Installation and substructure

Nonlinear hydroelastic response of a monopile wind turbine foundation in regular waves

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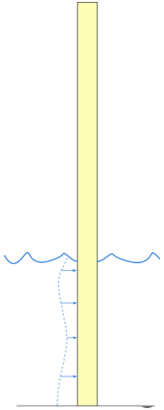
Context



Hydroelasticity of bottom-fixed wind turbines foundations

> Morison, potential flow theory (FNV, …) for cylinders, simple geometries

Floatgen FWT ©Centrale Nantes/Above All

Floating wind turbines

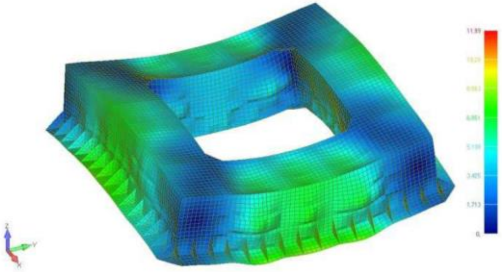
> Most of the numerical models are rigid-flexible: rigid hull + elastic tower, blades and drivetrain, ignoring the elasticity of the platform

> In design phases, current models assume a rigid hull to compute internal loads

Hydrodynamic loads are computed with

- Linear potential flow theory – possibly multi-body
- Morison equation and linear or 2nd order wave kinematics

Hydrodynamic loads ⟷ Structure internal loads and deformations

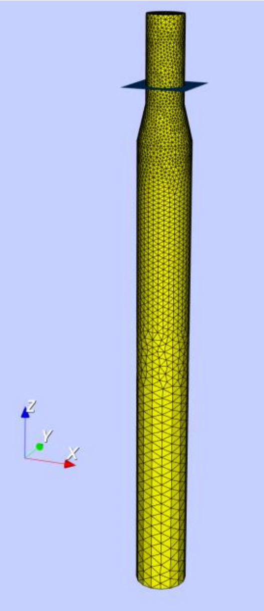


(Guignier et al., 2016))

Project HeloFOW

Hydroelasticity of large FWT platforms

Financed by WEAMEC
Centrale Nantes LHEEA (France) / NTNU IMT (Norway)



Numerical

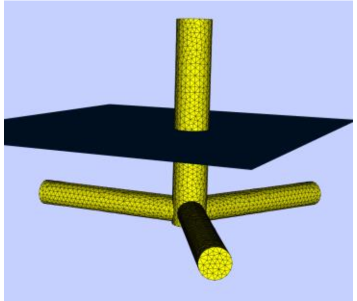
> How to account for elasticity in hydrodynamic calculations? (coupling)

→ Develop a coupling between non-linear potential flow solver and a FEM “beam” model

Experimental

> Experimental testing of flexible/segmented platform models

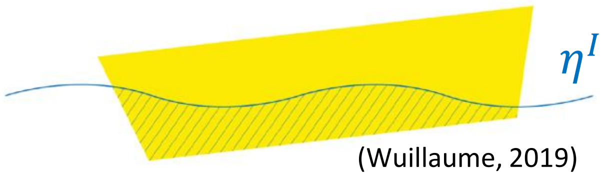
<u>First step:</u> implementation and verification on a monopile foundation



WSCN solver

Weak-scatterer theory

Solver developed in Centrale Nantes since 2011



(Wuillaume, 2019)

Assumptions

- Potential flow →$\Delta\phi = 0$ in the fluid
- Weakly non linear

Weak-Scatterer hypotheses: $\begin{cases} \phi = \phi^I + \phi^P \\ \eta = \eta^I + \eta^P \end{cases}$, with $\begin{cases} \phi^P = o(\phi^I) \\ \eta^P = o(\eta^I) \end{cases}$ and $\begin{cases} \phi^P \xrightarrow[r\to\infty]{} 0 \\ \eta^P \xrightarrow[r\to\infty]{} 0 \end{cases}$

- Free surface boundary conditions are written at incident wave elevation $\eta^I(x, y, t)$
- Loads

$$F_{hydro} = -\iint p\,\boldsymbol{n}dS \qquad \text{where} \qquad p = -\rho\left(\frac{\partial\phi^{\mathrm{I}}}{\partial t} + \boxed{\frac{\partial\phi^{\mathrm{P}}}{\partial t}} + \frac{1}{2}\nabla\phi^{\mathrm{I}}\cdot\nabla\phi^{\mathrm{I}} + \nabla\phi^{\mathrm{P}}\cdot\nabla\phi^{\mathrm{I}} + gz\right)$$

- Advantages: allows large motions and fully non-linear wave fields

WSCN solver

In a few lines, for a fixed or floating body

> 1^{st} Boundary Value Problem : 2^{nd} Green identity for velocity potential and its gradient

$$\phi^P(M) \text{ and } \frac{\partial \phi^P}{\partial n}(M)$$

> 2^{nd} BVP (Green identity) linking:

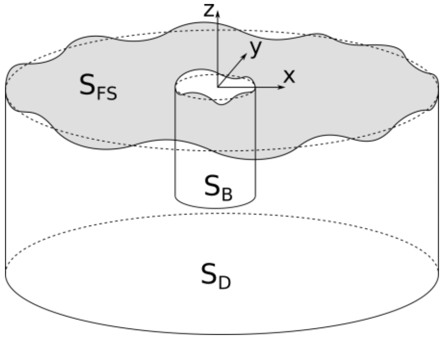
$$\boxed{\frac{\partial \phi^P}{\partial t}(M)} \text{ and } \frac{\partial^2 \phi^P}{\partial n \partial t}(M)$$

Gives the hydrodynamic loads

> …using the boundary conditions on the body:

$$\frac{\partial^2 \phi^P}{\partial n \partial t}(M) = \boxed{\ddot{\boldsymbol{x}}(M)} \cdot \boldsymbol{n} + q$$

Fluid-structure coupling: node acceleration



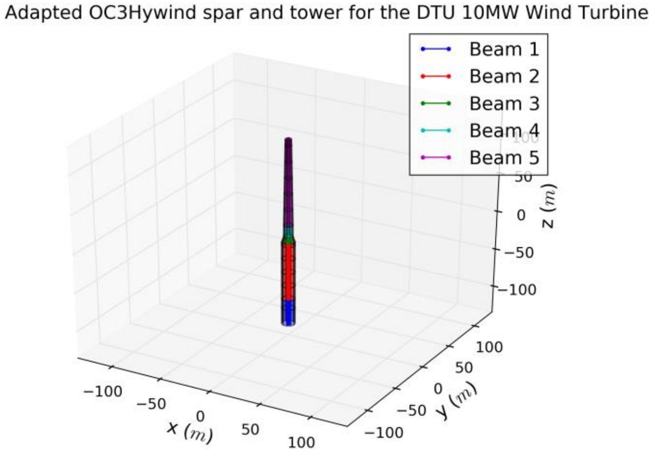
Structural solver: FEM analysis

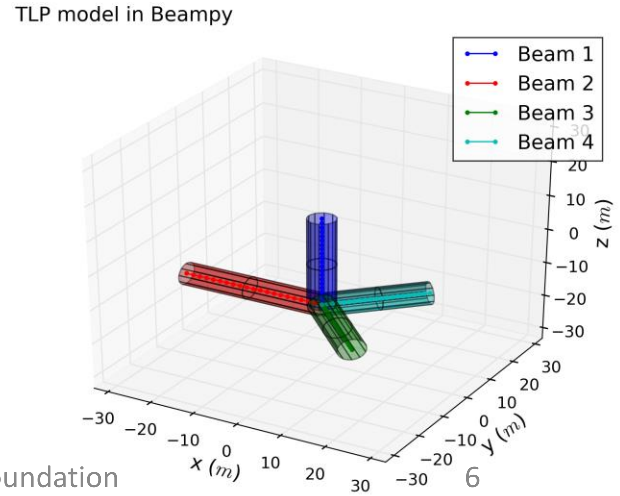
Python FEM solver for beams: “*beampy*”

> Based on Euler-Bernoulli theory

> Verified with comparison to other models

> Dynamics solved with modal superposition

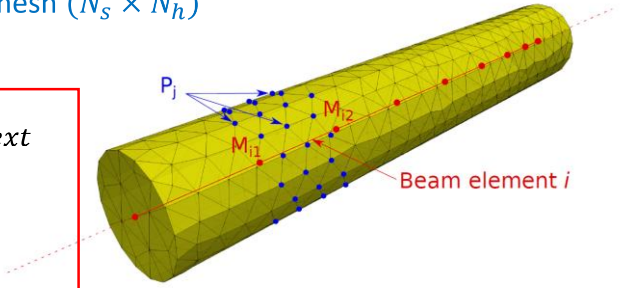




Fluid-structure coupling

> Hydrodynamic force: $\mathbf{F}^{WSC} = -\iint p\boldsymbol{n}dS = \mathbf{F}_0^{\text{WSC}} + \iint \rho \frac{\partial \phi^P}{\partial t}\boldsymbol{n}dS = \mathbf{F}_0^{\text{WSC}} + \mathrm{L}\dot{\boldsymbol{\phi}}$

- L represents the projection of the hydrodynamic mesh on the structure mesh $(N_s \times N_h)$



> Equation of motion:

BVP2:

Boundary condition (body):

$$\begin{cases} \mathrm{M}\ddot{\boldsymbol{u}} - \mathrm{L}\dot{\boldsymbol{\phi}} = -\mathrm{C}\dot{\boldsymbol{u}} - \mathrm{K}\boldsymbol{u} + \mathbf{F}_0^{\text{WSC}} + \mathbf{F}^{ext} \\ \mathrm{G}\dot{\boldsymbol{\phi}} = \mathrm{H}\dot{\boldsymbol{\phi}}_{\boldsymbol{n}} \\ \dot{\boldsymbol{\phi}}_{\boldsymbol{n}} - \mathrm{D}\ddot{\boldsymbol{u}} = -\dot{\boldsymbol{\phi}}_{\boldsymbol{n}}^{I} + \boldsymbol{B} + \boldsymbol{Q} \end{cases}$$

Solved at the same time in a RK4 integration scheme.

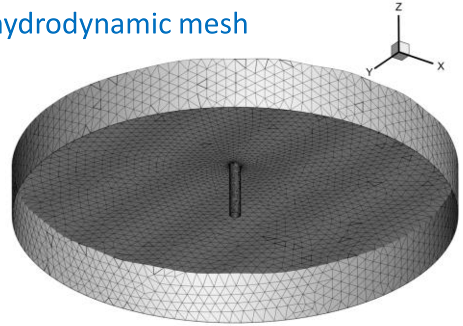
> With modal superposition: $\psi^T \mathbf{M}\psi\ddot{y} - \psi^T\mathbf{L}\dot{\phi} = -\psi^T\mathbf{C}\psi\dot{y} - \psi^T\mathbf{K}\psi y + \psi^T\left(\mathbf{F_0}^{WSC} + \mathbf{F}^{ext}\right)$

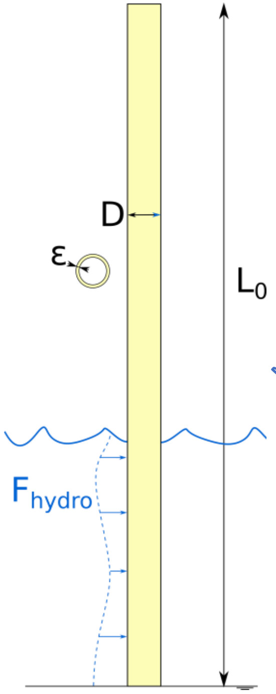
Verification on a bottom-fixed wind turbine

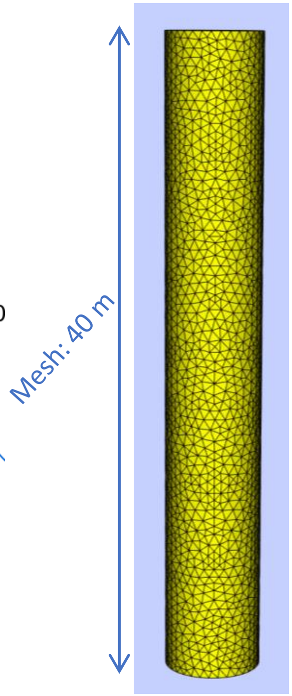
Monopile foundation

> Geometry: uniform beam, embedded at the mudline

- Length $L_0 = 100\ m$
- Diameter $D = 6\ m$
- Thickness $\epsilon = 7.5\ cm$
- Water depth $d = 30\ m$
- 50 beam elements, 2100 nodes in hydrodynamic mesh







> Aims:

- Verify the accuracy of the coupling in linear waves
- Observe non-linear and coupling effects in steep waves

Verification on a bottom-fixed wind turbine

Reference and load cases

> Reference models

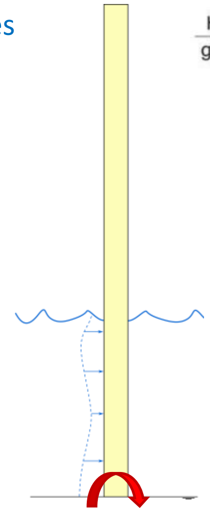
1. Sima (SINTEF):
   Morison equation + Stokes 2nd order wave + direct FEM
   No viscous forces ($C_d = 0$), C_m chosen from MacCamy-Fuchs
2. “Semi-analytic”: analytic modes + Morison with Airy waves

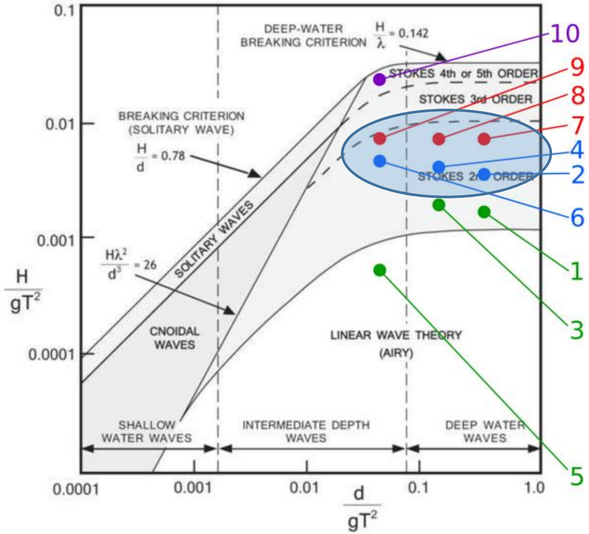
> Set of 10 regular waves (Airy, Rienecker-Fenton)

- Waves periods from 3 to 8s, amplitudes from 0.1 to 6 m, with 1.3 to 39% steepness (kA)

> Compare

- Hydrodynamic forces
- **Mudline bending moment**
- Tower mid-height and top displacement





(Le Méhauté, 1976)

Verification

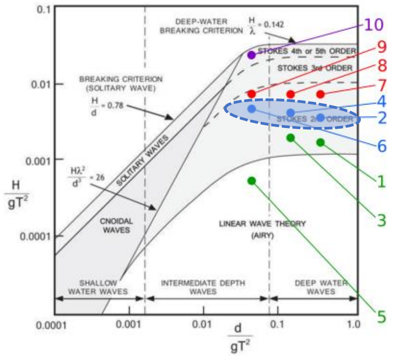
Regular waves (1)

> Rienecker-Fenton (WSCN) / Stokes 2nd order (Sima)

> **Mudline bending moment**

> DLCs:

$(T = 3\ s, A = 0.15\ m)$ and $(T = 5\ s, A = 0.5\ m)$ and $(T = 8\ s, A = 1.6\ m)$



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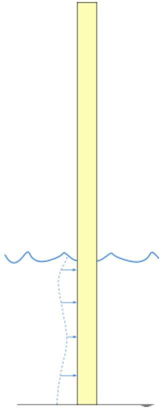
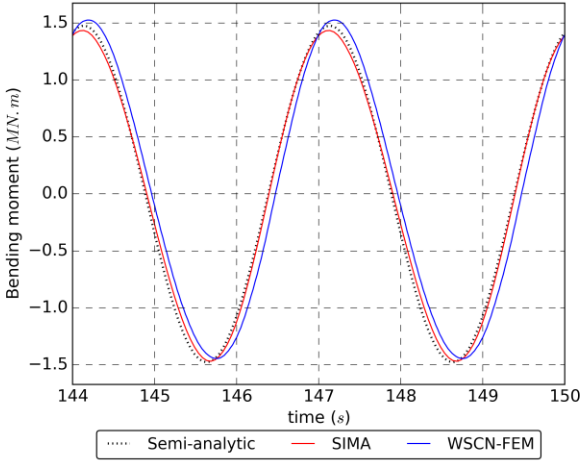
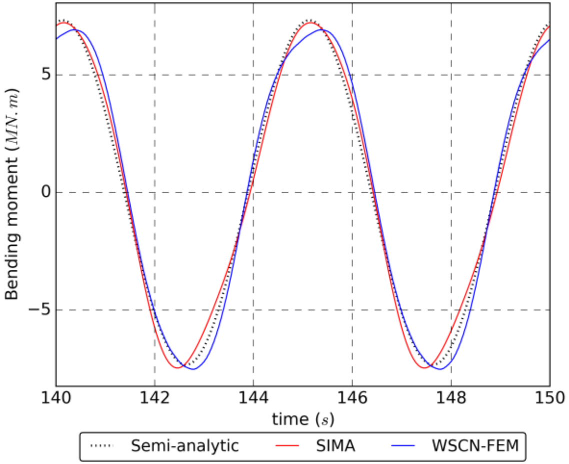
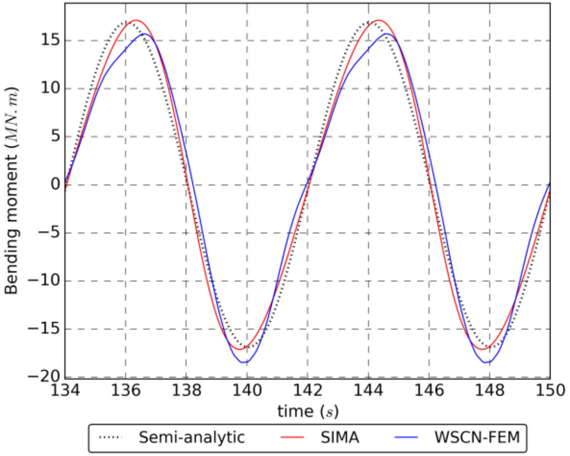






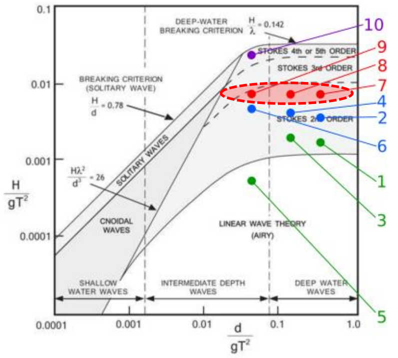


Verification

Regular waves (2)

> Rienecker-Fenton (WSCN) / Stokes 2nd order (Sima)

> **Mudline bending moment**



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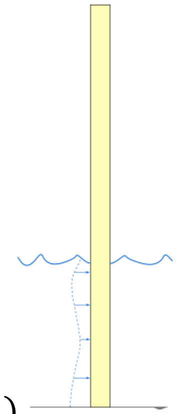
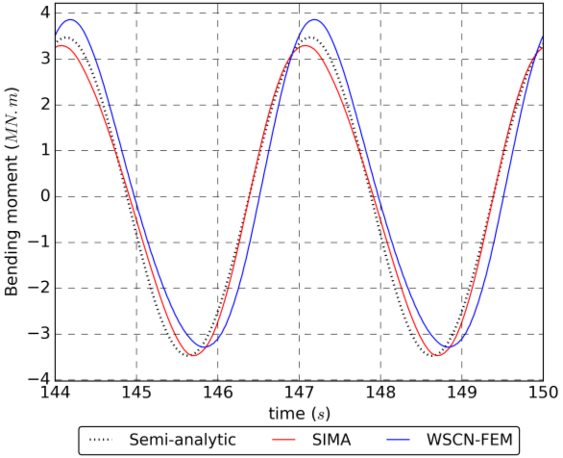
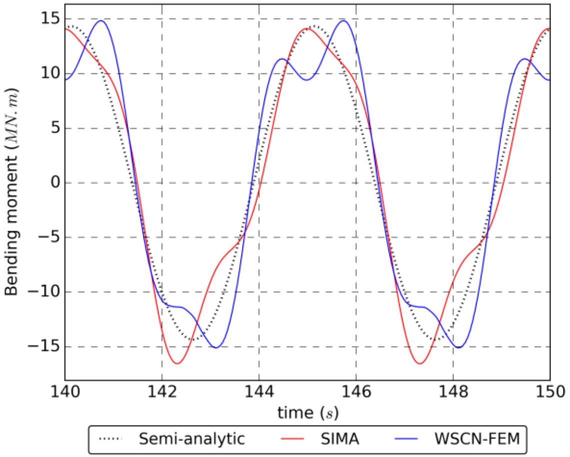
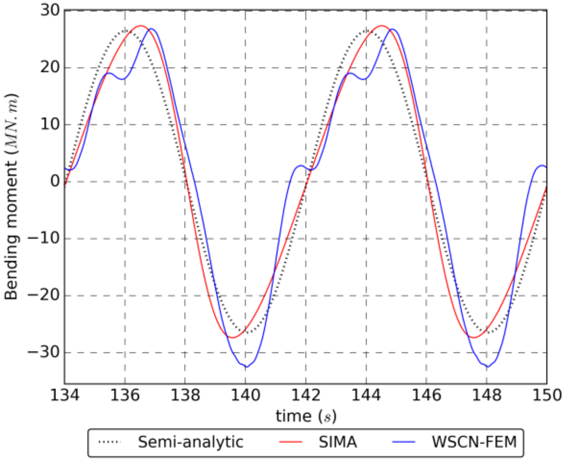


> DLCs:

$(T = 3\ s, A = 0.353\ m)$ and $(T = 5\ s, A = 0.981\ m)$ and $(T = 8\ s, A = 2.511\ m)$



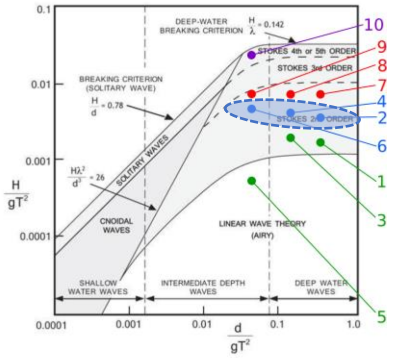




Verification

Regular waves (1)

> Rienecker-Fenton (WSCN) / Stokes 2nd order (Sima)
> **Mudline bending moment harmonics**



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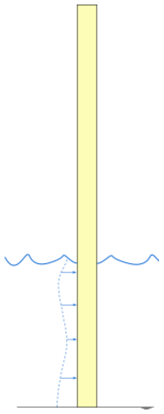

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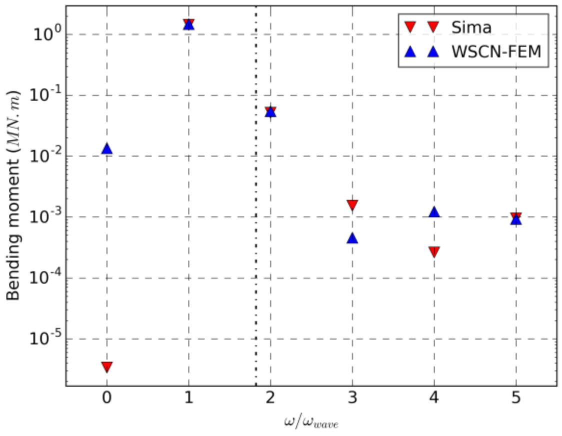

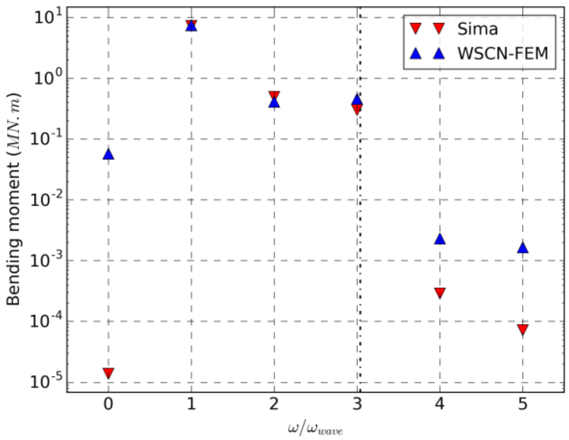

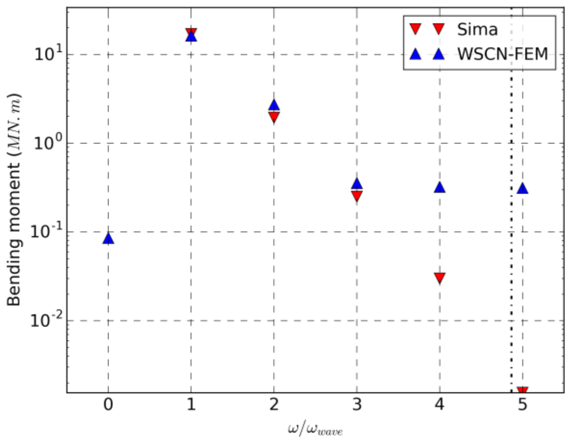

Verification

Regular waves (2)

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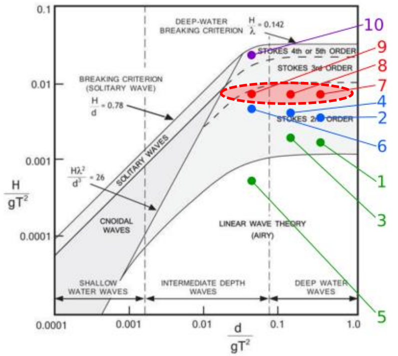
> **Mudline bending moment harmonics**



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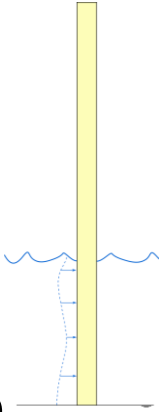

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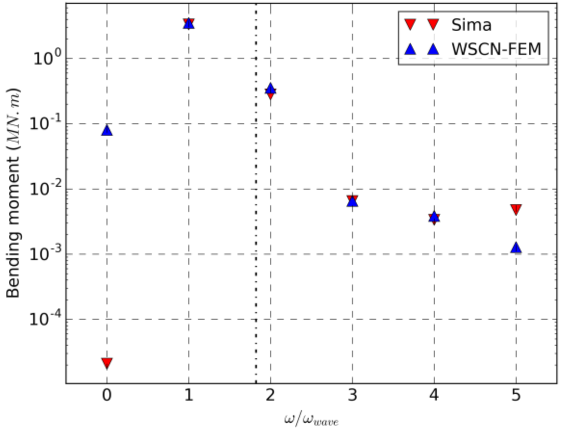

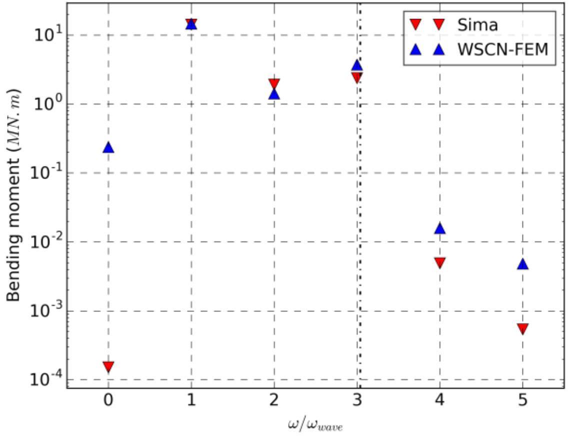

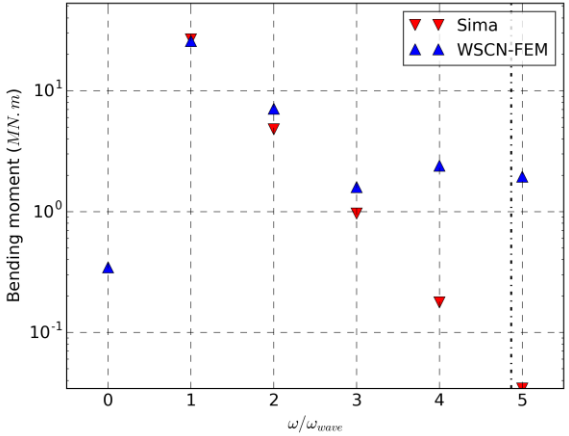

Conclusions, future works

> Implementation of a non-linear hydro-elastic coupling between WSCN and FEM

> Comparison with Morison + Stokes 2nd order waves, on the case of a monopile

- Good agreement on 1st order and 2nd order harmonics
- Differences in steep waves, particularly on high order harmonics

> Comparison with experimental data on a flexible monopile

> Simulation of Floating Wind Turbines

> Experimental studies at Centrale Nantes (next year)

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Thank you for your attention