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Comparison of laboratory wave generation techniques on response of a large monopile in irregular sea

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Abstract. As the offshore wind industry moves toward larger monopile turbines, model testing and validation of hydrodynamic load models become more important for new designs of turbines. Wave generation is an important aspect of hydrodynamic model testing. When generating irregular waves with a piston-type wavemaker, first order wavemaker theory is commonly used. This leads to generating spurious free waves in the tank. Using second order wavemaker theory reduces the generation of these spurious waves. In this study, the two wave generation techniques have been used in the measurement of the dynamic responses of a monopile with (full-scale) natural period of 5 sec. The effect of superharmonic spurious waves on the response statistics was minor. A marginal improvement in experimental repeatability of the second mode response in large wave events was observed by using second order wavemaker theory.

1. Introduction

Motivated by the increased interest in renewable energy, the industry is pushing towards larger offshore wind turbines. Large diameter monopile foundations are considered for intermediate water depths due to the levelized cost of energy. The eigenfrequency of the monopile supporting the larger turbines is tending to get closer to twice the wave peak frequency in severe sea states. To ensure a safe design, validated hydrodynamic load models for prediction of the responses of larger monopiles to nonlinear wave loads, e.g. ringing [1] and slamming [2] in ULS design analysis is needed. Model testing, as an important tool for accurately estimating the loads and the responses, has been carried out for the new designs of such monopile structures in projects such as WAS-XL [3], WiFi [2], WaveLoads [4].

Understanding the sources of uncertainties in model testing is important when validating numerical models. For example, the wave generation technique might introduce uncertainities. A common practice is to use first order wavemaker theory which is simple and well established. Schäffer [5] presented a second order wavemaker theory for irregular waves, for piston and hinged-type wavemakers. In the basin, spurious waves are generated by mismatch of the velocity profile on the wavemaker when using linear wavemaker theory. A second order correction of the wavemaker signal, would help to prevent the generation of free spurious waves.

For regular waves, the second order spurious waves correction has already been caried out in many experiments, e.g. Kristiansen & Faltinsen[6]. For focused waves, Sriram et al. [7] experimentally generated the waves using linear and second order wavemaker theory with a piston-type wavemaker.

For irregular waves, Pierella et al. [8] numerically reconstructed superharmonic spurious waves using a phase separation technique to study the effect of the spurious waves on wave force maxima on a rigid monopile.
Subharmonic spurious waves has been studied by Stansberg & Kristiansen [9] and Fonseca et al.[10] for low-frequency horizontal motions of moored floating structures.
The authors [11] previously studied the effect of superharmonic spurious waves on the response of a monopile with natural frequency of three times the wave frequency. The spurious waves changed the wave breaking process and can significantly affect the individual events, however, statistically they had minor effects compared to stochastic variations in the irregular sea states.
The present work is a continuation of the previous experimental study. Here, a monopile with natural period of 5 sec is tested to investigate whether correcting the wavemaker up to second order affects the statistical results when a natural frequency of monopile is close to twice the peak wave frequency in ULS conditions. Moreover, previous results showed that the effect and importance of the correction varied among realizations. Here, the number of realizations is increased to 40 to better evaluate the effect of correction. A repeatability study, with and without correction, was also performed.
We first present the experimental comparison and verification of the two wave generation techniques for a JONSWAP spectrum. Then, response measurements of a fully flexible monopile model in the same sea states will be discussed.

2. Model test setup

Experiments were conducted in a medium size tank ("Lilletanken") at NTNU with Froude scale 1:50. The main dimensions of the tank are shown in Figure 1. A piston-type wavemaker is located at one end of the tank and there is an adjustable parabolic beach on the other end, as shown in Figure 1. The beach reflection is expected to be between 6 to 8% based on[12]. A new wavemaker actuator-board was installed in 2020, which improved the ability of the wave maker to follow high-frequency command signals. Two wave generation techniques with first and second order wavemaker theory based on Schäffer's work were used. Two irregular sea-states were tested with the two techniques, as summarized in Table 1. The results presented in this paper are from the steepest sea state with significant wave height $H_s = 8.6$ m, and peak period $T_p = 11$ s.

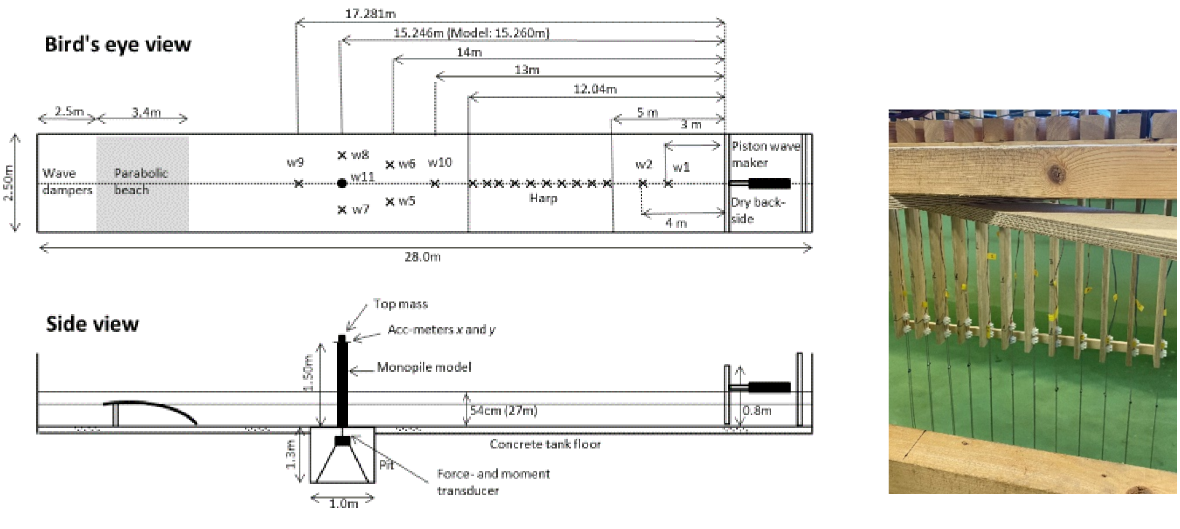


Figure 1. Top view of the tank, indicating the location of the wave probes in the wave only test. The side view of the tank shows the location of the model (same as W11 in the wave test). The right photo shows the harp with 11 wave probes used for measurements over a length of 7 meter (model scale).

To separate the bound wave from the spurious wave and compare the two wave generation techniques in the wave only tests, the wave elevations were measured over a length of 7 m with a step of 0.08 m (model scale) in the similar way as our previous test [11].

In the next step, model tests were performed with the monopile wind turbine. The tower and the monopile are representative of a 10 MW monopile wind turbine. Except for the increased top mass to achieve the desired natural period, the details of the model structure were identical to previous tests[3]. Based on wet decay tests, the first and second natural frequencies of the model are 0.2 and 1.57Hz, and the first and second modes have critical damping ratios of 2% and 0.4%, respectively.

Table 1. Irregular sea states with JONSWAP spectrum. The steepness is defined as $s = H_s/\lambda$, where λ is the wavelength related to the peak period. The two values of steepness for each sea state are calculated using both the linear and nonlinear dispersion relations. Two seeds (two 3-hour wave realizations) of the steepest sea states were repeated 8 times in the wave only tests and 12 times in the tests with the model.

H_s (m)	T_p (s)	γ(peakedness parameter)	steepness	No. of realizations	repetitions
8.6	11	4.2	0.057-0.059	40	8-12
9	12.5	2.6	0.050-0.052	10	

3. Verification of the implementation of the second order correction

The generated spurious free wave, and the second order bound wave, with the same frequency propagate with different speeds in the tank. This is due to the fact that the two wave systems follow different dispersion relations (Figure 2). This could be used as the basis for distinguishing the two wave systems using 2D Fourier transform of the recorded wave elevation in space and time. The longer measurements with smaller steps, in space and time, increase the accuracy of the analysis. However, in the lab test, practical limitation of the number and spacing between the wave gauges limits the achievable resolution.

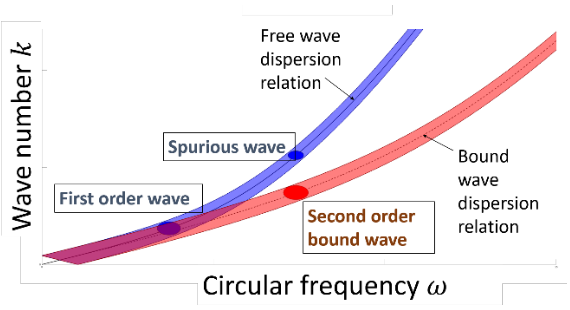


Figure 2. Dispersion relation for bound and free waves is plotted schematically.

Figure 3(a) shows the results of a 2D Fourier analysis for a JONSWAP spectrum with $T_p = 11$ s, $H_s =$ 8.6 m (model scale peak frequency of 4.039 rad/sec) generated by first order wavemaker theory (without correction). The two lines show the dispersion relations for the second order spurious and bound waves. The largest energy content is around the peak frequency, and it spreads along the two dispersion curves. However, distinguishing between the first order bound waves and the second order spurious wave is not straightforward. Since these follow the same dispersion relation and the wave spectrum is relatively wide, there is energy overlap in the vicinity of the frequency of second harmonic wave. To illustrate the performance of the implemented correction, we have subtracted the Fourier coefficient of the two tests, i.e., with first and second order wavemaker (or equivalently without and with second order correction). The result is shown in Figure 3(b).

The corresponding energy reduction in spurious wave within the frequency range of 6 to 12 rad/sec (model scale value) is about 30% of the spurious wave energy in the test without correction. However, since the spectrum is not narrow banded, the first order wave and second order free wave overlap, and the percentage of the energy reduction might contain some error.

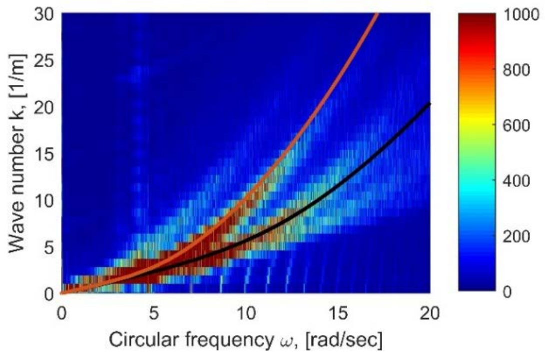
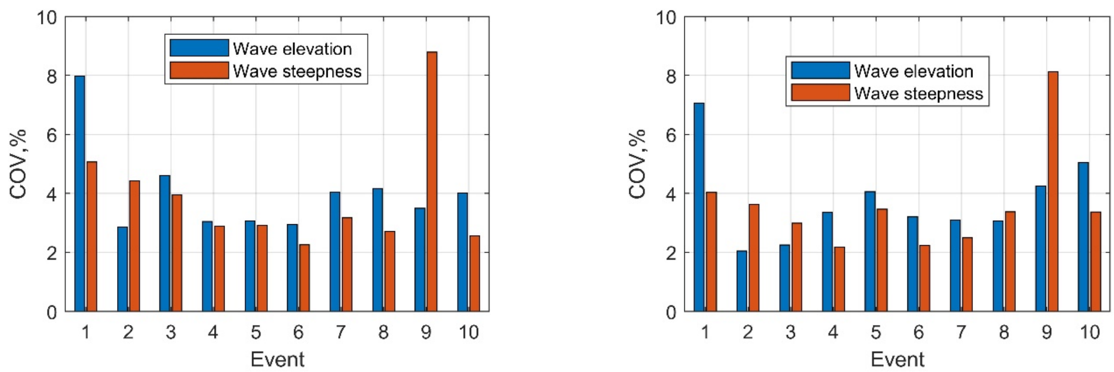


Figure 3. (a) 2D Fourier transform of wave signal from test without correction for a JONSWAP spectrum with $T_p = 11$ s, $H_s = 8.6$ m (full scale values). (b) Difference in 2D FFT amplitude from the test without and with correction corresponding to the reduction in spurious wave energy/amplitude. Results are shown at model scale (1:50). Lines are the dispersion relation for bound (black) and free waves (red). Warm colors represent higher amplitudes on a linear scale.

4. Repeatability in wave measurement

In order to make a better comparison between the tests with the two wave generation techniques, two of the 3-hour realizations of the steepest sea state were repeated 8 times with and without correction (without the model present).

The coefficient of variation (COV, standard deviation divided by mean) of the wave elevation and the local wave steepness has been calculated for 10 events. Here, the local steepness is calculated based on the crest front amplitude and period (crest front height divided by wavelength, where the wavelength is calculated based on linear dispersion for intermediate water depth and the observed crest front half period). The 10 events are chosen based on the largest bending moment maxima in the monopile response measurement test. As Figure 4 shows, the coefficient of variation in largest event wave is about 8% and 7% in the test without and with correction, respectively. The mean of the coefficient of variation of the wave among the 10 events are 4% and 3.7% in the test without and with correction. Similar behaviour is observed for the wave steepness in the largest events. The largest COV of steepness is for event number 9 and it is about 8.8% and 8.1% for the test without and with correction, respectively. A slight decrease in the average COV for these events (from 3.88% to 3.59%) is seen when correcting the wavemaker motion.



a) Without correction b) With correction

Figure 4. Coefficient of variation (COV) for the 10 largest bending moment maxima in 8 repetitions of one realization, (a) test without correction (b) test with correction.

5. Repeatability in response measurement

The same two 3-hour realizations were repeated 12 times with the monopile with and without correction. Figure 5 shows all the repetitions of the measured bending moment response in largest extreme event. The measured bending moment response is filtered into contributions near the structural first and second natural frequencies similar to Suja-Thauvin et al. [2]. For isolating the dynamic response near the first natural frequency, a bandpass filter with frequency range of 0.14 to 0.26 Hz is used. For brevity, the resulting bandpassed signal is referred to as first (F1) mode response. The frequency band of 0.785 to 2 Hz is used for the second natural frequency, which is referred to as second (F2) mode response. The higher frequencies have been removed from the response signal by lowpass filter with cut-off frequency 2Hz. The remaining part of the response is referred to as a quasi-static (QS) response. In Figure 5, the total bending moment responses as well as first and second mode responses together with the corresponding wave are shown for the test without and with correction. This is a large slamming event, and the second mode is excited in all repetitions for both tests without and with correction. However, as Figure 5 (d) shows, the wave elevation in the test with correction has a better repeatability (consistent with Figure 4). This better repeatability in the wave elevation and steepness results in a better repeatability in second mode response. Although the amplitude of the second mode response varies from one repetition to another, in the test with correction this high frequency response is more in-phase for different repetitions. Dadmarzi et. al[11] show that the spurious wave in the tank affects the breaking/slamming events. The repeatability test here suggests that removing spurious wave might increase the repeatability of the experiment in the slamming events.

a) b)

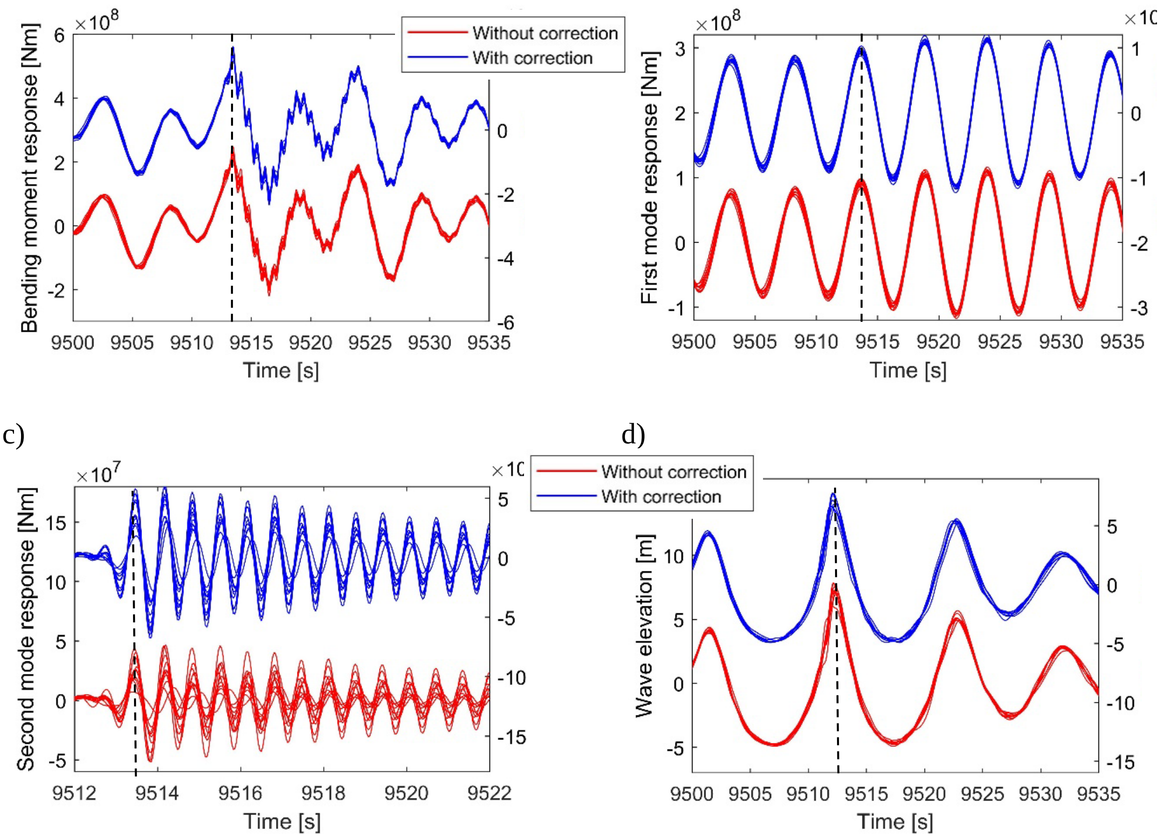
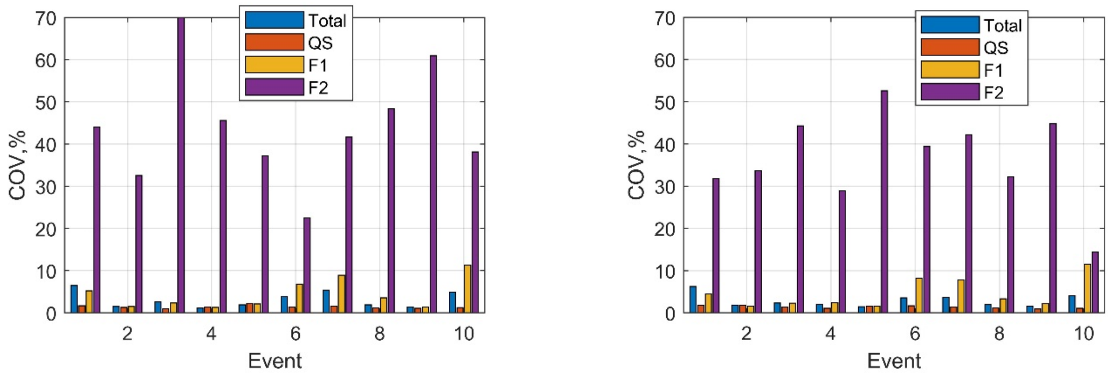


Figure 5. 12 repetitions of bending moment response (a), and its components i.e. first mode (b) and second mode (b) response as well as the wave elevation (d), for the test without and with correction. The results of the test with correction are plotted against the right y-axis. Red and blue lines are for the tests without and with the 2nd-order wavemaker correction, respectively. The time of the maximum response is indicated by dashed line.

Figure 6 shows the COV for the contributions from each response component, at the exact time of maximum total response, for the 10 largest events in one 3-hour realization. For both tests without and with correction, the quasi-static responses have COV of less than 2%. The COV for the total bending moment and for the contribution near the first natural frequency is less than approximately 11% (as in our previous tests[11]). For the responses near the second natural frequency, the COV reaches 73% for the test without correction, which again is similar to our previous test campaign[11]. The maximum COV is less than 52% for the test with correction. The mean COV for the second mode response at the 10 events is about 44% and 36% for the test without and with correction, respectively. The reason for the apparently improved repeatability, especially in the response near the second natural frequency, in the test with correction compared to the test without correction needs more investigation. As mentioned in [11], the higher order interaction between the spurious waves and the bound waves, or reflections from tank walls and beach, may influence the repeatability. Further work is needed to better understand the importance of these issues.

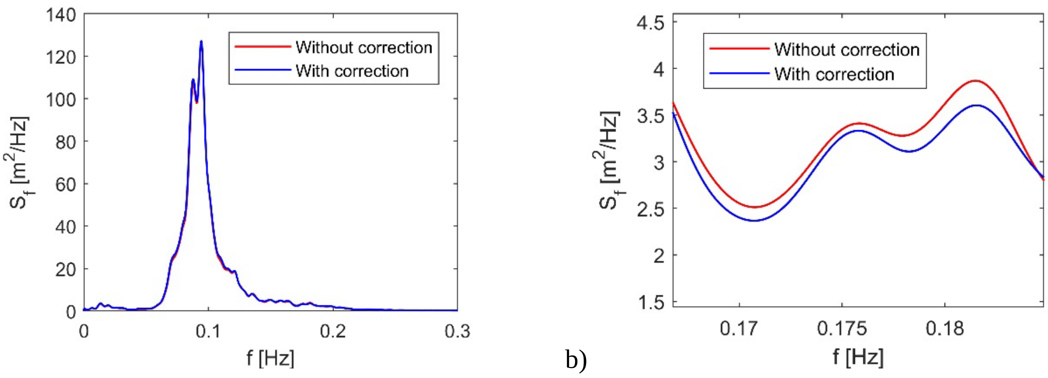


a) Without correction b) With correction

Figure 6. Coefficient of variation (COV) for the 10 largest bending moment maxima in 12 repetitions of one realization, (a) the test without correction (b) test with correction.

6. Wave measurements

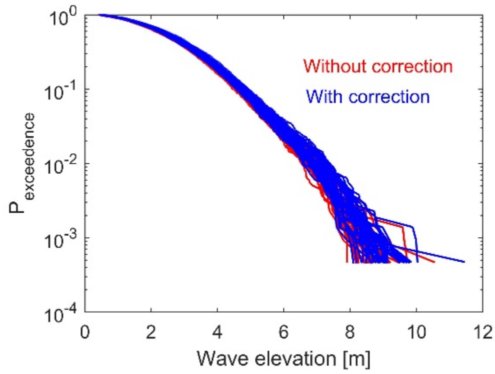
Figure 7 shows the wave elevation spectrum for a realization of the sea state ($H_s = 8.6$ m and $T_p = 11$ s), and for the tests without and with correction. Similar to our previous study[11], the difference in wave elevation spectrum for the tests without and with correction is small and varies among the 40 realizations.



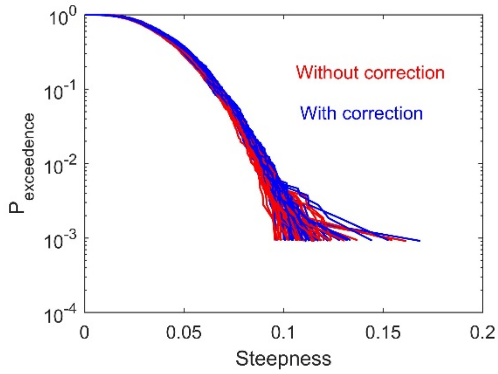
a) b)

Figure 7. a) Wave elevation spectrum for one 3-hour realization (b) Zoomed view of main spectra around twice the wave peak frequency.

The empirical probability of exceedance for the wave elevation is compared in Figure 8(a) for the tests with and without correction. All 40 3-hour realizations of the steepest sea state ($H_s = 8.6$ m and $T_p = 11$ s) are considered. The observed differences between the tests with and without correction are smaller than the spread in the extreme values in different realizations of each test. The exceedance probability of local steepness (based on the crest front amplitude and period) for 40 3-hour realizations of the same sea state for the tests with and without correction is shown in Figure 8(b). Similar to the wave elevation, the differences observed in the test without and with correction are small. However, the exceedance probability suggests having slightly steeper waves in the main body of the tests ($P_{exceedance} > 0.01$) with correction. The differences between the extreme values from the tests without and with correction are within the boundaries of differences between realizations.



a)

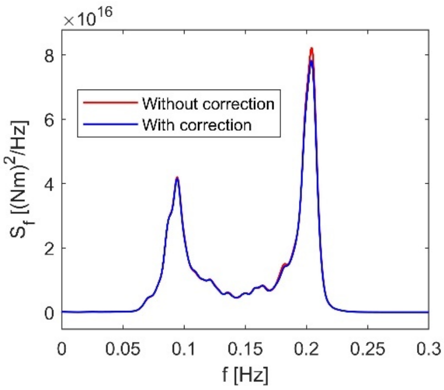


b)

Figure 8. Exceedance probability of the wave elevation (a) and local wave steepness (b), for 40 3-hour realizations of a sea state ($H_s = 8.6$ m and $T_p = 11$ s). Red and blue lines are for the tests without and with the 2nd-order wavemaker correction, respectively.

7. Bending moment response

The power spectra of bending moment response is shown Figure 9(a,b) for one realization of the same sea state ($H_s = 8.6$ m and $T_p = 11$ s) for the tests with and without correction. Note that 'response' refers to the mudline bending moment measured for the flexible model. The peak frequency of the wave (0.09 Hz) corresponds to the largest peak in the spectra. The second and third peaks in the spectra are at the first (0.2 Hz) and second (1.56 Hz) natural frequencies of the structure. Again, the differences in the peak frequencies in spectra are small between the tests with and without correction and vary from one realization to another.

a)


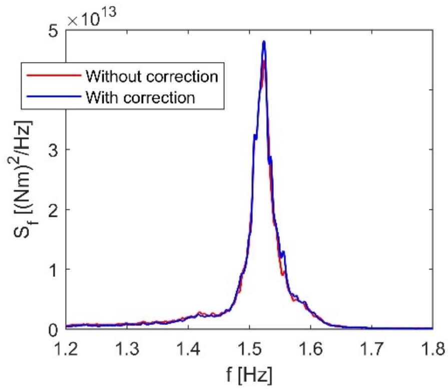
b)


Figure 9. (a) Power spectra of one 3-hour realization of the mudline bending moment response (b) Zoomed view at the second natural frequency.

Figure 10 shows the probability of exceedance for the total measured response and filtered first mode and second mode responses. For the main body of the tests, $P_{exceedance} > 0.01$, the measured responses are very similar in both tests (without and with correction). The largest events in the tests with correction are slightly larger than the tests without correction, but the deviations for larger responses between tests without and with correction are within the observed spread among the realizations of each test. Compared to previous tests, a larger number of realizations of a sea state (40 realizations) was tested to better evaluate the effect of correction. However, like our previous observation[11], the present results also indicate that correcting the wavemaker motion up to second order does not greatly affect the statistical results.

a) b) c)

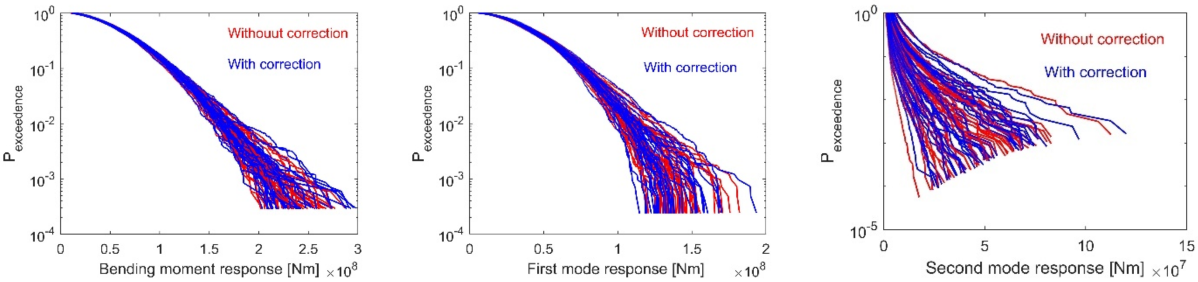


Figure 10. Exceedance probability of the total bending moment response(a) as well as first (b) and second (c) mode response for 40 3-hour realizations of a sea state.

Figure 11 shows the exceedance probability of the total measured response as well as first mode and second mode responses, for one realization of the same sea state ($H_s = 8.6$ m and $T_p = 11$ s), repeated 12 times. As Figure 11 shows, the total moment as well as the first and second mode responses in the test with correction have larger extremes in this realization, especially in the first mode response, with good repeatability. The similar repeatable behaviour was also seen in another realization with 12 repetitions. This would suggest that the minor change in the statistical results by second order correction of the wavemaker is due to the sample variability among the different realizations rather than the uncertainty of the experiments.

a) b) c)

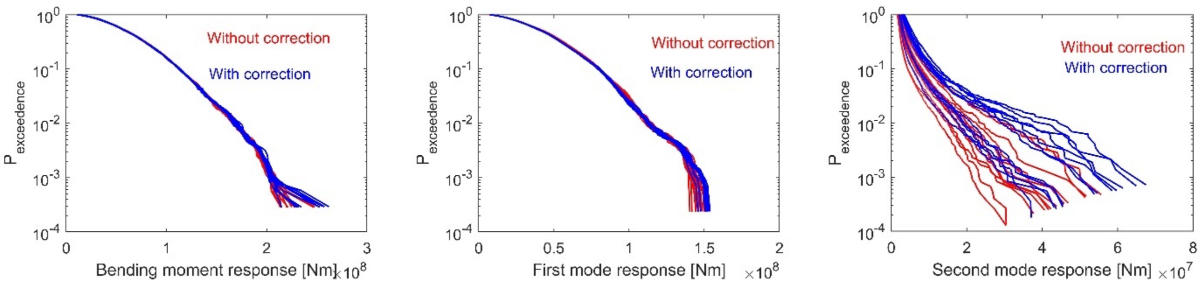


Figure 11. Exceedance probability of the total bending moment response(a) as well as first (b) and second (c) mode response for one 3-hour realizations of a sea state, repeated 12 times.

The effect of spurious waves varies from one 3-hour realization to another one. The Gumbel distribution for the maximum bending moment based on 40 3-hour realizations in Figure 12 shows that extreme responses are slightly larger when second order wavemaker theory is employed. The 90th percentile mudline bending moment are 262 MNm and 267 MNm in the tests without and with second order correction, respectively. However, this 2% increase in the 90th percentile mudline bending moment is considered within the uncertainty of the experiment.

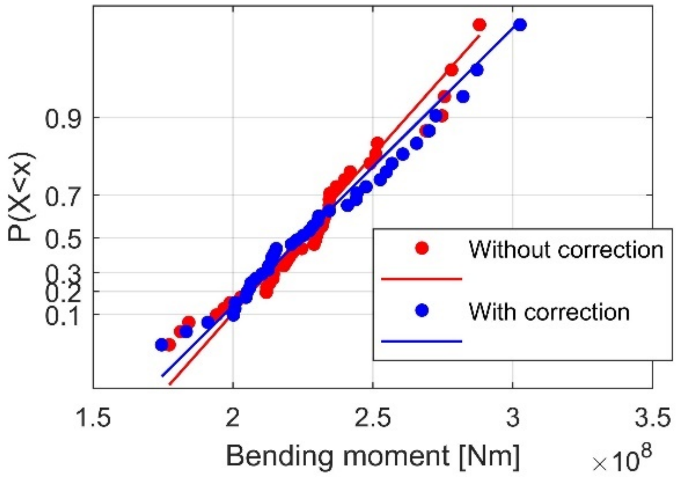


Figure 12. Gumbel distribution of maximum bending moment of 40 realizations of a sea state with $H_s = 8.6$ m, $T_p = 11$ s. Red and blue lines are for the tests without and with correction, respectively.

8. Conclusions

Model testing for measuring responses of a large monopile was performed with two wave generation techniques, i.e. first and second order wavemaker theory. Second order wavemaker theory for a piston-type wavemaker motion in irregular waves was implemented based on Schäffer [5]. Experimental measurement of wave elevation showed the reduction in the second order spurious wave component for a JONSWAP wave spectrum by adopting the second order correction. This experimental study was a continuation of a previously published similar experimental work[11], considering a longer structural natural period and greater number of realizations. Here we can summarize the observations from the present test together with the conclusions from our previous study:

- To better represent real sea states and for comparison with numerical codes, spurious waves should preferably be removed in model tests.
- A small improvement in repeatability in the wave elevation and steepness was observed by removing the spurious waves.
- Some improvement in the repeatability in the second order response was observed by the second order correction.
- The removal spurious waves does not introduce any statically significant change in the monopile responses.

Acknowledgments

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