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Wave loads on offshore wind turbines

Feasibility study using results of wave experiments executed by Electricité de France (EDF)

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Abstract

Electricité de France (EDF) has performed an experimental study on the wave loading on a cylindrical pile for offshore wind turbines in shallow water depths. A report with the results of the experimental study has been provided to ECN.

The aim of the feasibility study is to investigate whether the results of the wave experiment can be used for further research and contribute to the implementation of 6000 MW in the Dutch Exclusive Economic Zone by the year 2020.

The study is divided in three parts:

- a literature survey
- a visit to the hydraulic laboratory
- an analysis of the experimental results

The results of the experimental study at EDF are analyzed. The conditions of the wave experiments are compared with conditions in the Dutch Exclusive Economic Zone and correspond well. Wave breaking statistics in the southern North Sea are discussed. Breaking waves are negligible for water depths greater than 20 m.

EDF also performed a numerical study on the wave loads. The wave loads are calculated according to different wave theories using the Morison equation. EDF compared the measured wave loads with the calculated wave loads. For non-breaking waves, which are expected in Dutch offshore wind farms, the wave loads can be calculated using the stream function wave theory. For breaking waves and post breaking waves the wave loads are underestimated using linear wave theory and stream function theory.

CONTENTS

NOTATIONS

α_i	scale factor for different dimensions i	
C_d	drag coefficient	
C_m	inertia coefficient	
d	water depth	$[m]$
D	diameter	$[m]$
E	modulus of elasticity (Young's modulus)	$[N/m^2]$
H	wave height of regular wave	$[m]$
H_{m0}	significant wave height	$[m]$
I	moment of inertia (second moment of area)	$[m^4]$
F	wave force	$[N]$
Fr	Froude number	
g	acceleration	$[m/s^2]$
KC	Keulegan Carpenter number	
λ	wave length	$[m]$
L	length	$[m]$
ν	kinematic viscosity	$[m^2 s]$
ρ	density	$[kg/m^3]$
t	time	$[s]$
T	wave period of regular wave	$[s]$
T_p	wave peak period	$[s]$
T_{m0}	zero up crossing wave period	$[s]$
U	fluid velocity	$[m/s]$

SUMMARY

In North West Europe offshore wind energy is seen as an important source of renewable energy. The target of the Dutch government is to have 6000 MW of offshore wind turbines installed in the Dutch Exclusive Economic Zone by the year 2020. Moving offshore means that the wind turbine will experience additional loading due to waves, current or ice. Compared to other fixed offshore structures wind turbines are more dynamic.

At this moment much research in ongoing on the hydrodynamic loading on a wind turbine and how it should be calculated. Hydrodynamic knowledge is available from offshore engineering for the oil and gas industry and coastal engineering for shore protection. The offshore wind turbine is located in water depth between deep water offshore and the shallow water depth of the coastal area. In this project, supported by Novem, the knowledge within ECN and EDF is combined to adapt the hydrodynamic load model to offshore wind energy.

Electricité de France (EDF) has performed an experimental study of the wave loading on a cylindrical pile. This pile is representative for offshore wind turbines in intermediate and shallow water depths. A report [12] with the results of the experimental study has been sent to ECN.

The aim of the feasibility study is to investigate whether the results of this wave experiment can be used for further research and can contribute to the implementation of 6000 MW in the Dutch Exclusive Economic Zone by the year 2020.

A literature survey was carried out to gain insight in the way wave experiments are performed. Emphasize was on experiments with wave loading on a cylinder. Literature has been used about the wave flume, scaling laws, the experimental set-up and the analysis of the results.

In April 2003 ECN visited EDF R&D National Hydraulics and Environment Laboratory. Visiting the hydraulic laboratory is the best way to see how the experiments are executed. Also the visual observations give additional information besides the time series and the report. A demonstration of the wave experiments was given. The demonstration in the laboratory gave a good impression of the wave experiments.

The results of the experimental study at EDF are analyzed. The conditions of the wave experiments are compared with wave conditions in the Dutch part of the North Sea. Wave breaking statistics in the southern North Sea are discussed. EDF also performed a numerical study on the wave loads. The wave loads are calculated according to different wave theories using Morison equation. The calculated wave loads are compared with the measurements.

Based on the analysis of the wave experiments at EDF the following can be concluded:

- The wave conditions in the wave experiment correspond with the conditions in the Dutch Exclusive Economic Zone.
- Using the Morison equation and the stream function wave model an acceptable prediction of the wave loads can be made for non-breaking waves.
- For post-breaking and breaking waves the Morison equation and the stream function wave underestimate the wave loads.
- For the water depths considered in the wave experiment the linear regular Airy wave is insufficient.
- Wave breaking due to shallow water in the southern North Sea is negligible for water depth greater than 20 m. For the typical wave climate in this region most wave breaking takes place in depths less than 10 m.

- ECN uses the stream function wave together with the Morison equation for extreme wave conditions (Eecen [4]). For wind farms in the Dutch Exclusive Economic Zone with a water depth of about 20 m this is justified.
- For impact loads due to breaking waves more advanced models are available like the Boussinesq wave model (Madsen [13]) and the wave impact load model of Wienke [19].

The data of the experiment is already used by EDF for comparison between the measured and calculated wave loads. No further analysis of the data is recommended.

In case new wave experiments are considered, other subjects are recommended for investigation, for instance:

- elastic modeling of the wind turbine support structure
- random (non-linear) waves
- wave-current interaction

1 INTRODUCTION

In North West Europe offshore wind energy is seen as an important source of renewable energy. The target of the Dutch government is to have 6000 MW of offshore wind turbines installed in the Dutch Exclusive Economic Zone by the year 2020. The offshore wind turbine is a dynamic system influenced by the hydrodynamic loading of waves and current.

At the moment much research is ongoing on the hydrodynamic loading on a wind turbine and how it should be calculated is a research topic. Hydrodynamic knowledge is available from offshore engineering for the oil and gas industry and coastal engineering for shore protection. The offshore wind turbine is located in water depth between deep water offshore and the shallow water depth of the coastal area. In this project, supported by Novem, the knowledge within ECN and EDF is combined to adapt the hydrodynamic load model to offshore wind energy.

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The aim of the feasibility study is to investigate whether the results of this wave experiment can be used for further research and can contribute to the implementation of 6000 MW in the Dutch Exclusive Economic Zone by the year 2020.

First a literature survey was carried out to gain insight in the way wave experiments are performed. Emphasize was on experiments with wave loading on a cylinder. The survey is presented in chapter 2.

In April 2003 ECN visited EDF R&D National Hydraulics and Environment Laboratory. A demonstration of the wave experiments was given. The demonstration in the laboratory gave a good impression of the wave experiments. The travel report is included in chapter 3.

In chapter 4 the results of the experimental study at EDF are analyzed. The conditions of the wave experiments are compared with wave conditions in the Dutch part of the North Sea. Wave breaking statistics in the southern North Sea are discussed. EDF also performed a numerical study on the wave loads. The wave loads are calculated according to different wave theories using Morison equation. The calculated wave loads are compared with the measurements.

Conclusions and recommendations are given in chapter 5.

2 LITERATURE SURVEY

2.1 Introduction

A literature survey about wave experiments has been carried out. First the wave flume will be described. In a wave experiment the full scale situation is modeled. Scaling laws are applied in order to have similarity in behaviour of the full scale prototype and the physical model. The scaling laws will be discussed. The design of the test set-up depends on the issues to be studied with the wave experiment. In this case focus is on wave loads on cylinders. Finally the way the results of the experiments are analyzed is discussed.

2.2 Wave flume

In hydraulic laboratories it is possible to investigate waves and wave load characteristics in controlled conditions. The wave experiments are executed in wave flumes. A wave flume is an elongated rectangular basin. The wave maker is on one side and a beach is on the other side to absorb the wave energy, see figure 1. A general description of a wave flume and wave experiments can be found in reference books like Sorensen [17].

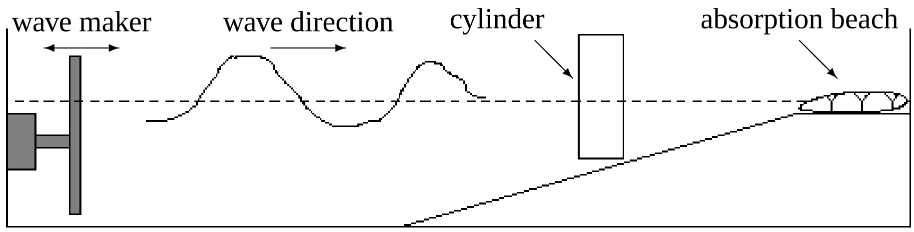

Figure 1: General set-up of wave flume

In a wave flume regular, bi chromatic and random wave can be generated. There are different wave makers available. Most wave makers consist of a hydraulic device which drives the piston and the wave flap. The wave flap displaces the water. The vertical wave flap can be move forwards and backwards in horizontal direction and generate waves. Another possibility is to connect the wave flap to the bottom of the flume with a hinge. The piston rotates the wave flap around the hinge. Also combinations of the two are possible, see figure 2.

Figure 2: Different types of wave generators

To avoid reflection of the waves in the wave flume the waves are absorbed on a beach at the end of the wave flume. The beach has a flat slope of pea gravel. Another way is to detect the reflection and compensate the reflected wave using the wave maker.

2.3 Scaling

In model experiments the behaviour of the model should be similar to the behaviour of the prototype (full scale). This means that the dimensions, kinematics and dynamics have to be scaled. The scaling from prototype to model scale is treated in hydrodynamic reference books like Newman [14] , Sarpkaya [16] and Journée [9]. The dimensions are scaled with the length scale factor α_L. The velocity and acceleration scale according to the velocity scale factor α_U and the acceleration scale factor α_g, with gravity g. The fluid density ρ and the kinematic viscosity ν are scaled by the following factors α_ρ and α_ν respectively. These scale factors are the basis for the scales of time, forces, mass, inertia and volume.

In wave experiments the inertia forces and the gravity force are of importance because of the free surface flow. When the response of the structure is near the natural frequency then the damping is of influence for the dynamics of the structure. The ratio of the different types of forces is often presented by non dimensional numbers. For instance the Reynold number expresses the ratio between the inertia forces and the viscous forces. In wave experiment scaling is usually according to Froude law. In waves gravity is of importance. The Froude number Fr is the square root of the ratio between the inertia force and the gravity force.

$$Fr = \frac{U}{\sqrt{gL}} \tag{1}$$

Here U is the velocity $[m/s]$, g is the gravity $[m/s^2]$ and L is the length $[m]$.

When experiments are scaled according to Froude law the Froude number Fr is kept the same for model and prototype. The density scale factor α_ρ and the acceleration scale factor α_g are both equal to 1. Table 1 shows the various dimensions scaled according to Froude law.

Table 1: Scaling factors according to Froude law

Dimension	description
Time	$\sqrt{\alpha_L}$
Velocity	$\sqrt{\alpha_L}$
Mass	α_L^3
Force	α_L^3

2.4 Experimental set-up

For the design of the experimental set-up it is important to know what the goal of the wave experiment is. In this feasibility study the main goal is to investigate the effect of wave loads on cylindrical substructures of wind turbines. The way the cylindrical model is constructed depends whether the elasticity of the substructures should be considered in the model tests or not. When the dynamics of the model are not important a stiff cylinder can be used during the wave experiment. In that case the mass distribution and the elasticity of the model are not important.

In case the dynamic behaviour has to be modeled, it is important that the natural frequency is scaled correctly. The natural frequency depends on the mass distribution, the modulus of elasticity E of the used material and the bending stiffness EI. The moment of inertia of the cross-sectional area I can be adjusted by changing the wall thickness of the cylinder model keeping the outer diameter constant (Sarpkaya [16], Journée [10]).

During the wave experiment certain types of behaviour are investigated. Therefore measurements have to be performed. Not only the signals from the measurement devices are of interest also visual observations can be useful for the interpretation of certain behaviour, for instance wave run-up and breaking waves at the location of the cylinder.

For wave experiments where the waves and the wave loads on a vertical cylinder are subject of investigation, often the following characteristics can be measured:

- wave height
- wave kinematics
- wave loads on cylinder
- displacements and acceleration of elastic cylinder

2.4.1 Wave height and wave kinematics

The wave height, rapid changes in water levels, are measured with so called wave probes. A wave probe consists of a pair of stainless steel wires. When the wave prove is submerged a current will flow between the probe wires. The current is proportional to the depth of immersion. One or more wave probes are located in front of the cylinder in order to measure the undisturbed wave profile. Also a wave probe is located next to the cylinder, so the wave height at the cylinder can be measured.

To validate wave theories and investigate phase differences between the wave loads and wave kinematics it is necessary to measure the velocity of the water particles. In literature there are different measuring devices found to measure the velocity of the water particles.

- Laser Doppler velocity meter (Vugts [18])
- Acoustic Doppler velocity (Kriebel [11])
- Electromagnetic flow meters (Davies [1])
- Particle Image Velocity (PIV) (Jensen [8])

For the use of the Laser Doppler and Acoustic Doppler velocity meter seeding particles are added to the water of the wave flume. Light or sound are transmitted to the flow. The reflection of the light or sound by the seeding particles is received. Next the velocity of the water particles can be determined from the Doppler shift.

When the electromagnetic flow meter is used, the velocity of the flow is measured by generating a magnetic field in the the fluid. The voltage developed across the electrodes by the magnetic field is measured. The voltage is proportional to the velocity of the fluid.

Another method to measure the velocity in a fluid is the Particle Image Velocity (PIV) method. Again particles are added to the fluid. A target area in the fluid is illuminated twice with a known time step. At each light pulse an image of the particles in the target area is made. By comparing two successive images the displacement of each particle can be determined. With the known time step this means that the velocity is known.

2.4.2 Wave loads and structural dynamics

The wave loads on the vertical cylinder are measured with force transducers. Force transducers are based on strain-gauge measurement of shear forces and bending moments. For a vertical cylinder this means that inside the cylinder there is a frame with the force transducers. This inner frame is connected to the wave flume. The outer cylinder is fixed to the inner frame. The wave loads on the outer cylinder are now transfered to the inner frame. In figure 3 a possible construction is given. See also Huseby [7]

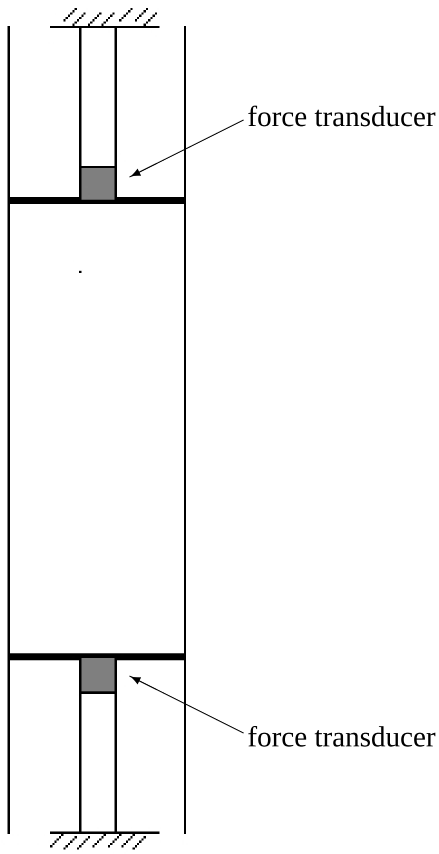

Figure 3: Test set-up of vertical cylinder

When the model is elastic and the structural dynamics is of importance the displacements of the vertical cylinder can be measured by mounting accelerometers on the cylinder. Gründlehner [6] used soft spring displacement gauges to measure the horizontal displacement of a jack-up.

2.5 Analysis of test results

Keeping the goal of the wave experiments in mind the results of the model tests are analyzed. In case of a wind turbine substructure modeled by a vertical cylinder the (breaking) wave and the corresponding wave load are of interest. By visual observation it is possible to identify whether the wave is post-breaking, breaking or non-breaking. By analyzing the signals of the wave elevation and the wave kinematics it is possible to find the wave theory which models the wave the best. This wave model can be used as input for the numerical wave load model to compare the calculated and measured wave loads.

A vertical cylinder representing a wind turbine substructure can be considered to be a slender structure for the waves that are investigated. The definition of a slender cylinder is a cylinder with a diameter D relatively small compared to the wave length λ. The *diffraction parameter* D/λ for a slender cylinder has a value less then 0.2 (Sarpkaya [16]). In offshore practice the wave loads on a slender body are approximated using Morison's equation. In equation 2 F is the force per unit length experienced by the cylinder. In the Morison's equation the wave force consists of a part due to the drag and an inertia part. In the equation this is expressed by the introduction of a drag coefficient C_d and an inertia coefficient C_m.

$$F = \frac{1}{2} C_d |U| U + C_m \rho \frac{\pi D^2}{4} \frac{dU}{dt} \tag{2}$$

Where U is the undisturbed fluid velocity, $\frac{dU}{dt}$ the acceleration of the fluid, ρ the water density and D the diameter of the cylinder.

The results of the wave experiment can be used for verification of numerical wave load models or for an estimation of the drag and inertia coefficient in Morison's equation. Differences between the results of the wave experiment are caused by the differences in the wave kinematics, the Morison equation and the damping in the case of a dynamic structure. In Gründlehner [6] first the measured wave kinematics are compared with kinematics of different wave models. The wave kinematics are measured at the location of the jack-up, but without the jack-up in the model basin. This gives the undisturbed wave kinematics as input for the Morison equation. After a proper wave theory has been selected the wave loads can be calculated and compared with the wave load measurements. The drag and inertia coefficients are selected for instance based on offshore standards, literature or wave experiments. When structural dynamics are included in the wave experiment, then the damping is of real importance to have the same loads measured and calculated. A good estimate of the total damping is vital. The total damping consist of damping by wave radiation, viscous fluid damping, structural damping.

To estimate the drag and inertia coefficient in equation 2 measurements of the water particle velocity and acceleration should be available. In text books like Sarpkaya [16], Journée [9] and Dean [3] many methods are given all resulting in different C_d and C_m values. It is impossible to determine exact values for the coefficients. A tolerance of several percents is the best one can expect (Journée [9]). In Dean [3] two methods for determining drag and inertia coefficients are mentioned. The problem is that Morison's equation is one equation with C_d and C_m as two unknown parameters.

The first method is to solve Morison's equation when the velocity or the acceleration of the fluid is zero. In case the velocity is zero the inertia coefficient C_m can be determined. When the acceleration is zero the drag coefficient C_d can be estimated. Disadvantage of the method is that only small a amount of the available data is used. Also the method is sensitive to errors in the velocity resulting in a significant phase shift (Journée [9]). The second method is based on the least square method. Here the mean squared error ϵ^2 between the measured and the computed forces is minimized with respect to the unknown C_d and C_m. The computed and measured force data is divided in groups with approximately the same Reynolds number in order to account for the Reynolds dependency.

3 VISIT WAVE EXPERIMENTS

On April the 28th 2003 Leo Machielse and Johan Peeringa visited EDF R&D at Paris (Chatou). Aim of the visit was to get an impression of the facility and the way the experiments are executed.

The morning program was split in two parts. In the first part EDF gave two presentations. Next there was a visit to the wave flume, where a demonstration of the wave experiments was presented.

3.1 Presentations

The subject of the first presentation was wave modeling at EDF and the wave experiment. Marilyne Luck gave the presentation. First the different flow regimes and the validity of the Morison equation are discussed. When the Morison equation is applied the wave kinematics and the hydrodynamic coefficients C_d and C_m are of importance. Note that the coherence between the hydrodynamics and wave kinematics should be respected. Different modeling strategies are discussed depending on the level of wave information and on the level of bottom information.

Two wave models are presented. First there is the wave description based on the stream function method (Dean [2]). This wave theory is applied for flat bottoms and without wave breaking. When there is a sloping bottom and wave breaking occurs another wave model is used, based on the non-linear Boussinesq equation, with surf-breaking dissipation included for the spilling case.

Two approaches are given to include the impact load due to breaking in the design:

- Addition of a term in the Morison equation
- Usual use of Morison equation, but using the 'exact' wave kinematics in the breaking zone

Further research perspectives according to EDF are:

1. Shallow water effects
   - Asymmetry of waves (elevation, velocity, ...)
   - Breaking waves (impact forces, ...)
   - Wave-current interaction
   - Scouring risks (bottom protections, ...)
2. Improvement/modification of existing models
   - Extension of Morison approach
   - Hydrodynamics: non-linear wave modeling
   - Experimental data on hydrodynamic coefficients
3. Validation on experimental studies

Non-linear waves, breaking waves and wave load calculations receive a lot of attention in the offshore wind research community. At the moment scour seems to be a cost issue. Should scour protection be applied or not? The decision to apply scour protection or not should be accounted for in the design of the wind turbine. Wave-current interaction is not a research issue in the offshore wind, but should be considered in the design. See the paper of Peters [15] about the fatigue loading on the Europlatform approximately 60 km offshore Hoek van Holland, at the entrance of the Rotterdam harbour channel, in 32 m water depth. The occurrence of tidal current simultaneously with sea waves has a significant influence on the fatigue life of the platform.

The second presentation was about load calculations. Clément Buvat gave the presentation. EDF has done some load calculations on a wind turbine with a lattice support structure. The non-linear waves were modeled using the program Streamfm. The program Streamfm uses the stream function wave model. The finite element model of the lattice tower was modeled in EDF's open-source code Aster. For the turbine a simple aerodynamic model was used.

3.2 Demonstration of wave experiments

The objective of the experiments is to study wave loading on offshore piles in shallow water (10-20 m). Both non-breaking and breaking cases will be studied. In the first test program for regular waves the following parameters will be changed:

- bottom slope (2)
- water depth at pile location (4)
- wave periods (3)
- wave heights (4)

The values of the parameters are presented in paragraph 4.2.

The dimensions of the flume tank are LxBxH = 72 x 1.5 x 1.2 m. In the wave flume a current and a wave can be generated. A wave maker of the piston type generates the waves. By circulating the water in one of the directions a current can be generated.

For the model tests a scale of 1/25 is used. The scaling is done according Froude law. The diameter of the cylinder now corresponds to a real diameter of 5 m, which is typical for offshore foundations of wind turbines. At the location of the cylinder the bottom of the wave flume has a slope. In the test set-up the cylinder consists of an inner cylinder, which is attached to the top and the bottom. The outer cylinder is connected to the inner cylinder by force transducers at the rear with respect to the wave direction. The outer cylinder is free at the top and at the bottom (2 mm).

Wave probes measure the wave profile and the wave run-up at the cylinder. For the wave elevation at the cylinder a wave probe is attached at the front of the cylinder. To measure the wave profile (asymmetric form of the crest) several wave probes are located along the slope and the wave flume.

A demonstration of the wave experiment was arranged for the visit to the wave flume. The conditions of these experiments were as follows (regular waves):

- sloping bottom of 5 degree,

Figure 4: Test set-up (source: EDF presentation by Marilyne Luck)

- water depth of 15 m at the location of the cylinder (= 60 cm on model scale) and 25 m offshore,
- wave periods of 9 s and 12 s (corresponding to 1.8 s and 2.4 s on model scale),
- offshore wave heights from 5 to 10 m (corresponding to 20 to 40 cm on model scale).

4 ANALYSIS OF WAVE EXPERIMENT AT EDF

4.1 Introduction

In this section the results of the wave experiment at EDF are analyzed. Aim of the feasibility study is to investigate whether the results of the wave experiment can be used for further research and contribute to the implementation of 6000 MW in the Dutch Exclusive Economic Zone by the year 2020.

First the wave experiments are discussed. For the sea defense works of the Netherlands there is monitoring network on the Dutch part of the North Sea. The conditions during the wave experiments are compared with the environmental conditions at the survey location IJmuiden munitiestortplaats. The survey location IJmuiden munitiestortplaats is one of the locations in the monitoring network. The position of IJmuiden munitiestortplaats is near the planned Dutch offshore wind farms Q7 and the Near shore Windpark (NSW).

Finally the results of the wave experiments and the relation with the Dutch situation is discussed.

4.2 Wave experiment at EDF

In this section the test set-up used by EDF is described briefly. The National Hydraulic and Environment Laboratory (LNHE) has a wave flume with the following dimensions:

Length	72 m
Width	1.5 m
Depth	1.5 m

With the wave maker of the piston type both regular and random waves can be generated. The wave maker is computer controlled and has an active wave absorption system. In the flume at the opposite site of the wave maker there is a wave absorption beach. Tests are performed for two bottom slopes $\frac{1}{20}$ (5 %) and $\frac{1}{40}$ (2.5 %). The bottom slopes are made of concrete.

Wave loads are measured on a stiff cylinder. The cylinder is located on the sloped bottom 0.40 m above the flat bottom. The horizontal forces and overturning moments on the cylinder are measured on the cylinder with two force-sensors. The free surface elevation is measured using wave probes. Wave probes are located along the wave flume. There are 3 probes in the offshore part to determine the incident wave, 7 probes along the slope and 1 on the cylinder. Visual observations are used to locate the position of the breaking point of the wave.

In Luck [12] the numerical values of the wave conditions are presented by the parameters of the incoming offshore waves. Information about the waves properties near the cylinder are shown in the figures. In table 2 the wave conditions at the cylinder are given for the various test conditions. The ranges are an estimation derived from the figures. For one test condition the water depth at the cylinder was 5 m. The wave conditions at the cylinder for this water depth are not presented in the figures.

During the experiment regular waves are generated. Due to the bottom slope the waves are transformed. Before the test results are analyzed the mean free surface elevation signals and the mean force signals are generated. Individual waves are identified by a zero up crossing method. Five consecutive waves are used to generate the mean wave and the associated mean force. The results in the EDF report are based on the mean signals over five waves.

The wave force regime is determined. In Sarpkaya [16] the wave force regime is characterized by a so called diffraction parameter and the Keulegan Carpenter (KC) number. The body size

Table 2: Wave conditions in EDF experiment at the position of the cylinder

water depth [m]	wave period [s]	wave height [m] slope 2.5 %	wave height [m] slope 5 %
7.5	8 - 12	3.5 - 6.0	3.8 - 5.3
10.0	8 - 12	4.0 - 6.9	3.0 - 7.0
15.0	8 - 12	5.6 - 9.5	3.5 - 10.4
20.0	8 - 12	5.8 - 9.8	3.5 - 10.2

to wave length ratio $\frac{D}{\lambda}$ is defined as the *diffraction parameter*. For large bodies with respect to the wave length, $\frac{D}{\lambda} \geq 0.2$, wave diffraction becomes important. The Keulegan Carpenter number is given by:

$$KC = \frac{U_m T}{D} \tag{3}$$

With U_m the maximum velocity, T the wave period and D the cylinder diameter .

The Keulegan Carpenter number is a measure for the viscous effects. An increasing KC value means that flow separation becomes important. For the wave experiment the diffraction number is always smaller than 0.2. The cylinder can be considered a small body with respect to the wave length. The Keulegan Carpenter number ranges from $3 < KC < 25$. The KC value corresponds with velocities determined by nonlinear stream function wave models. The values of the KC number mean that both the drag and inertia component are important for the horizontal wave force in the wave experiment.

For each test condition the minimum and maximum wave forces are determined. The maximum forces are positive working in the wave direction. The maximum wave force range from 16 to 166 kN. The minimum forces work in opposite wave direction. The minimum forces range from -9 to -69 kN. Figure 5 in the Luck [12] shows that the extreme horizontal forces increase globally with the local wave height and the local water depth. The outliers in the figure are caused by an impact component in the total wave force due to a breaking wave on the structure or before it.

EDF compared the measured wave loads with calculations. The wave loads on the cylinder are calculated using Morison equation. The wave kinematics (velocity, acceleration) are estimated using three wave models:

- linear wave theory
- regular stream function theory (Dean [2])
- irregular stream function method (Dean [2])

For the linear wave theory and the regular stream function theory the mean wave height and period are used as input. The irregular stream function method uses the recorded wave elevation time series as input. The measured extreme forces are compared with the calculated extreme forces according to the three wave theories. The ratio between measured and calculated extreme wave force is used for comparison. When comparing the results a distinction should be made between non-breaking waves and breaking or post-breaking waves.

For non-breaking waves the ratio between measured and calculated extreme wave force for the two stream function methods ranges from 0.8 to 1.3. For linear wave theory the values of the ratio are general between 1 and 1.5, but can reach the value of 2.

For breaking and post-breaking waves the difference between measured and calculated wave forces is large. The linear wave theory gives a maximum ratio of 4. The stream function method gives a maximum ratio of 2.35. For the irregular stream function method the ratio has values between 0.75 and 2.

In the case of non-breaking waves the EDF report concludes, that for the water depths and wave conditions in the wave experiment acceptable estimate of the wave forces are found using the Morison equation together with the stream function. However for breaking and post-breaking waves the applied methods underestimate the hydrodynamic forces. Applying linear wave theory the measured wave forces can be four times higher than the model predicts. In case of the stream function method the measured forces can be 2.35 times higher.

When the location of the wind farm is in an area where breaking waves are expected other models should be used to calculate the breaking wave load. This means that an other wave theory or load model should be selected. Wienke [19] has performed research on the breaking wave impact on slender cylindrical piles. In his study a theoretical model was developed and compared with results of wave experiments.

EDF applied Morison equation for the wave load calculation and focused on the wave models. For the regular and irregular stream function method the calculated wave force profiles are compared with the measured wave force profiles. Since the irregular stream function uses the wave profile as an input the wave force profile corresponds better with the measurement than the results with the regular stream function method. The regular stream function method shows poor results for the wave height to water depth ratio $\frac{H}{d} > 0.4$. This is the range where breaking and post breaking occur. The better results of the irregular stream function method imply that the asymmetry of the wave is important. Therefore it is suggested to model the wave transformation due to the bottom slope by a Boussinesq wave. In research there is renewed interest in this Boussinesq wave (Madsen [13]) and its application is discussed in the offshore wind community.

4.3 Environmental conditions of Dutch Exclusive Economic Zone

For comparison of the conditions of wave experiment the environmental conditions for future wind farms in the Dutch Exclusive Economic Zone should be known. In particular for the wave experiments it is necessary to know something about the seabed slope, the water depth, extreme wave conditions and the occurrence of breaking waves.

As can be seen in Figure 5 most of the area of the Dutch Exclusive Economic Zone has 20-40 m water depth. The bathymetry consists of sand banks and sand waves. The length of a sand wave is 100-800 m and the height about 5 m. Therefore a seabed slope can be expected in a wind farm. It should be noted that future wind farms are only allowed outside the 12 mile zone. See the red line in Figure 5. This means that most of the offshore wind farms will be in water depths greater than 15 m.

For the sea defense works of the Netherlands there is monitoring network on the Dutch part of the North Sea. The network consists of nine survey locations. See figure 6. At the survey locations the environmental conditions like wind speed, current, water level, wave height and wave period and directions are monitored for 20 to 30 years now. The data of the measurements and the results of the analysis of the data are available to the public (www.golfklimaat.nl). The data is provided by the National Institute of Coastal and Marine Management (RIKZ). Now for

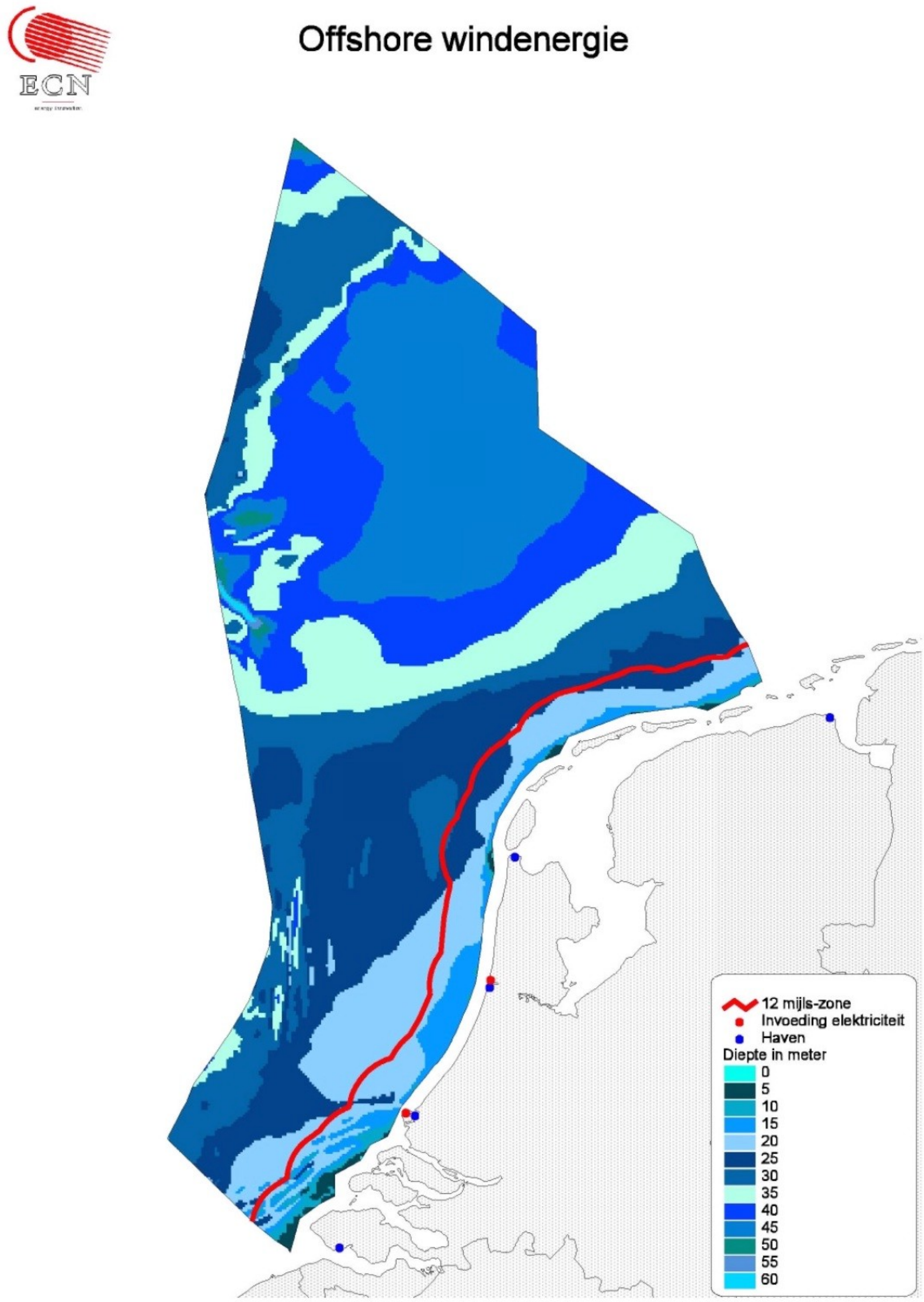

Figure 5: Water depth in the Dutch exclusive economic zone

some survey locations at the North Sea the scatter diagram can be generated and the extreme significant wave heights are estimated.

At the moment there are two offshore wind farm projects planned in the Dutch Economic Exclusive Zone. The water depth in the wind farms is about 20 m. The offshore wind turbines

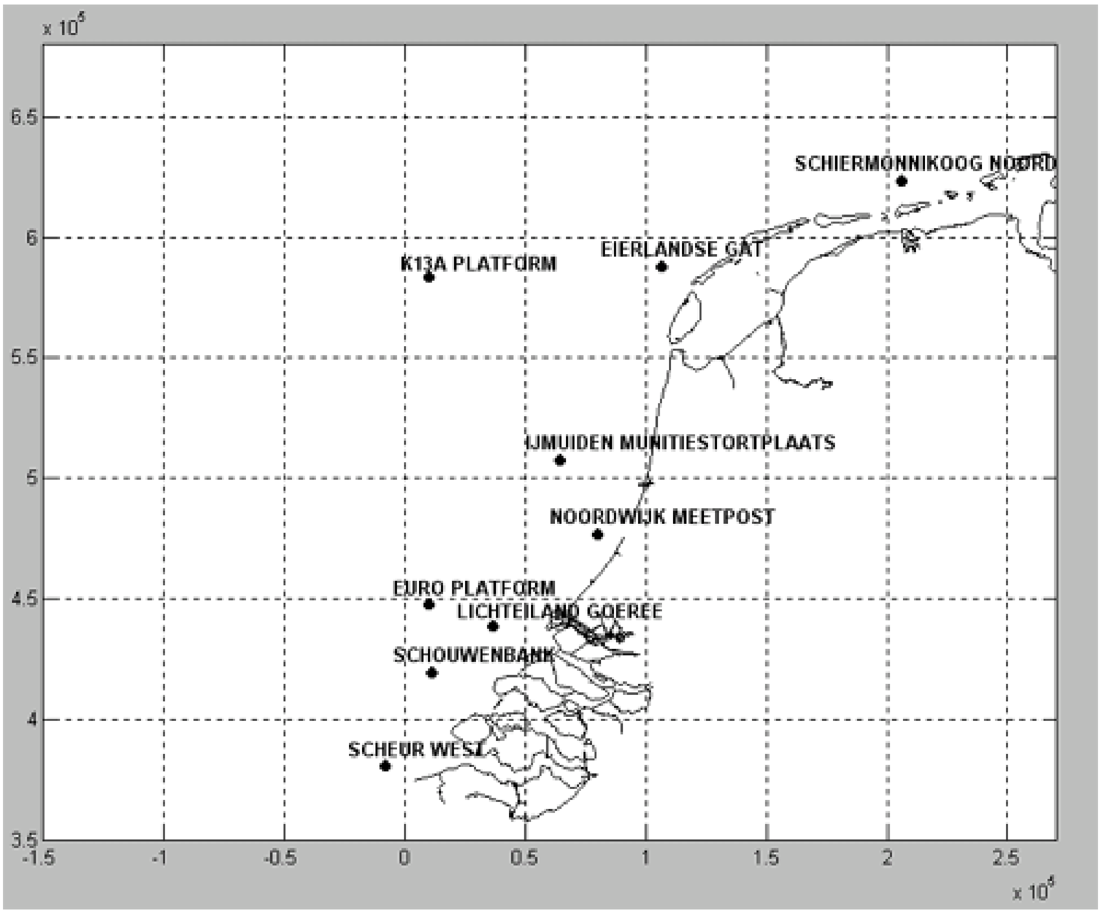

Figure 6: Survey locations of monitoring network RIKZ (source: RIKZ www.golfklimaat.nl)

constructed at the moment have a substructure of the monopod type. The diameter of these monopods will be about 4-6 m. The survey location IJmuiden munitiestortplaats is selected for comparison of the dutch offshore environmental conditions with the wave experiment conditions. The IJmuiden munitiestortplaats is a survey location near Q7 wind farm and the Near Shore Wind farm (NSW). The scatter diagram of the significant wave height and zero up crossing period is given in table 3.

For five locations the extreme significant wave height H_{m0} and the extreme peak wave period T_p are estimated. The results are based on measurements over the period 1979 - 1993. In table 4 the extreme significant wave height and the corresponding peak wave period are given for IJmuiden munitiestortplaats for different return periods.

During the wave experiment breaking waves are observed. For offshore wind farm design it is interesting to know how often breaking waves occur in the Dutch Exclusive Economic Zone. Ewing [5] presents statistics of wave breaking in the southern North Sea. The statistics are based on wave measurements, hindcast data and visual observation. The main conclusion in the report is:

Wave breaking due to shallow water in the southern North Sea is negligible for water depth greater than 20 m. For the typical wave climate in this region most wave breaking takes place in depths less than 10 m.

ECN uses the stream function wave together with the Morison equation for extreme wave

Table 3: Scatter diagram of Hs and Tz at IJmuiden munitiestortplaats. The bold conditions correspond with the wave conditions of the wave experiment

	T_{m0} [s]					
H_{m0} [m]	2.00 - 4.00	4.00 - 6.00	6.00 - 8.00	8.00 - 10.00	10.00 - 12.00	all
0.00 - 1.00	25.606	18.717	0.458	0.009	0.000	44.789
1.00 - 2.00	3.910	33.008	0.769	0.004	0.003	37.695
2.00 - 3.00	0.000	11.415	**1.250**	**0.004**	0.000	12.670
3.00 - 4.00	0.000	1.089	**2.587**	**0.007**	0.000	3.684
4.00 - 5.00	0.000	0.006	**0.924**	**0.015**	0.000	0.945
5.00 - 6.00	0.000	0.000	**0.134**	**0.048**	0.000	0.182
6.00 - 7.00	0.000	0.000	0.007	0.024	0.000	0.031
7.00 - 8.00	0.000	0.000	0.000	0.004	0.000	0.004
8.00 - 9.00	0.000	0.000	0.000	0.000	0.000	0.000
9.00 - 10.00	0.000	0.000	0.000	0.000	0.000	0.000
> 10.00	0.000	0.000	0.000	0.000	0.000	0.000
all	29.516	64.235	6.130	0.116	0.003	100.000

conditions (Eecen [4]). Looking at the breaking wave statistics and the results of the wave experiment this is justified for wind farms in the Dutch Exclusive Economic Zone with a water depth of about 20 m.

Table 4: Extreme conditions at IJmuiden munitiestortplaats

return period [year]	10	100	1000	10000
wave height H_{m0} [m]	6,71	7,64	8,42	9,10
peak wave period T_p [s]	12,4	13,7	14,7	15,7

4.4 EDF wave experiments and future research

The wave experiment at EDF and the environmental conditions in the Dutch Exclusive Economic Zone have been discussed in the previous sections. Here the wave experiment will be compared with the situation for typical wind turbine design in the Dutch Exclusive Economic Zone. Furthermore it will be discussed whether the data of the wave experiment can be used for further research.

First the full scale dimensions of monopod, the water depth and wave conditions in the North Sea will be compared with the wave experiments. The full scale diameter of the cylinder is 5 m, which is in good agreement with the diameter for monopod structures. In the Dutch Exclusive Economic Zone the offshore wind farms are expected to be located outside the 12 miles zone in water depths of 15 m and more. Wave experiments are executed with local water depths at the cylinder of 7.5, 10, 15 and 20 m. The results at 15 and 20 m water depth are of interest for Dutch offshore wind farms.

The wave height and the wave period in table 3 are defined as the significant wave height and the zero up crossing wave period. The regular waves in the wave experiments are defined by a wave height H and an associated wave period T. The relations between the wave height H

and the significant wave height H_{m0} and the associated wave period T and the peak period T_p is given in equation 4

$$
\begin{aligned}
H &\approx 1.8\, H_{m0} \\
T &= T_p \approx 1.4\, T_{m0}
\end{aligned}
\tag{4}
$$

Comparing the wave experiment conditions in table 2 with the conditions at IJmuiden munitiestorplaats in table 3 and table 4 shows that about 5% of the scatterdiagram in table 3 corresponds with the wave experiments conditions. The corresponding wave conditions are shown bold in table 3. It can be concluded that the conditions of the experiment correspond with the conditions in the Dutch Exclusive Economic Zone.

EDF compared the experimental wave loads with numerical wave load models. A next step could be a wave load calculation using a Boussinesq wave model. To study the load impact of a breaking wave it is necessary to have information about the wave kinematics, which are not measured during the wave experiment.

The results are summarized below.

- The wave conditions in the wave experiment correspond with the conditions in the Dutch Exclusive Economic Zone.
- Using the Morison equation and the stream function wave model an acceptable prediction of the wave loads can be made for non-breaking waves.
- For post-breaking and breaking waves the Morison equation and the stream function wave underestimate the wave loads.
- For the water depths considered in the wave experiment the linear regular Airy wave is insufficient.
- Wave breaking due to shallow water in the southern North Sea is negligible for water depth greater than 20 m. For the typical wave climate in this region most wave breaking takes place in depths less than 10 m.
- ECN uses the stream function wave together with the Morison equation for extreme wave conditions (Eecen [4]). For wind farms in the Dutch Exclusive Economic Zone with a water depth of about 20 m this is justified.
- For impact loads due to breaking waves more advanced models are available like the Boussinesq wave model (Madsen [13]) and the wave impact load model of Wienke [19].
- The data of the experiment is already used by EDF for comparison between the measured and calculated wave loads. No further analysis of the data is recommended.

5 CONCLUSIONS AND RECOMMENDATIONS

A feasibility study has been performed to see whether the results of the wave experiments at EDF can be used for further research and whether the results contribute to the Dutch target of 6000 MW by the year 2020. The conditions of the wave experiment are compared with the conditions in the Dutch Exclusive Economic Zone. For water depth greater than 15 m there is good agreement. It is expected that Dutch offshore wind farms will be constructed 12 miles or more offshore. Here the water depth is 15 m or greater.

In the wave experiment report measured wave loads are compared with calculated wave loads using Morison equation. The conditions of the wave experiment are compared with the wave conditions in the Dutch part of the North Sea. The statistics of wave breaking in the southern North Sea is used. Based on this the following can be concluded:

- The wave conditions in the wave experiment correspond with the conditions in the Dutch Exclusive Economic Zone.
- Using the Morison equation and the stream function wave model an acceptable prediction of the wave loads can be made for non-breaking waves.
- For post-breaking and breaking waves the Morison equation and the stream function wave underestimate the wave loads.
- For the water depths considered in the wave experiment the linear regular Airy wave is insufficient.
- Wave breaking due to shallow water in the southern North Sea is negligible for water depth greater than 20 m. For the typical wave climate in this region most wave breaking takes place in depths less than 10 m.
- ECN uses the stream function wave together with the Morison equation for extreme wave conditions (Eecen [4]). For wind farms in the Dutch Exclusive Economic Zone with a water depth of about 20 m this is justified.
- For impact loads due to breaking waves more advanced models are available like the Boussinesq wave model (Madsen [13]) and the wave impact load model of Wienke [19].

The data of the experiment is already used by EDF for comparison between the measured and calculated wave loads. No further analysis of the data is recommended.

In case new wave experiments are considered, other subjects are recommended for investigation, for instance:

- elastic modeling of the wind turbine support structure
- random (non-linear) waves
- wave-current interaction

The three subjects are discussed briefly below.

An offshore wind turbine is a dynamic system excitated by stochastic wind and waves. The dynamics are more important than for other offshore structures. To include the dynamics of the structure in the wave experiment it may be interesting to model an elastic cylinder.

Due to the dynamic behaviour of an offshore wind turbine the loading is best described using random waves. However for shallow water and extreme wave conditions non-linearities in the waves become more important. Wave experiments using random waves can be used to study which wave theory is best to model the extreme wave load on a wind turbine in relative shallow water. Is it the regular wave, the linear random wave or the non linear random wave?

The effect of combined action of waves and currents on the fatigue life of a monopod in the Dutch part of the North Sea is described by Peters [15]. The tidal currents change the encounter frequency of the waves, the wave spectrum and the shape of the wave. Since the natural frequency of the wind turbine is in the region of wave spectrum the loading is sensitive to a shift of wave frequency by a current. The effect of combined waves and currents on the dynamics of a wind turbine should be studied.

REFERENCES

[1] Davies, M.J.S. Wave loading data from fixed vertical cylinders. Technical Report OTI 92558, Health & Safety Executive HSE, 1992.

[2] Dean, R.G. Stream function representation of nonlinear ocean waves. *Journal of Geophysical Research*, 70:4561–4572, 1965.

[3] Dean, R.G. and R.A. Dalrymple. *Water wave mechanics for engineers and scientists*. World Scientific Publishing Co. Pte. Ltd., 1991.

[4] Eecen, P.J. Wind waves : Forces due to waves on offshore wind turbines. Technical Report ECN-C–03-097, Energy research Centre of the Netherlands ECN, September 2003.

[5] Ewing, J.A. Statistics of wave breaking in the southern North Sea. Technical Report OTO 93026, Health & Safety Executive HSE, 1993.

[6] Grundlehner, G.J. Systematic model tests on a harsh environment jack-up in elevated conditions. In *Proceedings of* 5^{th} *international conference on jack-up platforms*, London, September 1995. City University.

[7] Huseby, M. and J. Grue. An experimental investigation of higher harmonic forces on a vertical cylinder. *Journal of Fluid Mechanics*, 414:75–103, 2000.

[8] Jensen, A., M. Huseby, J.K. Sveen and J. Grue. Measurements of velocities and accelerations in steep irregular water waves. In *Proceedings of* 10^{th} *International Symposium on Application of Laser Techniques to Fluid Mechanics*, 2000.

[9] Journée, J.M.J. and W.W. Massie. Offshore Hydromechanics. Technical report, Delft University of Technology, Delft, January 2001. `http://www.ocp.tudelft.nl/mt/journee/#LINK3`.

[10] Journée, J.M.J., W.W. Massie, B. Boon and R. Onnink. Model Experiments on Jack-Up Platform Hydromechanics. Technical Report 0809-P, Delft University of Technology, Delft, November 1988.

[11] Kriebel, D.L., E.P. Berek, S.K. Chakrabartie and J.K. Waters. Wave-current loading on a shallow water caisson. In *Offshore Technology Conference*, Houston, May 1996. OTC 8067.

[12] Luck, M., M. Benoit and J.M. Menon. Experimental study of wave loading on offshore pile for wind turbines in shallow water depth. Technical Report HP-75/03/078/A, Electricité de France, EDF R&D, December 2003.

[13] Madsen, P.A., H.B. Bingham and Hua Liu. A new Boussinesq method for fully nonlinear waves from shallow to deep water. *Journal of Fluid Mechanics*, 462:1–30, 2002.

[14] Newman, J.N. *Marine Hydrodynamics*. MIT Press, Cambridge, Massachusetts, 1977.

[15] Peters, H.C. and H. Boonstra. Fatigue loading on a single pile platform due to combined action of waves and currents. In *Behaviour of Offshore Structures*, pages 1015–1035, Trondheim, 1988. Tapir Publishers.

[16] Sarpkaya, T. and I. Isaacson. *Mechanics of wave forces on offshore structures*. Van Nostrand Reinhold Company Inc., 1981.

[17] Sorensen, R.M. *Basic wave mechanics for coastal and ocean engineers*. John Wiley & Sons, 1993.

[18] Vugts, J.H. and A.G. Bouquet. Frequency domain description of wave forces on an element of a vertical pile in random seas. In *Behaviour of Offshore Structures*, pages 239–253, Amsterdam, 1985. Elsevier Science Publishers B.V.

[19] Wienke, J. *Druckschlagbelastung auf schlanke zylindrische Bauwerke durch brechende Wellen*. PhD thesis, Technischen Universität Carolo-Wilhelmina, Braunschweig, Juli 2001. `http://opus.tu-bs.de/opus/frontdoor.php?source_opus=294`.