Experimental study of the effect of second order wavemaker theory on the response of a large diameter monopile in irregular sea

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(WAS-XL: Wave loads and soil support for extra large monopiles)

Background/Objectives

- Larger offshore wind turbines -> longer eigenperiods and increased dynamic response to nonlinear wave loads
- Model testing:
  - Understanding hydrodynamic loads and structural responses
  - Validating numerical models
- Need to investigate uncertainties and effects of testing techniques

- ***How important is the second order wavemaker correction for the measured responses?***

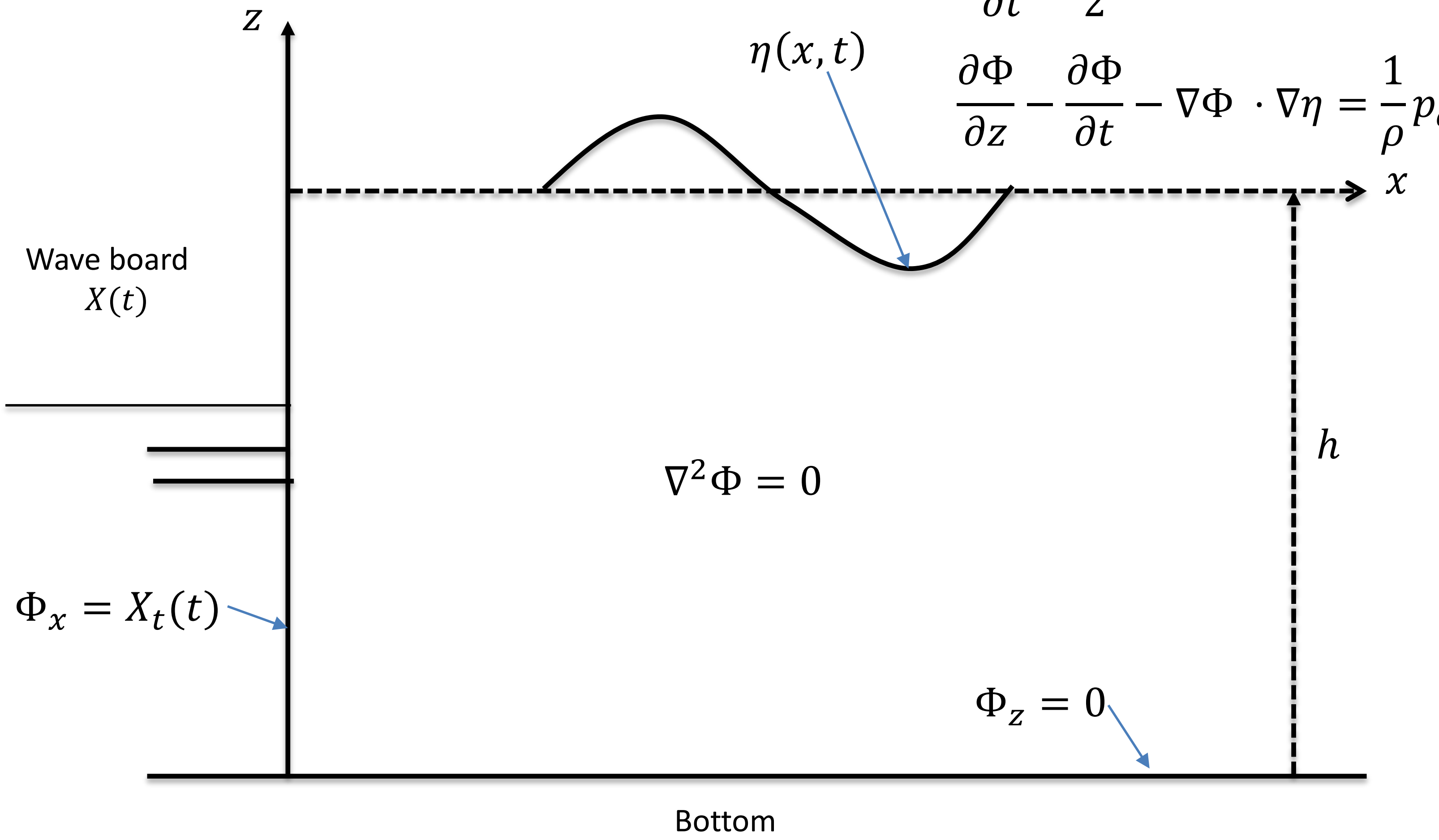
Outline

- Second order wavemaker correction
  - Theory
  - Implementation and experimental assessment
- Monopile testing
  - Experimental setup
  - Repeatability
  - Statistical results
  - Sample events of extreme responses

Wavemaker theory (piston-type wavemaker)

$$-\frac{\partial \Phi}{\partial t} - \frac{1}{2}\nabla\Phi \cdot \nabla\Phi - gz = 0 \quad \text{KFSBC}$$

$$\frac{\partial \Phi}{\partial z} - \frac{\partial \Phi}{\partial t} - \nabla\Phi \cdot \nabla\eta = \frac{1}{\rho}p_a \quad \text{DFSBC}$$



Second-order wavemaker theory for irregular waves, Hemming A. Schäffer, Ocean Engng, Vol. 23, No. 1, pp. 47-88. 1996

First and second order wavemaker motion

- First order wavemaker motion
  - Sum of harmonic components

$$X_0^{(1)} = -i \sum_{n=1}^{M} X_n e^{i\omega_n t}$$

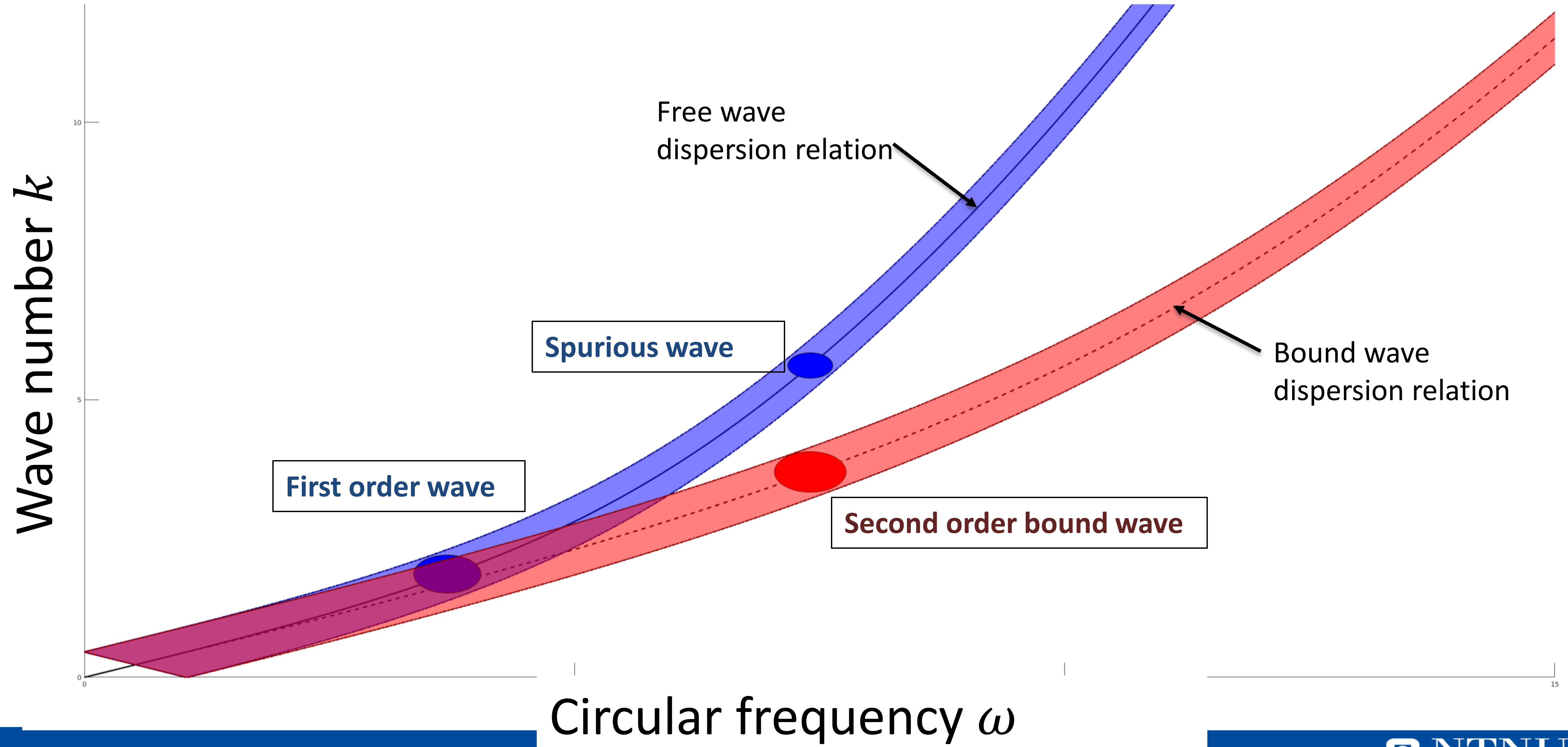
- This motion results in generation of
  - Desired first order waves
  - Desired second order bound waves
  - Undesired second order spurious waves
  - And even higher order waves

$$X_0^{(2)} = \sum_{n=1}^{M} \sum_{m=2}^{M} \left\{ -iF_{nm}^{+} \frac{A_n A_m}{h} e^{i(\omega_n + \omega_m)t} \right\}$$

- Second order wavemaker motion is added to counter the spurious waves

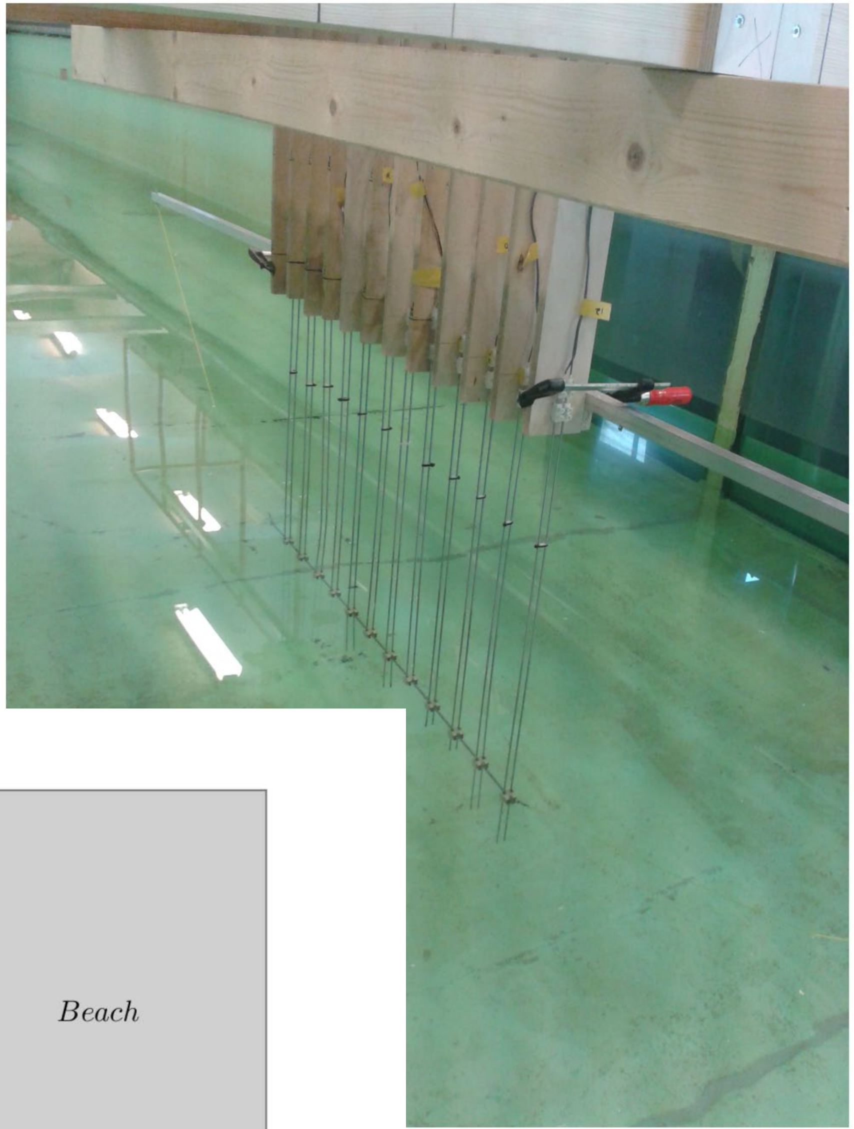
Second-order wavemaker theory for irregular waves, Hemming A. Schäffer, Ocean Engng, Vol. 23, No. 1, pp. 47-88. 1996

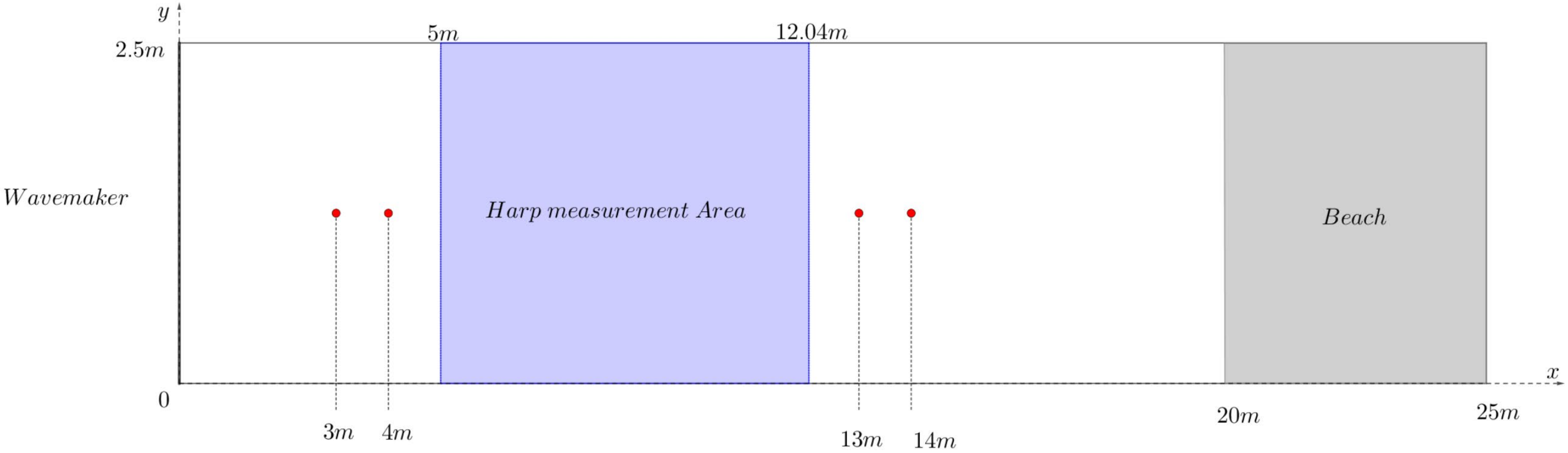
Dispersion relation



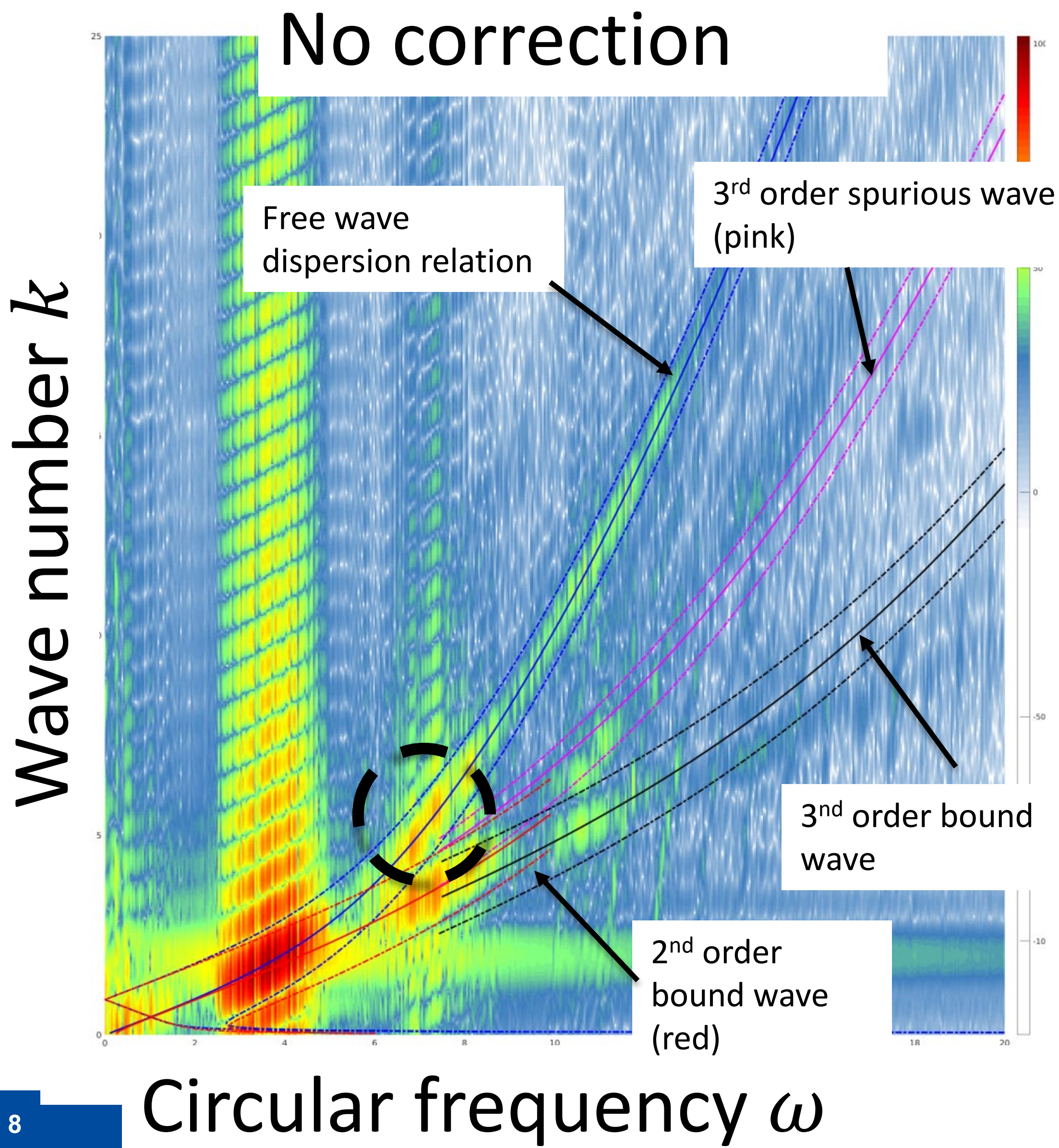
Experimental setup *wave probes*

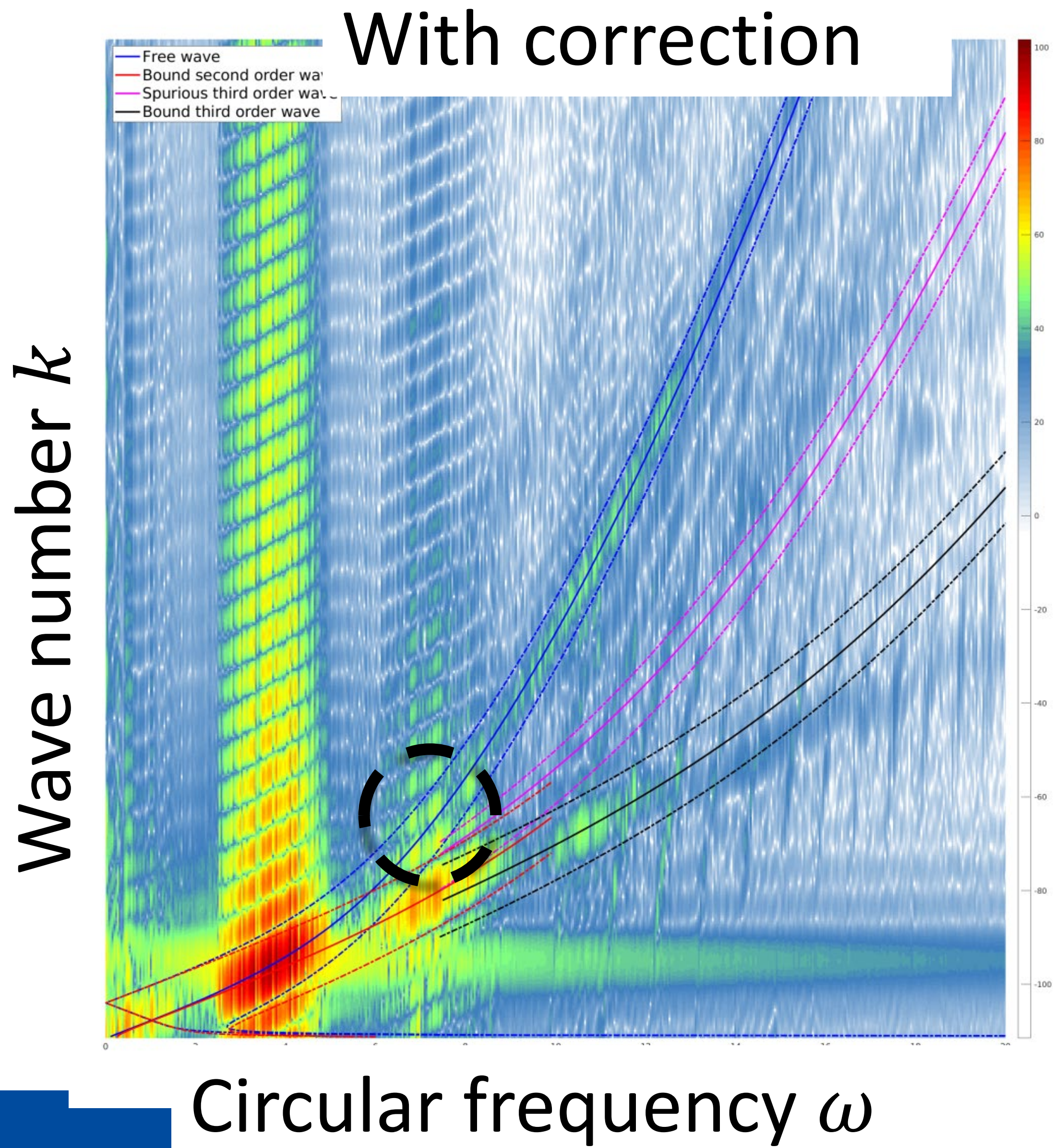
- Wave elevation measurement along 7m length of the tank centerline with a step of 0.08m
- Acceptable resolution for calculating 2D FFT





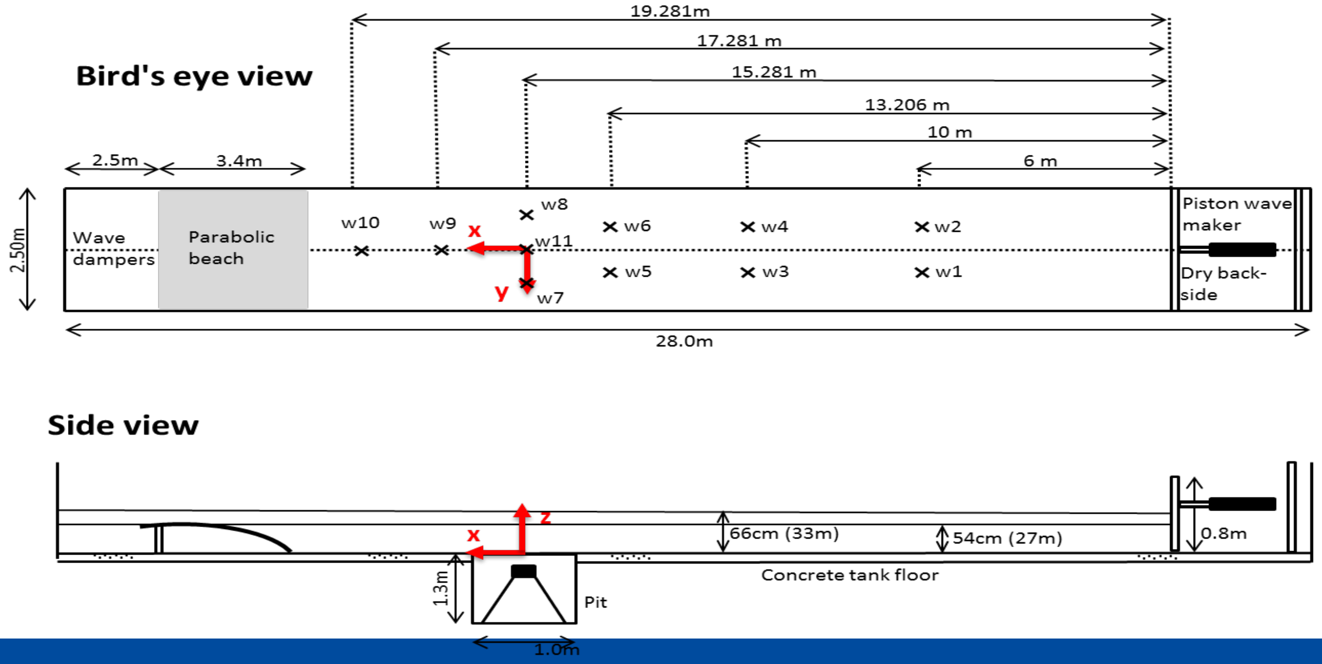
Dispersion relation: Gaussian spectrum Tp = 12s, Hs = 4m

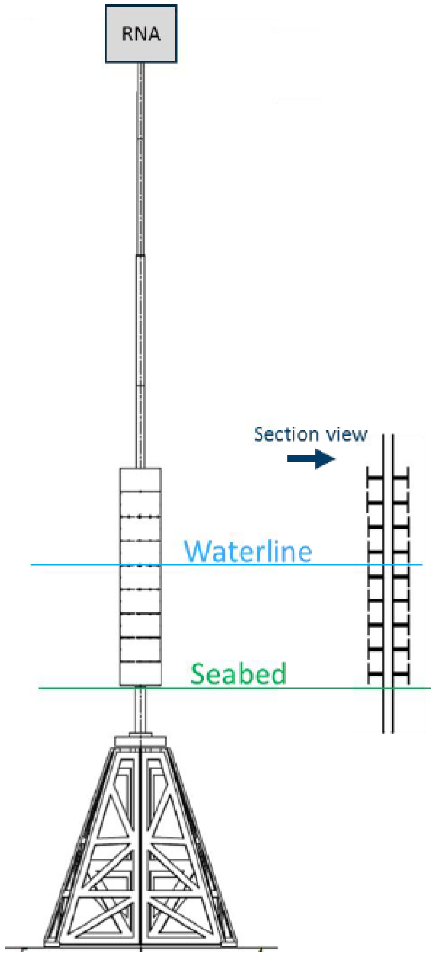




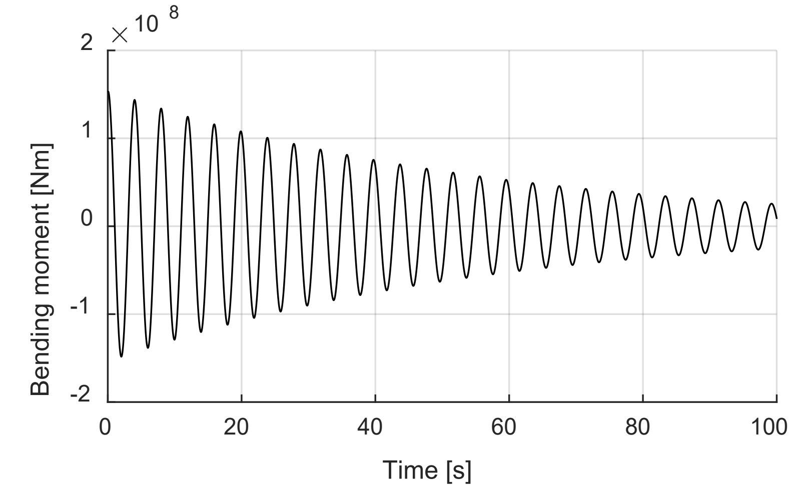
Monopile testing: experimental setup

- Instrumentation: 11 wave probes, water temp, wavemaker position, strain gauges and 6DOF force transducer
- Water depth: 27 m
- Monopile diameter: 9 m
- Automated test setup for increased statistics

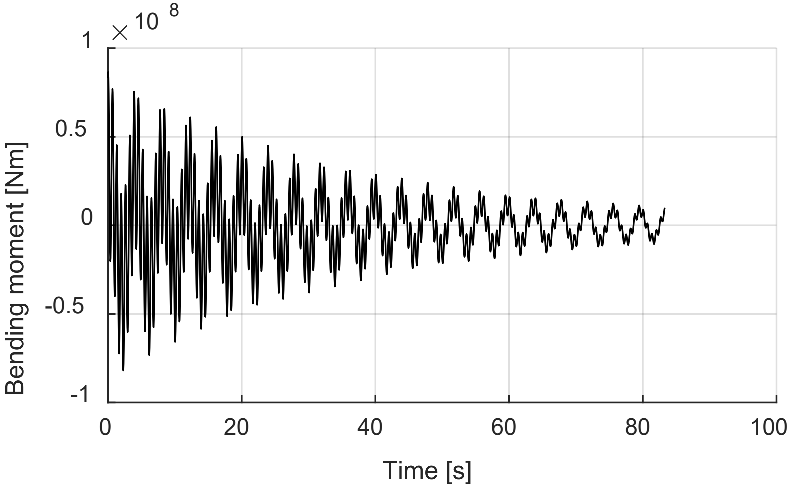




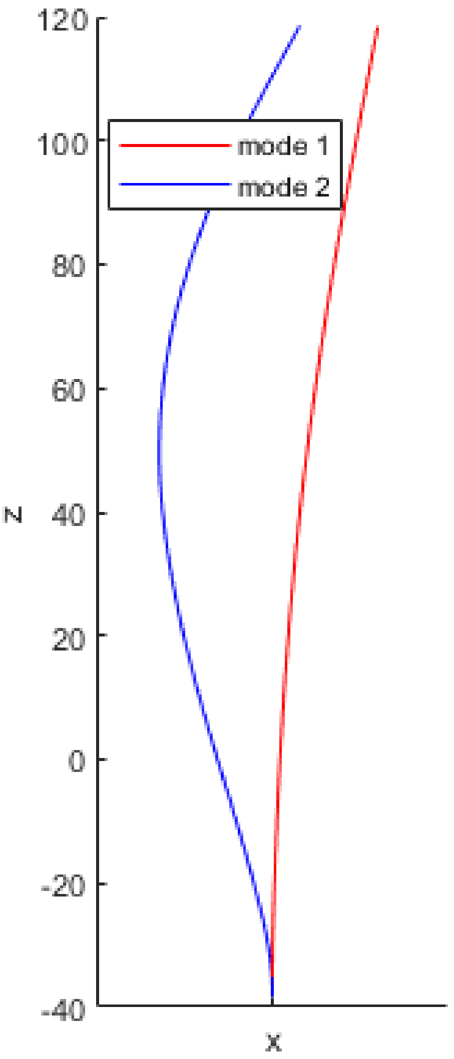
Decay tests



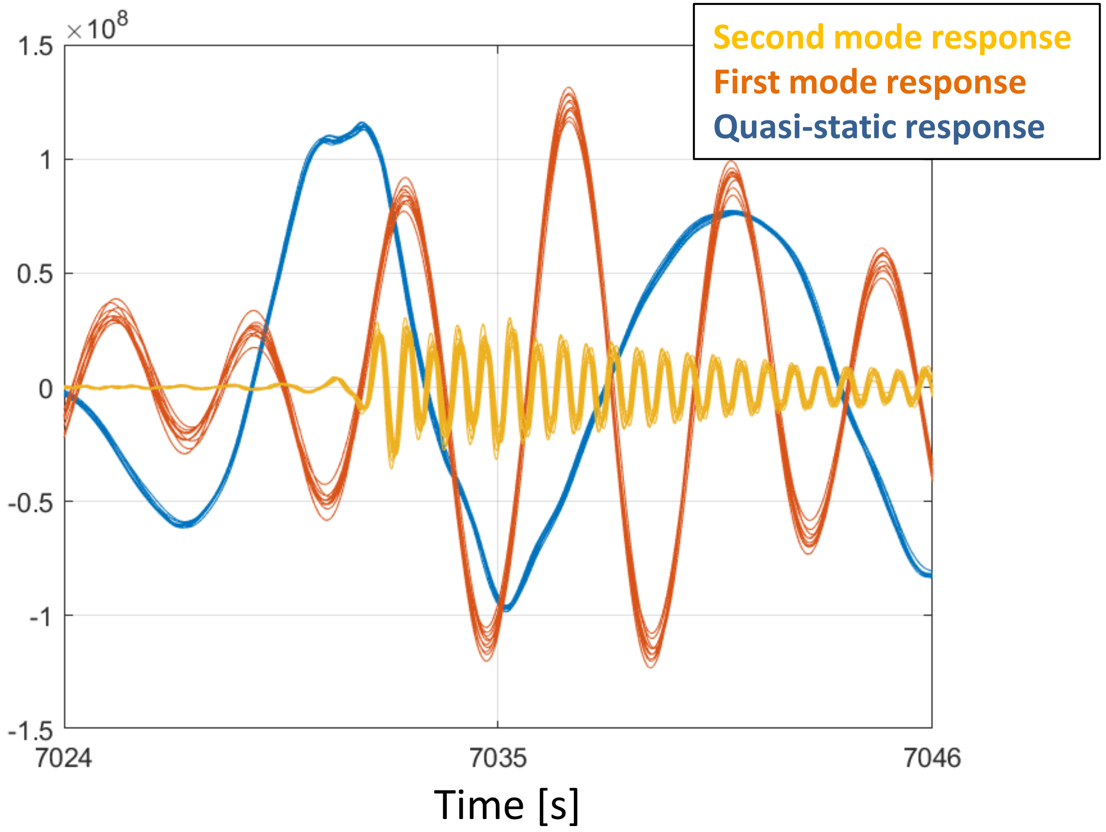
First mode:
$f_1 = 0.25$ **(Hz)**
Damping ratio: 1.1%

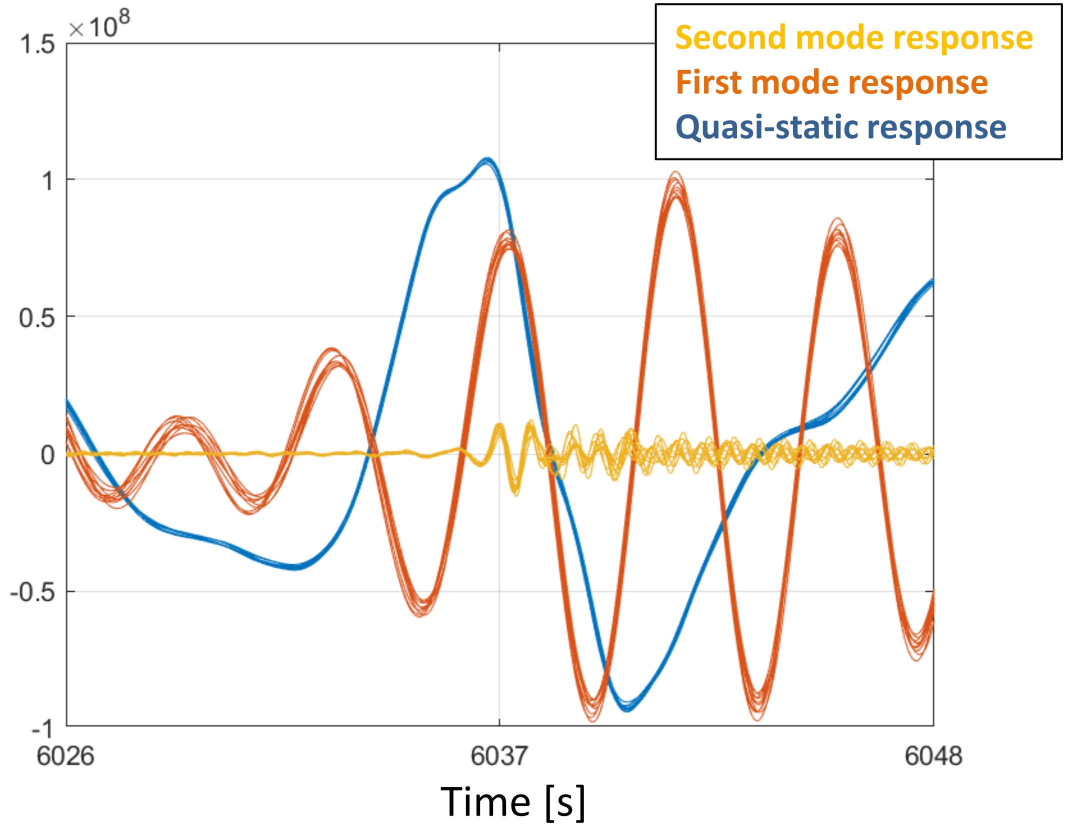


Second mode:
$f_2 = 1.58$ **(Hz)**
Damping ratio: 0.4%



Repeatability of bending moment response at two largest events from 10 test repetitions



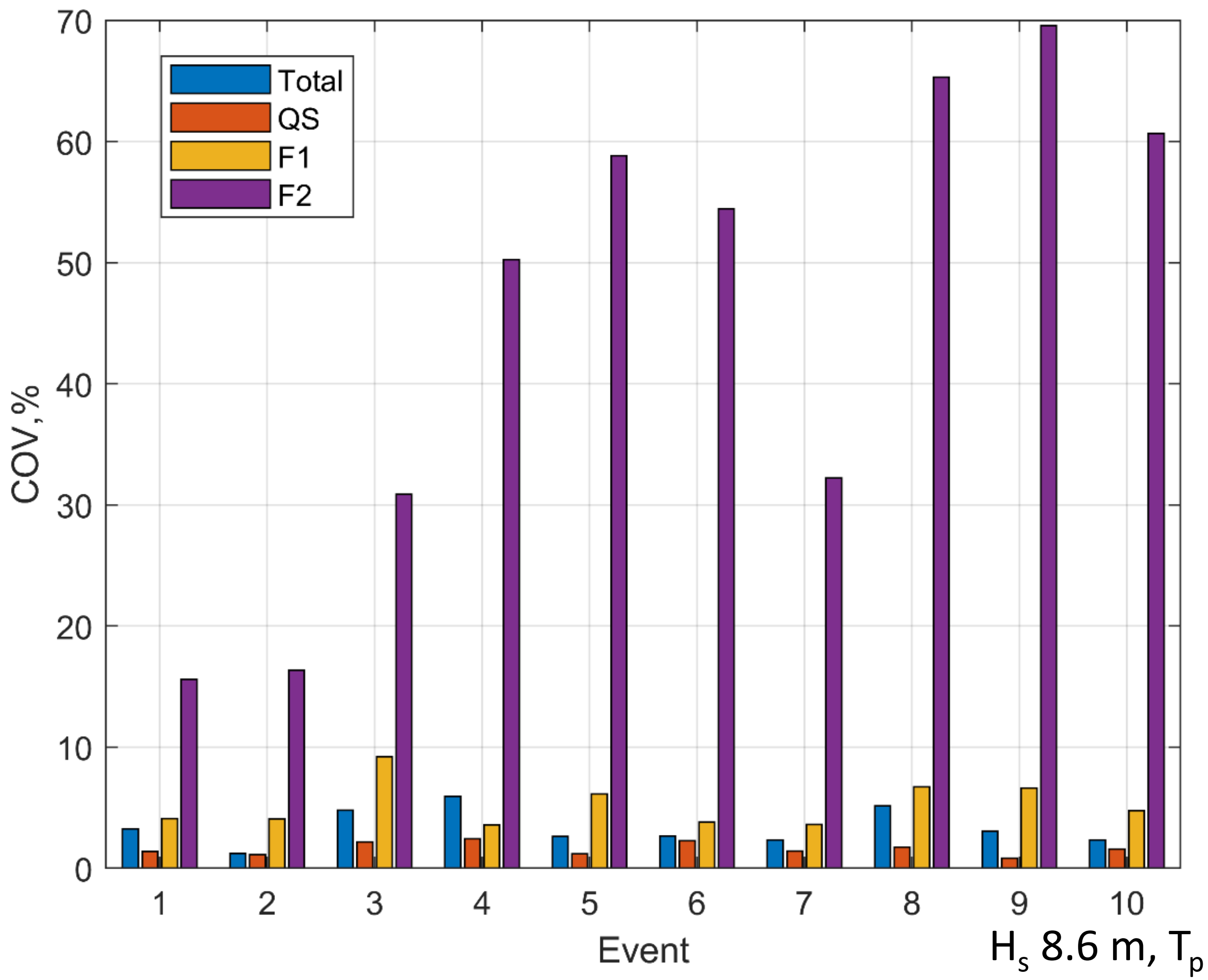


H_s 8.6 m, T_p 11 s

Repeatability of the phase of the responses at second natural frequency.

Coefficient of variation (COV) for the 10 largest bending moment maxima in 10 repetitions of one seed

Contributions calculated at the exact time of the maximum total moment.



H_s 8.6 m, T_p 11 s

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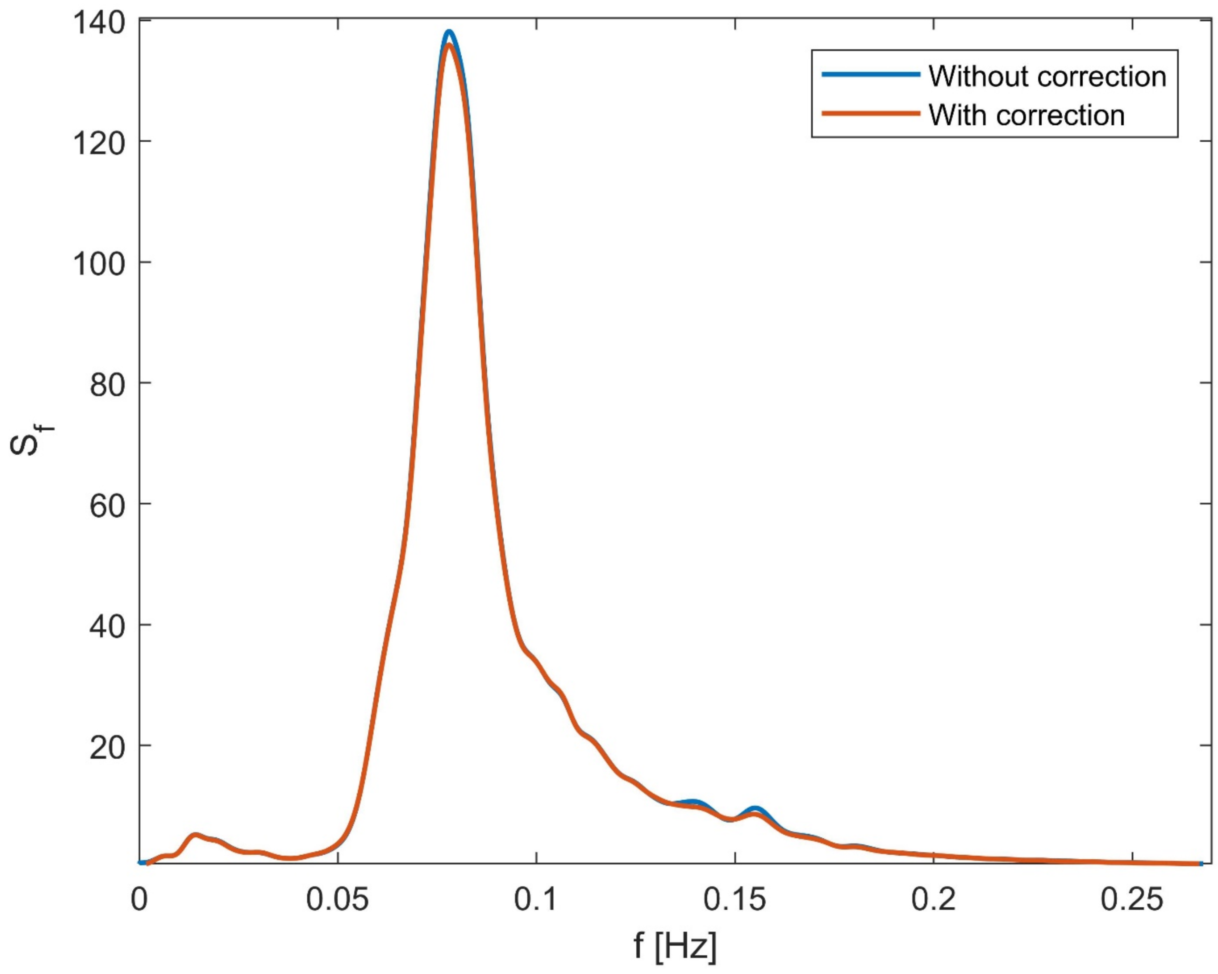
Effect of second order correction on the wave elevation



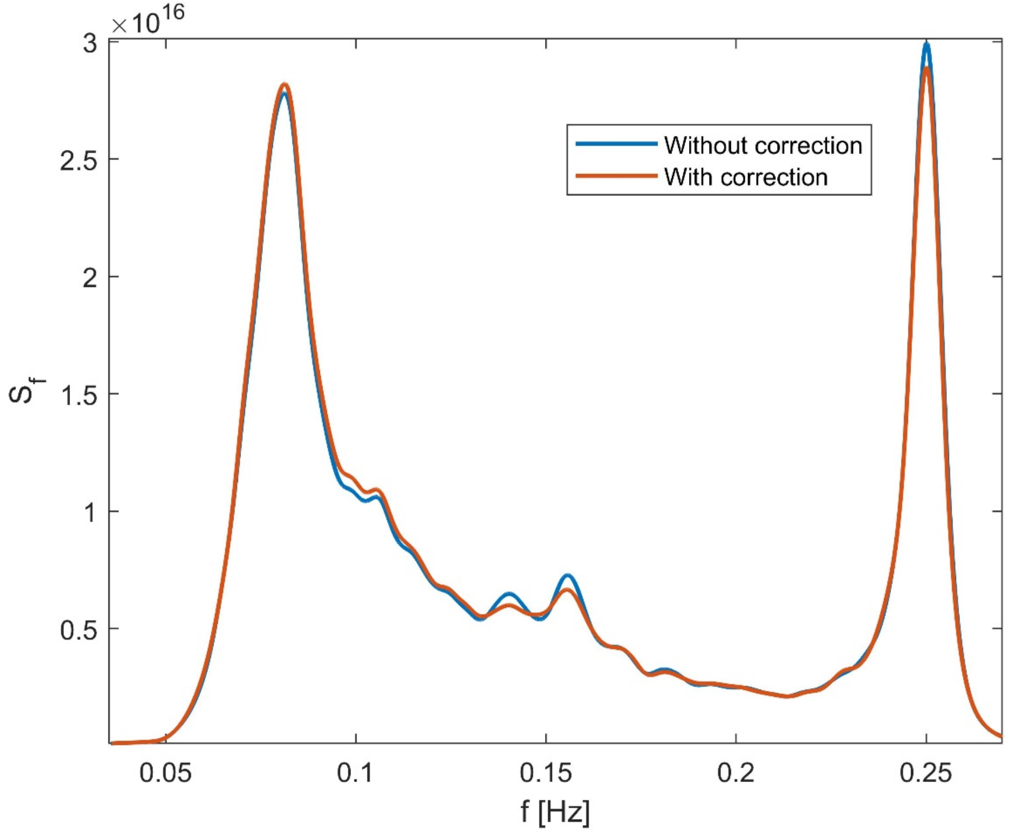
Mean spectrum of the wave

10 realizations of the same sea state

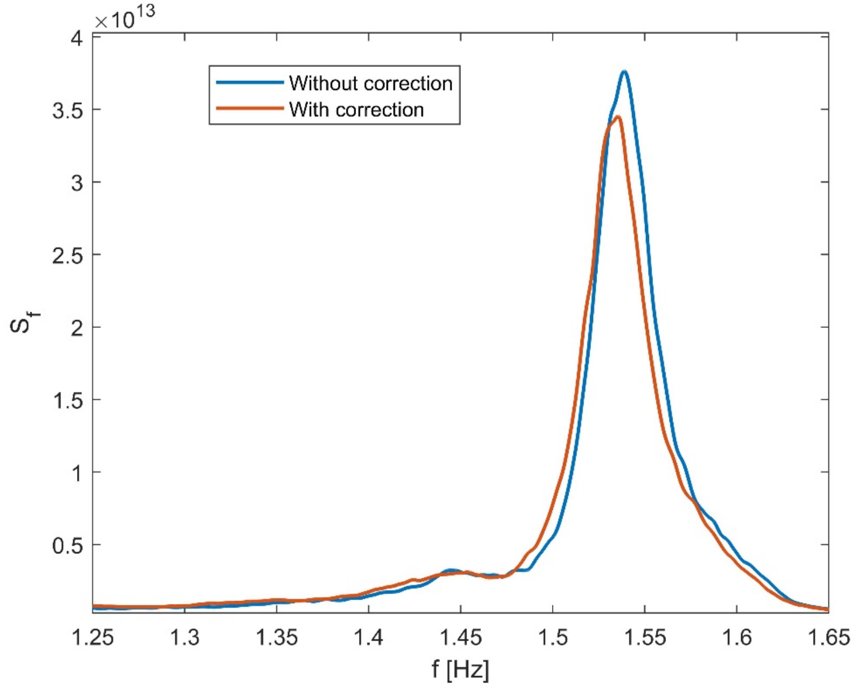
Little change in wave elevation statistics using this correction

H_s 9.0 m, T_p 12.5 s

Mean spectrum of the mud-line bending moment response

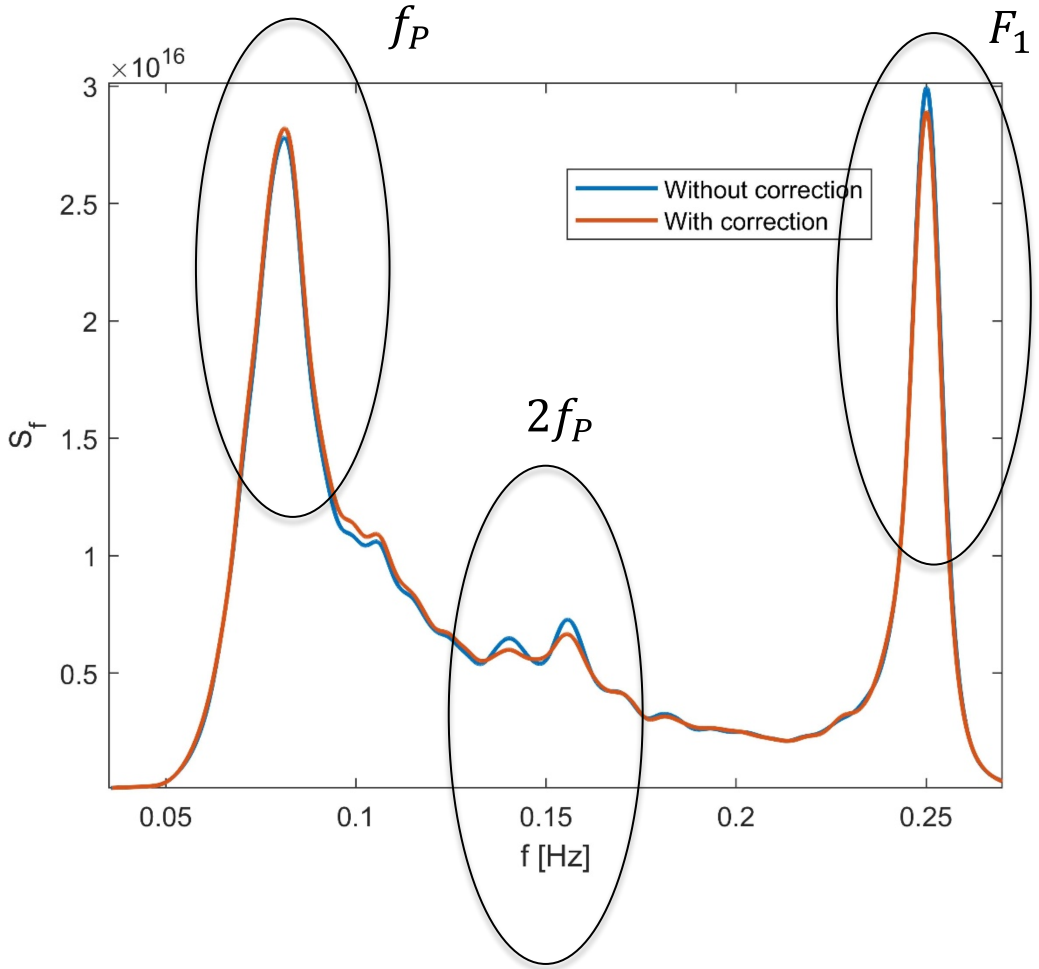


Mean spectrum around the second natural frequency

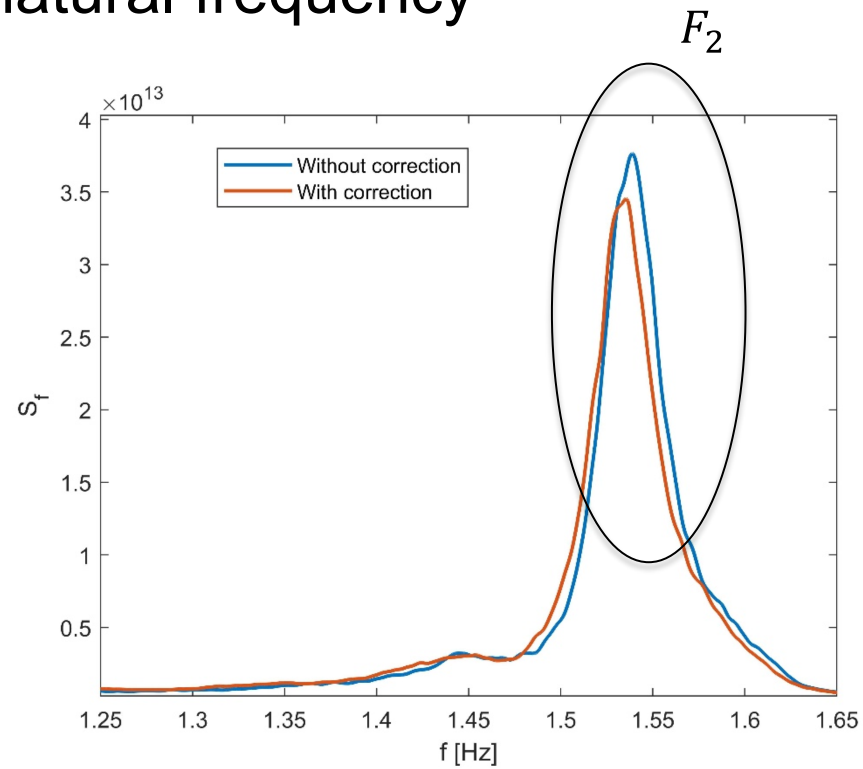


H_s 9.0 m, T_p 12.5 s

Mean spectrum of the mud-line bending moment response

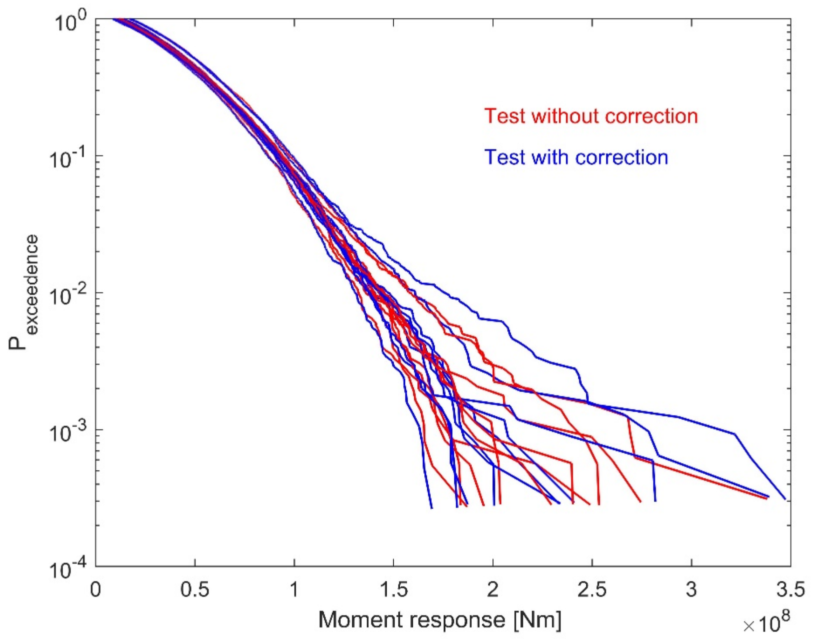


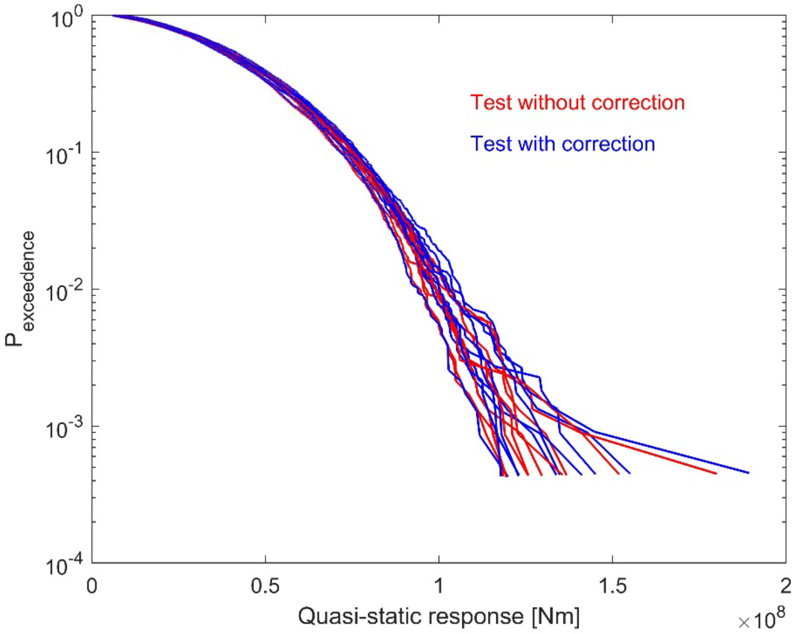
Mean spectrum around the second natural frequency

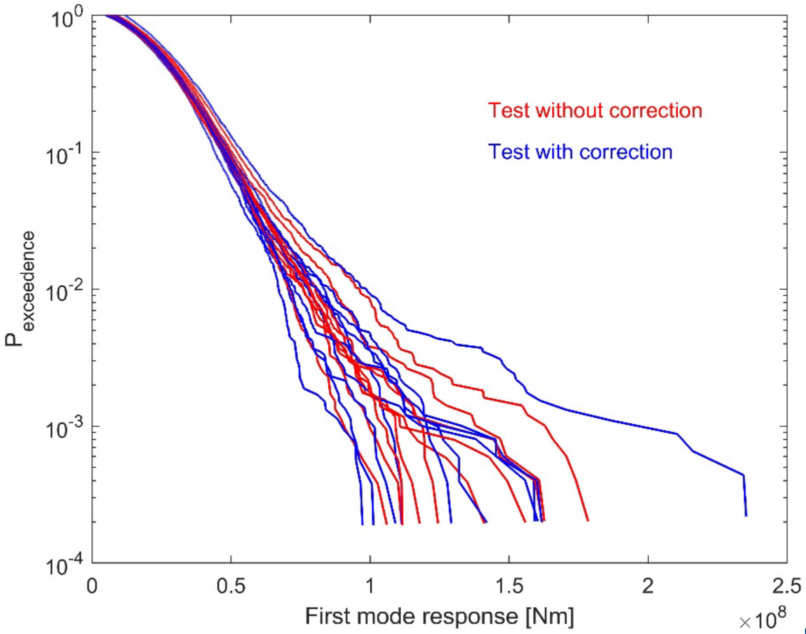


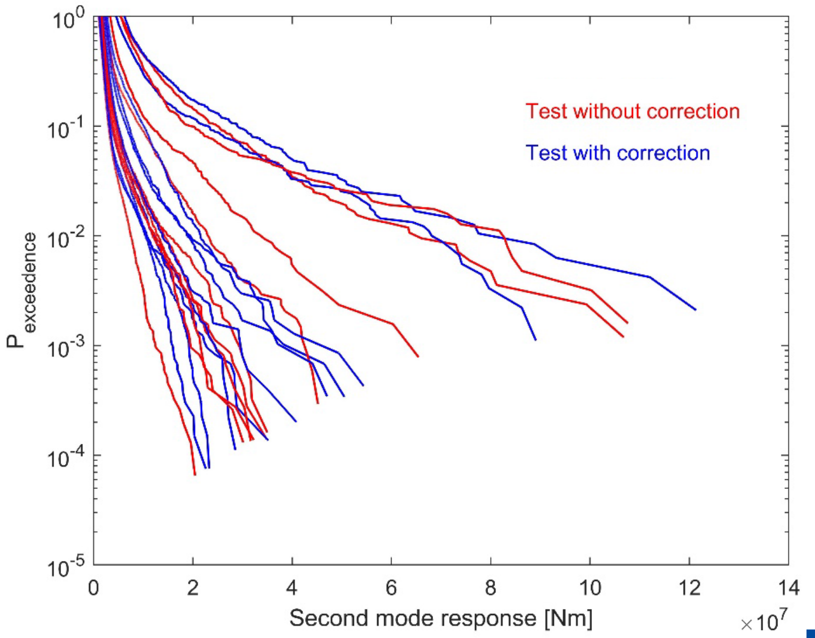
H_s 9.0 m, T_p 12.5 s

Exceedance probability of bending moment response for 10 realizations of the tests without and with second-order correction

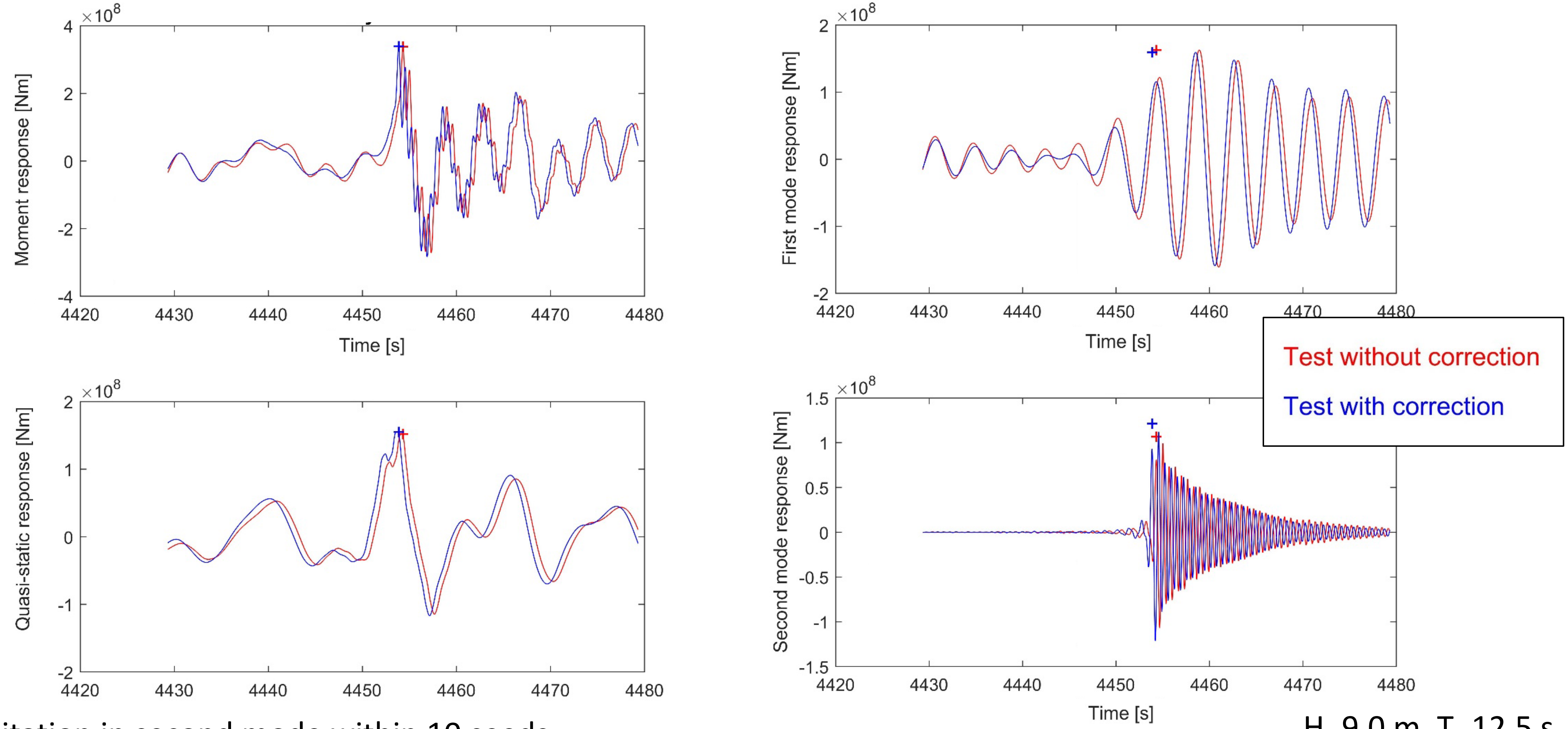








Bending moment response in the tests without and with wavemaker second-order correction

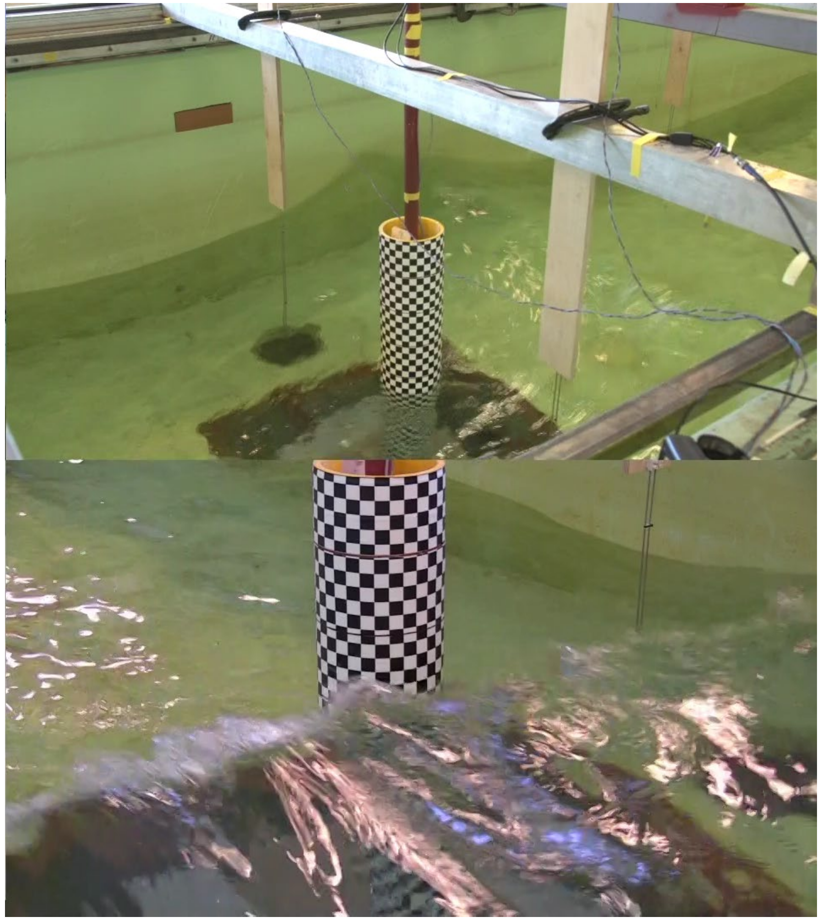


Largest excitation in second mode within 10 seeds

H_s 9.0 m, T_p 12.5 s

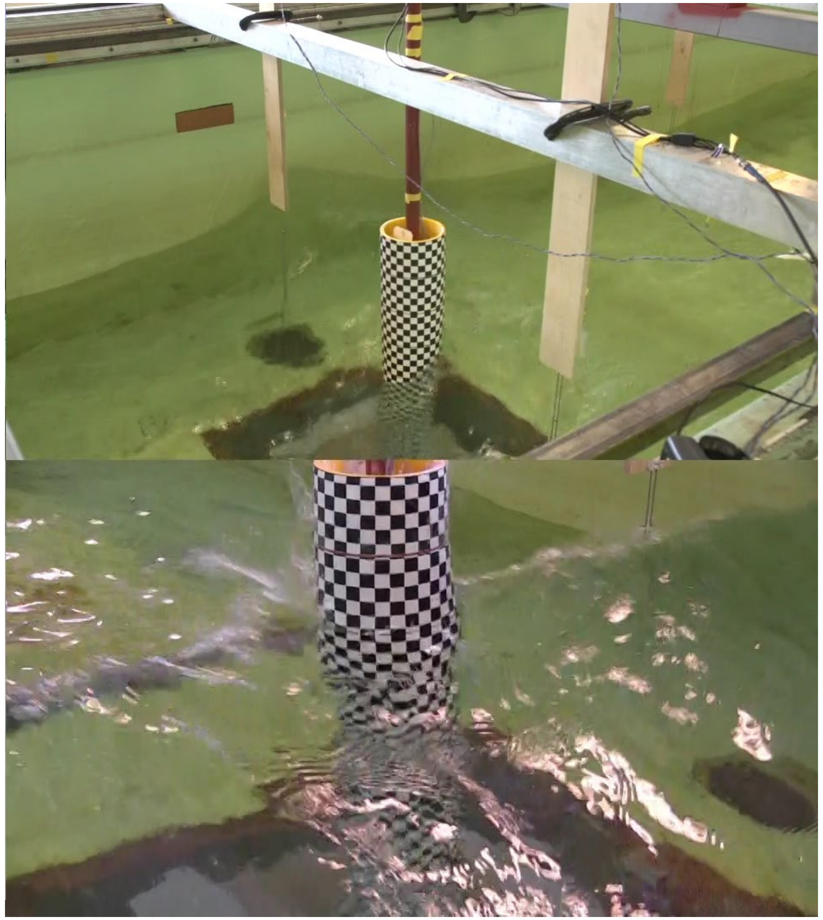
Snapshots of the wave at the model for the tests without and with wavemaker second-order correction

Without correction

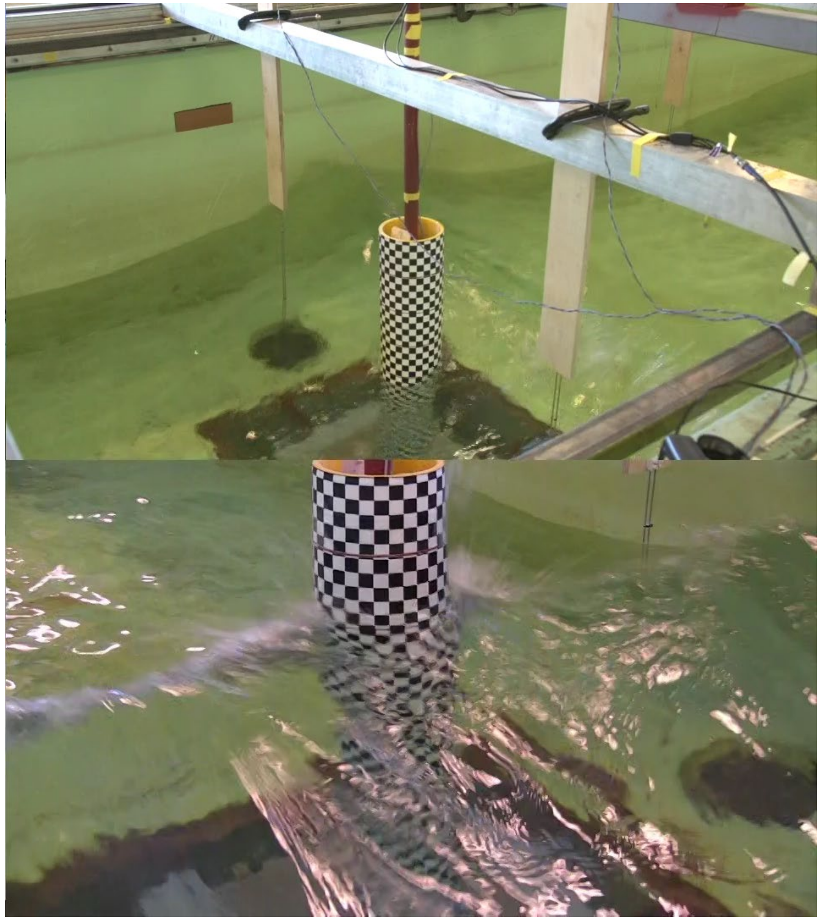


With correction

Snapshots of the wave at the model for the tests without and with wavemaker second-order correction

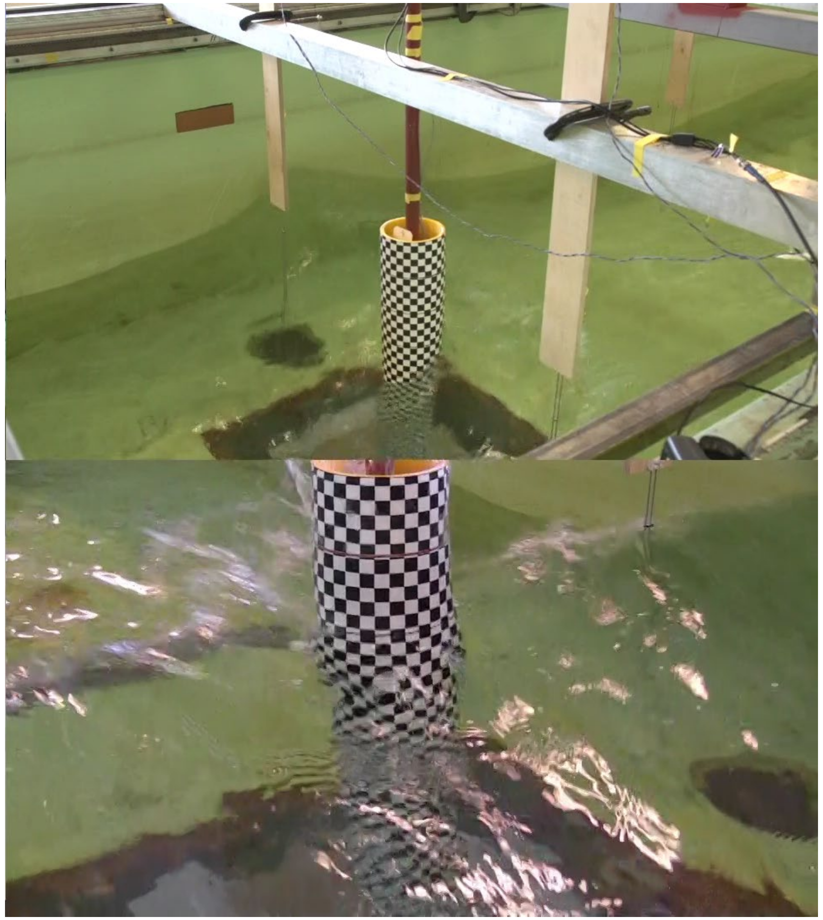


Without correction

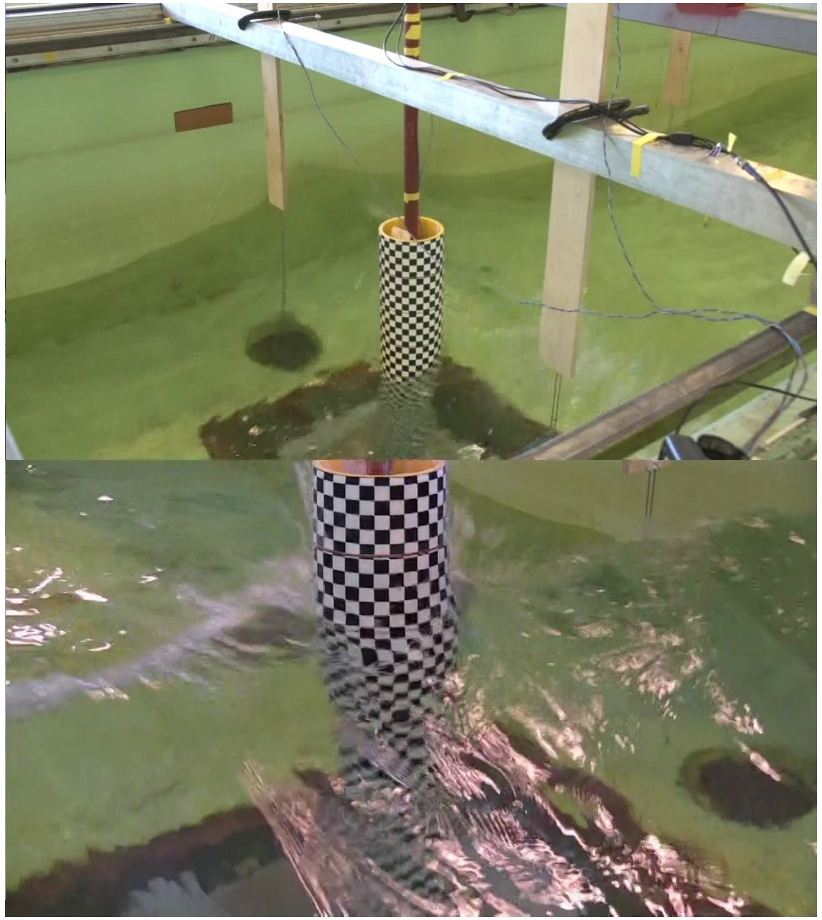


With correction

Snapshots of the wave at the model for the tests without and with wavemaker second-order correction

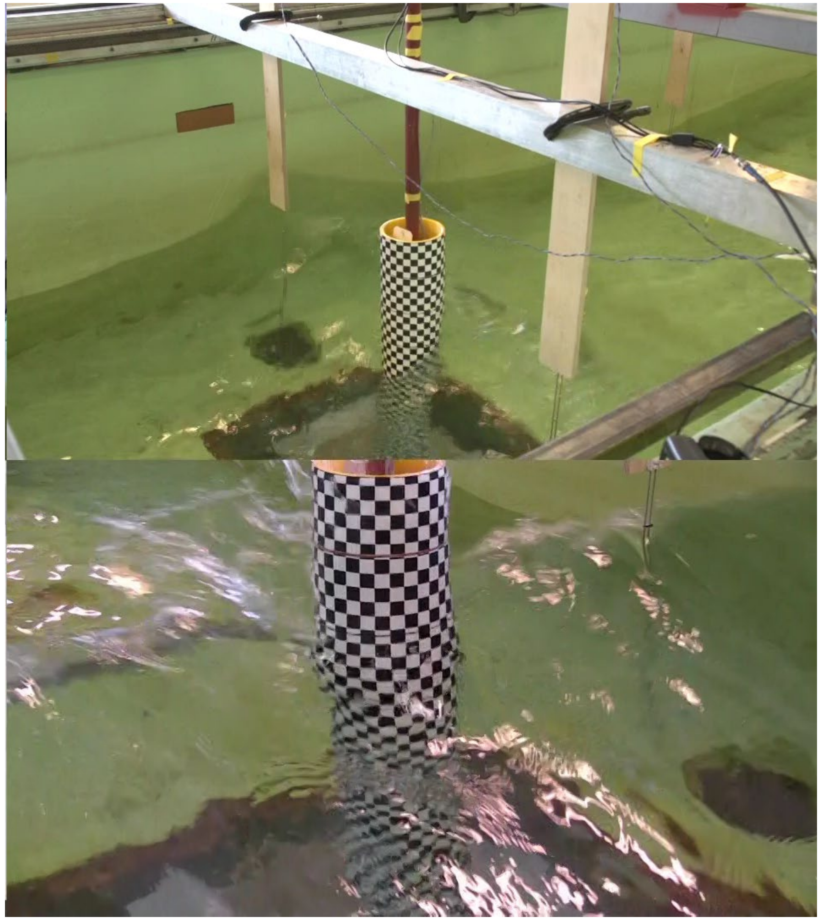


Without correction



With correction

Snapshots of the wave at the model for the tests without and with wavemaker second-order correction



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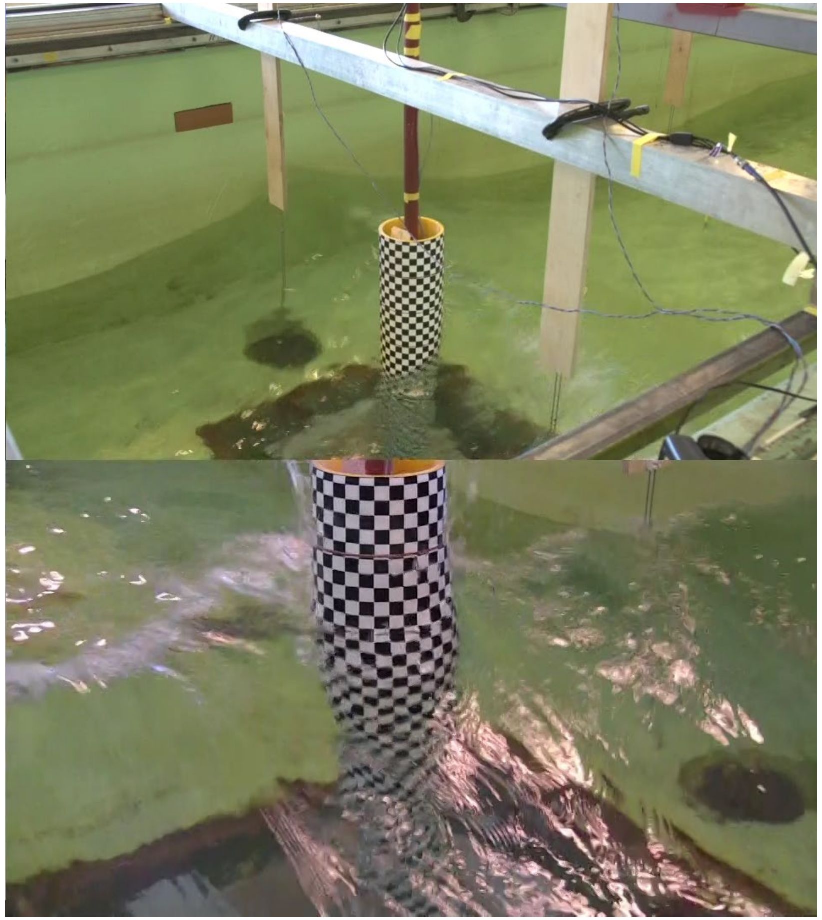
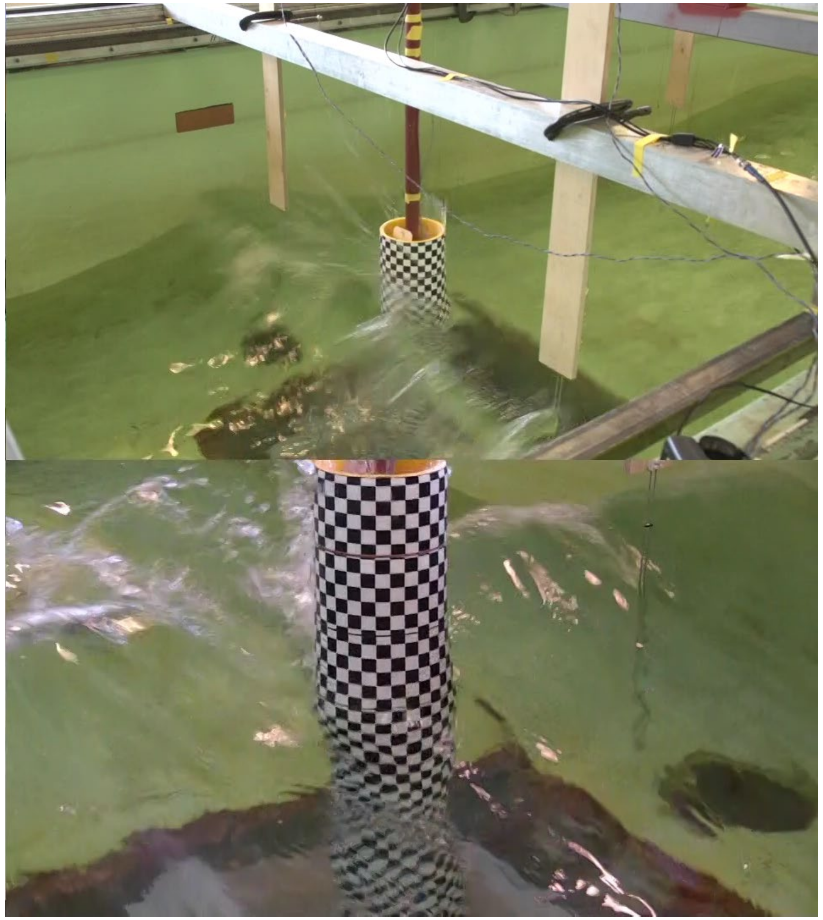
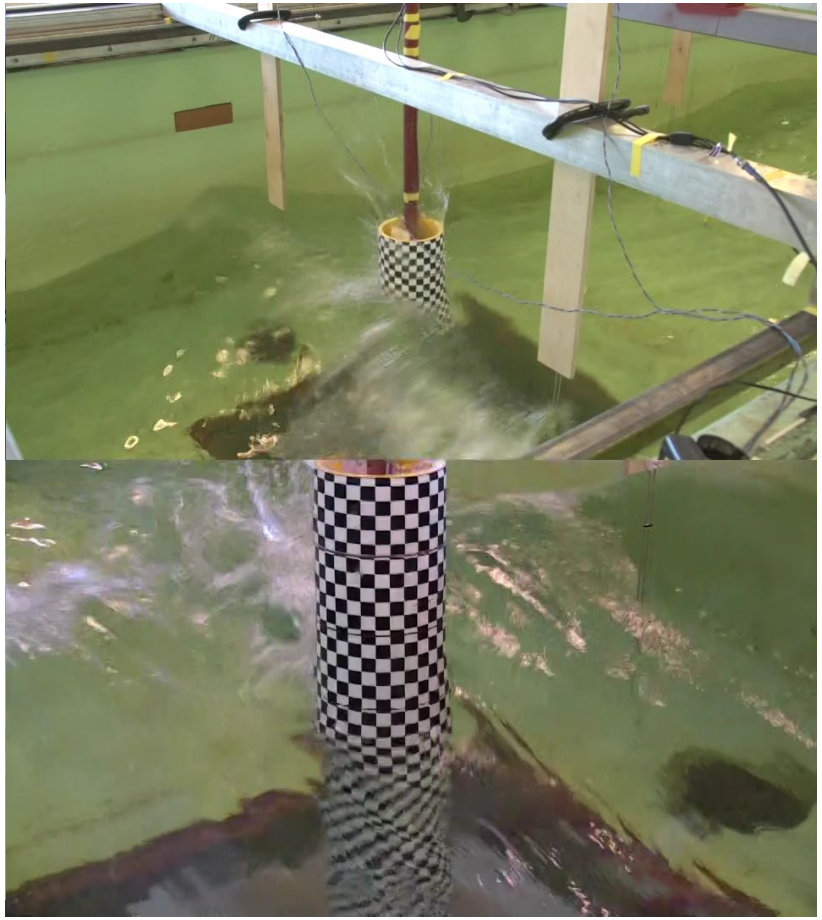


With correction

Snapshots of the wave at the model for the tests without and with wavemaker second-order correction

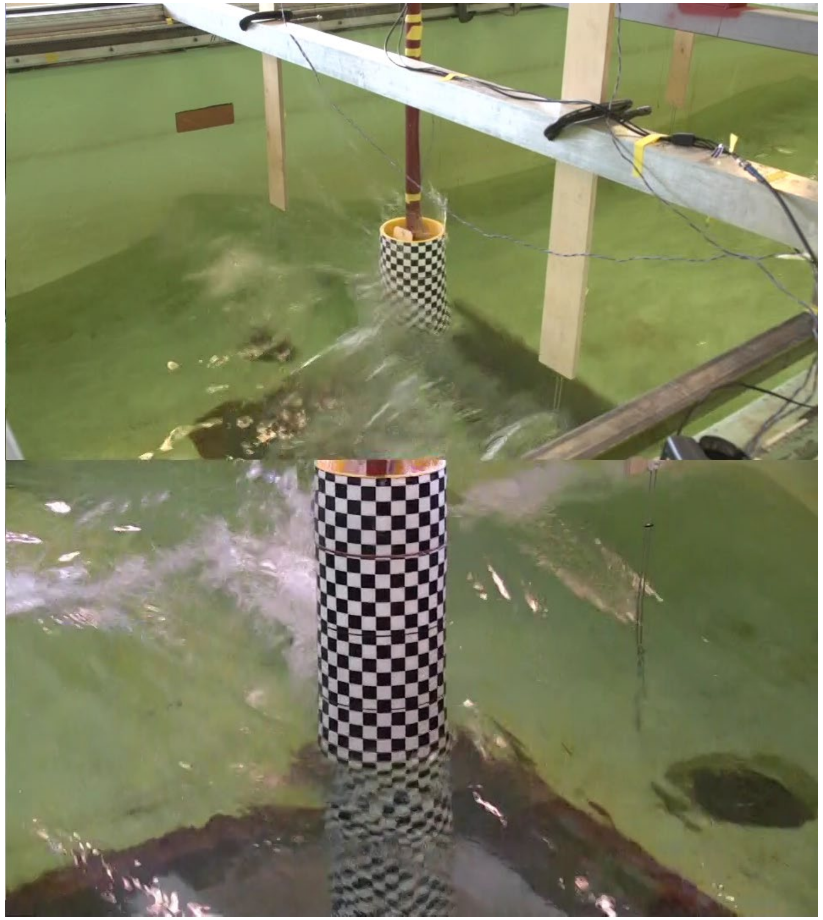


Without correction

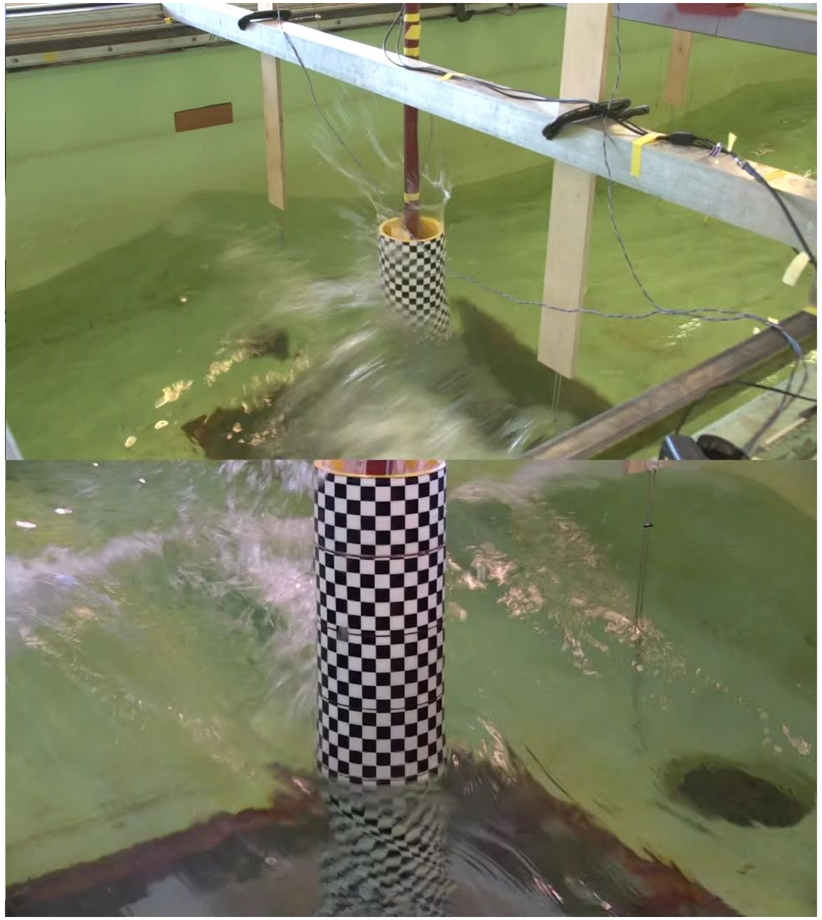


With correction

Snapshots of the wave at the model for the tests without and with wavemaker second-order correction

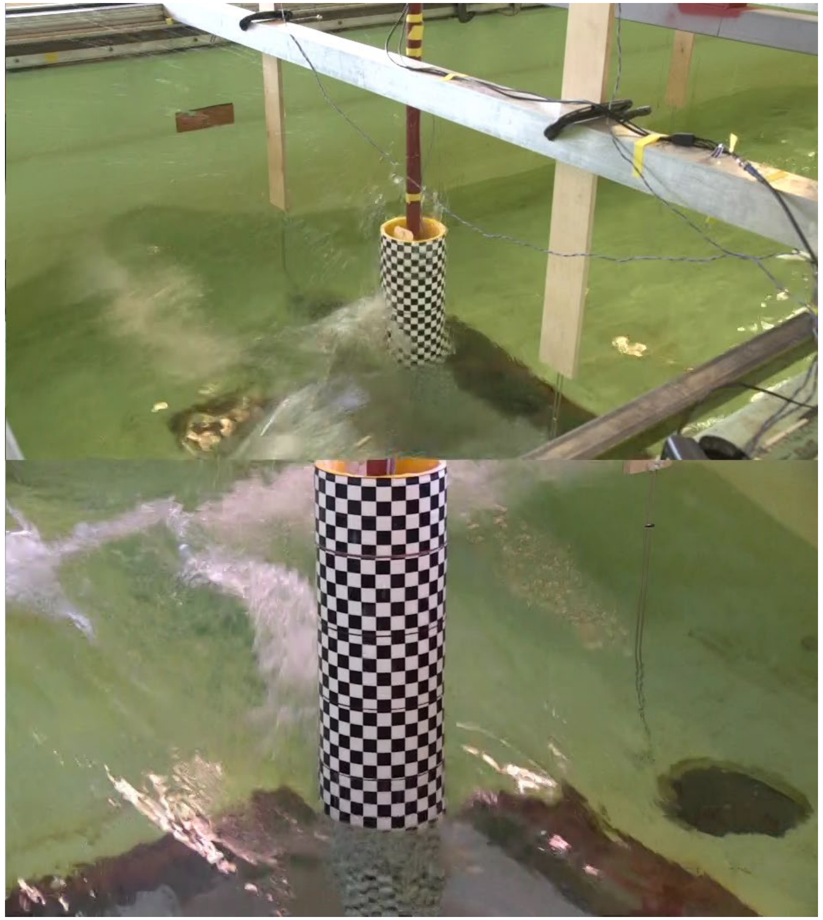


Without correction



With correction

Snapshots of the wave at the model for the tests without and with wavemaker second-order correction



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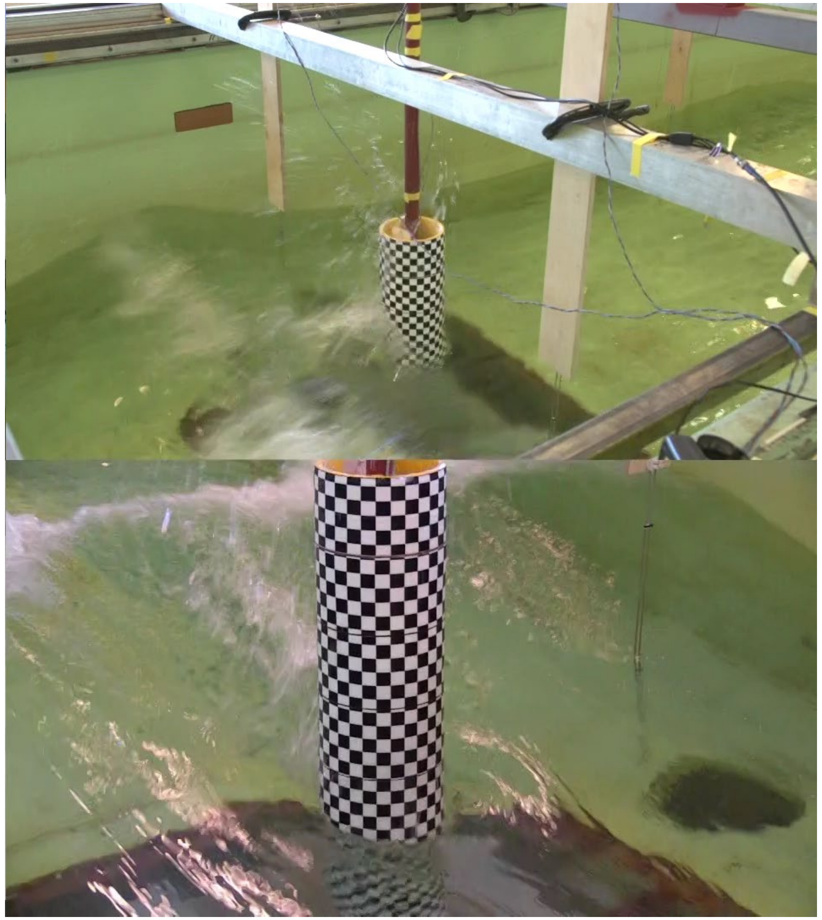
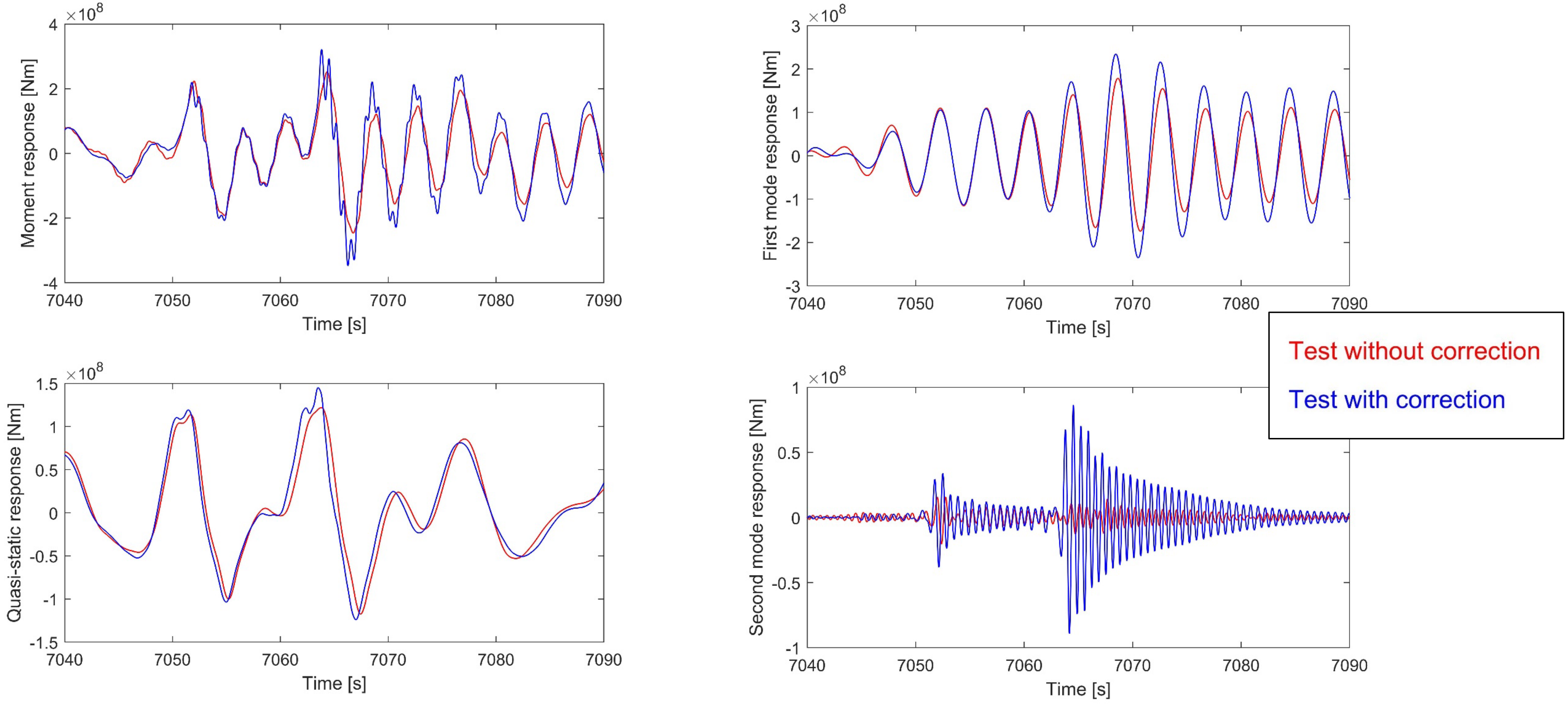
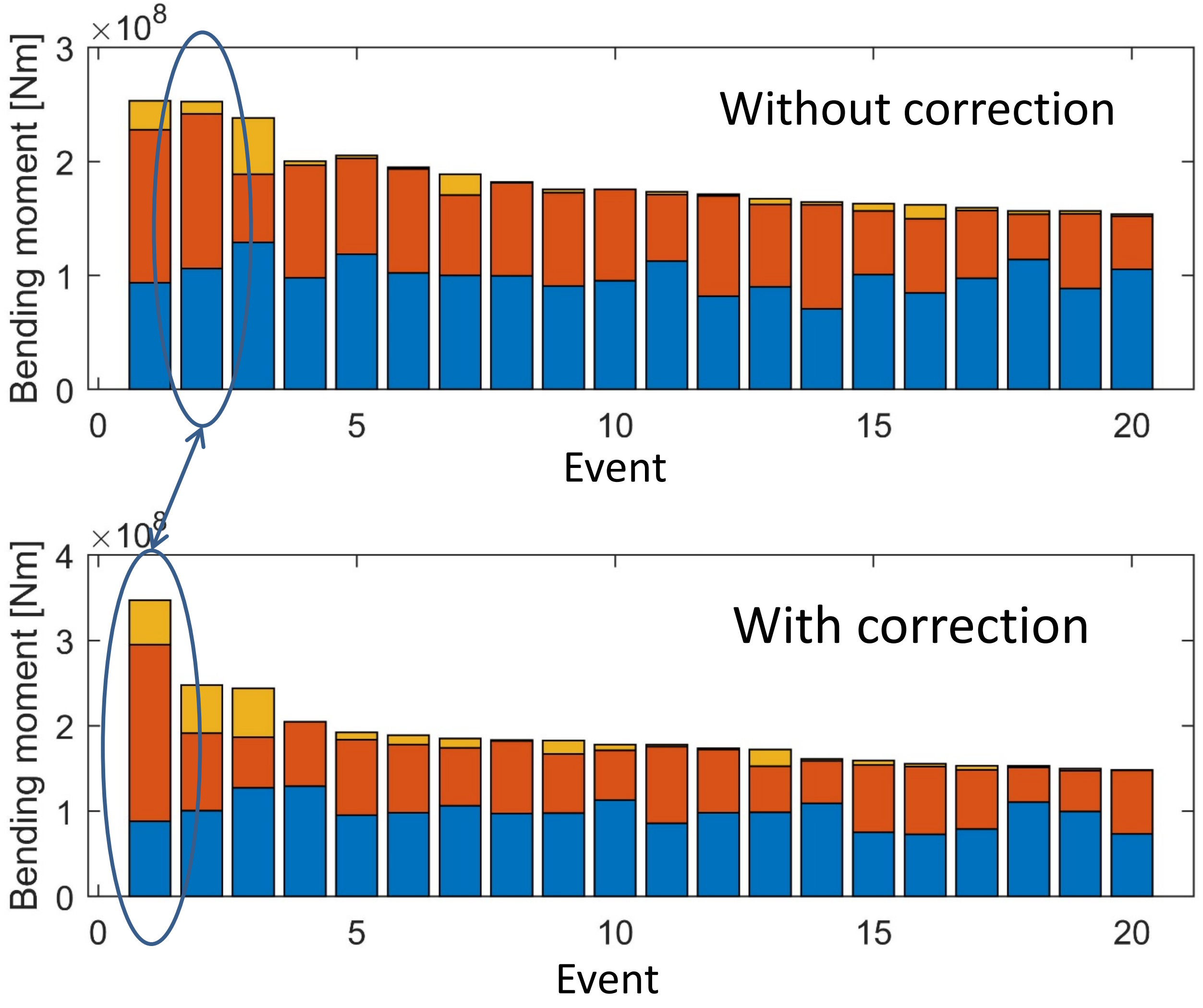


With correction

Bending moment response in the tests without and with wavemaker second-order correction



Frequency content of 20 extreme responses from a single realization



Response at second natural frequency
Response at first natural frequency
Quasi-static response

H_s 9.0 m, T_p 12.5 s

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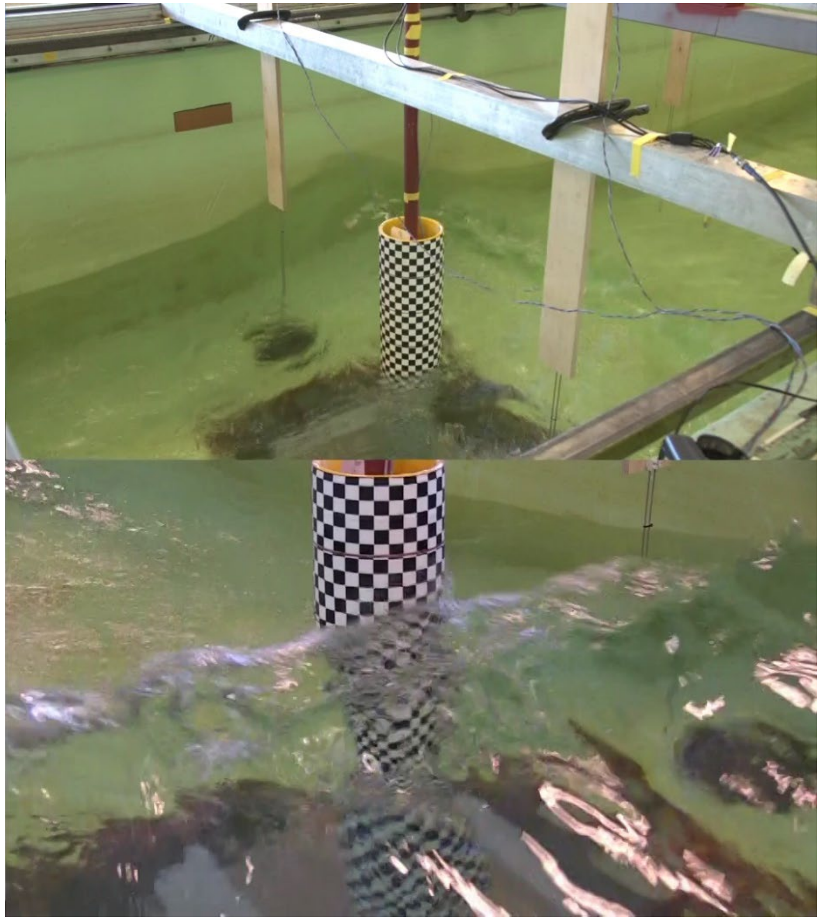
Snapshots of the wave at the model for the tests without and with wavemaker second-order correction

Without correction



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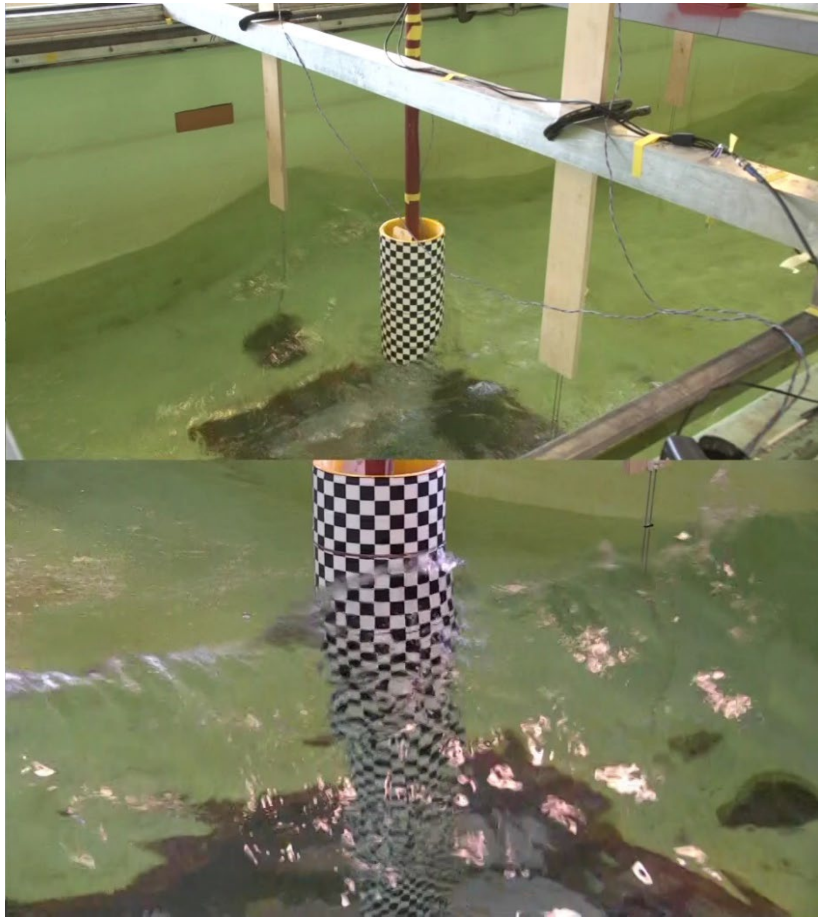

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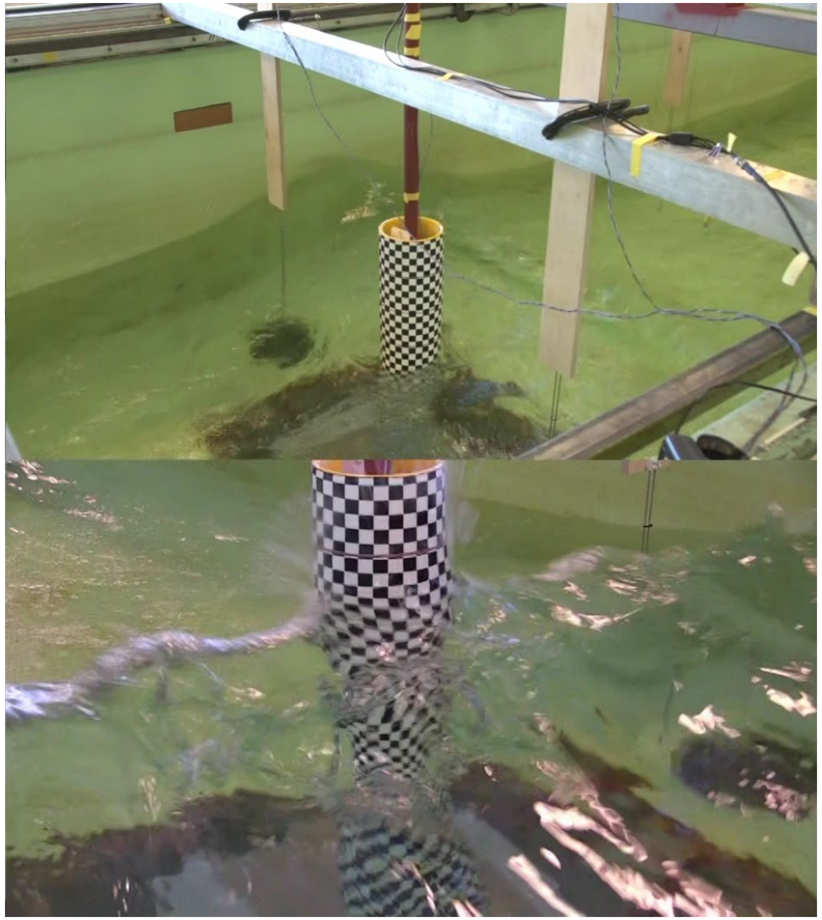

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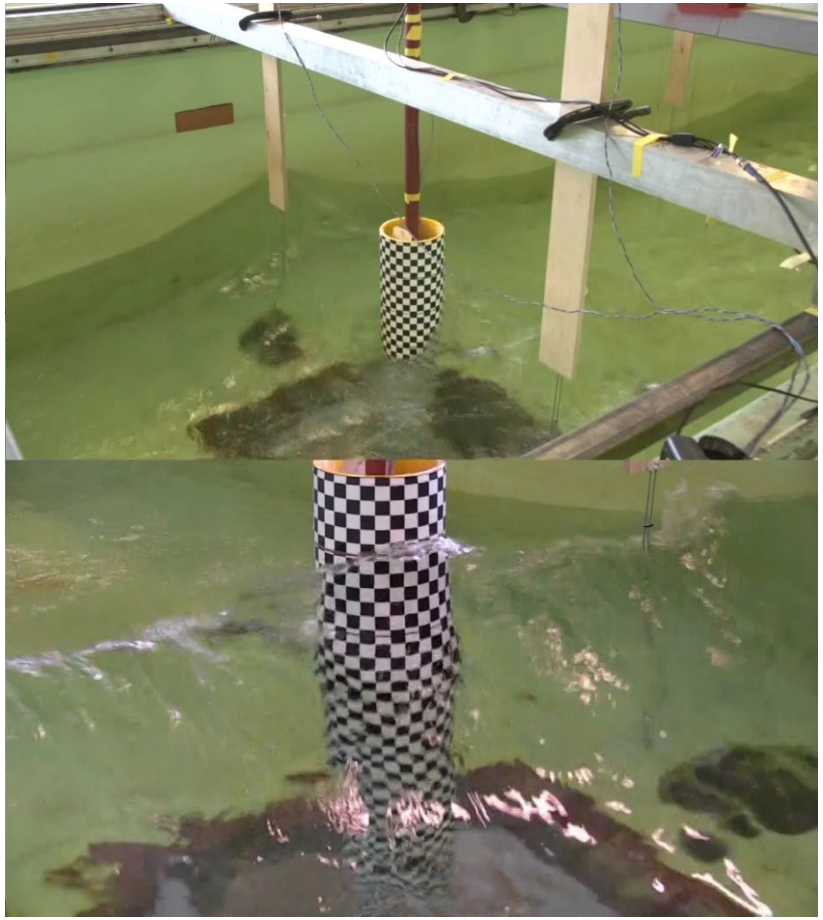

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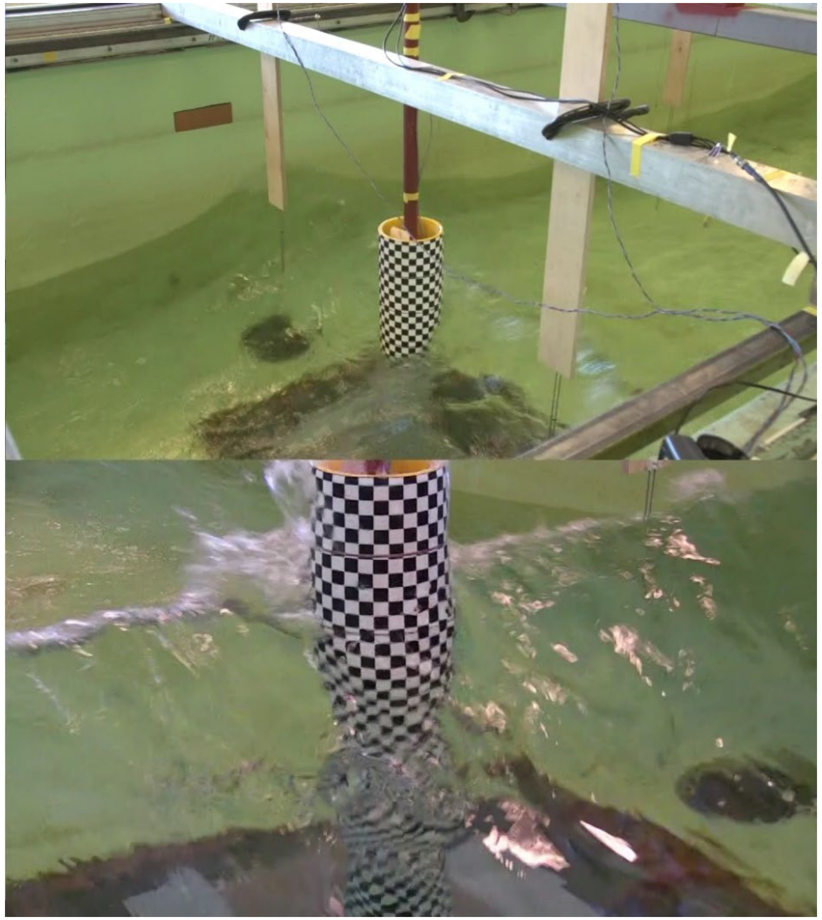

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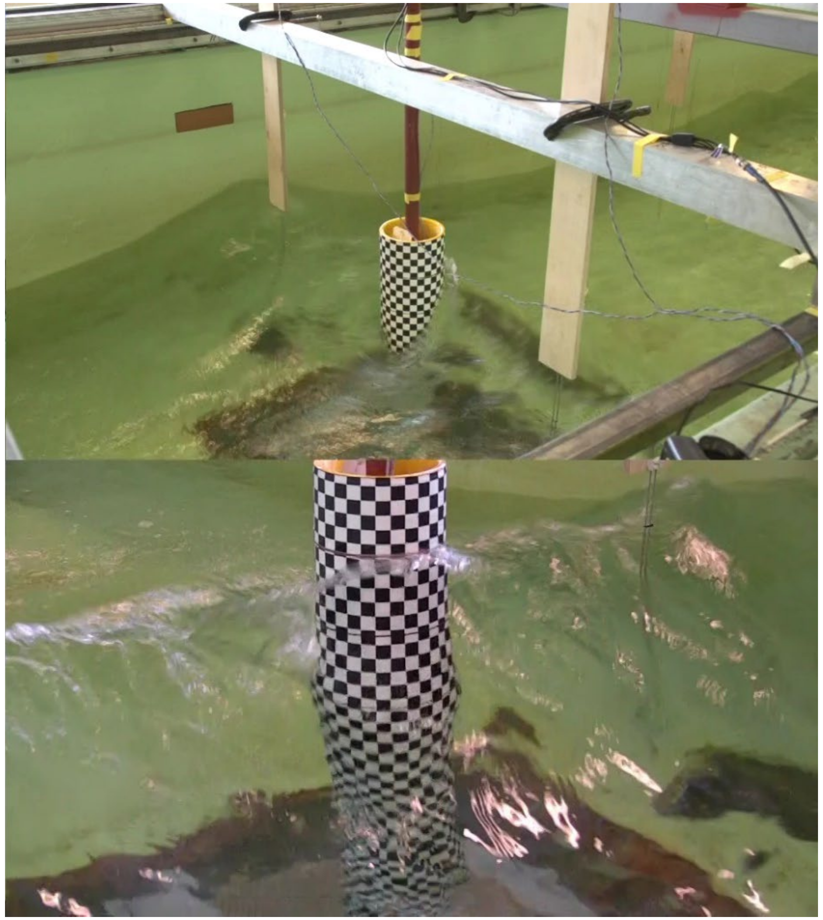

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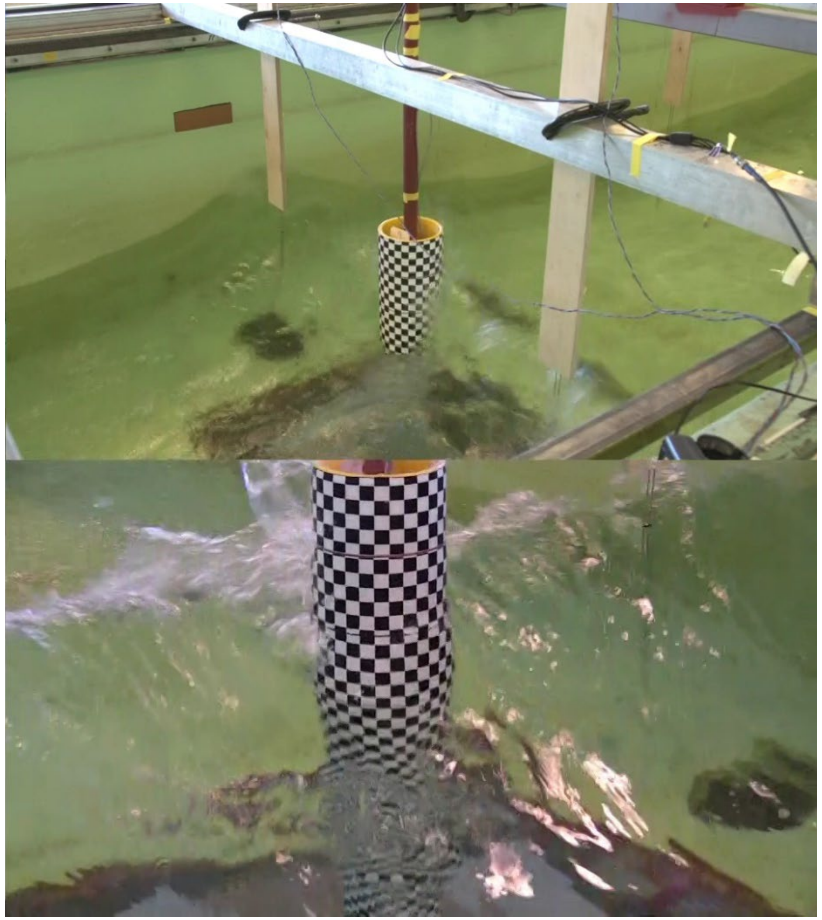

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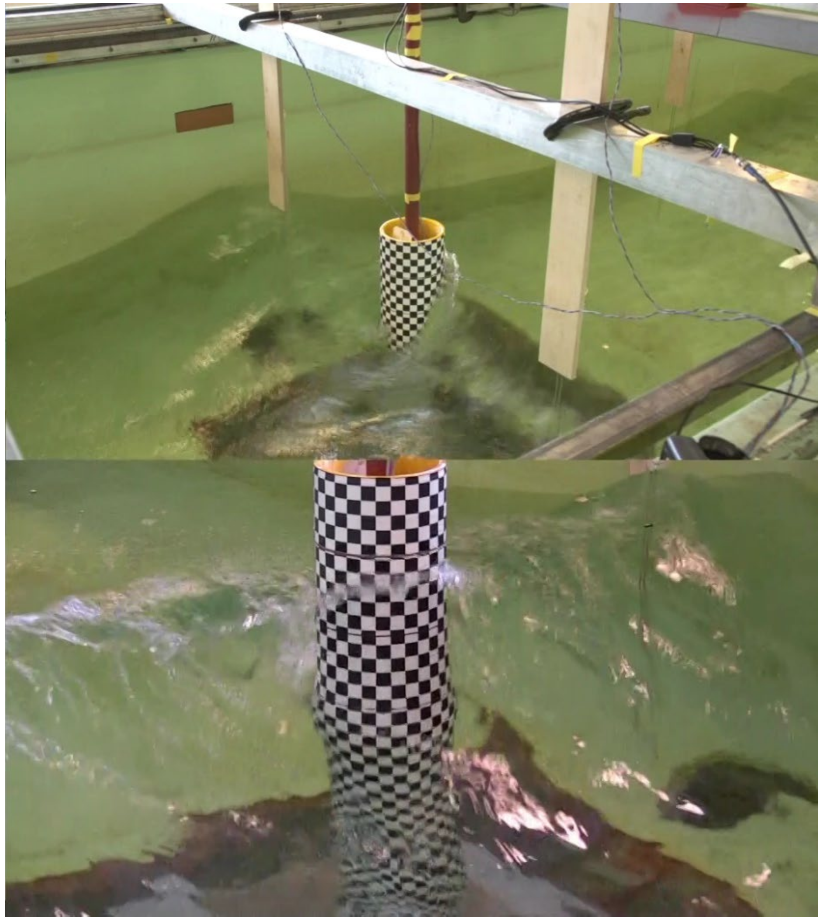

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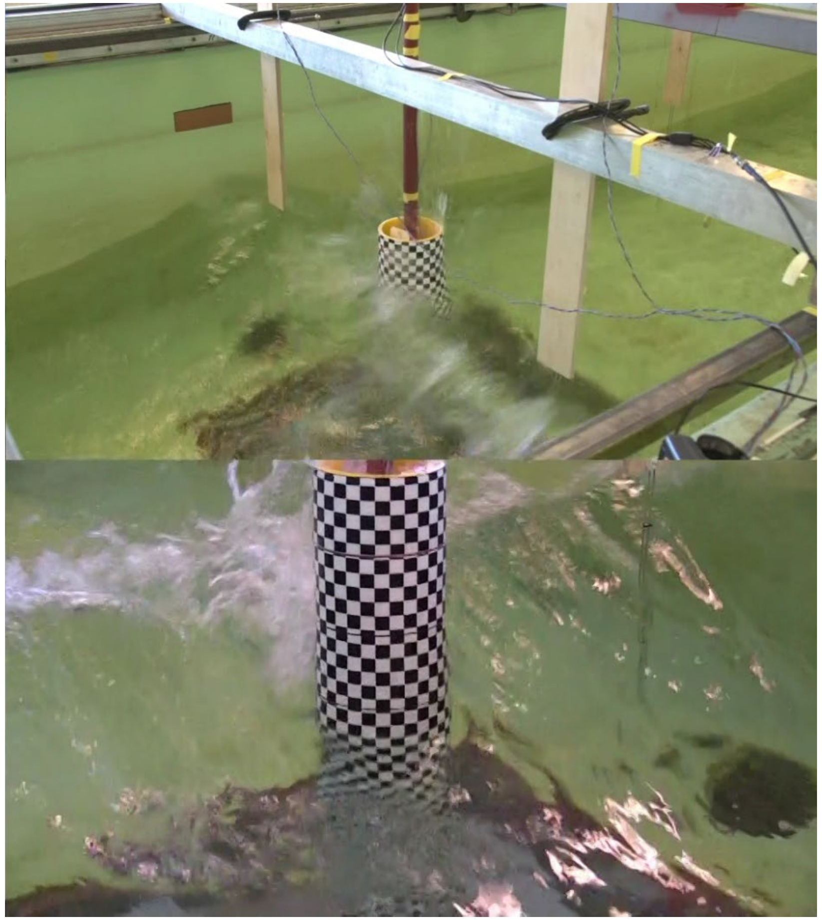

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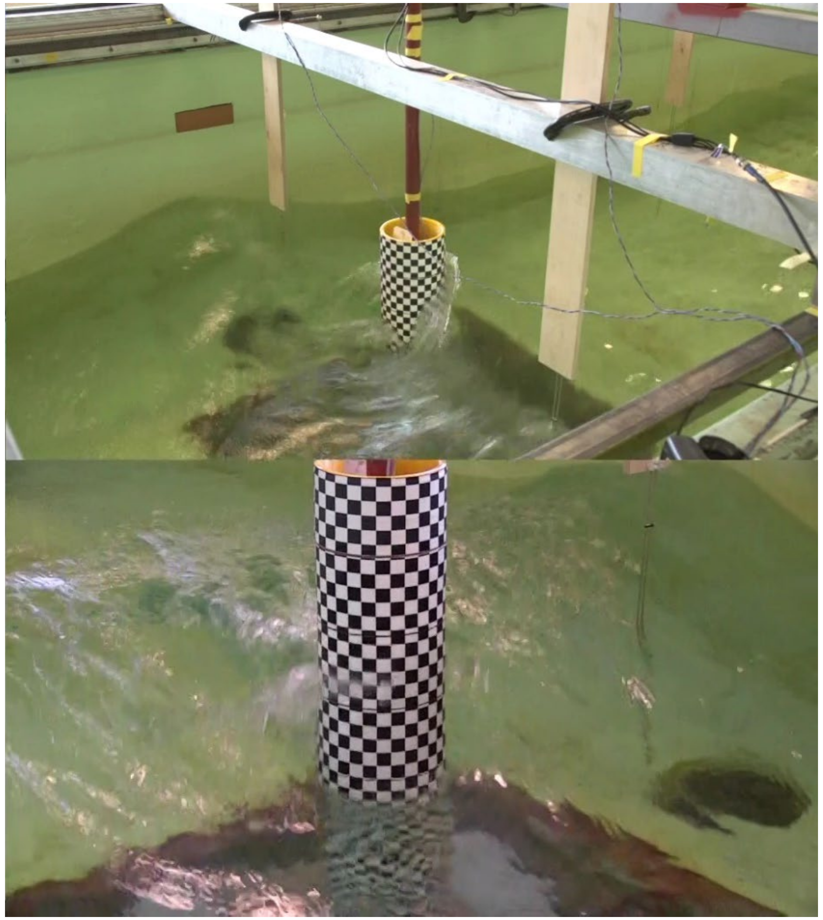

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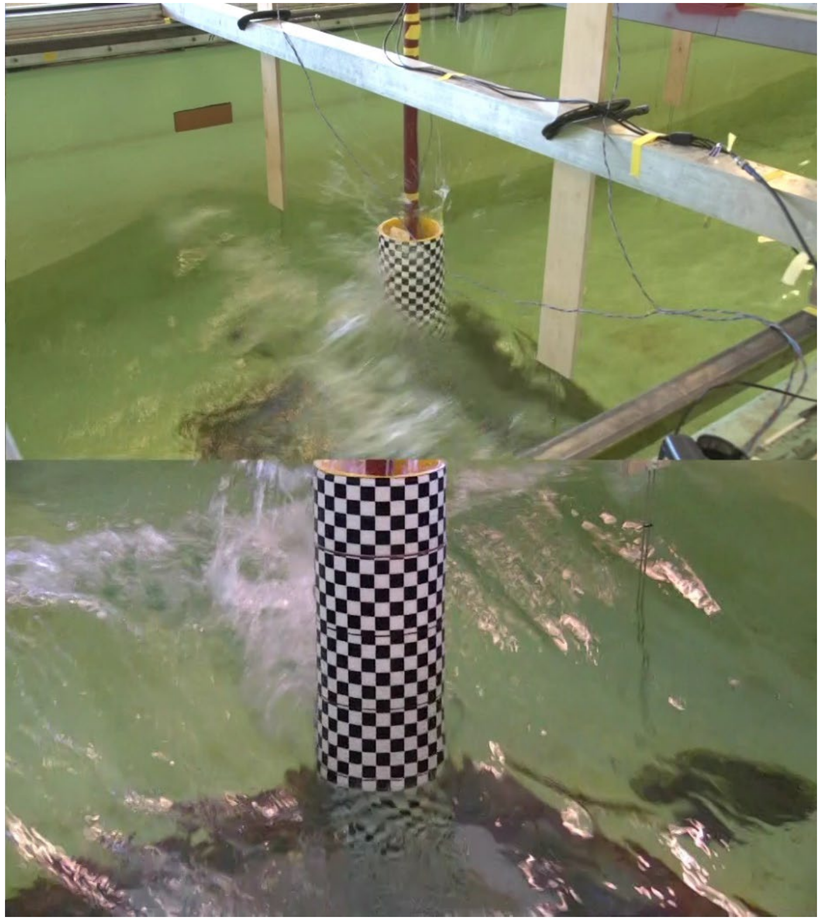

With correction

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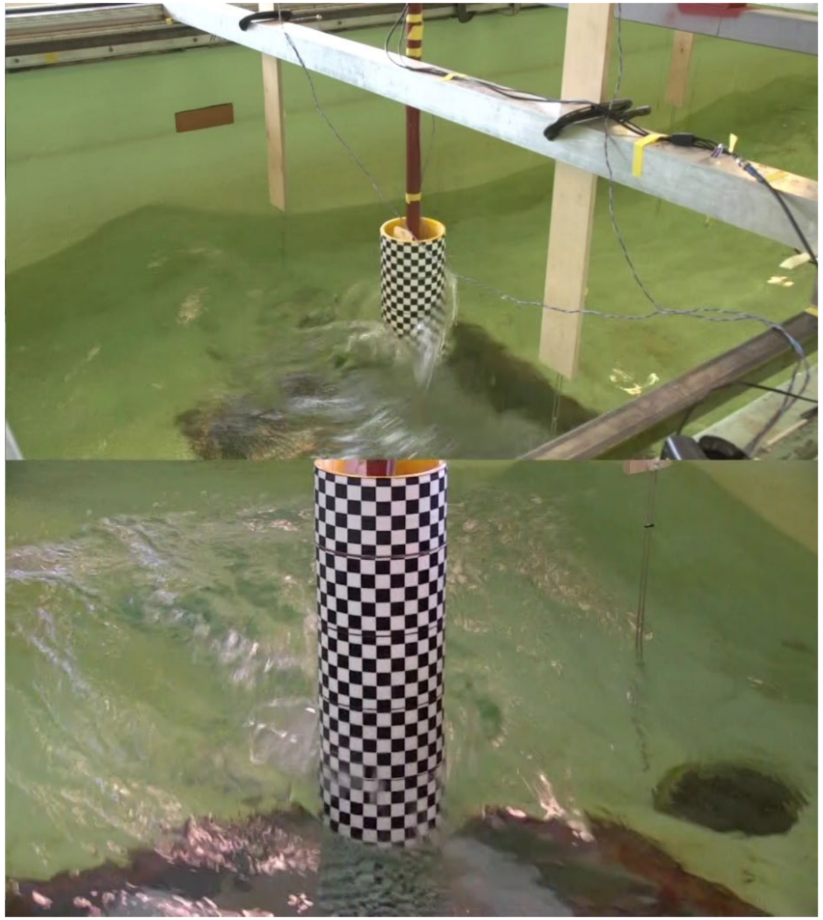
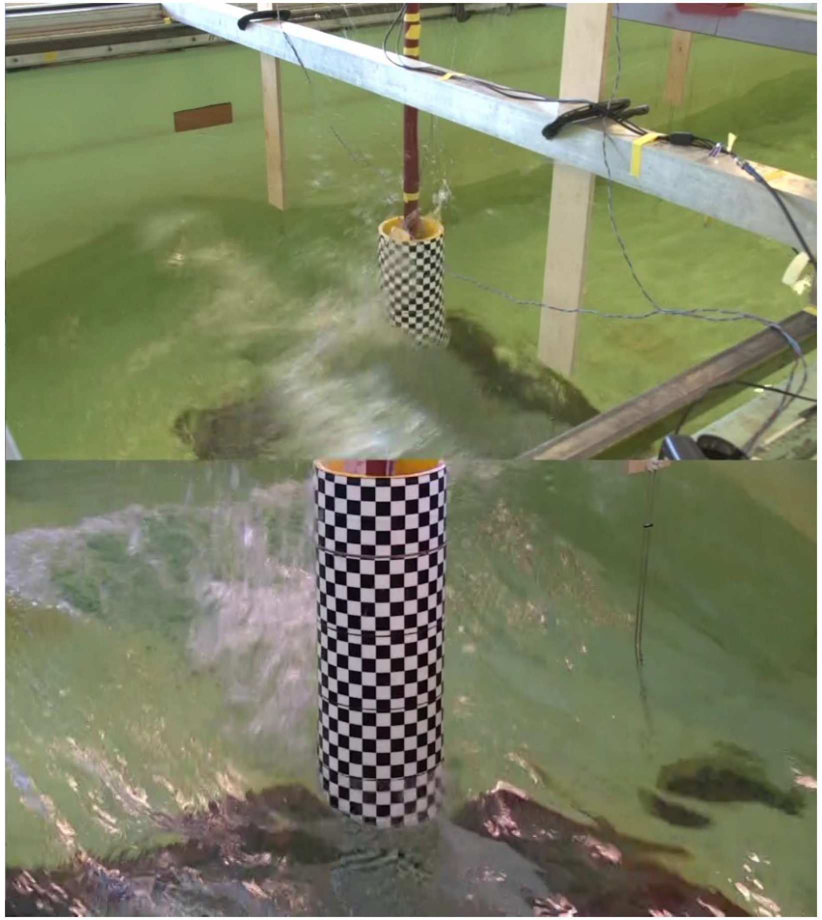


Without correction



With correction

Conclusions

- Second order wavemaker theory (developed by Schäffer) for piston-type wavemaker motion in irregular waves
- Experimental observation of reduction in the second order spurious wave component for Gaussian spectra
- Experimental study of the effect of the presence/absence of this spurious wave on the response of a monopile
- Statistically, minor effect on response measurements
- However, affects individual breaking wave events and slamming loads

Thank you!

This work is part of the Wave Loads and Soil Support for Extra Large Monopiles (WAS-XL) project, funded by NFR grant 26818 and industry partners