OTC 17487

Extreme Wave Amplification and Impact Loads on Offshore Structures

C.T. Stansberg, R. Baarholm, T. Kristiansen / MARINTEK; E.W.M. Hansen, G. Rortveit / Complex Flow Design A.S.

Abstract

The prediction of air-gap and deck impact on column-based platforms in steep and high waves is addressed. Numerical models based on linear and second-order diffraction-radiation analysis are validated against model test data, for various cases including fixed as well as floating structures. Significant higher-order effects are identified from systematic variations in the wave steepness. Wave-in-deck impact loads are modelled by a simple formulation similar to Kaplan's approach, but taking into account amplification effects from the large-volume hull. Predicted load time series compare quite well with model test data. Introductory CFD studies using a commercial Volume-of-Fluid type tool are presented, from which promising results are obtained, and challenges for future improvements are addressed.

Introduction

The calm-water air-gap under offshore platform decks is an important design factor, and is determined by the expected minimum air-gap in extreme design conditions. For column-based platforms such as semisubmersibles (Semi's), tension-leg platforms (TLP's) and gravity based structures (GBS's), the prediction of minimum air-gap in harsh environments, and of probabilities of deck impact events, is a challenging task. If linear theory could be assumed, the amplification of waves could be easily predicted by a standard numerical diffraction-radiation approach, or, for a circular fixed cylinder, by the classical analytical solution by McCamy & Fuchs /1/. However, experience shows that in steep waves there are significant nonlinear contributions /2,3,4,5/. This includes interaction effects as well as effects in the incident wave themselves. For design in extreme waves it may lead to a significant difference in height levels. In addition to the level prediction itself, nonlinear tools are also needed in the accurate prediction of resulting wave-in-deck loads in case of negative air-gap.

Most standard engineering tools of today are not capable of accurate or robust modelling of these contributions by theoretical approaches alone, and design load values are therefore most often based on model test experience. Still, second-order diffraction-radiation codes for prediction of the free-surface elevation have been developed within the last 10 – 20 years, see e.g. /3,6/. Experiences from use of such modelling and comparison to measurements show that it may represent a significant improvement relative to linear theory /3,7/. However, these and other works also show discrepancies which are not fully explained. Therefore there is a need for more testing and validation of such models. It can also be questioned whether or not higher-order or fully nonlinear models are needed for a satisfactory modelling, due to the strongly nonlinear effects observed. Such models are also in development, see e.g. /8,9/, although the use in engineering applications still seems to be in the future.

Various simplified wave-in-deck load models being used for jacket types of platforms have been reviewed in /10/. One such model was proposed by Kaplan /11/, based on the principle of conservation of fluid momentum. A two-dimensional fully nonlinear boundary element method was presented in /12/. None of the simple methods seem to take into account wave amplification due to a large-volume hull.

In the present paper, the prediction of air-gap and deck impact on various types of column-based structures in steep and high waves is addressed. First, some general characteristics of the physical problem are highlighted. The main part of this paper follows then, with a summary of a validation study of free-surface modeling by linear and second-order diffraction-radiation analysis, by comparing numerical and model test data. Some of these results (for a single column) are based partly on results previously presented in /7/. Furthermore, a brief description of a modified impact load model is given, based on a simple formulation similar to Kaplan's approach /11/ but taking into account the effects from columns. Introductory studies with fully nonlinear (Volume-of-Fluid) modeling using a commercially available tool are finally presented.

The described work has been carried out as a part of the WaveLand Joint Industry Project, Phase 2. The findings will subsequently be applied in the development of Guidelines for the analysis of air-gap and slamming problems.

Extreme waves and interaction with large-volume platforms

The problem investigated in this paper is schematically illustrated by Fig. 1. A large and steep wave is amplified by

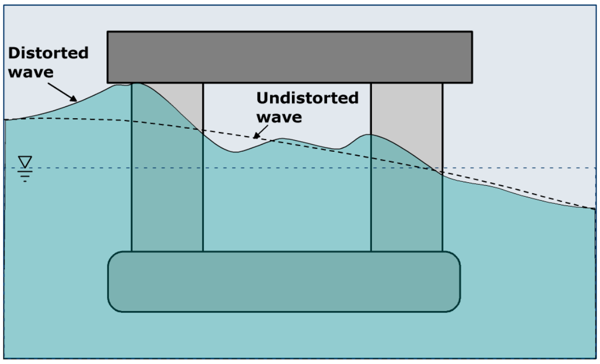


Fig. 1. Schematical illustration of problem.

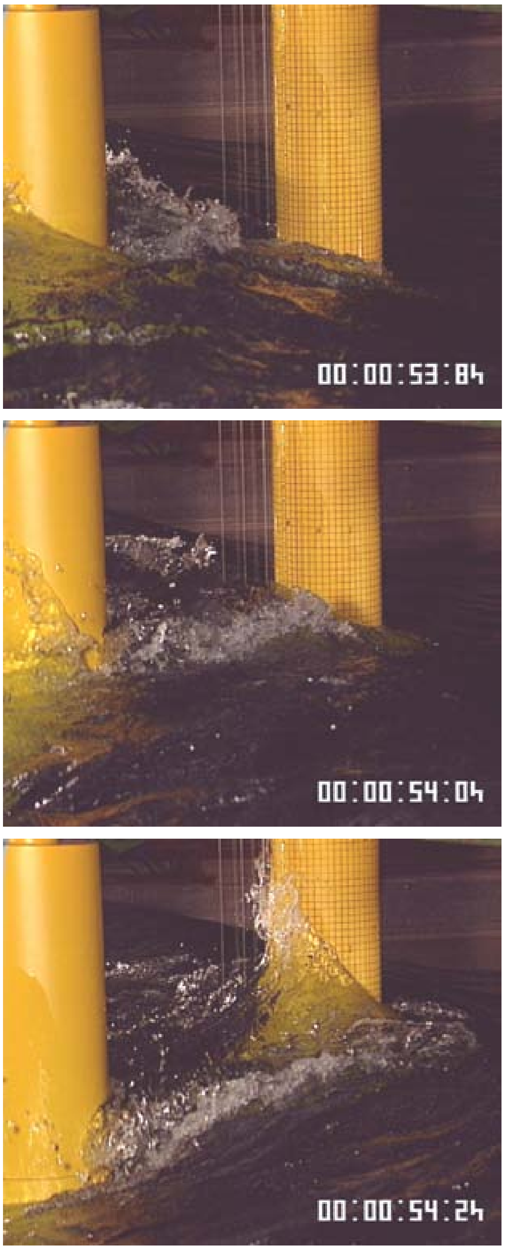


Fig. 2. From video of multi-column model test in steep waves.

the submerged part of the hull structure, and may hit the underside of the deck. This scenario includes various types of events, ranging from thin run-up jetting along columns, via local (but more "massive") wave amplification around alumns, to global deck impact resulting from a large wave which is amplified due to the platform. In this study, we shall primarily address the latter two "massive water" phenomena.

Standard modelling of the free-surface elevation may typically consist of linear diffraction/radiation theory, combined with empirical modifications based on model test experience to take into account nonlinear effects. For the illustration of the nonlinear nature of such problems, video snap-shots from a model test example showing the local amplification of a steep wave at an aft column is presented in Fig. 2.

For moored floaters, the relative wave motion is also influenced by the the vertical platform motions (heave, roll and pitch). This includes wave-frequency (WF) as well as low-frequency (LF) contributions. The WF vertical motions are often the largest, and are normally well predicted by linear models. LF contributions for roll and pitch may sometimes be important. LF heave is normally relatively small, expecially in long-periodic wave spectra where resonant motions are excited mainly by WF forces.

In cases with negative air-gap, the resulting wave-in-deck loads are calculated by a slamming model. This normally requires the estimation of an incident water velocity as well as a slamming coefficient, which is connected with a significant uncertainty. Thus, the combination with model test results is essential, which puts particular requirements on the quality of the load measurements. Development of new or improved impact models is in demand, for which model test data also play an important role in validation. An example on a severe wave-in-deck event from model tests with a GBS (fixed) platform /13/ is shown in Fig. 3. The upper plot shows the undisturbed and the amplified (relative) wave, the middle plot shows the total horizontal and vertical load on the deck and the lower one shows corresponding local deck slamming force measurements at the centre front location. (Notice that for the amplified wave record shown, the highest crest level measurements are disturbed by run-up along the topside wall).

Validity of linear and second-order wave amplification

A systematic investigation of the validity of linear and second-order numerical free-surface wave modeling, carried out on various column-based structure cases, is presented in the following. Results from numerical panel models established by use of WAMIT /14/ are compared to model test measurements carried out at MARINTEK. The actual case studies and their numerical modeling are first described, then selected results from the comparison are presented.

Case studies. Four different cases are included here:

a. A circular, fixed vertical column
b. Four circular, fixed vertical columns
c. Three-column GBS (fixed) with a caisson
d. Moored semisubmersible (floating)

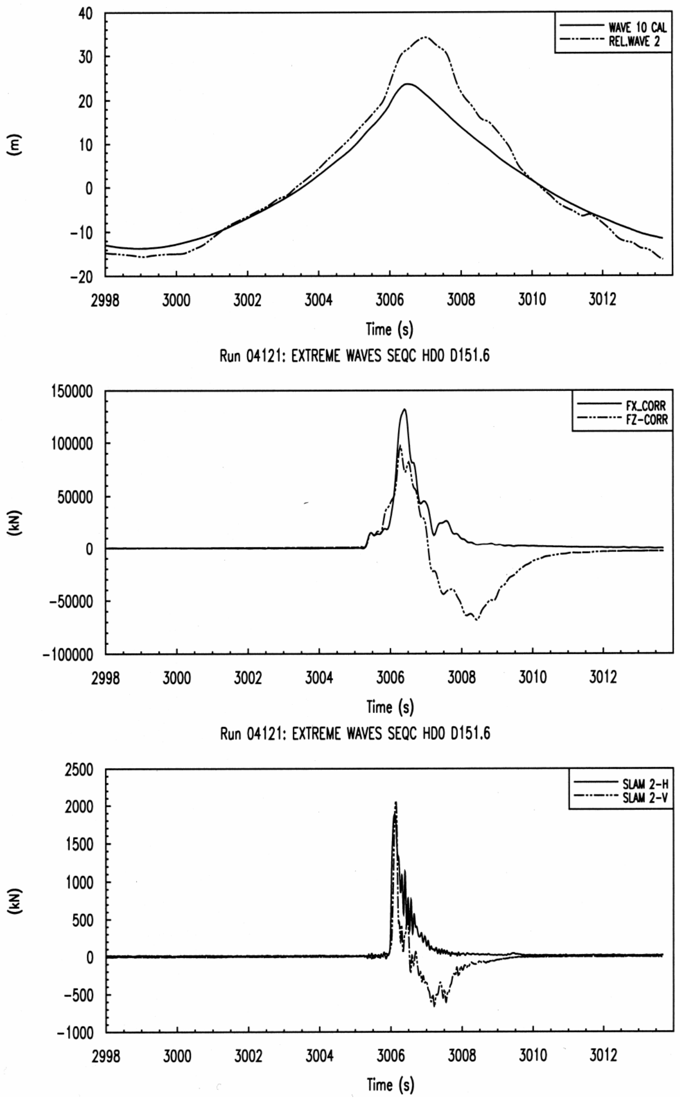


Fig. 3. Wave-in-deck records, GBS model test example (from /13/).

The horizontal geometries as seen from above are shown in Figs. 4a-d. (For the GBS, case "c", only the columns are indicated on the figure). The single column has a radius *a*=8.0m, a draft *d*=24m, and is located in 490m water depth. Model tests were run in scale 1:49. See also the descriptions in /4,5/. Among the large number of wave probes used in the measurements, we consider here four of them: two at a distance 1.5m from the column wall, at angles 0deg and 45 deg, respectively, and two at a distance 8.0m at the same angles. They are highlighted in Fig. 4a.

The four-column was an extension of the above 1:49 tests, using the same type of circular columns. The smallest centre-to-centre distance was *l*=68m. Here we concentrate on only two of the wave probes, at the centre and in between the two front columns (see Fig. 4b). Two headings are run: 0 deg and 45 deg. Tests were also run with square columns, for a single column and four columns, but they are not considered here.

The GBS (the Statfjord A platform, North Sea) is bottom-mounted in a water depth *h*=150.8m, with a circular column radius equal to *a*=6.6m at calm water level, and 10.35m at the top of the caisson. The column centre-to-centre distance is 34.6m. The height of the caisson is 65m, while its maximum horizontal dimensions are 99.9m and 89.2m. Model tests were run in scale 1:54, ref. /13/. We focus here on two of the upwave probes: No. 2 & 6 (ref. Fig. 4c), located 6.0m and 1.75m, respectively, from the nearest column. Two headings are included: 0 deg and -30 deg.

The semisubmersible (the Kristin platform, Norwegian Sea), moored in 350m water depth, has a square ring pontoon and four equal square-shaped columns with rounded corners. Column widths 2*a* are 17.92m. The column centre-to-centre distance *l*=64m, and the draft *d*=21.0m. A number of relative-wave probes were included in the model tests, from which we focus here on no. 1 and no. 8, 2m in front of an upwave and a down-wave column, respectively, ref. Fig. 4d. From the relative-wave measurements, the wave amplification (in global co-ordinates) was estimated by subtraction of corresponding vertical platform motion measurements made at the actual locations. The tests were run in scale 1:55.

Wave conditions in the original studies included a large number of regular as well as irregular waves, with variations of wave periods and steepness. For the fixed columns, bi-chromatic waves were also run. In this presentation, results from a few selected conditions only will be highlighted, while some main findings from other tests will also be summarized..

Illustrations of the 3-D geometries of the actual hull structures (submerged parts) are given in the next section on numerical modeling, see Fig. 5.

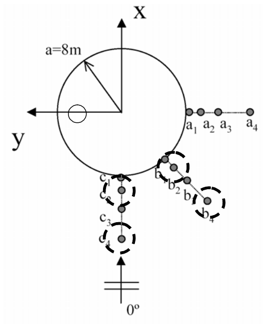
Numerical modeling. Linear and second-order numerical panel models for free-surface analysis are established by use of the diffraction-radiation code WAMIT /14/. In contrast to the linear models, the second-order models require panel modeling of the free surface. As pointed out in /15/, the proper choice of panel models is particularly critical for the second-order contribution. Systematic convergence studies on the surface area and panel resolution were therefore carried out in the present cases before the actual models were selected. A brief summary of the chosen models is presented below, while more details on the actual modelling have been given in /7,16/.

Fig. 5 shows a visual impression of the models. It is found that the spatial panel resolution is more critical than the total surface area modeled, and also more critical than the body discretization.. For the single column, the total body is discretized into 2640 panels, while the free surface has totally 16000 panels. In the 4-column case, each column has 1740 panels, while the total number of free-surface panels is 12544. The total number of body + surface panels is here limited by the capacity of the computer. For the GBS and semi, numerical models were established on basis of the experience from the column models.

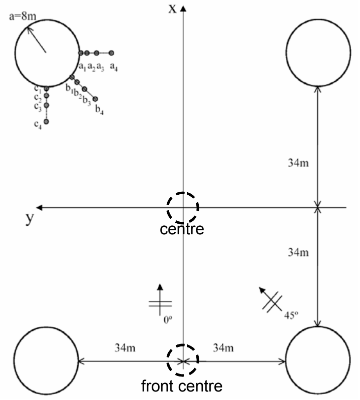
Linear and quadratic transfer functions (denoted as RAO's and QTF's, respectively) for the distorted wave elevation at the actual locations, obtained from the panel models, are combined to estimate linear and second-order time series. This is carried out for regular as well as irregular waves. More details on the treatment of RAO's, QTF's and time series in this study are given in /7,16/.

For the Semi, the net air-gap from including effects due to WF motions are also numerically modeled, using motions derived from the linear diffraction-radiation model.

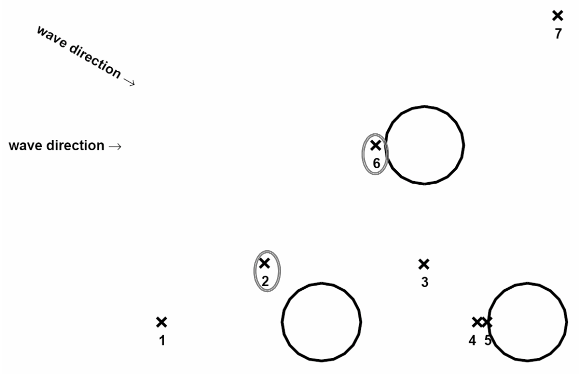
a) Single column:



b) Four columns:



c) GBS columns:



d) Semisubmersible:

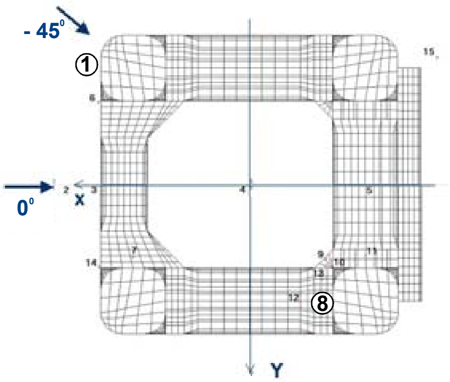
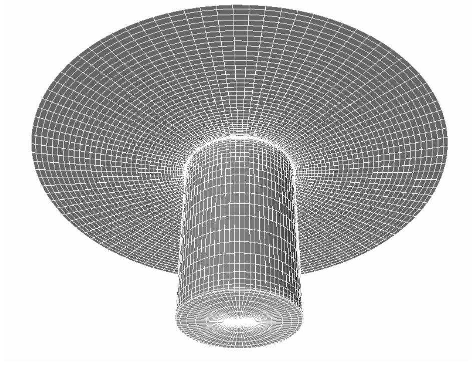
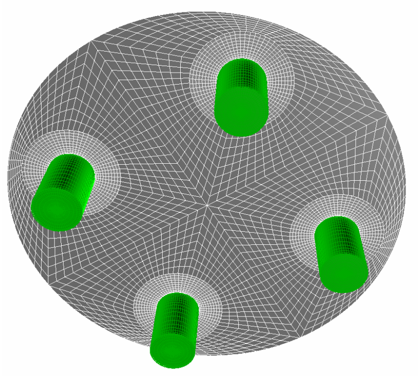


Fig. 4. Bird's eye view of four case study geometries. Wave probe locations used in this presentation are highlighted.

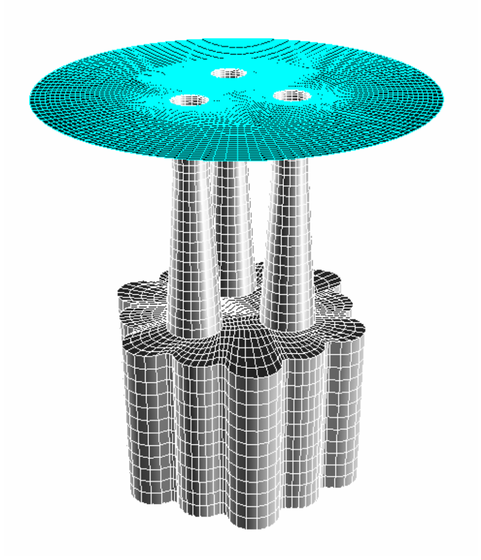
a) Single column:



b) Four columns:



c) GBS:



d) Semisubmersible:

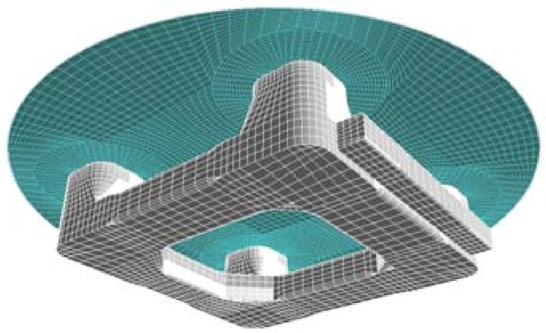


Fig. 5. 3-dimensional illustrations of second-order numerical panel models with free surfaces. Same structures as in Fig. 4.

Selected results, regular waves. In the following, maximum crest heights A_{tot} predicted by linear and second-order models are compared to the corresponding measurements. All results are normalized by the 1st harmonic amplitude, A_0, of the incident (undisturbed) wave, as pre-calibrated without the structures present. Results are shown explicitly in Fig. 6a-d for the locations and wave headings defined earlier, and for selected wave periods as follows:

Single column:	T = 12s
Four columns:	T = 12s
GBS:	T = 15.5s
Semi:	T = 10s

For the single column and GBS cases, analysis of a wider range of conditions is presented in /7,16/. The results in Fig. 6 are shown as a function of the incident wave steepness kA_0, which ranges approximately from 0.1 to 0.3, where k = angular wave number = $2\pi/L$, with L = wave length. It should be noticed that for these particular wave conditions, the GBS cases correspond to quite long wavelengths compared with the column diameter, with $ka \approx 0.1$, corresponding to almost no linear amplification.t The Semi cases is in a different range, $ka \approx 0.4$, for which linear theory can predict significant amplification depending on the location. It is seen from the plots that the second-order models predict almost a linear increase with kA_0 in most cases, although it is not perfectly linear since phase effects between the first- and second-order parts may disturb the picture.

While it is observed that the linear models generally underpredict the measurements quite significantly, the second-order models work much better in most cases. There are some discrepancies, however, especially in the steepest wave conditions. For up-wave locations quite close to the column wall (< 2m), the models most often under-predict the measurements. In /7,16/, this deviation has been studied in more detail for a wider range of wave periods. It was found to be due to an underprediction in the first harmonic amplitude, and it showed some correlation with .the kinetic energy of the incident free-surface wave orbitals. A possible explanation could be flow separation. Further away from columns, however, or at a downwave column, the models seem to overpredict in many cases. The in-depth studies in /7,16/ showed that this is due to an over-prediction in the 2nd harmonics, which is consistent with findings in /17/. These discrepancies are found to be correlated with very high local steepness values in the predicted second-harmonics components, and could partly be due to dissipation / breaking.

The under-prediction at the aft Semi column (location 8) could also be linked to influences from the pontoon. Furthermore, for the GBS there may also be un-explained effects due to the large caisson.

Selected results, irregular waves. The numerical wave amplification in irregular waves is compared to measurements through direct comparison of random, extreme events in the time series. The events are selected on basis of very high measured amplified crest levels. For the numerical reconstructions, the undisturbed, pre-calibrated wave record is used as input to a second-order formulation as described in /18/. In this procedure, an attempt is made to remove the nonlinear contents in the incident wave by a quadratic filter approach. The same approach was used in /19/, with quite reasonable results.

Results are included for the following cases:

1) Single column, Hs=12m, Tp=12s (Fig. 7).
2) Semi, Hs=14m, Tp=15.3s, 0 deg (Fig. 8).

In Fig. 7, snap-shots of amplified wave elevation records, measured & reconstructed at the location 1.5m in front of the column, are shown for two different events. For each of the events, two different plots are included, as follows: Upper plots show the total reconstructed signal together with the individual linear and second-order sum- and difference-frequency contributions. Lower plots show the total reconstructed compared to the measured signal.

In fig. 8, similar snap-shots are shown for the Semi, but grouped in a slightly different manner. Only one event is included, but at two different locations: Probe 1 (at the up-wave column), and Probe 8 (at the aft column). For each location, two plots are shown. Upper plot: The total reconstructed amplified signal (in global co-ordinates) compared to the measured, together with the individual linear and second-order sum- and difference-frequency contributions. Lower plot: Corresponding air-gap signals.

The observations from this limited number of examples seem to confirm the findings from the regular waves, as described in the following: A significant under-prediction by the linear models is seen. Second-order models more or less under-predict the crests at locations 1.5m – 2.0m in front of up-wave columns, and over-predict at the aft Semi column. Further investigations of the total records and spectra (not shown here) indicate that the discrepancies in the second-order models are connected with the first- and second harmonics in the same manner as for the regular waves above. It is evident in the lower plots of Fig.8 that the overprediction there is due to an unreasonably high second-harmonic signal.

In the Semi case, the air-gap measurements also include some effects from low-frequency vertical motions which are not included in the numerical model. It does not appear to be a major effect in the results shown.

A simplified wave-in-deck load model

A simplified method for solving the water impact force due to propagating waves underneath decks of offshore structures is developed. The current approach is based on potential theory and can be used to solve wave impact on both jacket type platforms and large-volume platforms such as semisubmersibles, TLPs and GBSs. Integrated forces over the area defined by the wetted underside of the deck are found. A summary of the method is given in the following, while more details are given in /20, 21/. Vertical loads are empasized here, but it can also be used for horizontal loads.

The method is based on a two-dimensional approach for computing wave-in-deck loads of jacket-type offshore platforms /11/. We generalize the original approach to account for three-dimensional effects and wave amplification from the

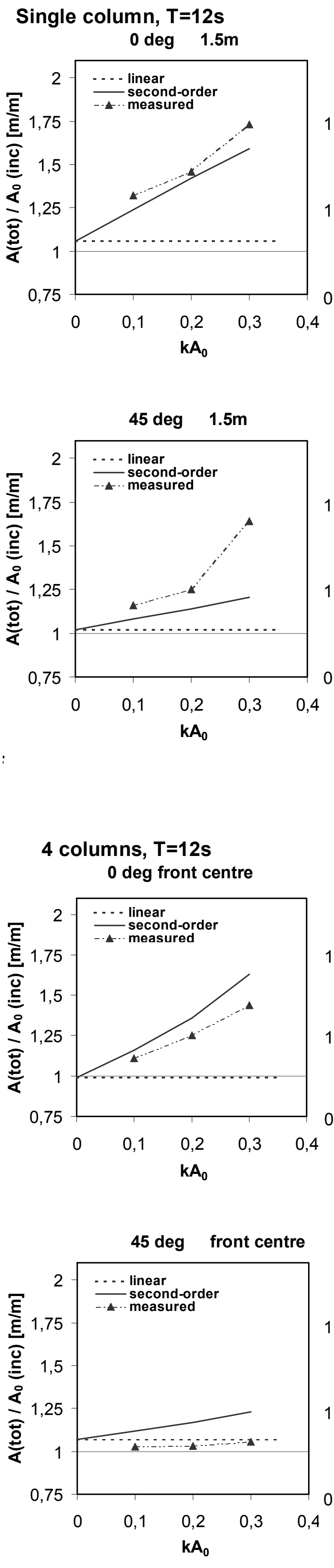


Fig. 6a-b. Crest amplification for single column and four columns.

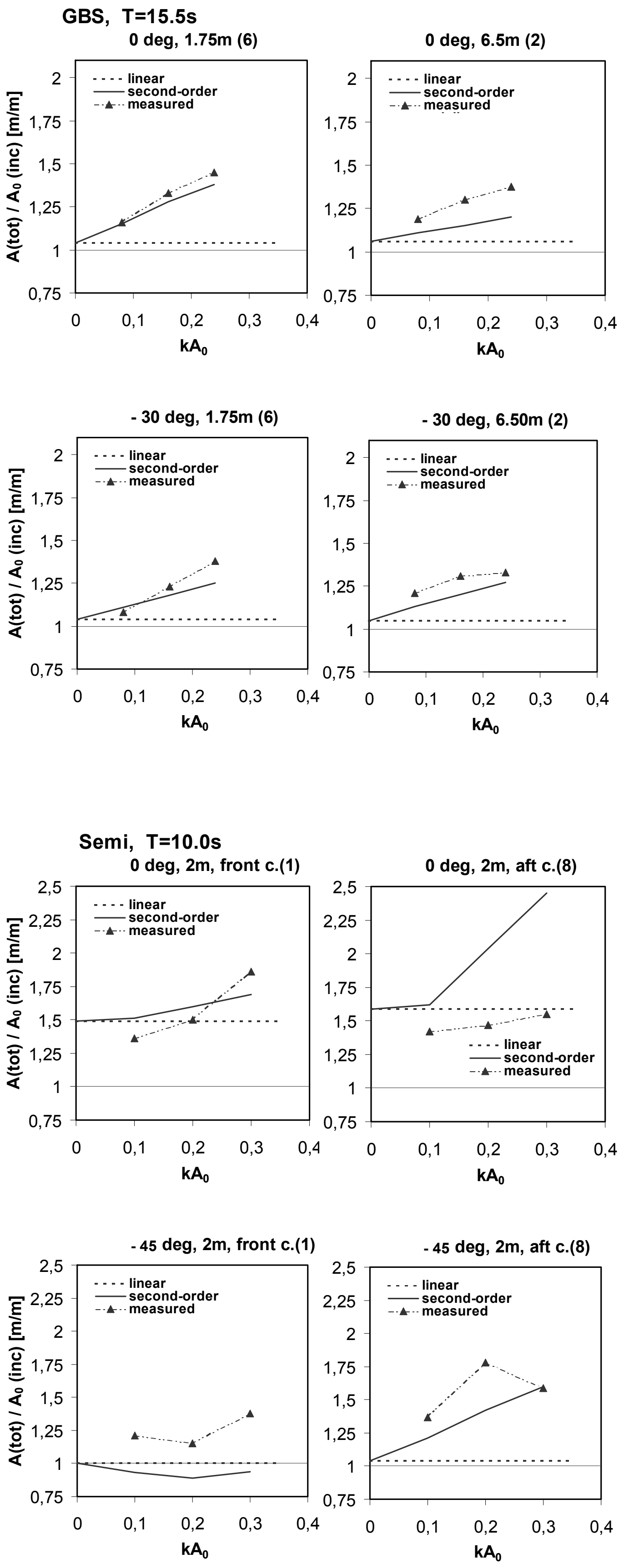


Fig. 6c-d. Crest amplification for GBS and Semi cases.

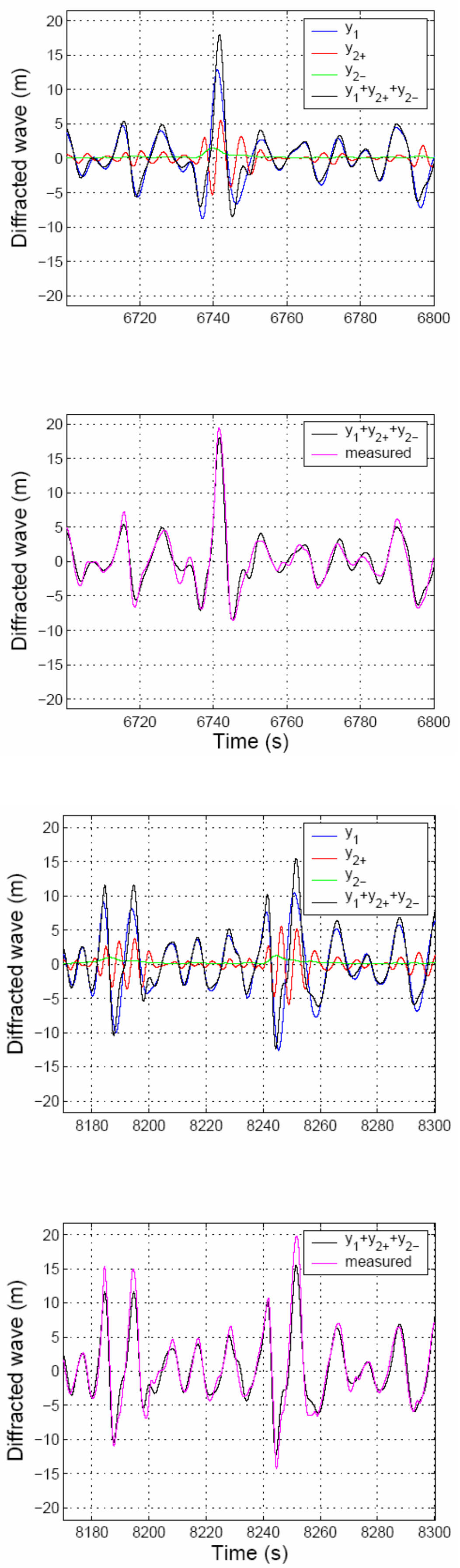


Fig. 7. Predicted elevations vs. measurements (single column). Wave probe 1.5m in front of column; two random events..

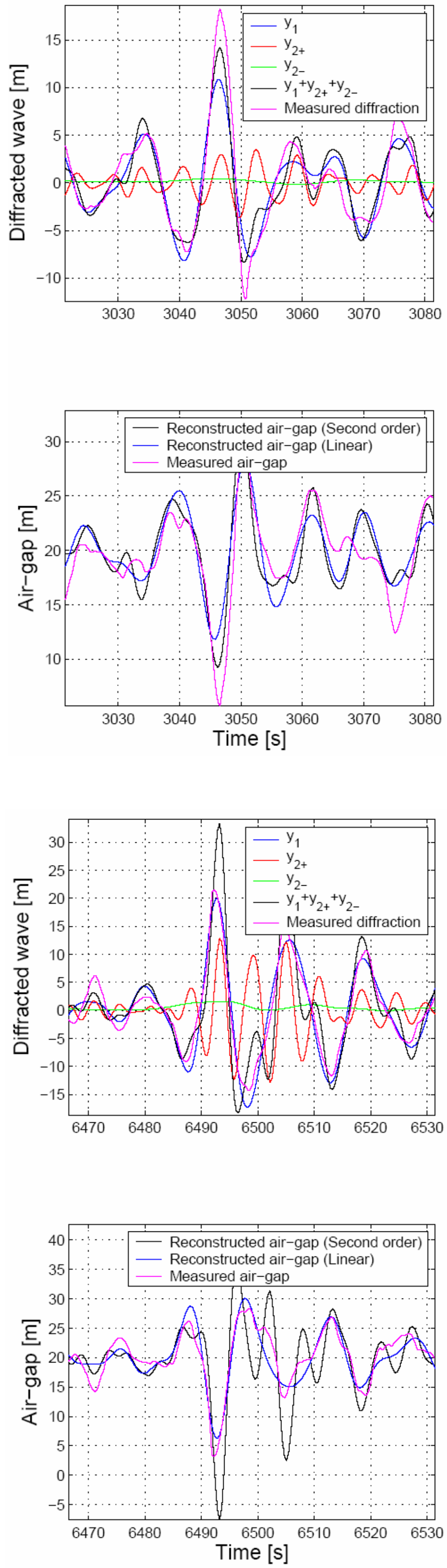


Fig. 8. Predicted elevations and air-gap vs. measurements (Semi). Wave probes no.1 (upper two plots) and 8 (lower two plots).

submerged part of the hull. The method requires a priori second order diffraction analysis of the platform hull. Thus the computed RAOs and QTFs from the diffraction analysis are used as input. In this work, WAMIT /14/ has been used for the diffraction analyses.

The water impact process is simulated in time. By applying the principle of conservation of fluid momentum, the hydrodynamic force on the deck structure is solved at each time step. Both the water entry phase and the water exit phase are simulated. In principle a boundary value problem is set-up at each time step. However, by imposing certain assumptions and simplifications, the boundary problem as such does not need to be solved in order to evaluate the resulting force. The computation is simple and fast, taking only a few minutes.

When a wave hits the deck, the structure experiences an upward directed slamming dominated force due to the upward water velocity during the initial water entry phase, followed by a negative force during the water exit phase. A negative added mass force due to negative vertical fluid particle accelerations in the wave crest dominates the force in the latter phase. The positive force peak is highly dependent on the impact condition and is especially sensitive to the initial deck clearance. The magnitude of the negative force peak is less dependent on the impact condition, but it depends greatly on the size of the maximum wetted deck area. This peak occurs when the wetting is at its maximum and its magnitude may be larger than the positive force peak. Thus, the water exit phase is important for global effects. The initial impact yields the highest average pressures and may be critical for local structural responses in the deck.

The vertical water kinematics (velocity and accelerations), which plays an important role for the resulting loads, is estimated from the second-order diffracted wave field.

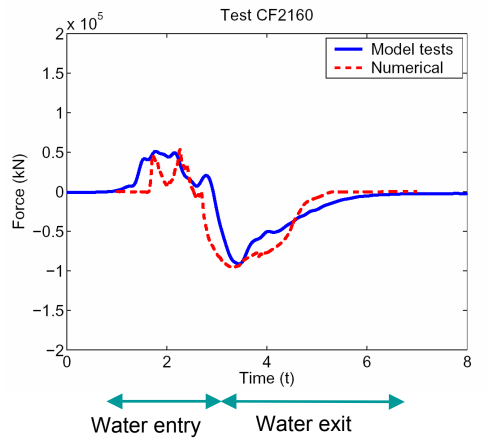
A comparison to vertical deck loads from model test data in /13/ is shown in Fig. 9. The actual platform (Statfjord A) is the same as in the case in Fig. 3, for which the hull is illustrated in Figs. 4c, 5c. Here, two regular wave conditions are run (i.e. not the wave in Fig. 3), both with very high waves:

H=37m, T=15.5s, 270 deg, deck height 21.7m
H=40m, T=17.0s, 270 deg, deck height 21.7m

The results show quite promising comparisons.

Although only the integrated force is found, and not the pressure distribution, the time-varying wetted area is known, and the time-varying spatially averaged pressure can therefore also be found.

T=15.5s, **H=37m,**
270deg, ηdeck=21.7m



T=17s, **H=40m,**
270deg, ηdeck=21.7m

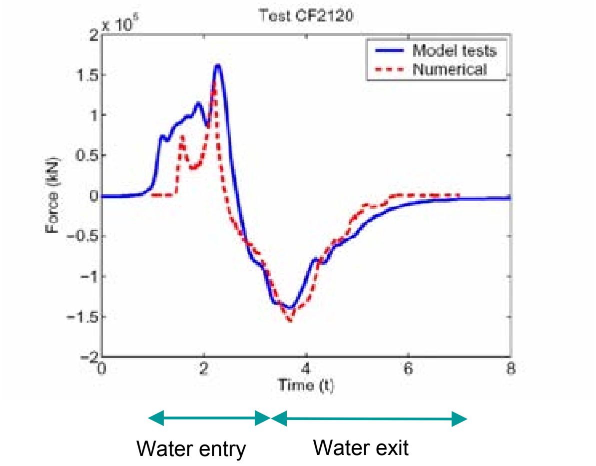


Fig. 9. Computed vs. measured vertical wave-in-deck load events (based on /20/).

Fully nonlinear modeling: Introductory study using commercial CFD tool

Due to strongly non-linear wave-column interactions observed in the wave amplification and impact problem, an investigation of the feasibility of using fully nonlinear models has been initiated. A Volume-of-Fluid method is considered, using the commercial code Flow-3D /22/. In a previous study on the green water loading of an FPSO /23/, this tool was applied with promising results. In the following, an introductory study on the following two cases is briefly described:

- The 3-D wave flow around a circular cylinder
- A 2D wave-in-deck study

3-D wave flow around circular cylinder. The free-surface water kinematics around large-volume cylinders in steep waves is a critical input for the improved wave-in-deck load modelling. It is necessary to verify existing kinematics models, but there seems to be little data available for this. In addition to experimental data, studies by use of of fully nonlinear models are considered helpful, at least as a qualitative check of nonlinear phenomena, but in future also quantitative verifications should be possible.

The single column case from Figs. 4a, 5a is modelled in a numerical wave tank with length 220m, width 96m and depth 70m. A “frozen” snap-shot of a zoomed-in section of the tank with the column is shown in Fig. 10. Wave generation is modeled from the right, by specifying time-varying wave particle velocities from linear theory up to the free surface. In the present study, the numerical grid size is 1.0m (full scale).

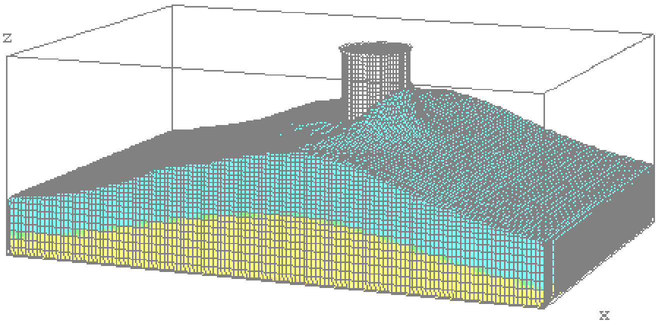


Fig. 10. Zoomed-in section of numerical wave tank with column in wave H=22m, T=12s.

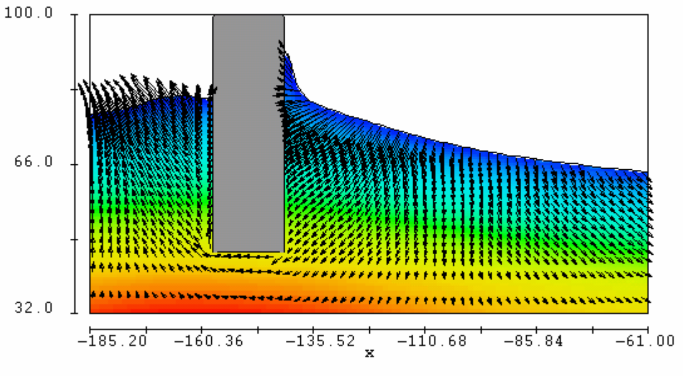


Fig. 11. Velocity field in central plane.

In order to minimize numerical reflection problems at the boundaries, which inevitably grow with time, it is desirable to model the tank as large as possible, while on the other hand the finite computer speed will be a limiting factor. This also limits the useful time window to a few wave cycles. The corresponding computed velocity vector field in the central plane is shown in Fig. 11. By more detailed investigations, from which some results are presented in /24/, it is found that significant nonlinear contributions are predicted in the free surface zone. In the same work, preliminary comparisons to experimental results from Particle Imaging Velocimetry (PIV) show promising results, although further investigations are currently underway for more accurate comparisons.

Wave impact under deck. A 2-D study of the wave impact under a deck is carried out. The case is the same as the one modeled in /12/. No submerged hull structure is present. The case is modeled in model scale. The velocity field at one instant is illustrated in Fig. 12. An example of wave load time series is shown in Fig.13. Although there are some noisy spikes in the result, which are not unusual in VoF modelling, it has been found that the load picture, and magnitude level, is in fact reasonably similar to that obtained by boundary element modeling and model tests in /12/.

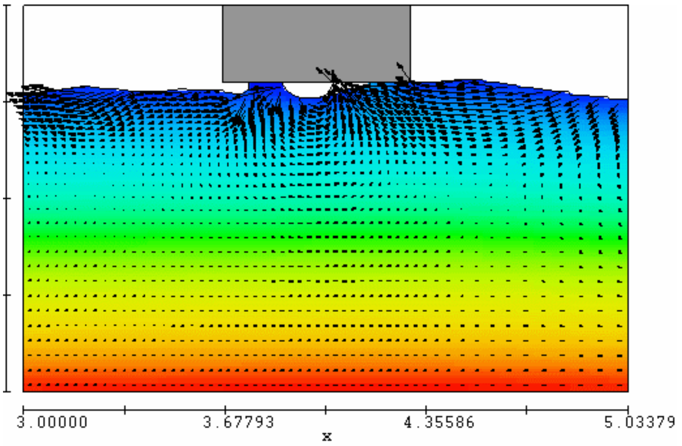


Fig. 12. Snap-shot of velocity field, 2D wave-in-deck study.

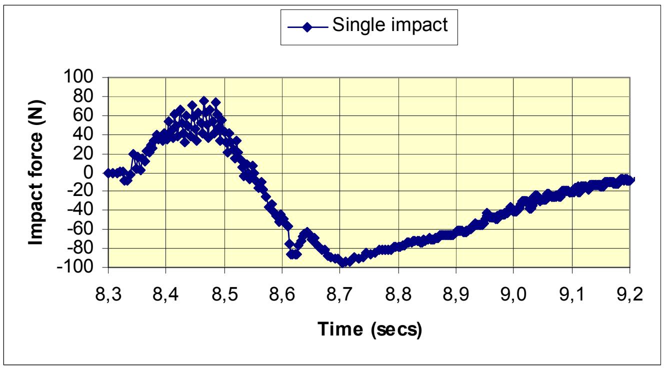


Fig. 13. Deck impact force time history example.

Conclusion

Case studies have been carried out with linear and second-order numerical modeling of free-surface wave elevation around and between columns, for four different structures. From systematic convergence studies, final numerical models were selected. The spatial panel resolution on the free-surface was found to be more critical than on the body. The maximum predicted crest heights at various locations, and for various steepnesses, were compared to model test measurements.

Linear predictions are clearly too low, while second-order corrected values compare reasonably well in many cases. Some discrepancies have been identified, however, especially in steep waves. Thus the model somewhat under-predicts the measurements within a a range of some meters from up-wave columns. This has been interpreted to be due to under-prediction in the basic harmonic amplification. For locations further away, and around an aft Semi column, the opposite has been observed, with over-prediction of the second-harmonic component.

A simplified wave-in-deck load model has been described, based on a combination of Kaplan's approach (the principle of conservation of momentum) and a second-order amplification of the incident waves due to the hull structure. Time-varying integrated loads are computed. The method is fast due to an efficient approximation in the computation of time-varying added mass. Results show good comparisons to global deck load measurements on a GBS.

Introductory studies with fully nonlinear modeling using a commercial Volume-of-Fluid code have shown promising results. Resulting wave kinematics and deck loads are in a reasonable range, although further improvements can be done. The compromise between a large numerical wave tank domain and computer capacity is presently a challenge, due to reflections from boundaries.

Further work is recommended for the interpretation and practical implementation of the findings for the free-surface elevation. Especially, the robust use of the results in engineering applications should be addressed. More validation cases of the wave-in-deck model, also including local impact events, are recommended, and the practical use of the method should be addressed. Finally, more work is recommended in the use and validation of fully nonlinear tools. The choice of spatial and time resolution, and proper initial and boundary conditions, are among the important issues.

Acknowledgements

This work is a part of the Norwegian WaveLand JIP, Phase 2. Participants in the JIP include: Statoil, Health and Safety Executive (UK), Norwegian Petroleum Directorate, ABB Lummus (USA), Deepwater Technology Group Pte, AkerKvaerner, Det Norske Veritas, and Marintek. Model test data were made available from experiments financed by Norsk Hydro, Statfjord Late Life Project, AkerKvaerner and Marintek. The authors also wish to thank Frøydis Solaas and Vibeke Moe for valuable contributions in the numerical modelling and data analysis.

References

1. McCamy, R. and Fuchs, R. (1954), "Wave forces on piles: A diffraction theory", Tech. Memo No. 69, Beach Erosion Board, U.S. Army Corps of Engineers, Washington D.C, USA.
2. Niedzwecki, J.N. and Duggal, A.S. (1992), "Wave runup and forces on cylinders in regular and random waves", *Journal of Waterways, Port, Coastal, and Coastal Engineering,* ASCE, Vol. **118**, pp. 615-634.
3. Kriebel, D.L. (1992), "Nonlinear wave interaction with a vertical circular cylinder. Part II: Wave run-up", *Ocean Engineering,* Vol. **19***,* pp. 75-99.
4. Stansberg, C.T. and Nielsen, F.G. (2001), "Nonlinear wave-structure interaction on floating production systems", *Proc., Vol. IV, 11th ISOPE Conference*, Stavanger, Norway, pp. 363-372.
5. Nielsen, F.G. (2003), "Comparative study on airgap under floating platforms and run-up along platform columns", *Journal of Marine Structures*, Vol. **16**, PP. 97-134.
6. Kim, M. and Yue, D. (1989), "The complete second order diffraction solution for an axisymmetric body. Part 1: Monochromatic incident waves", *Journal of Fluid Mechanics,*Vol. **200**, pp. 235-264.
7. Kristiansen, T., Baarholm, R.J. and Stansberg, C.T. (2004), "Validation of second-order analysis in predicting diffracted wave elevation around a vertical cylinder", *Proc., 14th ISOPE Conference*, Toulon, France.
8. Ferrant, P. Malenica, S. and Molin, B. (1999), "Nonlinear wave loads and runup on a vertical cylinder", in *Nonlinear Water Wave Interaction*, Eds. O..Mahrenholtz and M. Markiewicz, WIT Press, Southampton, UK, pp. 101-135.
9. Büchmann, B., Ferrant, P. and Skourup, J. (2000), "Run-up on a body in waves and current: Fully nonlinear and finite order calculations", *Applied Ocean Research*, Vol. **22**, pp.349-360.
10. Health & Safety Executive (UK) (1998), "Review of wave in deck load assessment procedure". Offshore Technology Report – OTO 97 073.
11. Kaplan P. (1992), "Wave impact on offshore structures: re-examination and new interpretations", *Proc. 24th Offshore Technology Conference*, Houston, TX, USA.
12. Baarholm, R. and Faltinsen, O. (2004), "Wave impact underneath horizontal decks", *J. Ma.r Sci. Technol.*, Vol. **9**, pp. 1-13.
13. Stansberg, C.T., Baarholm, R., Fokk, T., Gudmestad, O.T. and Haver, S. (2004), "Wave Amplification and Possible Deck Impact on Gravity Based Structure in 10^{-4} Probability Extreme Crest Heights", Paper No. 51506, *Proc., 23rd OMAE Conference*, Vancouver, BC, Canada.
14. WAMIT Version 5.3s (1995), "A radiation-diffraction panel program for wave-body interaction", Report, Dep. of Ocean Eng., MIT, Cambridge, Mass., USA.
15. Birknes, J. (2001), "A convergence study of second-order wave elevation on four cylinders", Proc., Vol. III, *11th ISOPE Conference*, Stavanger, Norway, pp. 392-399.
16. Stansberg, C.T. and Kristiansen, T. (2005), "Non-linear scattering of steep waves around vertical columns", submitted for publication.
17. Sweetman, B., Winterstein, S.R. and Meling, T.S. (2002), "Airgap prediction from second-order diffraction and Stokes Theory", *International Journal of Ocean and Polar Engineering,* Vol. **12**, No. 3, pp. 184-188.
18. Stansberg, C.T. (2001), "Data Interpretation and System Identification in Hydrodynamic Model Testing", *Proc., Vol. III, the 11th ISOPE Conference*, Stavanger, Norway, pp. 363-372.
19. Stansberg, C.T. and Gudmestad, O.T. (1996), "Nonlinear Random Wave Kinematics Models Verified Against Measurements in Steep Waves", *Proc. Vol. IA, the 15th OMAE Conf.,* Florence, Italy, pp. 15-24.
20. Baarholm, R. and Stansberg, C.T. (2005), "Extreme vertical wave impact on the deck of a Gravity-Based Structure (GBS) platform", *Proc., Rogue Waves 2004,* IFREMER, Brest, France, held in Brest, October 2004.
21. Baarholm R. (2005), "A simple numerical method for evaluation of water impact loads on decks of large-volume offshore platforms", *Proc. OMAE 2005,* Paper no. OMAE-67097, Halkidiki, Greece.
22. Flow-3D (2002), User's Manual, Vols. 1 & 2, Flow Science.
23. Stansberg, C.T., Berget, K., Hellan, O., Hermundstad, O.A., Hoff, J.R., Kristiansen, T. and Hansen, E.W.M. (2004), "Prediction of green sea loads on FPSO in random waves", *Proc., ISOPE 2004*, Toulon, France,.
24. Kristiansen, T., Baarholm, R., Stansberg, C.T., Hansen, E.W.M. and Rortveit, G. (2005), "Kinematics in a diffracted wave field: Particle Imaging Velocimetry (PIV) and numerical models", *Proc., OMAE 2005,* Paper No. OMAE-67176, Halkidiki, Greece.