Loads and response from steep and breaking waves on monopiles

Bredmose, Henrik; Schløer, Signe; Sahlberg-Nielsen, Lasse; Slabiak, Peter; Larsen, Torben J.; Kim, Taessong; Paulsen, Bo Terp; Bingham, Harry B.; Jacobsen, Niels Gjøl; Tornfeldt Sørensen, Jacob; Schlütter, Flemming; Nielsen, Anders Wedel

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Loads and response from steep and breaking waves on monopiles

Henrik Bredmose
Associate prof, DTU Wind Energy

With contributions from
Henrik Bredmose
Signe Schløer
Lasse Sahlberg-Nielsen
Peter Slabiak
Torben J. Larsen
Taessong Kim
Bo Terp Paulsen
Harry Bingham
Niels Gjøl Jacobsen
Jacob Tornfeldt Sørensen
Flemming Schlütter
Anders Wedel Nielsen
Statkraft
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 equation

Advanced: CFD and coupled CFD

Zang and Taylor (2010)
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

**Task D:**
Physical validation test

**Task A:**
Boundary conditions for phase resolving wave models

**Task C:**
Aero-elastic response to fully nonlinear waves

**Task B:**
CFD computation of monopile loads
Forces from a fully nonlinear potential flow solver

Allan Engsig-Karup, Harry Bingham and Ole Lindberg

\[ \partial_{t} \eta = - \nabla \eta \cdot \nabla \tilde{\phi} + \tilde{w} (1 + \nabla \eta \cdot \nabla \eta), \]
\[ \partial_{t} \tilde{\phi} = -g \eta - \frac{1}{2} (\nabla \phi \cdot \nabla \tilde{\phi} - \tilde{w}^2 (1 + \nabla \eta \cdot \nabla \eta)) \]

\[ \nabla^2 \phi + \partial_{zz} \phi = 0 \]
\[ \partial_{z} \phi + \nabla h \cdot \nabla \phi = 0 \]
Response in bottom of tower
Fully nonlinear waves versus linear waves

\[ H_s = 9.4 \text{ m}, \quad T_p = 14.2 \text{ s}, \quad W = 5 \text{ m/s} \]
The OC4 jacket

Jacket and reference turbine modelled in Hawc2. Fully nonlinear wave loads.

Storm sea state. Turbine standstill.

Severe ringing/impulsive excitation.

Torben Juul Larsen
Taesong Kim
Larsen et al., Europ. Offsh. Wind 2011
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

- **Task D:** Physical validation test
- **Task A:** Boundary conditions for phase resolving wave models
- **Task C:** Aero-elastic response to fully nonlinear waves
- **Task B:** CFD computation of monopile loads
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
Platform height of 8.96m

$t=58.8\text{s}$

Bredmose & Jacobsen OMAE 2011
Platform height of 8.96m

t=58.9s
Platform height of 8.96m

t=59.0s
Platform height of 8.96m

$t=59.1s$
Platform height of 8.96m

$t=59.2s$
Platform height of 8.96m

$t = 59.3s$

$z_p = 8.96$ m
Platform height of 8.96m

t=59.4s
Platform height of 8.96m

t=59.5s
Platform height of 8.96m

t=59.6s
Platform height of 8.96m

$\text{t}=59.7 \text{s}$
Platform height of 8.96m

$t=59.8s$
Platform height of 8.96m

t=59.9s
Platform height of 8.96m

$t=60.0s$
Platform height of 8.96m

t = 60.1s
Platform height of 8.96m

t=60.2s
Platform height of 8.96m

t=60.3s
Platform height of 8.96m

t=60.4s
Platform height of 8.96m

\[ t = 60.5 \text{s} \]

\[ z = 8.96 \text{ m} \]
What is ringing?

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

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

secondary load cycle

Bo Terp Paulsen
Third-harmonic force compared to FNV theory

Terp Paulsen et al
IWWFB 2012
Coupling of OpenFOAM and OceanWave3D

Compute outer flow field with potential flow wave model
Compute inner field with wave-structure interaction with CFD-VOF model

Terp Paulsen et al (2012)
Coupling of OpenFOAM and OceanWave3D

- Irregular waves: JONSWAP($T_p = 12s, H_s = 8m$)
- Large domain $\Rightarrow$ Impossible to resolve with CFD alone!
- Rather trivial test case as it serves as validation

Terp Paulsen et al (2012)
Coupling of OpenFOAM and OceanWave3D

- 3 hours times series of 2D irregular waves computed in hours with OceanWave3D
- Selected event analysed with OpenFOAM (~1 day)

Terp Paulsen et al (2012)
Coupling of OpenFOAM and OceanWave3D

- Small “warmup” period for the CFD-computations: No initialization of pressure and pseudo air velocities
- Morison forces and CFD-computations agrees for small wave heights
- Discrepancies after passage of main event is attributed to diffraction effects

Terp Paulsen et al (2012)
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

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Statkraft

DTU Wind Energy
Department of Wind Energy

DTU Mechanical Engineering
Department of Mechanical Engineering
Wave loads Task D
Physical validation test

New tests at DHI with a rigid and a flexible structure

DHI:
Flemming Schlütter
Anders Wedel Nielsen
Jacob Tornfeldt Sørensen

DTU:
Henrik Bredmose
Torben Larsen
Signe Schløer
Bo Terp Paulsen
Harry Bingham
Wave loads Task D
Physical validation test

PVC pipe
Scale 1:80
Two masses
→ right
natural frequencies (1,2)
Experimental setup

Wave maker

Rock berm

0.36

1.00 6.75 2.25 5.25 1.75 2.00

side-view

top-view of wave gauges
Results and brief analysis for flexible pile

Irregular JONSWAP waves, unidirectional
h=20m
Tp=14s
Hs=11m

Free surface elevation 0.15m from pile
Measured inline force on pile
Acceleration of top point
Displacement of top point
Results and brief analysis

![Graphs showing measurements of wave height (\(\eta [m]\)), force, top acceleration (\([m/s^2]\)), and top displacement (\([m]\)]).]
'continuous' forcing of 1st natural mode from wave-nonlinearity

Impulsive load from breaking/near breaking wave
Which waves give the largest accelerations?

acceleration in top accelerometer [m/s²]

Bredmose et al (OMAE 2013)
Which waves give the largest accelerations?

$H_s = 11\, \text{m}$

$H_s = 8.3\, \text{m}$

$h = 40.8\, \text{m}$

$h = 30.8\, \text{m}$

$h = 20.8\, \text{m}$

Bredmose et al (OMAE 2013)
Numerical reproduction of experiments

Linear wave detection

Nonlinear wave transformation

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

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

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

\[ \partial_z \phi + \nabla h \cdot \nabla \phi = 0. \]

FEM model

Force model

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

\[ f(t, z) = \rho_w \mathcal{A} c_m (\dot{u} - \dot{X}) + \rho_w A \ddot{u} + \rho_w \mathcal{A} c_m w_z (u - \dot{X}) + \frac{1}{2} \rho_w c_D D (u - \dot{X}) |u - \dot{X}| \]
Wave transformation
Response, $h=40.8$ m

[Graphs showing various responses over time]
Response, h=20.8 m
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

**Task D:**
Physical validation test
- Experiments with flexible monopile
- Impulsive response
- Numerical reproduction
- Higher-harmonic loads (ringing loads)
- Coupling of pot flow model and CFD
- Structural excitation from nonlinear waves

**Task A:**
Boundary conditions for phase resolving wave models

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Henrik Bredmose, hbre@dtu.dk
Associate prof, DTU Wind Energy