WAVE INTERACTION EFFECTS FOR NON-COMPLIANT TLP

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ABSTRACT

The paper investigates the problem of estimating the deck clearance for a TLP under extreme wave conditions. Numerical predictions obtained with a second order diffraction program is compared to experimental results from model tests in an offshore basin. The main focus is put on evaluating higher order wave effects and related topics. The variability and quality of laboratory waves is considered to be particularily relevant, and is discussed in some detail. Wave surface effects are approached at different levels of complexity in order to highlight the more fundamental aspects of non linear wave diffraction:

- For plane, progressive waves in the absence of the structure, the linear and second order potential solutions are compared to corresponding results obtained from experiments.
- Wave diffraction effects in periodic waves is investigated for a range of frequencies at designated locations within the confines of the TLP. The relevance of non linear corrections of order higher than two is discussed at some length.
- Extreme value predictions for wave height/deck clearance are obtained from stochastic analysis performed on extensive experimental wave records.

INTRODUCTION

To maintain positive air gap under extreme storm conditions is generally regarded to be among the most important design requirements for multicolumn structures. However, raising the deck is an expensive measure that affects the entire design; unnecessary conservatism with respect to the deck level therefore carries a considerable penalty.

Unfortunately, the state of affairs with respect to air gap predictions leaves a lot to be desired. For one thing there is a significant uncertainty (perhaps the most important one) with respect to the tail end distribution of large (freak) waves in the open ocean. In addition, the traditional methodology of employing linear diffraction theory to characterize the wave field around a given structure is certainly inadequate, being based on the assumption of small (infinitesimal) wave heights and linearized boundary conditions.

A logical extension of linear calculations is to include higher order terms in the perturbation expansion of the fluid potential. Presumably this will lead to more accurate predictions and improved confidence in air gap estimates. Historically, due to the growing complexity of the boundary conditions for the higher order potentials, it has rarely been attempted to employ the perturbation scheme for orders higher than two. Also, initial efforts by other authors to incorporate the second order correction in practical air gap calculations have largely proved futile (see e.g. Manuel, Sweetman & Winterstein, 2001), one possible reason being that the zero motion/non zero velocity boundary condition may introduce non trivial local errors.

In the present paper computed wave field estimates obtained from a second order diffraction code is compared with results from wave basin experiments. The local surface elevation is investigated for a multitude of predefined field points in the vicinity of a mini TLP, the particulars of which are defined in Table 1. As pointed out above, one important source of inconsistency between experiments and theory, associated with the "linearized" motions, might be eliminated by keeping the structure under consideration rigidly fixed. This will narrow down the focus to the relative importance of the non linear free surface boundary condition, and should thus improve the prospects of obtaining good correlation between theory and experiments. The

trade off is a possible loss of practical relevance, since, for a TLP, at least horizontal excursions are significant. However, at this stage it is more important to establish a basic understanding of which phenomena are the most critical in order to predict the extreme surface elevation close to marine structures.

TABLE 1: Main particulars of the rigid TLP.

Draught (m)	28.5
Column diameter (m)	8.75
Column spacing (m)	28.5
Pontoon height (m)	6.25
Pontoon width (m)	6.25
Water depth (m)	668.0

EXPERIMENTAL SET UP

The experiments were carried out at scale of 1:40 in an offshore basin with surface area 45.7×30.5 m^2, and with a 16.7 m deep pit, over which the measurements were made (the TLP was positioned over the center of the pit). The distance from the center of the pit to the wave maker is around 20 m. Outside the pit the depth of the basin is 5.8 m. For the present choice of wave periods, the finite depth correction is minimal, and has negligible influence on the results. The wave surface was measured at a total of 14 locations, all clustered around the TLP. Three of the wave probes were attached directly to the TLP, to measure wave run up on the columns. The exact locations of the different wave probes are are all identified in Table 2.

Prior to the main sequence of tests, a series of wave calibration tests were performed in the absence of the structure. These "wave alone" tests will be discussed in the next section. Tests with the TLP was conducted for two different wave headings, and for both regular, bichromatic and irregular unidirectional waves. The present paper highlights a subset consisting of the 0 deg heading tests (wave crest parallell to the front legs of the TLP), in regular and irregular waves.

NATURAL VARIABILITY OF PLANE, PERIODIC LABORATORY WAVES

The quality, regularity and repeatability of laboratory waves clearly is of decisive importance for the general confidence in experimental results. Figs. 1 to 3 show different examples of the evolution of laboratory waves for three different wave gauges positioned about a quarter of a wave length apart in the direction of wave propagation. Around 80 wave cycles have elapsed from the wave front arrives at the three wave probes untill the end of the wave record is reached. It is quite obvious from these three figures that great care has to be taken in selecting a suitable wave interval for subsequent analysis. After the arrival of the wave train there is a slight initial overshoot in the wave amplitude before it stabilizes. For the first few cycles after this "transient" has subsided, all the wave gauges yield similar results.

FIGURE 1: Time series of 8s laboratory wave, with amplitude approx. 10m. Initial cycles.

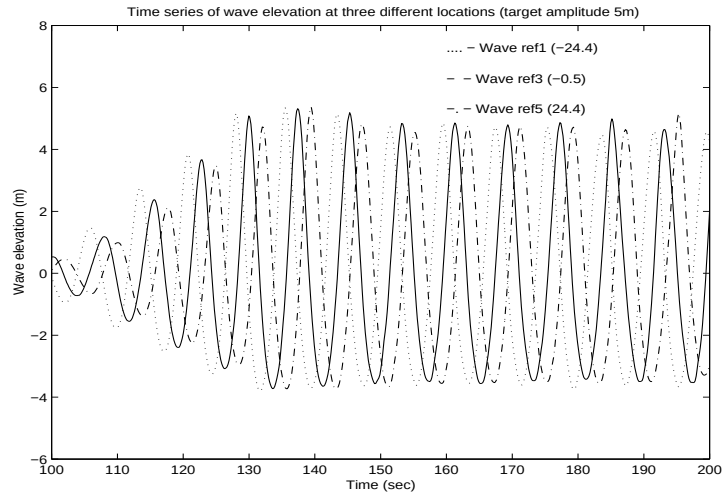
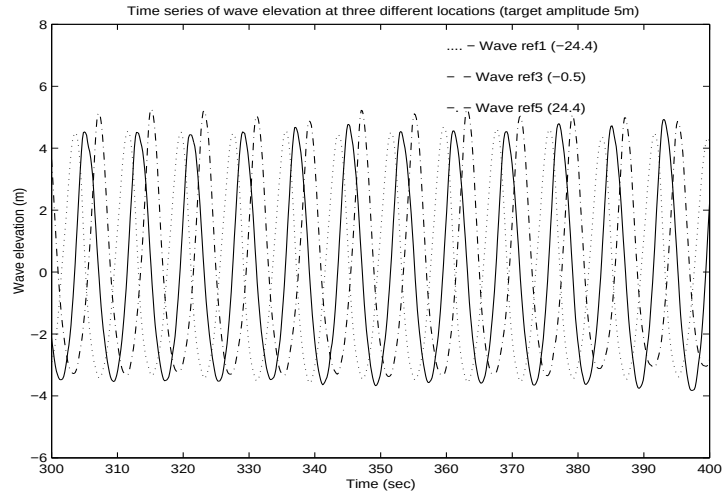


FIGURE 2: Time series of 8s laboratory wave, with amplitude approx. 10m. From 25 cycles onwards.



The first two figures are unaffected by reflections, while in the third one there could be some "contamination" by reflections from the beach. There is a consistent trend towards increased variability between the different wave gauges as time passes, and also a noticable tendency for modulations to occur. Part of the explanation could be the development of spurious higher harmonics which are not phase locked in the Stokes wave sense. In any case, the "natural" variability of laboratory wave, obviously also influence the degree of correlation that can be attained between a given theory and experiments.

COMPARISON OF NUMERICAL SOLUTIONS VS. EXPERIMENTAL RESULTS FOR MONOCHROMATIC WAVES

An impression of how well labory waves conform with Stokes wave theory for periodic waves can be obtained by consid-

FIGURE 3: Time series of 8s laboratory wave, with amplitude approx. 10m. From 50 cycles onwards.

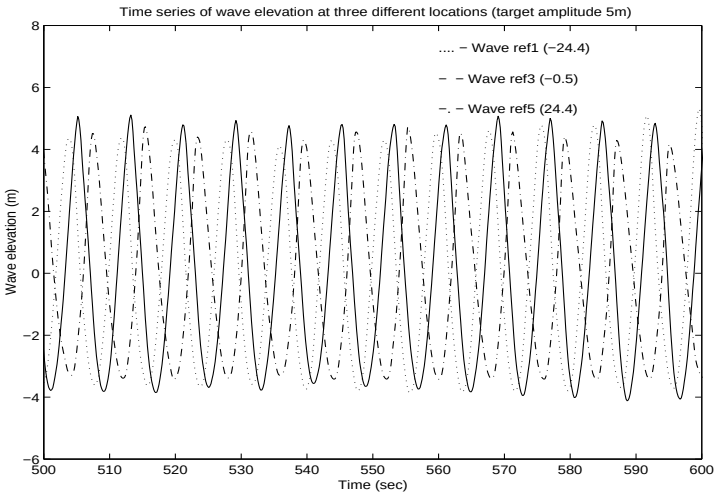
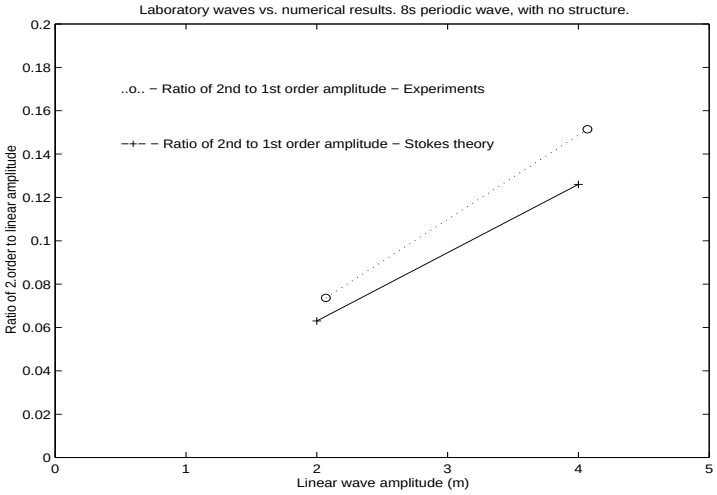


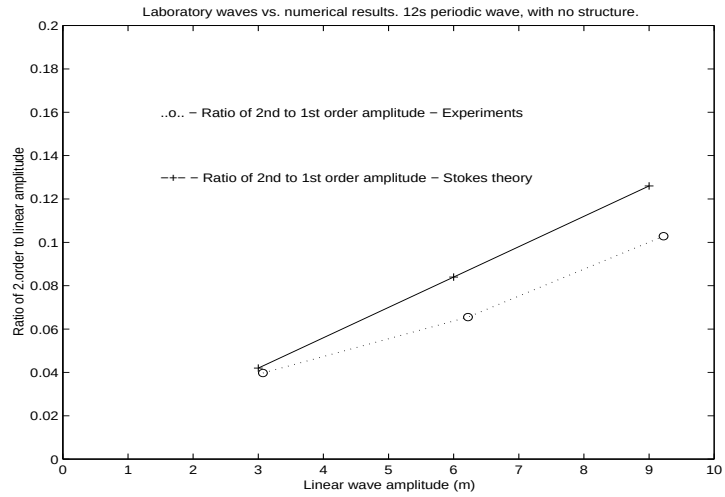
FIGURE 4: Ratio of second to first order wave amplitude. Comparison between experimental results and Stokes theory. Wave period 8 sec.



ering Figs. 4 to 6. Here the ratio of second order to linear wave amplitude is compared for three different wave periods. According to Stokes wave theory this ratio is a linear function of wave amplitude. Generally, and in broad terms, there is a reasonable agreement between the Stokes second order predictions and the experimental results. However, there is one apparent anomally: For the 16 second, 12 metre wave the upward "Stokes trend" is broken and the ratio of second to first order wave amplitude levels off.

Now, by considering different time intervals of the experimental time record, as noted above, a significant spreading can be observed. The experimental data presented in Figs. 4-6 are all based on a 3-cycle analysis of a part of the wave record that follows soon after the initial transient has subsided. Note that the levelling off of the second order amplitude is thought to be a fact of nature, being consistent with what can be observed by performing a fully nonlinear

FIGURE 5: Ratio of second to first order wave amplitude. Comparison between experimental results and Stokes theory. Wave period 12 sec.



numerical wave tank analysis.

WAVE DIFFRACTION EFFECTS FOR RIGID TLP

A much more challenging test case than plane, undisturbed waves, is wave surface effects in the vicinity of a structure. In particular for the shorter wave periods where diffraction effects are most prominent, the wave elevation is significantly influenced by the presence of the TLP. Also the relative importance of the higher order corrections in general, and second order effects in particular, seem to increase due to wave diffraction and wave interaction.

The linear and second order transfer functions for the wave elevation were obtained by a second order diffraction code, Wamit (Newman & Sclavounos, 1988, Lee & Newman, 1992). The mesh model for the TLP is presented in Fig. 7, and consists of around 3600 panels. A corresponding number of panels were used for the free surface mesh. The numerical data were carefully checked for convergence over a range of wave periods from 5 to 30 seconds, and, within the context of the present investigation, the given results can be considered to be fully converged.

Again long crested, periodic waves is a fundamental test case for checking the validity and relevance of the second order theory. As in the previous section monochromatic wave results are presented in Figs. 8-16, for three different wave periods, 8, 12 and 16 seconds, and for three different field points, one upstream of the TLP, one between the front legs and one at the TLP center. The precise coordinates of the field points are listed in Table 2.

There is no apparent "trend" to be observed in Figs. 8-16. The numerical data is sometimes above, and some times below the experimental results. Furthermore, with respect to second order effects, an impression of disappointingly poor correspondence between experiments and numerical predictions may easily be conveyed. However, one should bear in mind the extant temporal and spacial varibility of the laboratory waves as illustrated by Figs. 1-3, and further

FIGURE 6: Ratio of second to first order wave amplitude. Comparison between experimental results and Stokes theory. Wave period 16 sec.

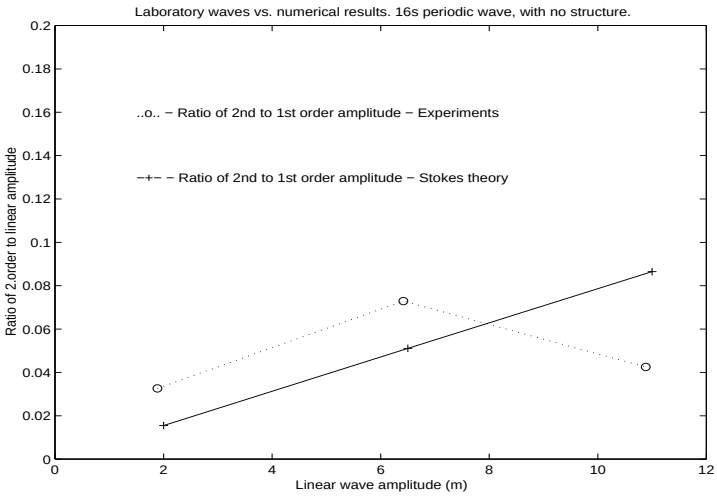
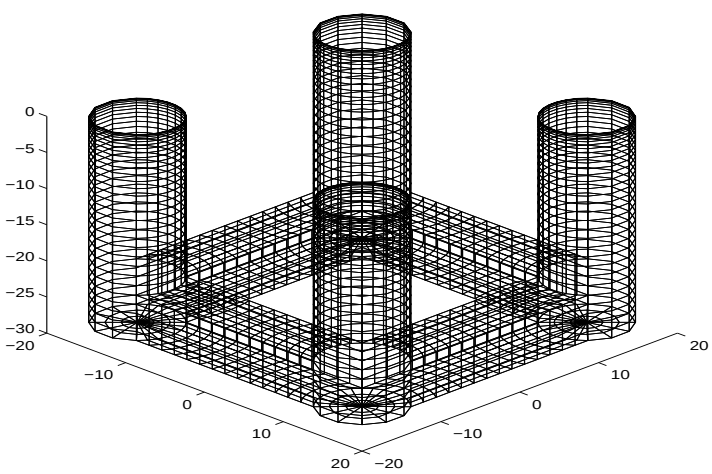


FIGURE 7: Mesh model of deep water TLP.



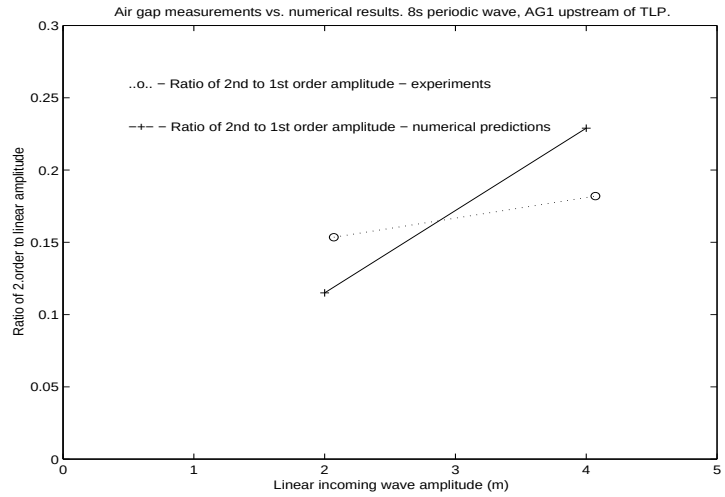
emphasized by Figs. 17 and 18. Obviously, there are no ultimately "true" results to check the predictions against, and the obtained results have to be assessed and interpreted in a broader and more approximate sense. Also, one should recognize that the observed variability in the experiments is a common characteristic of model testing, and not the results of poorly conducted experiments.

For the given TLP, linear diffraction effects are modest for the two longest wave periods (12 and 16 seconds), and accounts for around 5% or less of the total wave elevation at the three different field points. For the shortest wave period the situation is somewhat different, and the linear diffracted wave contribute up to about 25% of the the total wave amplitude[1], which is quite significant.

It should also be noted that the second order diffraction effects are much more conspicuous for the 8 sec. wave than

[1] At the TLP center location.

FIGURE 8: Comparison of linear and second order diffraction effects at field point 1. Wave period 8.0 sec.



for the longer wave periods. According to the numerical predictions, the second order diffracted wave is of comparable magnitude with the linear diffracted wave both between the front column and at the TLP center, for the steepest 8 sec. wave. Incidentally, the maximum wave steepness is 0.08 both for the 8 sec. and 12 sec. wave, and a little lower (0.055) for the 16 sec. wave. All of this is well below the classical breaking limit of 0.14.

The experimental results for the 8 sec. wave are more modest than the numerical ones with respect to second order content, the ratio of second order to linear wave amplitude being around 0.2 to 0.4. However, this is still an extremely important contribution to the maximum wave elevation, and a timely caveat that nonlinear effects should not be ignored.

In the case of the two longest wave periods, second order diffraction effects account for around 5% to 10% of the total wave amplitude. This is sufficient to cause some concern in connection with design, in particular since this is an important regime, energywise, in a storm situation. Also, observe that diffraction effects at an 8 sec. wave period for the mini TLP correspond to a 12 sec.wave for a geometrically similar, larger TLP with column diameter around 20 m. Such dimensions are much more typical for structures encountered in harsh environments. Hence, second order effects will presumably be an all important issue in relation to air gap considerations for floating, multicolumn structures in harsh environments.

FIGURE 9: Comparison of linear and second order diffraction effects at field point 1. Wave period 12.0 sec.

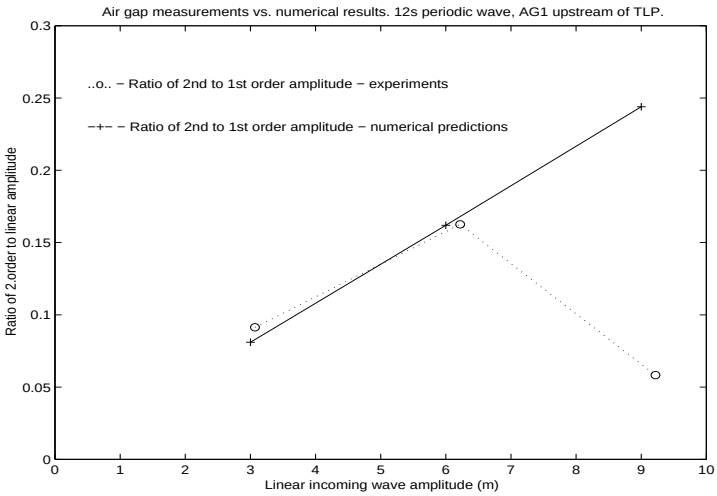


FIGURE 10: Comparison of linear and second order diffraction effects at field point 1. Wave period 16.0 sec.

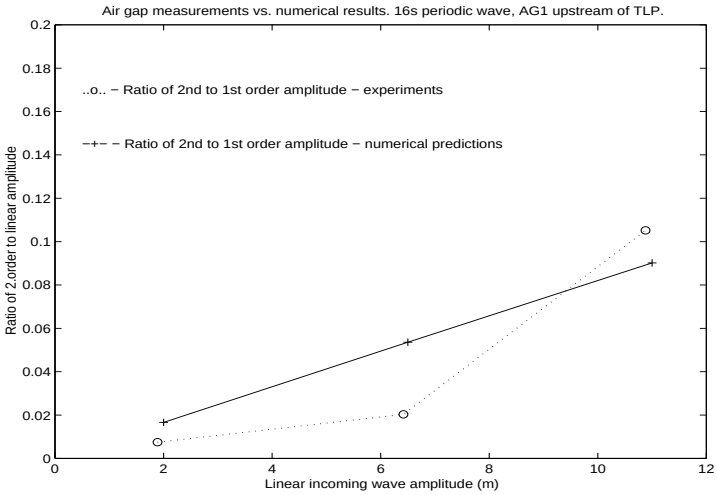


FIGURE 11: Comparison of linear and second order diffraction effects at field point 2. Wave period 8.0 sec.

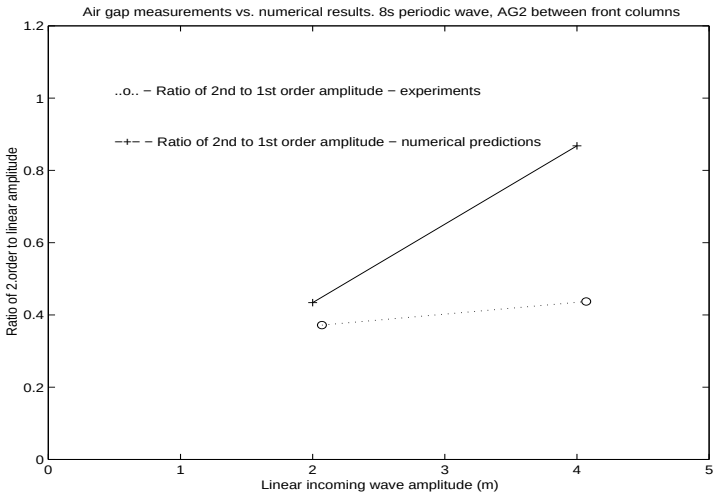


FIGURE 12: Comparison of linear and second order diffraction effects at field point 2. Wave period 12.0 sec.

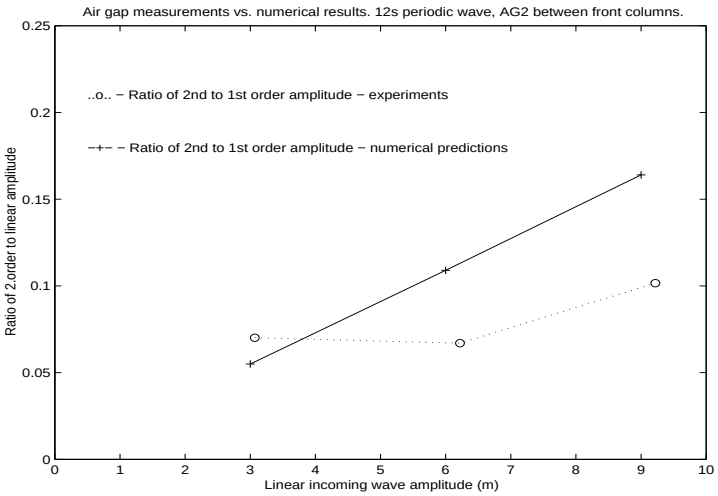


FIGURE 13: Comparison of linear and second order diffraction effects at field point 2. Wave period 16.0 sec.

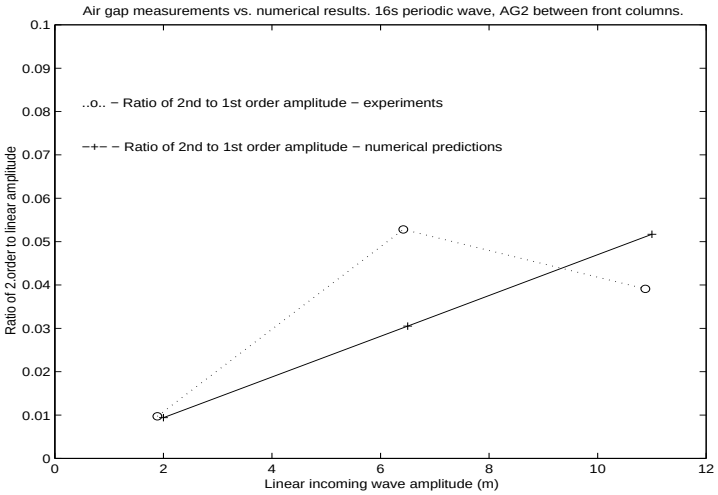


FIGURE 14: Comparison of linear and second order diffraction effects at field point 3. Wave period 8.0 sec.

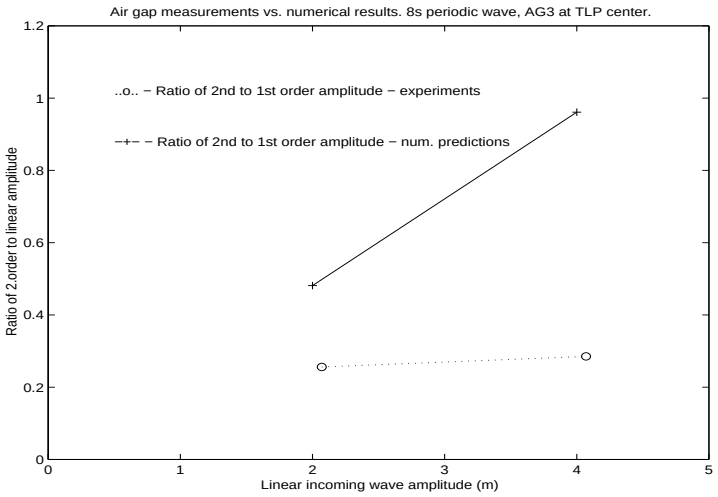


FIGURE 15: Comparison of linear and second order diffraction effects at field point 3. Wave period 12.0 sec.

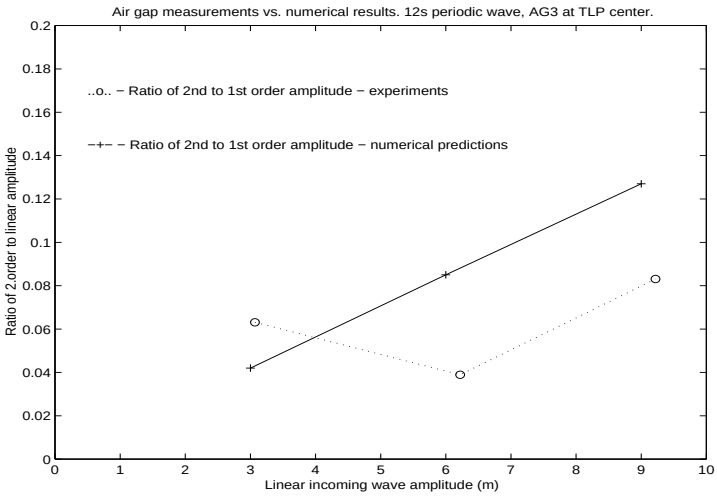
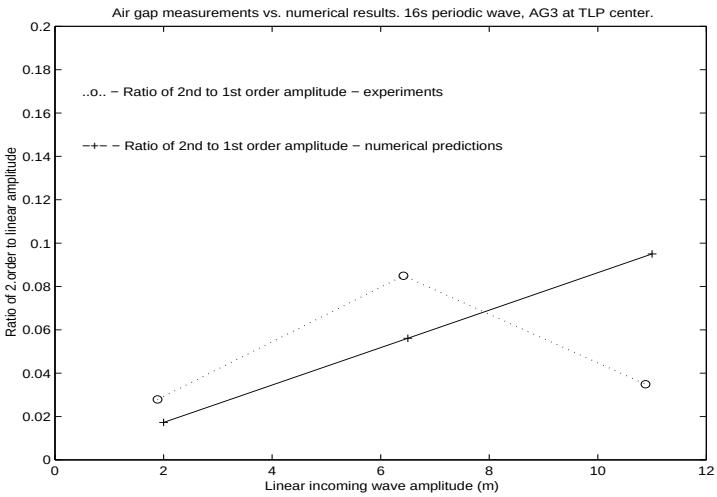


FIGURE 16: Comparison of linear and second order diffraction effects at field point 3. Wave period 16.0 sec.



NON LINEAR EFFECTS OF ORDER HIGHER THAN TWO

Non linear effects of order higher than two are difficult to quantify by the perturbation approach. Some scattered efforts have been made to extend the diffraction solution to 3rd order (Malenica & Molin, 1995, see also Malencia, Eatock Taylor & Huang, 1999), but only for monochromatic waves. However, just to get a feel for the relative importance of the 3rd and higher order terms in relation to wave surface effects, it is relatively easy to perform a Fourier analysis on the periodic time records from the experiments. An example of the outcome of such an analysis is shown in Table 3. There the amplitude ratio of the higher harmonics to the first harmonic is given for the wave elevation at the platform center.

What can be inferred from Table 3? For one, the 3rd and 4th order contributions are rather unimportant for the 16 sec. wave period, but so were the second order term,

TABLE 2: Location of air gap probes (A1 - AG4).

Global, full scale coordinates. Origin at platform center.

Verbal description	Name	x,y - coord. (m)
Upstream of TLP	AG1	(-31.7,0.0)
Between front columns	AG2	(-14.25, 0.0)
Platform center	AG3	(0.0,0.0)
Between aft columns	AG4	(14.25, 0.0)

TABLE 3: Amplitude ratio of first harmonic to higher harmonics at platform center (AG3).

Wave period 8.0 sec.				
Inc. wave ampl. (m)	1st harmonic (m)	Amplitude ratios		
		2nd/1st	3rd/1st	4th/1st
2.07	2.26	0.256	0.053	0.061
4.07	6.33	0.285	0.140	0.159
Wave period 12.0 sec.				
Inc. wave ampl. (m)	1st harmonic (m)	Amplitude ratios		
		2nd/1st	3rd/1st	4th/1st
3.07	3.36	0.063	0.021	0.036
6.22	6.57	0.039	0.069	0.019
9.22	9.06	0.083	0.108	0.014
Wave period 16.0 sec.				
Inc. wave ampl. (m)	1st harmonic (m)	Amplitude ratios		
		2nd/1st	3rd/1st	4th/1st
1.89	1.96	0.028	0.002	0.011
6.42	6.49	0.085	0.006	0.026
10.88	10.73	0.035	0.024	0.028

for this particular period. For the 12 sec. period, the 4th order term remains insignificant, while the 3rd order contribution is comparable to the second order one. Finally, for the 8 sec. wave period, the sum of the 3rd and 4th order amplitude is of similar size as the second order amplitude, at least for the steepest wave considered. Obviously, the most important conclusion to be drawn from this is that the 3rd and 4th order contributions cannot be discarded as insignificant, compared to the 2nd order contribution. Without the 3rd and 4th order terms, something important would be missing, although the main portion of the surface wave amplitude effect would still be captured by the first and second order diffraction terms.

Another important observation to be made is that although the 3rd and 4th order non linear contributions do not seem to be obey a cubic and biquadratic relationship to the first harmonic in the perturbation sense, at least in some cases, and more so for the 3rd than for the 4th order terms, there is a steep increase as a function of wave amplitude.

Yet another angle of approach in order to assess the importance of nonlinear terms, is to compare the sum of the

FIGURE 17: Wave elevation at TLP center. Comparison between time history from experiments and Fourier series representation. Wave period 8.0 sec. Amplitude of incoming wave 4m

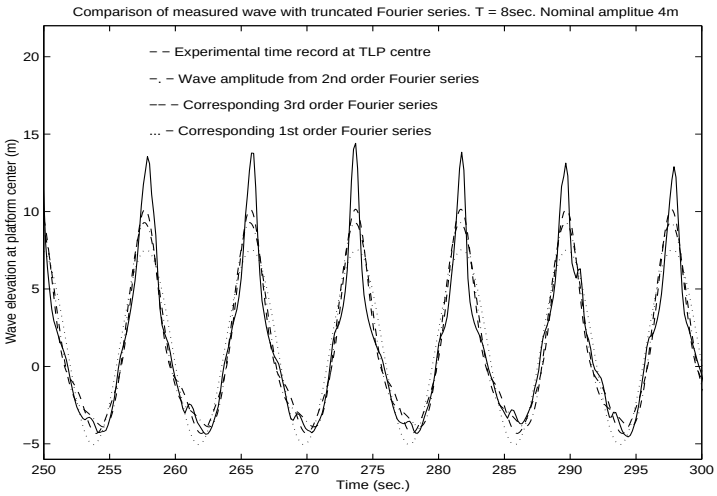
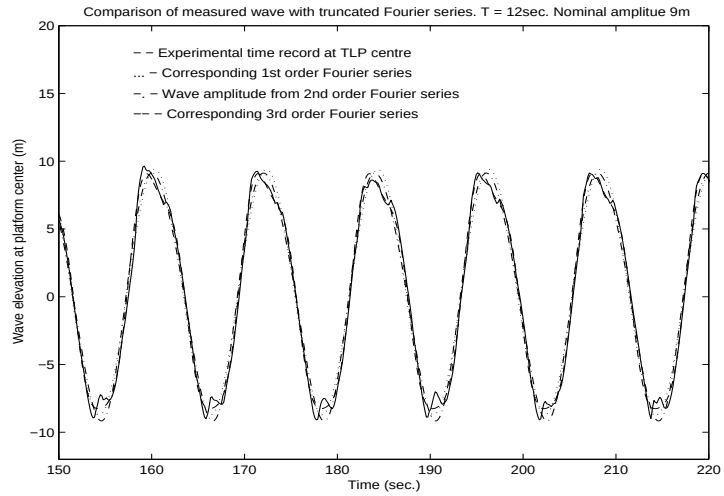


FIGURE 18: Wave elevation at TLP center. Comparison between time history from experiments and Fourier series representation. Wave period 12.0 sec. Amplitude of incoming wave 9m.



first harmonics to the actual recorded wave elevation for the given location, i.e. with $f(t)$ denoting the wave amplitude, one may compare $f(t)$ to

$$f_n(t) = a_0 + \sum_{i=1}^{n} a_i(t)\cos(i\omega t) + b_i(t)\sin(i\omega t) \qquad (1)$$

for n = 1,...4, and where a_i, b_i denote the Fourier coefficients. This option to visualize nonlinear effects is employed in Figs. 17 and 18 for the steepest 8 and 12 second waves.

The steepest 8 second wave is extremely asymmetric, with a peak that is nearly three times as high as the trough. Observe that in this case there is also a significant positive, mean component in the surface elevation. The mean plus the first harmonic only accounts for a meager 50% of the peak value. Including the second and 3rd harmonic, while yielding a fairly good fit for most values, still closes only half of the remaining gap. There is apparently a lot of higher order content in the given time history, and the prospectives of predicting this highly skewed behaviour with a second or third order theory are admittedly rather bleak. Inclusion of the 4th order terms will, incidentally, not alter this conclusion.

The situation for the 12 second wave is quite different, and perhaps more encouraging. Also in this case there is a substantial nonlinear content. However, this does not appear to influence the wave height, and the third order approximation actually gives a remarkably good fit. In fact, even the first order solution yields a reasonable representation of the recorded wave elevation, at least as far as the peak is concerned. All in all there is surprizingly little to be gained by including higher order terms for this particular wave period.

AIR GAP PREDICTIONS IN RANDOM SEAS

From the perspective of air gap predictions, the most relevant test of the capabilities of a given mathematical model, is to evaluate its performance for a random sea condition.

During the tests the present TLP structure was exposed to two different kinds of random environments, one mild, with an H_s of 4.0 m, the other one relatively harsh, with an H_s of 13.1 m. For the four given air gap probes (cf. Table 2), the main cumulants obtained from these experiments are presented in Table 4, along with corresponding results from 1st and 2nd order numerical simulations.

TABLE 4: Low order cumulants for measured wave elevation in random seas.

Benign environment				
Location	H_s (m)	T_p (s)	μ (m)	σ(m)
AG1	4.0	16.0	0.03	1.10
AG2	4.0	16.0	-0.02	1.09
AG3	4.0	16.0	-0.01	1.10
AG4	4.0	16.0	-0.05	1.05
Harsh environment				
Location	H_s	T_p	μ (m)	σ(m)
AG1	13.1	14.0	.38	3.71
AG2	13.1	14.0	.59	3.81
AG3	13.1	14.0	.26	3.56
AG4	13.1	14.0	.15	3.49

Apparently, there is not much variation in the wave surface standard deviation between the different locations, except possibly for the air gap probe between the hind legs (AG4), where the readings are consistently lower. The effect of diffraction, as such, on the main statistics is also moderate, the increase in the standard deviation being around

5-6% for the benign wave condition, and up to about 10% for the harsh environment one. Note that in the latter case there is also an increase in the mean water level at the location of the air gap probes. The modest influence from diffraction could suggest that the extreme wave elevation might effectively be predicted by a Gaussian approach. This will be discussed in the sequel.

In the context of deck clearance, or deck impact, the extreme value distribution is a far more critical issue than the magnitude of the low order cumulants. Following Teigen & Naess (2000), under the assumption that large maxima are independently distributed, and letting $\hat{\eta}(T) = \max(\eta(x,t); 0 \leq t \leq T)$ denote the extreme wave elevation at some particular loacation x, during the time period T, the extreme value distribution $F_{\hat{\eta}(x,T)}(z)$ of the wave elevation can be calculated by the formula

$$F_{\hat{\eta}(T)}(z) = \exp\{-\nu_x^+(z)T\} \tag{2}$$

where $\nu_x^+(z)$ denotes the average z-level upcrossing rate of the response process $\eta(x,t)$.

Assume now that we want to determine the level z that has a probability α of being exceeded in the given time interval T . Under the above assumptions we then have the relationship:

$$\nu_x^+(z) = \frac{1}{T}\ln(\frac{1}{1-\alpha}) \tag{3}$$

As an example, let $T = 3$ hrs (10800 sec), we then have

$$\alpha = 0.5 \Rightarrow \nu_x^+(z) \approx 0.642 \cdot 10^{-4} \tag{4}$$

$$\alpha = 0.1 \Rightarrow \nu_x^+(z) \approx 0.0976 \cdot 10^{-4} \tag{5}$$

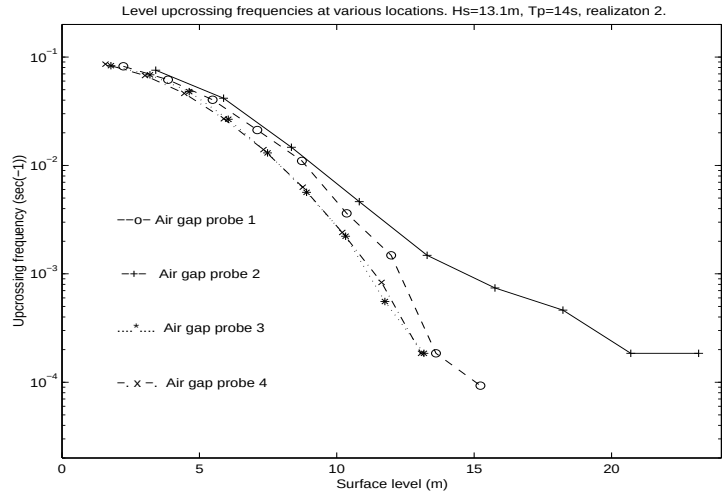
What is left in order to identify the level z with the exceedance probability α is to determine the function $\nu_x^+(z)$ and to invert it.

Fortunately, the average z-upcrossing frequencies for a given level z may, to a good approximation, be estimated from the experiments. The average level up-crossing frequencies from one 3 hr. realization of the harsh environment sea state (cf. Table 4) is plotted in Fig 19, wheras the accumulated information obtained from a total of 5 realizations of equal length is plotted in Fig. 20.

Clearly, in Figs. 19 and 20, the results for the air gap probe 2 deserve some explanatory comments. What is happening here is that the largest waves are impacting on the deck. The TLP deck level is located 15 m above the mean free surface, and this particular probe was attached to the front end of the deck. As soon as the diffracted waves rise above the 15 m threshold, there is a tendency for upwelling, or run up, to occur. Hence, in this case the function $\nu_x^+(z)$ will start to level off at the tail end.

For the harsh weather wave environment, extreme values at air gap probe locations 1, 3 and 4 have been roughly estimated from Fig. 20. In Table 5 the resulting extremes are compared with corresponding Gaussian estimates, computed from Ochi's formula (Ochi, 1973, for a brief discussion of this approach, see also Teigen & Naess, 1999). Note that the Gaussian results are obtained from the standard deviation and the mean level upcrossing frequency, which

FIGURE 19: Mean level upcrossing frequencies at the locations of the 4 air gap wave probes. Results from a single realization. $H_s = 13.1\text{m}$, $T_p = 14.0\text{s}$



are definitely more "robust" (experimental) quantities and require shorter time records to be evaluated.

TABLE 5: Estimates of extreme wave heights at different locations. $H_s = 13.1\text{m}$, $T_p = 14.0\text{s}$. **Duration 3 hrs.**

Probe identification	Level crossing appr.		Gaussian approach	
	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$
AG1	15.0	16.5	15.0	17.0
AG3	14.0	15.5	14.3	16.2
AG4	14.0	15.5	14.0	15.8

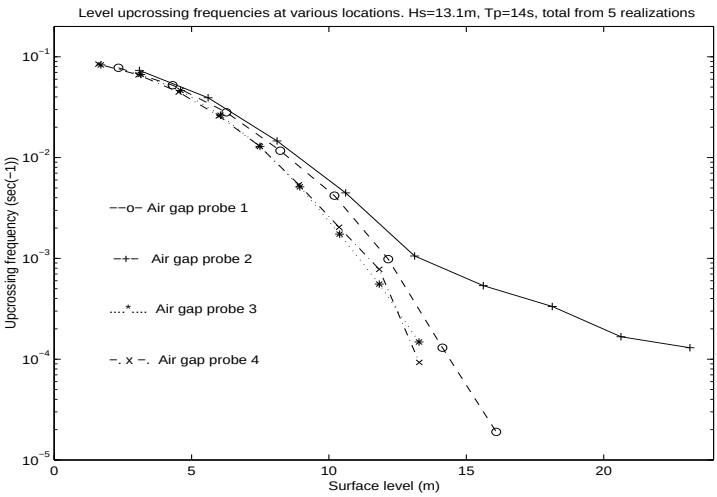
Anyhow, the results presented in Table 5 are strikingly consistent, with the Gaussian estimates slightly on the conservative side of those obtained by the level crossing method (equation 3). This observation agrees with what was conjectured above regarding the stochastic nature of the wave elevation at the location of the air gap probes.

CONCLUSIONS

Wave diffraction effects for a non-compliant mini TLP have been investigated both by experiments and by numerical methods. Considerable emphasis was put on exploring the general capabilities of the perturbation approach, and to establish how well it might conform with experimental results in a "realistic" wave regime, with finite wave heights. The performance of the second order approximation is also evaluated, and the errors introduced by neglecting higher order effects are discussed. Finally, two different methods are applied for predicting the extreme wave elevation within the confines of the TLP in a random sea situation. The most important conclusions from the paper are as follows:

- For regular, harmonic waves, in the absence of the structure, there is a rough correspondence between

FIGURE 20: Mean level upcrossing frequencies at the locations of the 4 air gap wave probes. Results from a total of 5 realization. $H_s = 13.1\text{m}$, $T_p = 14.0\text{s}$



second order Stokes theory and results obtained in the laboratory. One important source of uncertainty is the variability of laboratory waves.

- In the presence of the TLP structure, and for monochromatic waves, the second order perturbation approach seems slightly inadequate, and inconsistent with actual observations. Although 2nd order effects appear to be important they are generally, and some times significantly, overpredicted by the 2nd order theory.

- Higher order terms are probably more important for high frequency force contributions than for the wave height. However, the sum of the 3rd and 4th order amplitudes some times dominate the second order term. Observe that the experimental results do not in general indicate that any n'th order relationship exists between the amplitude of the n'th order terms and that of the linear wave.

- For the random wave conditions considered in the experiments two different methods have been applied to estimate the extreme wave elevation at designated locations around the TLP. The agreement is found to be rather satisfactory.

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