of Oxford.

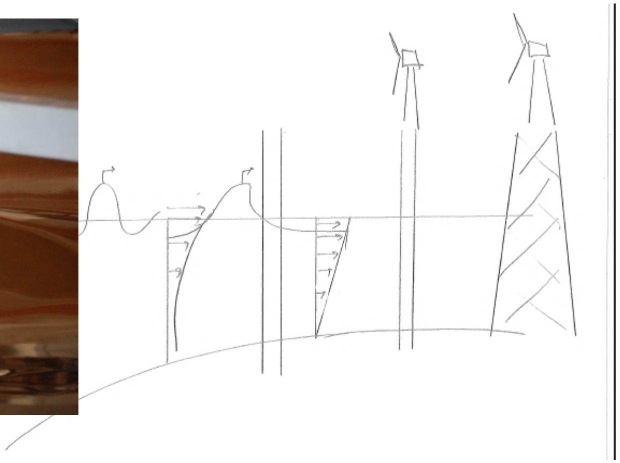


Validated load models





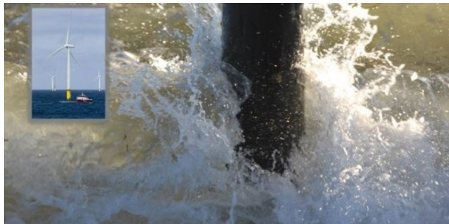




- Validated force model for steep and highly nonlinear waves.
- Validated force model for breaking wave loads.
- DES strategy for monopile CFD with inclusion of structural boundary layer.
- Load computations for drag-dominated wave impacts.

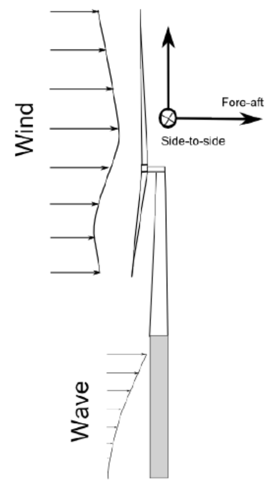
WP leader: Henrik Bredmose, DTU Wind Energy.

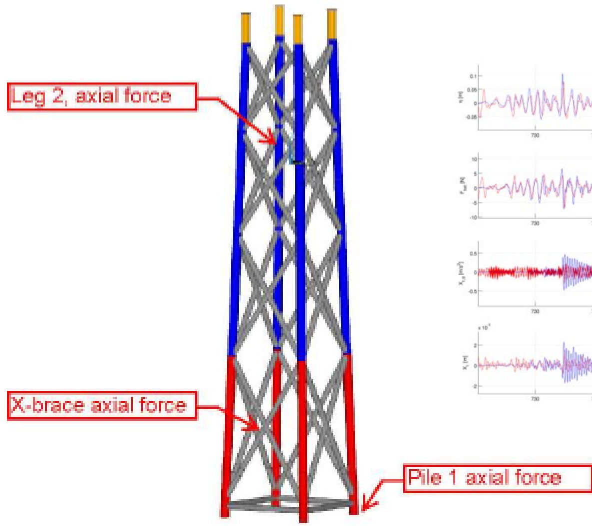
Partners: DTU Wind Energy, University of Oxford, University of Stavanger and Statkraft.

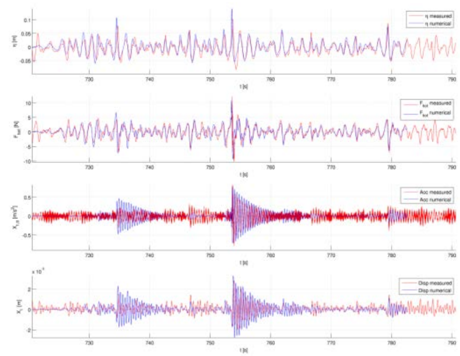


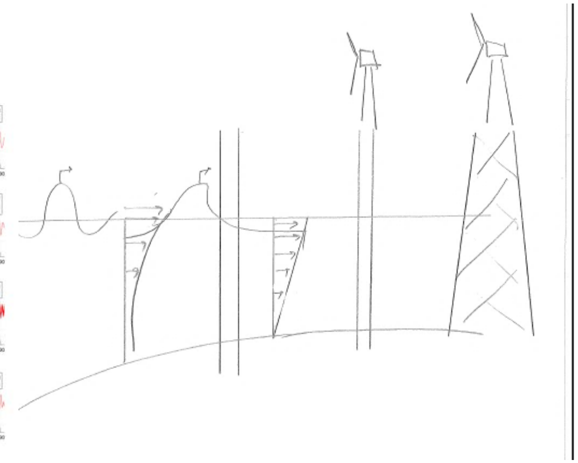
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

Response of wind turbine structures







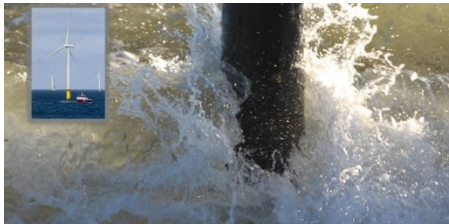


- Identification of critical load cases for jacket response to extreme waves.
- Analysis of the WaveSlam data set (NTNU, Stavanger University)
- Study of load effects from cyclic degradation of soil properties.
- Analysis of full scale data to identify the extent of ringing loads.
- Analysis and model formulation of current blockage effect for jackets

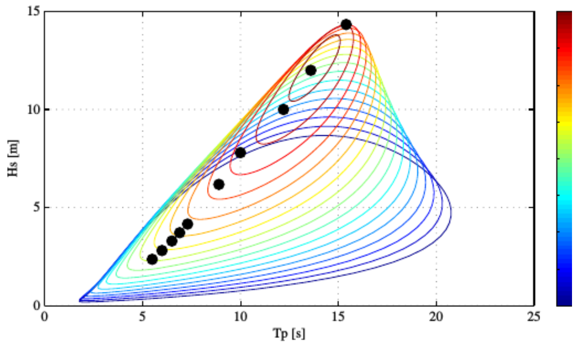
WP leader: Torben Juul Larsen, DTU Wind Energy.

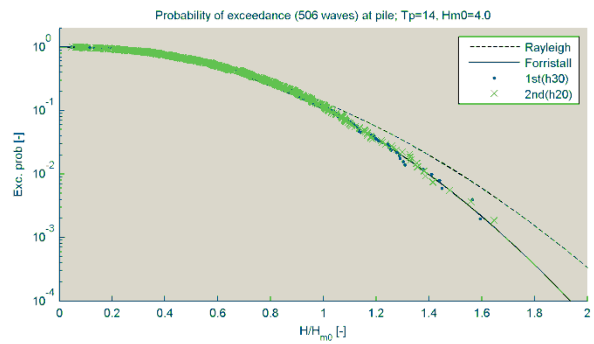
Partners: DTU Wind, University of Oxford, University of Stavanger, DONG.

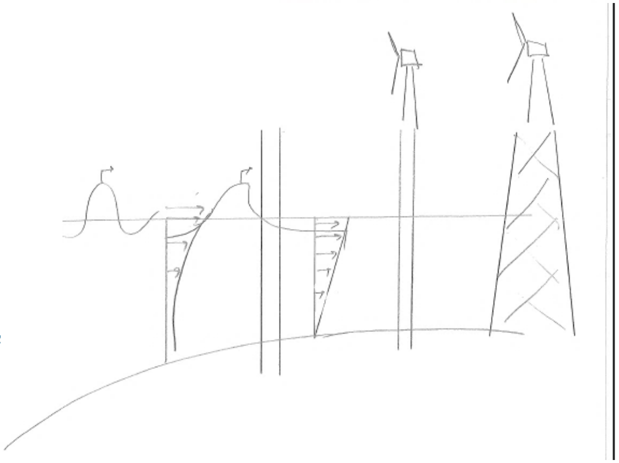
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures



De-risked design





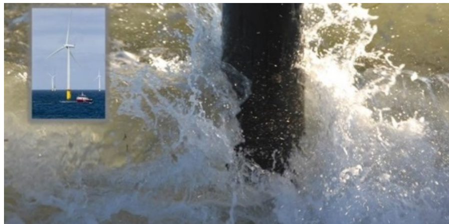


- White paper on the design chain from met-ocean data to design stress with discussion of the uncertainty.
- Uncertainty reduction for the statistical combination of extreme wind, sea and current data.
- Joint probability analysis methods that include structural response.
- A new load evaluation procedure based on fully nonlinear wave kinematics and the validated load models and an n¬-dimensional joint probability model of sea state parameters.

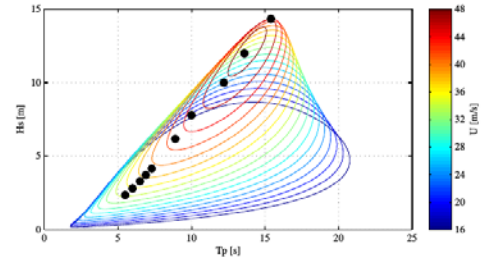
WP leader: Hans Fabricius Hansen, DHI.

Partners: DHI, DONG and DTU Compute.

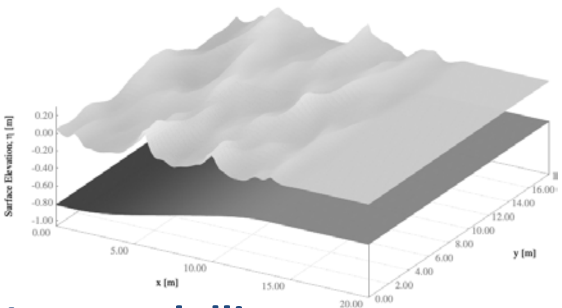
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures



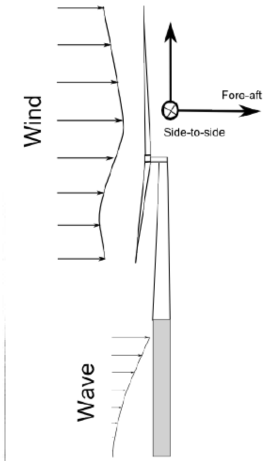
Elements of DeRisk

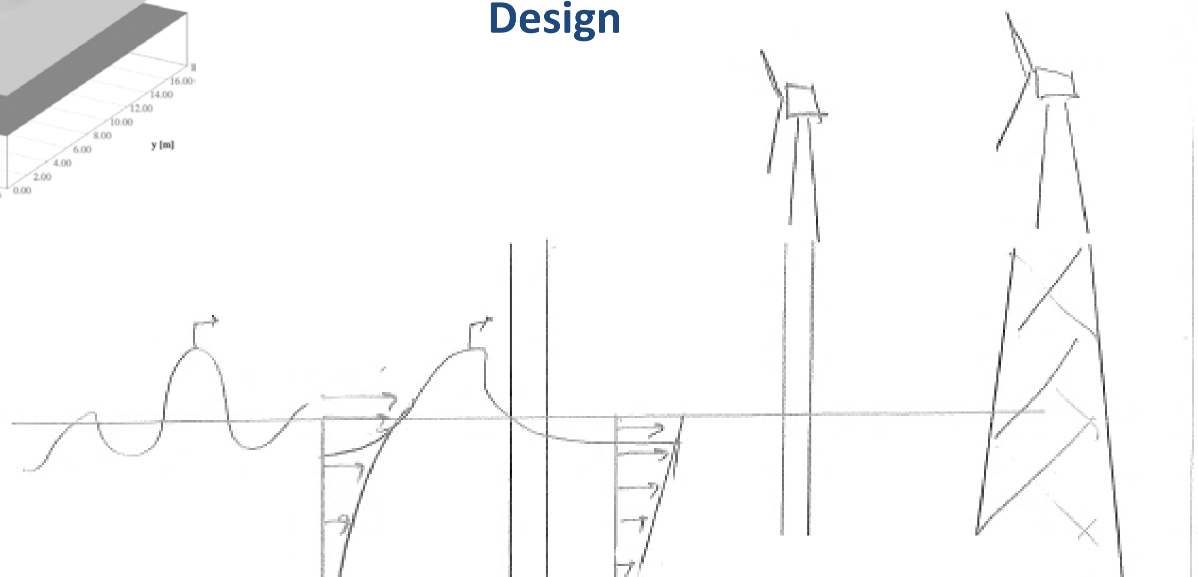


Design

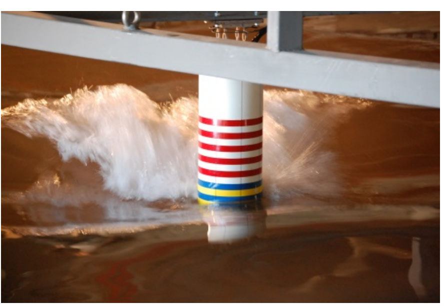


Wave modelling

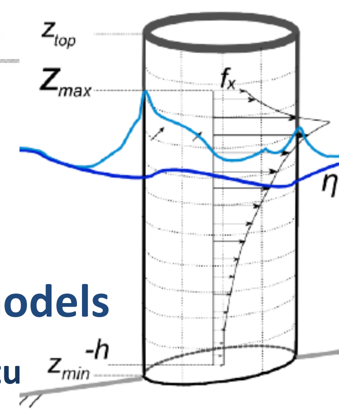




Structural response



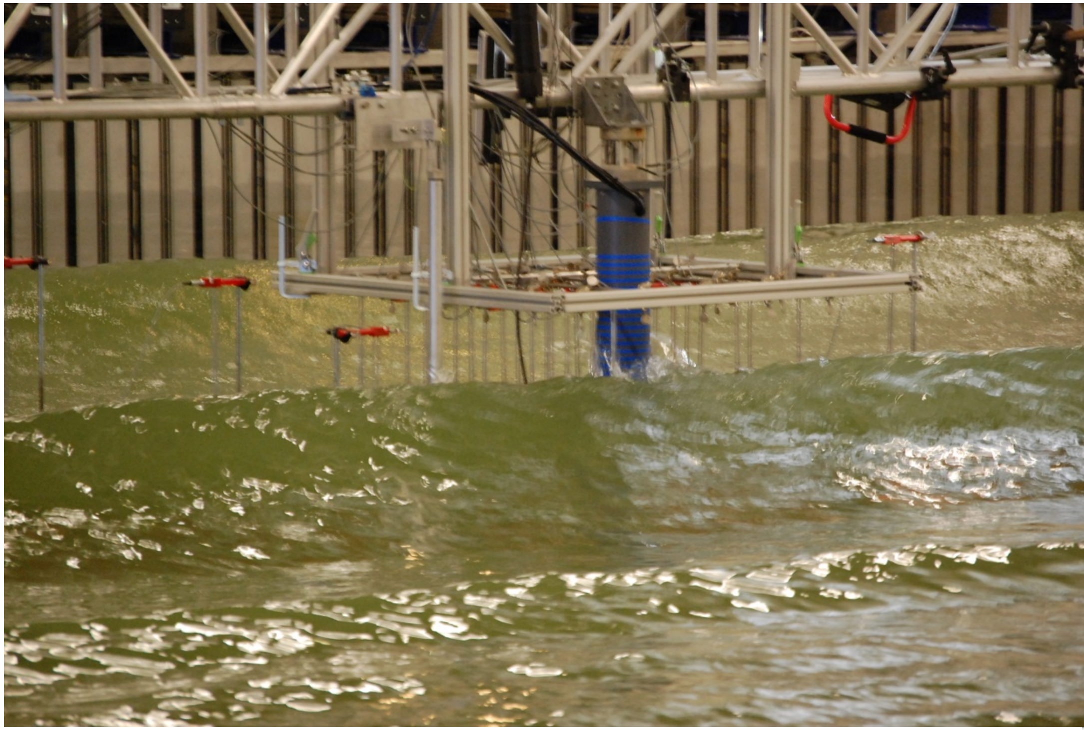
Wave physics

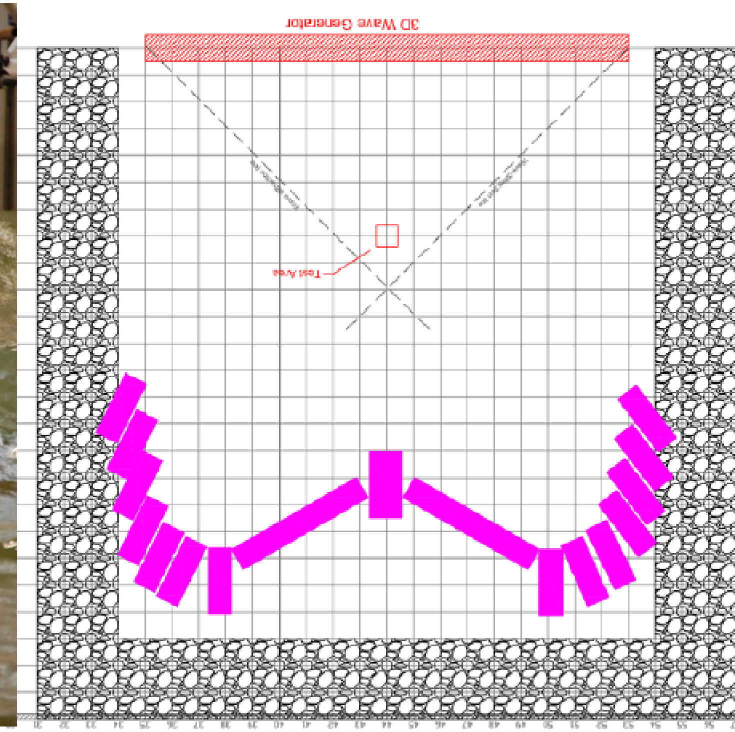


Load models

DeRisk – De-risking of ULS wave loads on offshore wind turbine structu

First results: Model tests at DHI





Led by Martin Dixen, DHI

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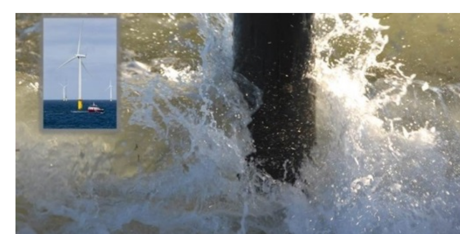
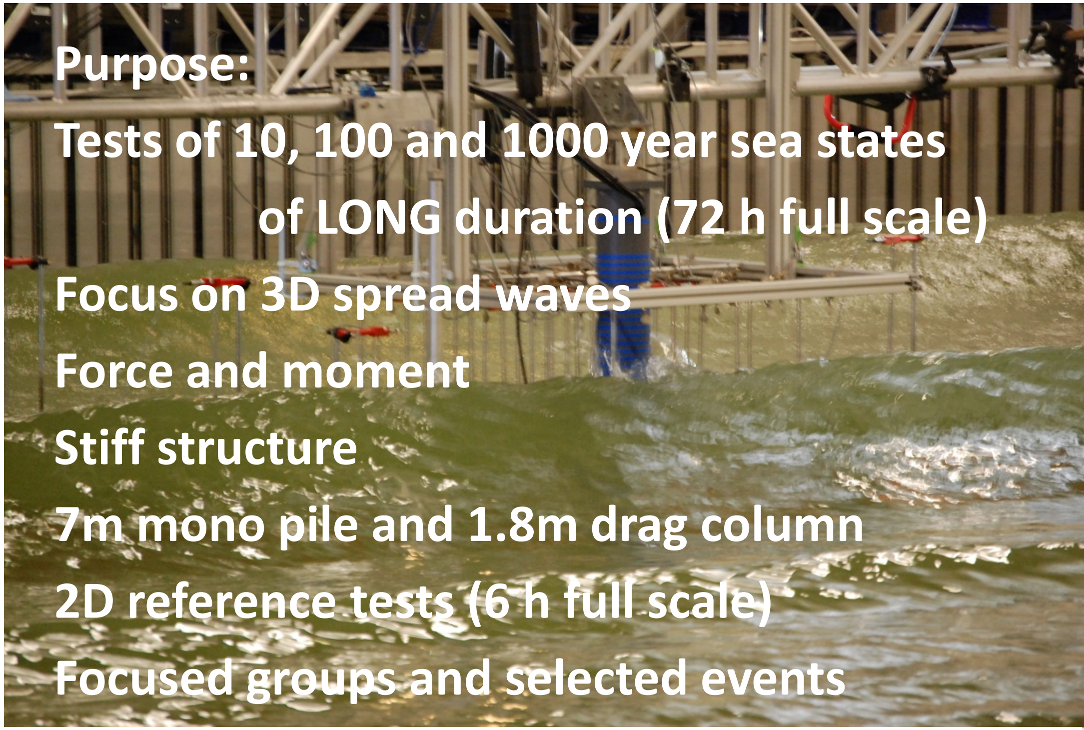


First results: Model tests at DHI



Purpose:

Tests of 10, 100 and 1000 year sea states of LONG duration (72 h full scale)

Focus on 3D spread waves

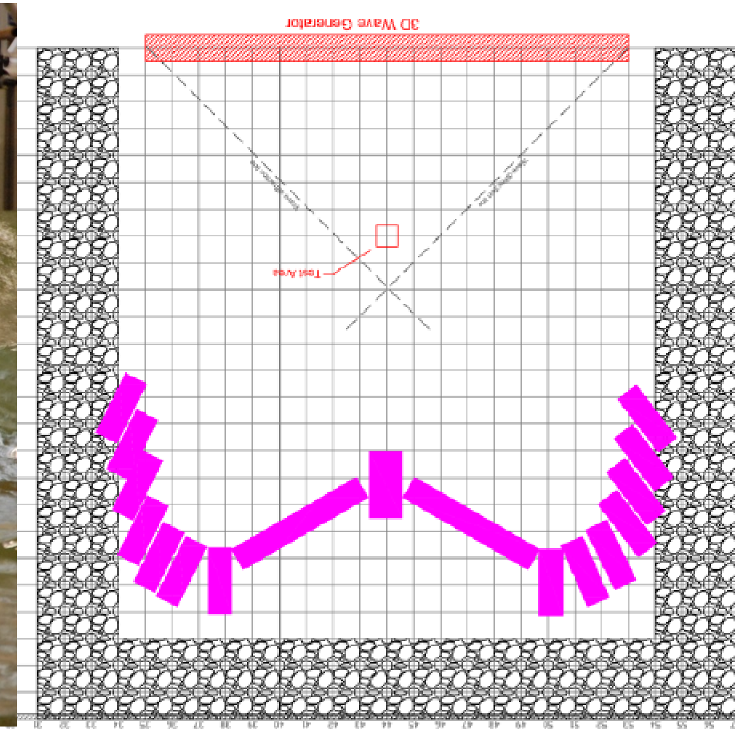
Force and moment

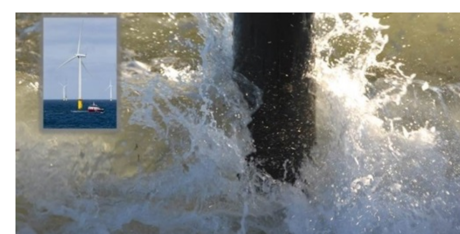
Stiff structure

7m mono pile and 1.8m drag column

2D reference tests (6 h full scale)

Focused groups and selected events





DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

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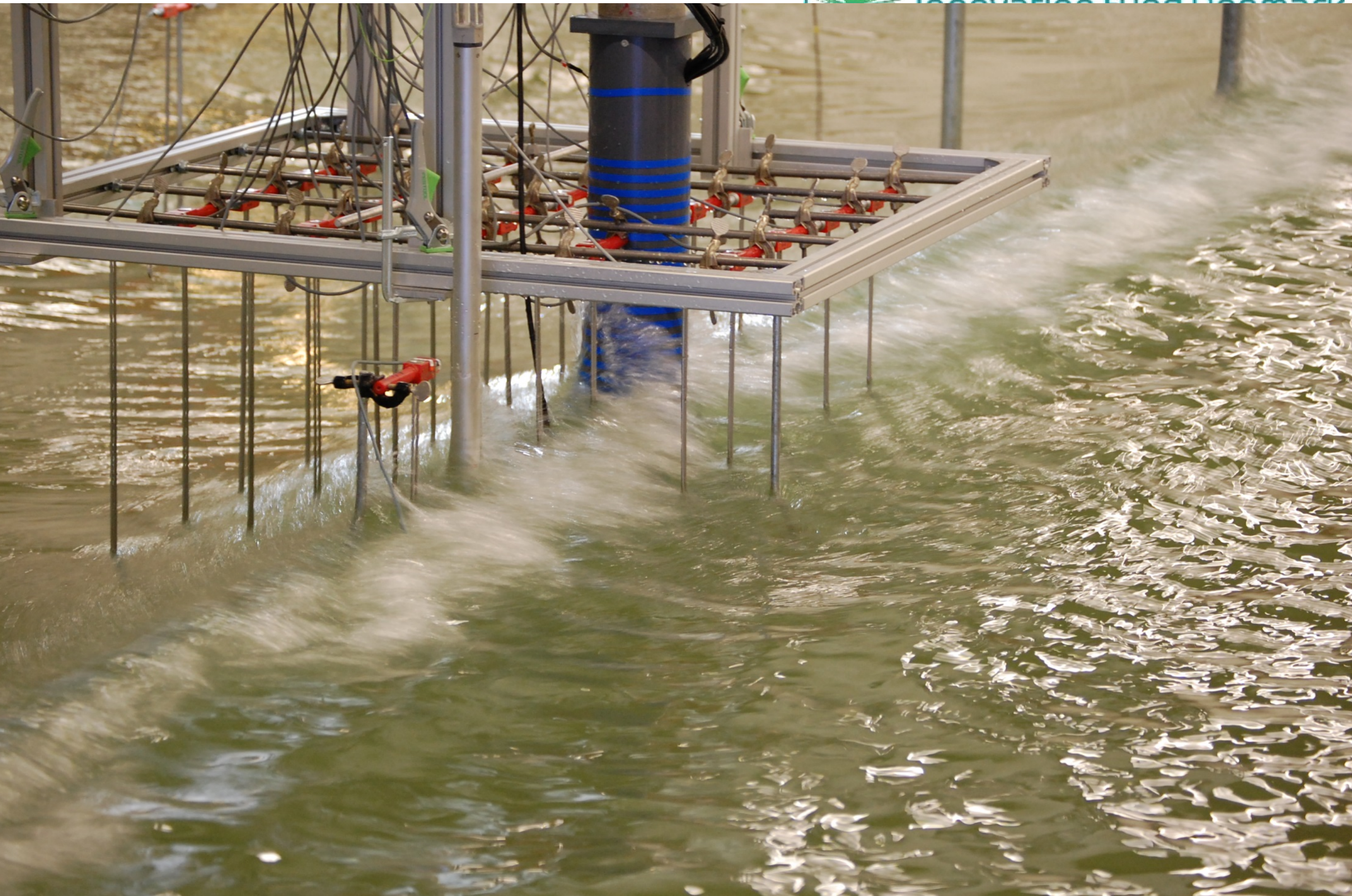
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures



DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

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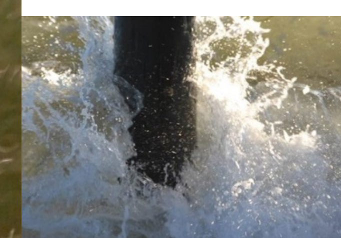

DeRisk – De-ri

Focused wave groups

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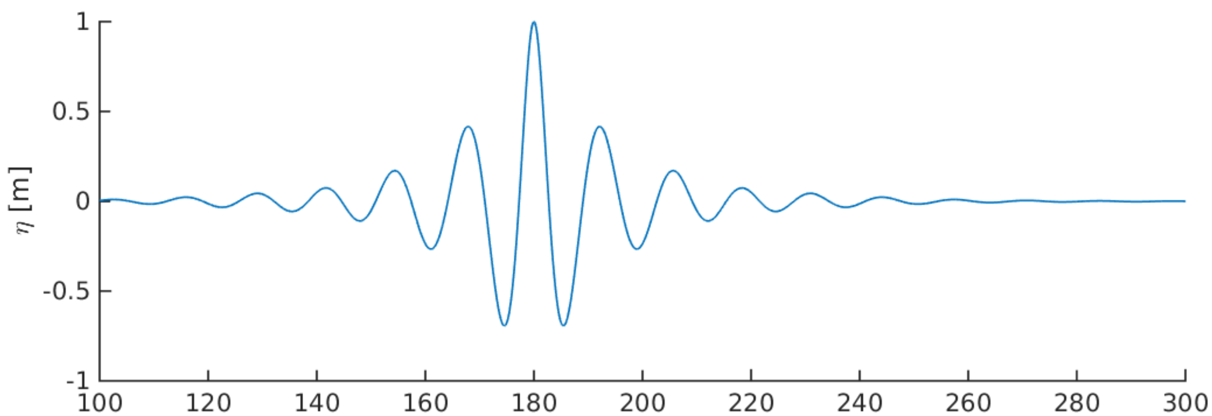
The New Wave Theory

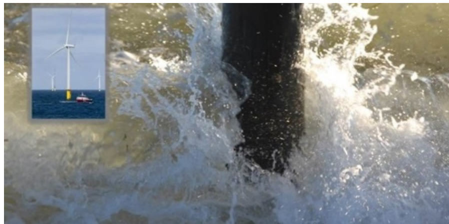
Lindgren (1970), Boccotti (1983), Tromans et al (1991)

Taylor et al (1995), Jensen (2005)

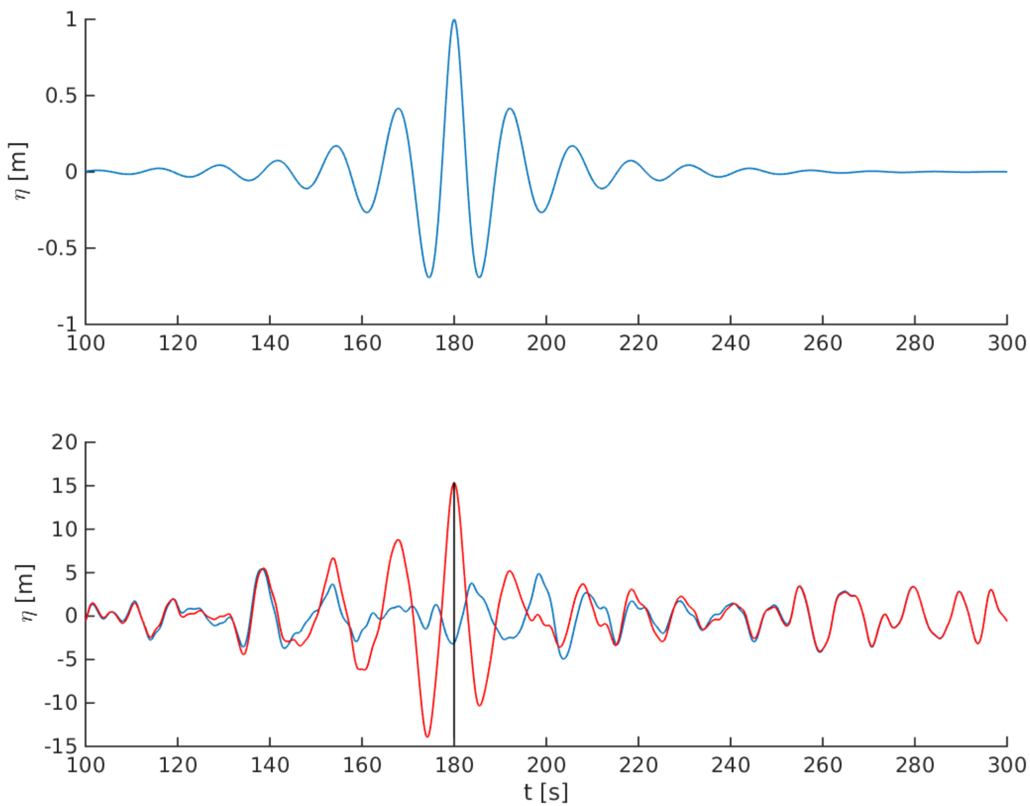
The most likely realization of a peak in a Gaussian process is the auto-correlation function of the free surface elevation

$$\eta(x,t) = \frac{\alpha}{\sigma^2}\sum_{j=1}^{N} S_\eta(f_j)\cos\left(\omega_j(t-t_0)-k_j(x-x_0)\right)\Delta f$$





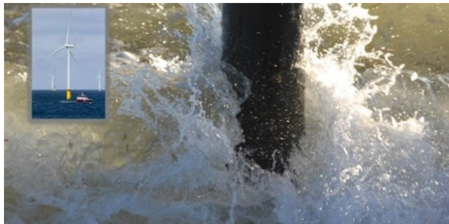
Focused wave groups



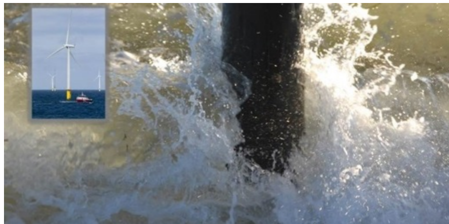
Can be embedded into background process

Directional focused version can be made too

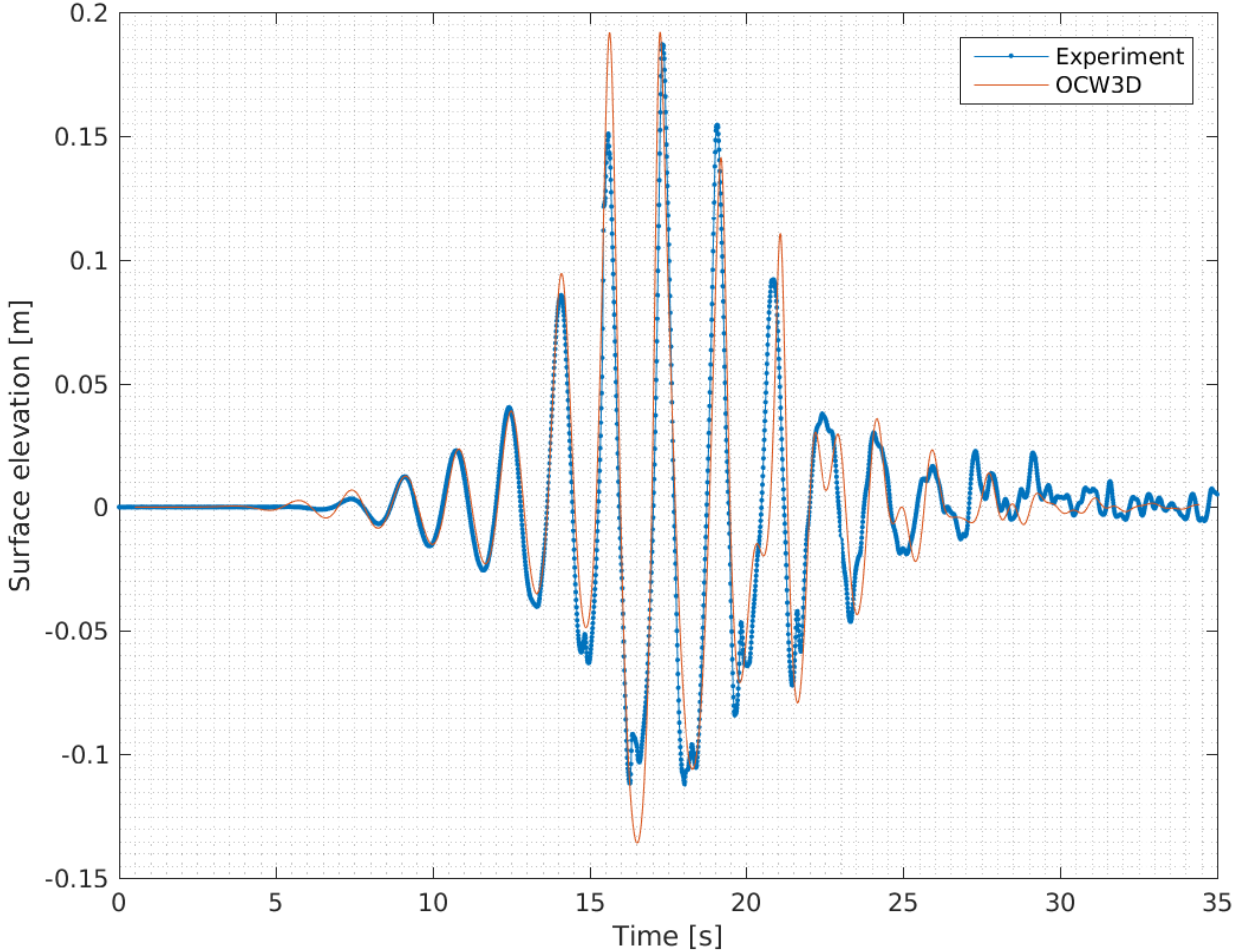
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures



Video



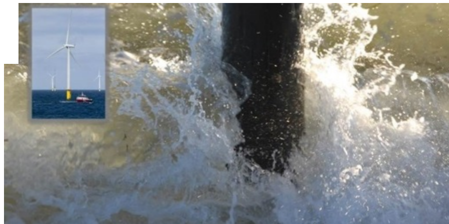
Numerical reproduction in OceanWave3D



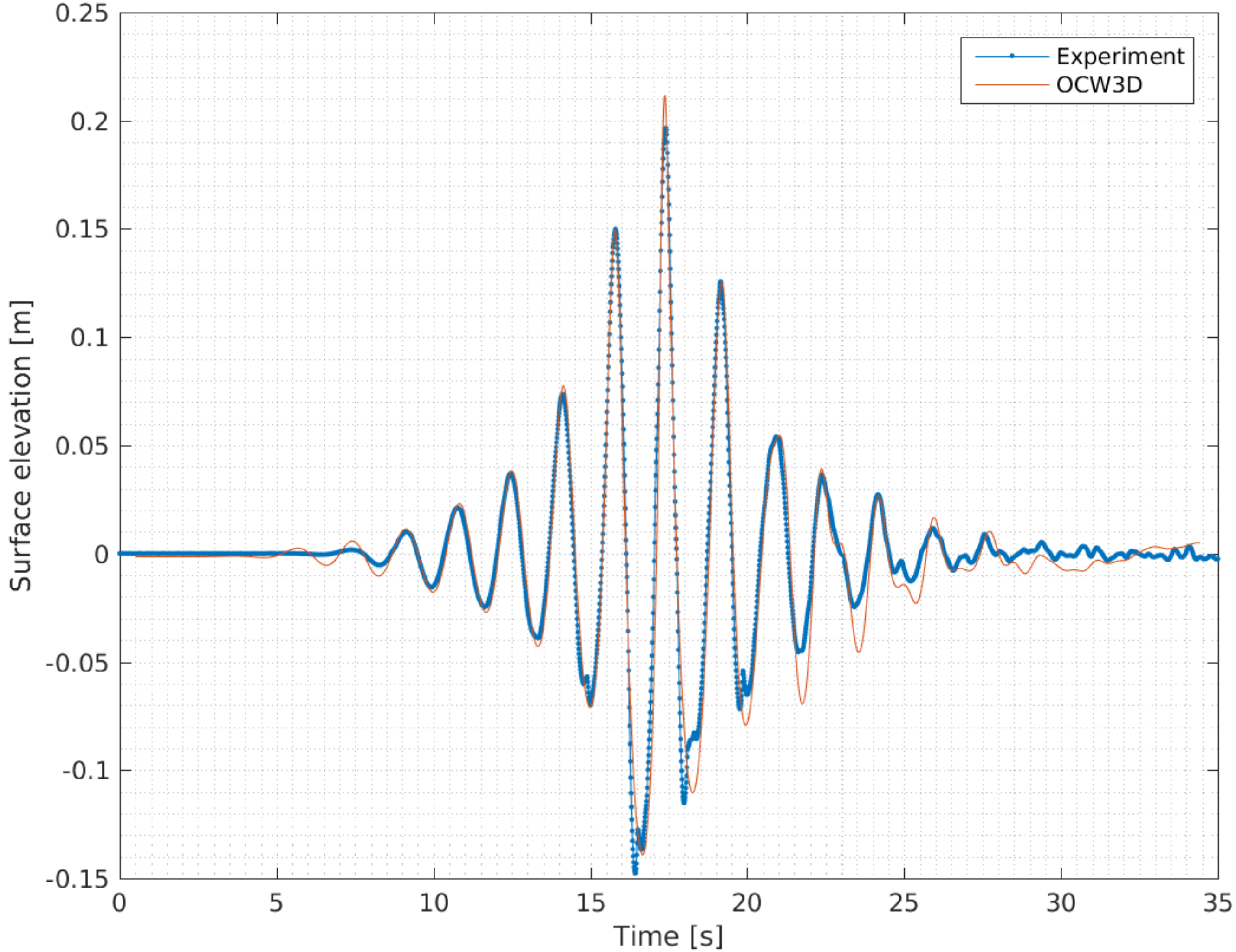
Computations by Amin Ghadirian

2D focused group

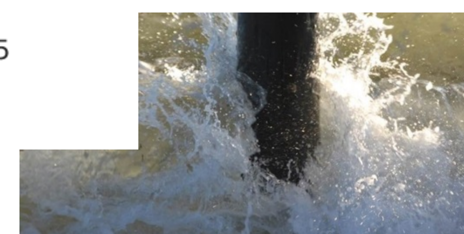
Corresponds to
Hs=9.5m
Tp=12s



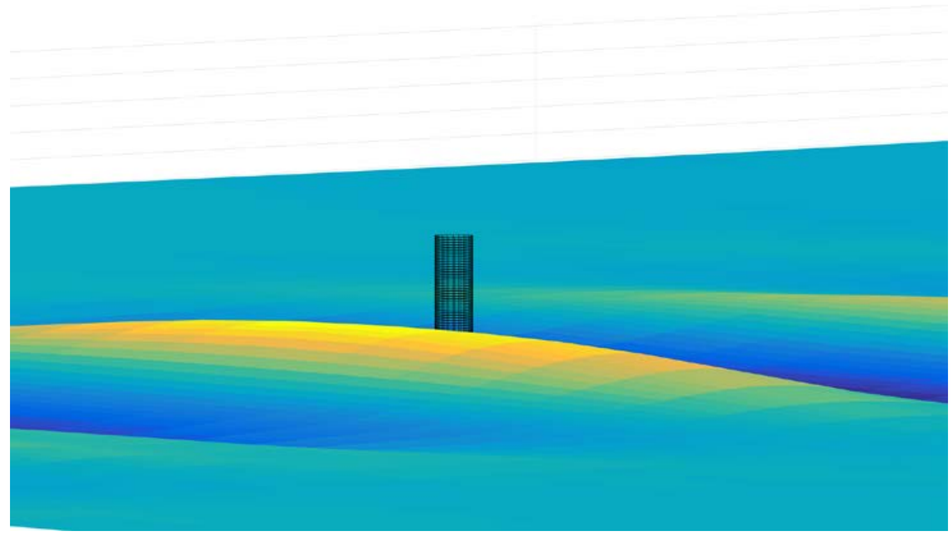
Reproduction of 3D group

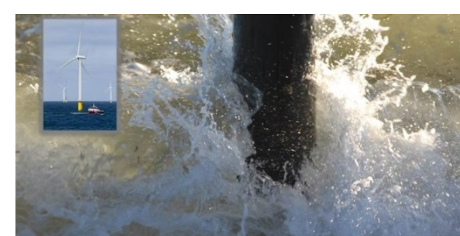


3D focused group

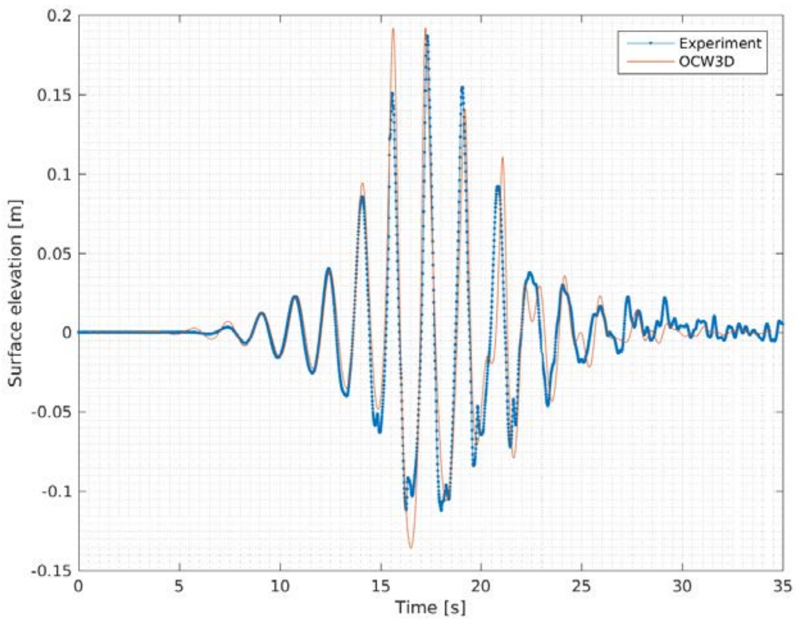


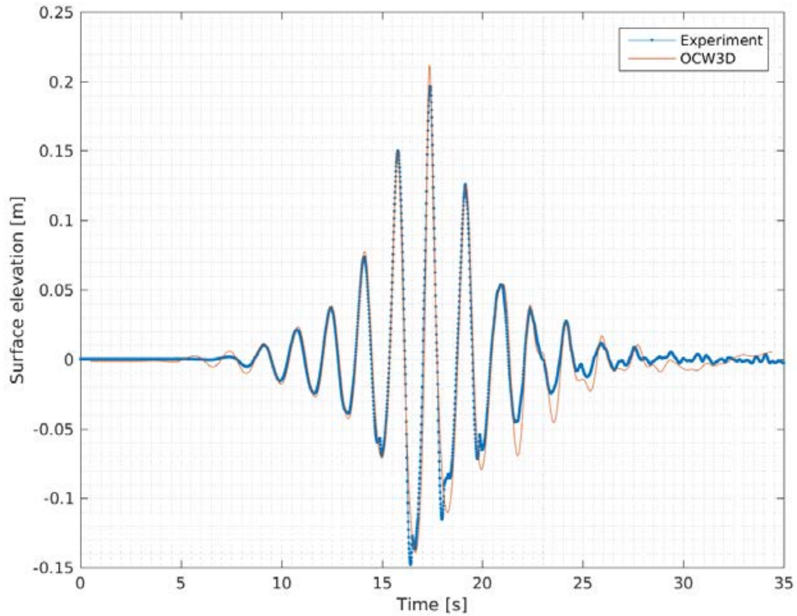
3D reproduction



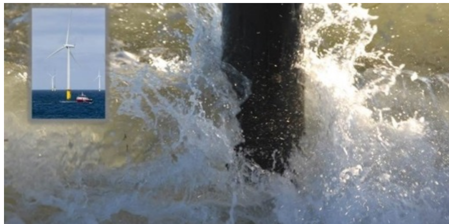


2D vs 3D dynamics





3D group can build up more rapidly
2D can only focus through dispersion

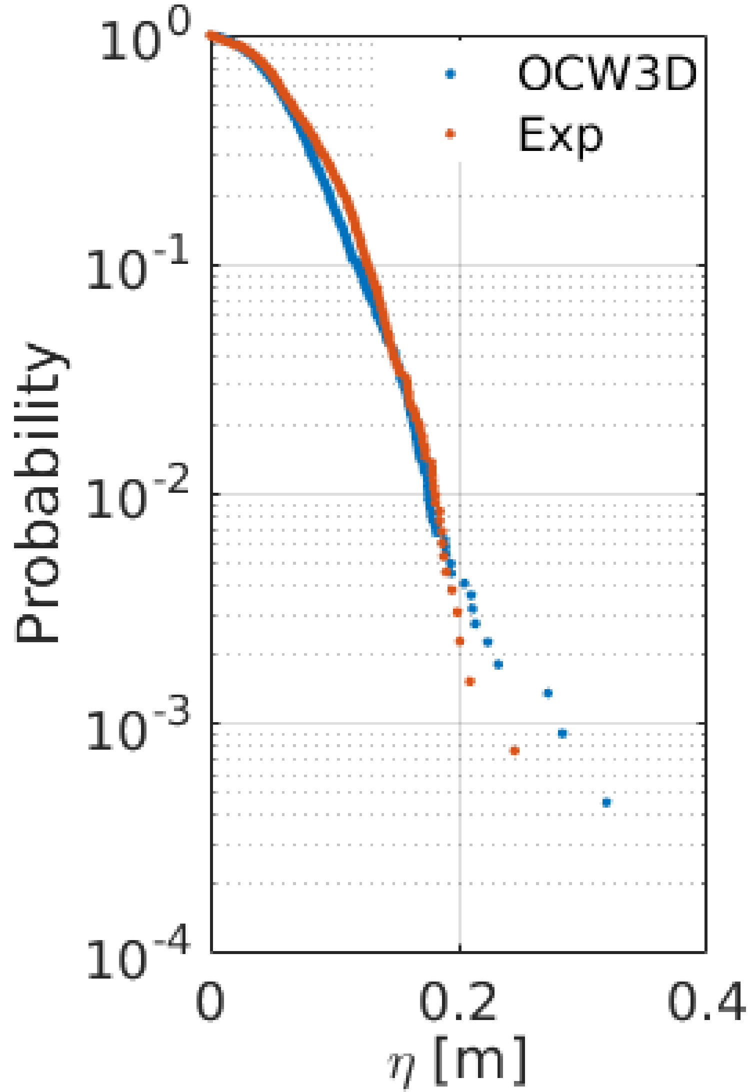


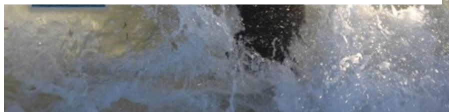
6 hour time series

Can we reproduce crest statistics of a 6 h time series?

Hs=9.5m

Tp=12s





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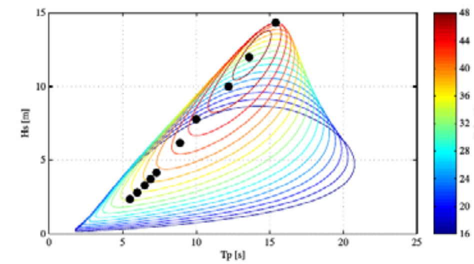
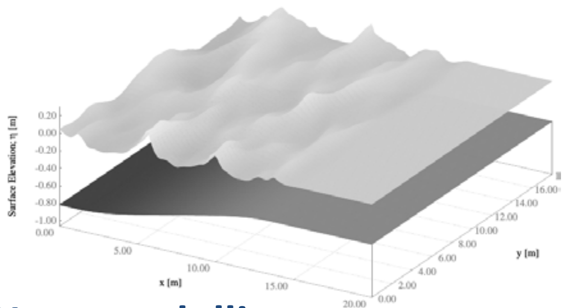
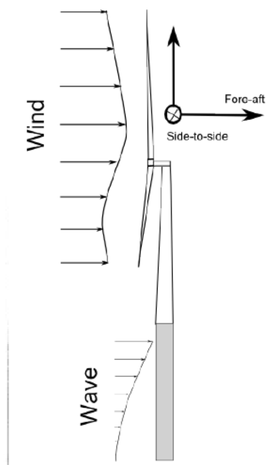
Elements of DeRisk



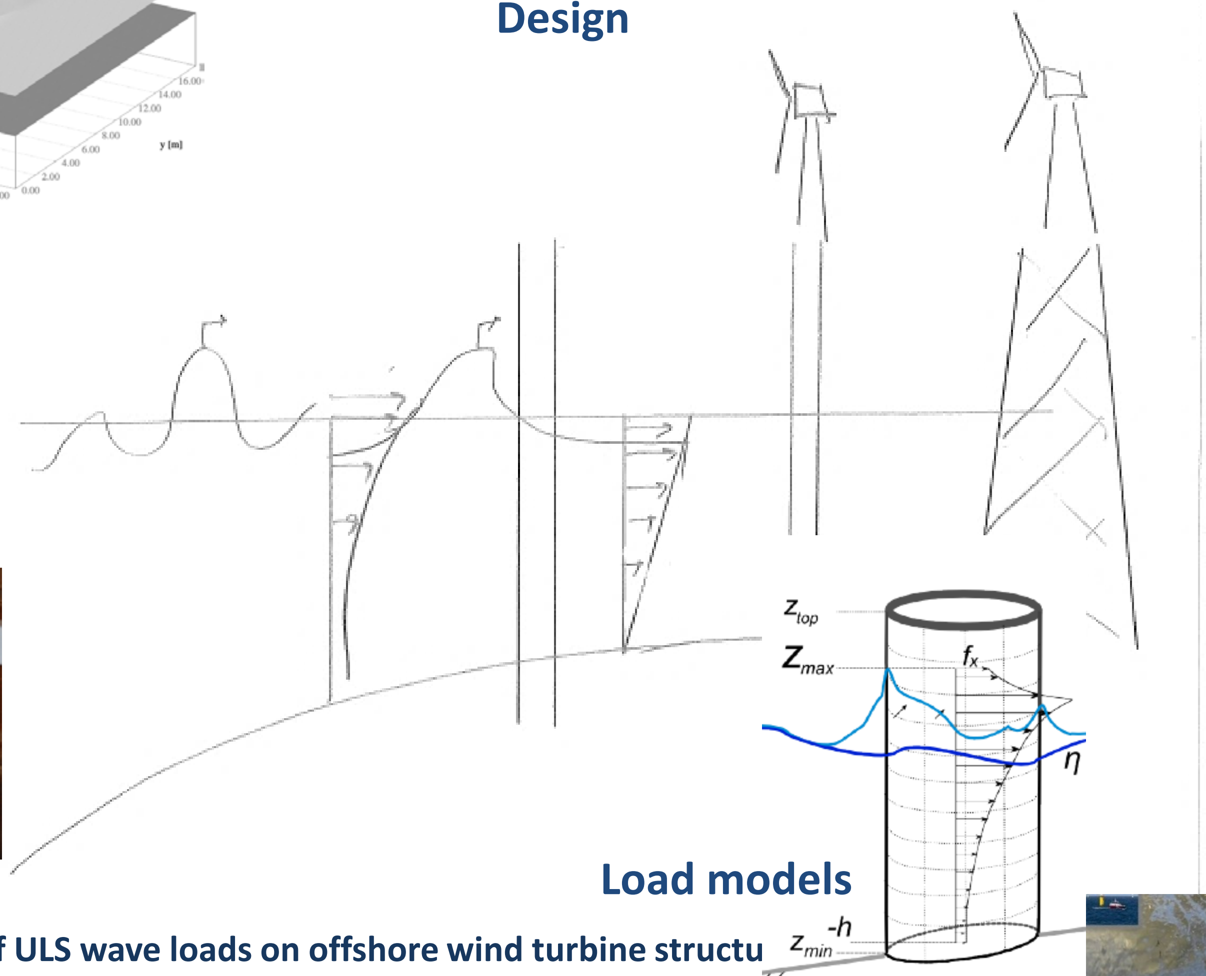
Design

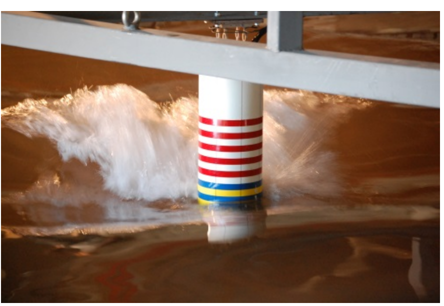


Wave modelling



Structural response





Wave physics

Load models

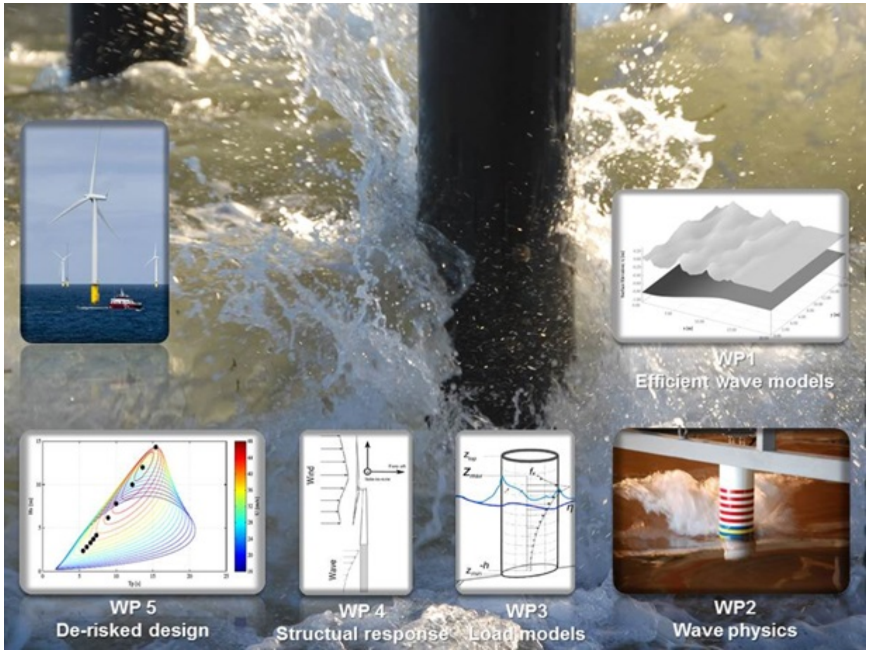
DeRisk – De-risking of ULS wave loads on offshore wind turbine structu

Summary

Opportunities for better description of ULS wave loads

Can contribute to reduced LCOE

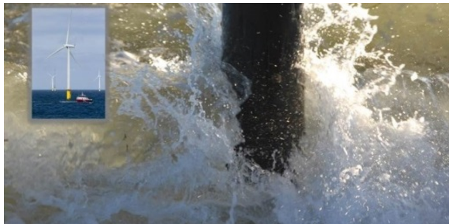
9 partners, 4 years, 2015-2019



3D wave basin experiments at DHI – long duration

Succesful reproduction with fully nonlinear wave solver

DeRisk – De-risking of ULS wave loads on offshore wind turbine structures



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ULS wave load symposium
August 2017 DTU

DeRisk

De-risked extreme wave loads for offshore wind energy

DeRisk delivers an improved and de-risked load evaluation procedure for extreme wave loads on offshore wind turbine substructures. Through ambitious research into wave physics, structural response and mathematical modelling, DeRisk provides a key contribution to the cost reduction of offshore wind energy.