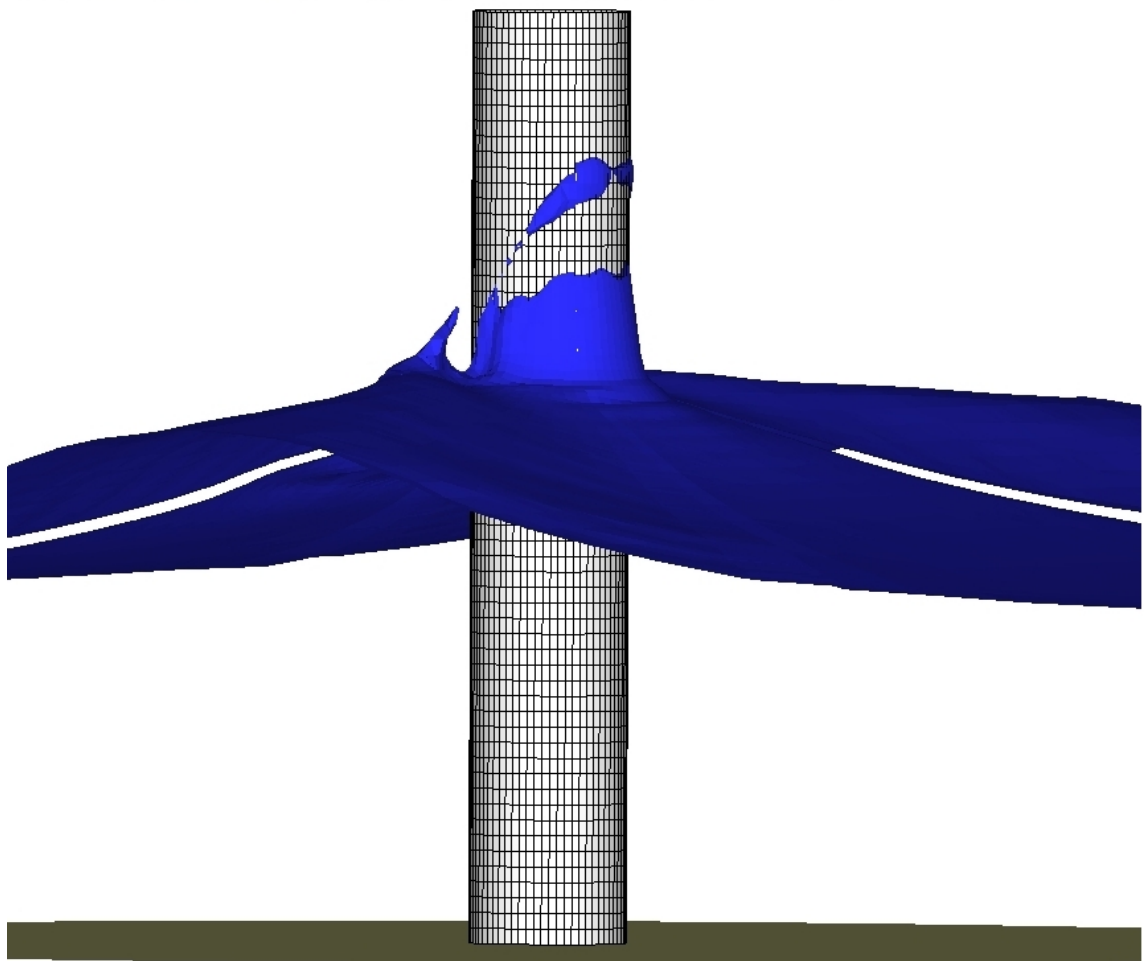


# Final Report on the PSO Project "Wave Run-up on Offshore Wind Turbines"



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September 2008

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Project		Project No			
Final Report on the PSO Project "Wave Run-up on Offshore Wind Turbines"		11700726-80135			
Authors		Date			
Anders Wedel Nielsen		17 September 2008			
		Approved by			
		Henrik Kofoed-Hansen			
2	Revised Final Report	AWN	EDC	HKH	17.09.08
1	Revised Final Report	AWN	HKH	HKH	17.07.08
0	Final Report	AWN	EDC	HKH	04.04.08
Revision	Description	By	Checked	Approved	Date
Key words		Classification			
Wave Run-up Offshore Wind Turbine Horns Rev		<input type="checkbox"/> Open <input type="checkbox"/> Internal <input checked="" type="checkbox"/> Proprietary			

Distribution		No of copies
Energinet.dk:	Mr Niels E Helstrup	PDF
DHI:	AWN, EDC, HKH, Library	PDF



## CONTENTS

1	RESUME .....	1
1.1	Fuldskalamålinger på Horns Rev I Vindmøllepark.....	1
1.2	Fysiske modelforsøg.....	1
1.3	Numeriske modelforsøg.....	2
1.4	Test af afværgeforanstaltninger .....	2
1.5	Retningslinjer for bølgeopløb på monopæle .....	3
2	SUMMARY .....	4
2.1	Full-scale Measurements at Horns Rev I Wind Farm .....	4
2.2	Physical Model Tests.....	4
2.3	Numerical Model Tests .....	5
2.4	Test of Deprecating Structure.....	5
2.5	Guidelines for Wave Run-up on Monopiles .....	6
3	FINAL REPORT.....	7
3.1	Part 1 – Analysis of the Horns Rev Run-up .....	8
3.2	Part 2 – Physical Model Tests of Run-up .....	9
3.3	Part 3 – Numerical Model Tests of Run-up.....	10
3.4	Part 4 – Test of Deprecating Structures .....	11
3.5	“Wave Run-up on a Wind Turbine Foundation” – Paper from EOW 2007.....	13
3.6	“Numerical Modelling of Wave Run-up on a Wind Turbine Foundation” – Paper from OMAE 2008 .....	14
3.7	“Design Loads on Platforms on Offshore Wind Turbine Foundations with Respect to Vertical Wave Run-up” – Paper from EOW 2007 .....	15
4	CONCLUSION.....	16



## 1 **RESUME**

Formålet med projektet var at:

- Bestemme det maksimale bølgeopløb på vindmøllefundamenter (monopæle)
- Bestemme hastighederne langs fundamentet
- Teste mulige måder at reducere bølgeopløbet

### 1.1 **Fuldskaletninger på Horns Rev I Vindmøllepark**

Bølgeopløbet på Horns Rev I Vindmøllepark blev estimeret på basis af to videoer på ca. 20 minutter hver. Videoerne var taget den 22-12-2004 og den 19-01-2005 under relativt normale vinterforhold. Antallet af bølgeopløb, der var store nok til at nå platformen placeret i 9 m (MSL), blev talt. Resultaterne af dette er, at ca. 15 bølgeopløb i timen kan forventes at ramme platformen. På basis af videoerne blev den vertikale hastighed i bølgeopløbet estimeret til ca. 20 m/s, målt som en gennemsnitshastighed mellem bølgetop og platform.

Videoerne viste, at alle de store bølgeopløb skyldtes brydende bølger. Baseret på dette kan det fastslås, at større bølgeopløb er begrænset til steder med brydende bølger. I områder med brydende bølger skal bølgeopløb betragtes som et almindeligt fænomen og i mange tilfælde den betydende designlast for eksterne platforme og stiger.

### 1.2 **Fysiske modelforsøg**

Fysiske modelforsøg blev udført i DHI's forsøgsfaciliteter. Forsøgene blev udført i et lavvandsbassin med en 3D bølgemaskine. Bassinets bund var horisontal, og vandstanden blev holdt konstant på 0,4 m. Der blev anvendt fase- og retningsfokuserede bølger i forsøgene. Bølgerne blev målt med bølgemålere placeret rundt om fundamentet og på forsiden af fundamentet. Fundamentet bestod af en plastcylinder med en ydre diameter på 0,164 m.

De horisontale laster på fundamentet blev målt med en 2D kraftmåler. Der blev udført forsøg med og uden erosionsbeskyttelse. Erosionsbeskyttelsen bestod af en krydsfinerblok med form sammenlignelig med formen af en typisk erosionsbeskyttelse.

For at opnå brydende bølger på den horisontale bund blev der anvendt fase- og retningsfokuserede bølger. Fasefokusering af bølger finder sted, når to eller flere bølgetoppe mødes i det samme punkt på grund af forskellig hastighed, og danner en, men større, bølge. Retningsfokusering af bølger er et tilsvarende fænomen, men her skyldes det bølger fra forskellige retninger, som mødes i samme punkt. Brugen af kombineret fase- og retningsfokuserende bølger giver en god kontrol over brydningspunktet, en nem måde at ændre for eksempel brydningspunktet i forhold til fundamentet. Desuden inkluderer de fase- og retningsfokuserede bølger nogle effekter af bølger fra forskellige retninger (3D bølger).

Bølgerne blev målt i et tæt net rundt om pælen ved brug af traditionelle bølgemålere.



Bølgeopløbet blev målt med en traditionel konduktivitsbølgemåler monteret direkte på pælen og ved hjælp af et højhastighedskamera. Højhastighedskameraet var nødvendigt af to årsager: bølgeopløbet tager i størrelsesordenen 0,1 s, og den traditionelle konduktivitsbølgemåler er ikke i stand til at måle det tynde vandlag i bølgeopløbet korrekt. Det var dog muligt at måle bølgeopløbet med stor præcision ved hjælp af højhastighedskameraet, og disse resultater blev anvendt til at kalibrere konduktivitsbølgemåleren med.

Resultatet af de fysiske modelforsøg var:

- Det maksimale bølgeopløb var ca. 1,8 gange vanddybden
- 3D bølger synes ikke at have nogen betydning sammenlignet med 2D bølger
- Erosionsbeskyttelsen synes ikke at have nogen betydning for bølgeopløbet på grund af store bølger
- Bølgeopløbets højde og vertikale hastighed er sammenlignelig for model og fuldskala

### **1.3 Numeriske modelforsøg**

Udvalgte forsøg fra de fysiske modelforsøg er reproduceret i en numerisk simulering ved hjælp af DHI's state-of-the-art FV/VOF CFD model (NS3). Beregningerne blev foretaget med et domæne med de samme geometriske dimensioner, som blev brugt til de fysiske modelforsøg. Det numeriske domæne bestod af 1,4 millioner netpunkter.

De numeriske simuleringer er i stand til at reproducere de fysiske modelforsøg, hvis det anvendte net er fint nok. Specielt nettet på overfladen af pælen skal være meget fint for at kunne opløse den tynde film af vand i bølgeopløbet. Det er muligt at beregne opløbet inden for 10% af resultaterne fra de fysiske modelforsøg, når der anvendes en netstørrelse på 2 mm nær pælens overflade.

### **1.4 Test af afværgeforanstaltninger**

Betydningen af platformens udformning er blevet undersøgt ved fortolkning af fysiske modelforsøg gennemført af DONG Energy og Aalborg Universitet. Disse forsøg blev finansieret af DONG Energy i forbindelse med designet af Horns Rev 2 Vindmøllepark. Resultaterne af forsøgene er stillet til rådighed til fortolkning som en del af dette projekt. Resultaterne fra de fysiske modelforsøg gennemført på DHI, som er en del af dette PSO-projekt, indgår ligeledes i analysen og fortolkningen.

Under forsøgene blev betydningen af platformens udformning undersøgt, trykket på såvel en konisk platform som en plan platform blev målt. Yderligere blev betydningen af hvorvidt platformen var konstrueret af massive plader eller riste undersøgt.

Resultatet viste, at en konisk platform gav anledning til væsentlig mindre laster end en plan platform. Endelig viste forsøgene, at anvendelse af riste frem for massive plader kan reducere lasterne på en platform med op til en faktor 5.



## 1.5 **Retningslinjer for bølgeopløb på monopæle**

Baseret på resultaterne fra projektet kan følgende retningslinjer for bølgeopløb opstilles:

- Bølgeopløb skal hovedsageligt tages i betragtning i områder med brydende bølger
- Det maksimale bølgeopløb estimeres til mere end 2 gange den lokale vanddybde
- Hastigheden af fronten af bølgeopløbet kan estimeres til ca. 20 m/s

Disse retningslinjer kan bruges i forbindelse med design af offshore vindmøllefundamenter af monopæl typen. Det anbefales dog at verificere designet i en fysisk eller numerisk model, da bølgeopskyllet afhænger af lokale hydrografiske og konstruktionsmæssige forhold.



## 2 SUMMARY

The objective of the project was to:

- Determine the maximum run-up on the turbine foundations (monopiles)
- Determine the velocities along the foundation
- Test possible methods to reduce the run-up

### 2.1 *Full-scale Measurements at Horns Rev I Wind Farm*

The run-up at Horns Rev I Wind Farm was estimated on the basis of two videos of approximately 20 minutes each. The videos were taken on 22-12-2004 and 19-01-2005 during relatively normal winter conditions. The number of run-ups large enough to reach the platform located in 9 m (MSL) was counted. The results of this are that approximately 15 run-ups/hour hitting the platform can be expected on each turbine. On the basis of the videos the vertical velocity of the water in the run-up is estimated to be approximately 20 m/s, measured as an average velocity between the wave crest and the access platform.

The videos showed that all the major run-ups were caused by breaking waves. Based on this it can be concluded that the problem with major run-ups is limited to areas with breaking waves. However, in areas with breaking waves the run-up should be considered a common phenomenon and in many cases the most important load case for external platforms and ladders.

### 2.2 *Physical Model Tests*

Physical model tests were carried out in the test facilities at DHI. The tests were conducted in a shallow water basin equipped with a 3D wavemaker. The bottom of the basin was horizontal and the water level was kept constant at 0.4 m. Phase and directional focused waves were used for the experiments. The waves were measured by wave gauges around the foundation and at the front of the foundation. The foundation was a plastic cylinder with an external diameter of 0.164 m.

The horizontal loads on the foundation were measured by a 2D force transducer. Tests with and without scour protection were carried out. The scour protection was made of a plywood block with the shape comparable to the envelope of a typical scour protection.

To obtain breaking waves on the horizontal bottom, phase and directional waves were used. Phase focusing of waves takes place when two or more wave crests meet at the same point because of different velocities, resulting in a single but larger wave. Directional focused waves are a similar phenomenon, but the reason is that waves from different directions meet at the same point. The use of combined phase and directional focused waves gives a good control of the breaking point, an easy way to change eg the breaking point relative to the pile and it includes some effect of waves from different directions (3D waves).



The waves were measured in a grid around the pile by traditional wave gauges.

The run-up was measured by use of a traditional conductivity wave gauge mounted directly on the pile and by use of a high-speed video camera. The high-speed camera was necessary for two reasons: the run-up takes place in the order of 0.1 s and the traditional conductivity wave gauge is not able to measure the thin layer of water in the run-up correctly. However, it was possible to measure the run-up with high precision by use of the high-speed camera and use these results to calibrate the conductivity wave gauge.

The main results of the physical model tests can be outlined as:

- The maximum run-up was approximately 1.8 times the water depth
- 3D waves appear not to influence the run-up compared with 2D waves
- Scour protection seems to have no effect on the run-up caused by large waves
- Run-up heights and vertical velocities in the model and full scale are comparable

## **2.3 Numerical Model Tests**

Selected tests from the physical model tests are reproduced in a number of numerical simulations using the state-of-the-art FV/VOF CFD model (NS3) by DHI. The calculation was using a domain with the same geometrical measures as the actual test area in the physical model tests. The numerical domain consists of 1.4 million grid points.

The numerical simulations are able to reproduce the physical model tests, if the applied grid is fine enough. Especially the grid spacing on the surface of the pile must be fine to be able to resolve the thin film of water in the run-up. It is possible to calculate the run-up within 10% of the physical model tests, when using a grid size of 2 mm near the pile surface.

## **2.4 Test of Deprecating Structure**

The influence of the shape of the platform has been investigated by interpretation of physical model tests carried out by DONG Energy and Aalborg University in corporation. These tests were financed by DONG Energy as part of the design for Horns Rev 2 Wind Farm. The results from the tests have been made available for interpretation as part of this PSO-project. The results from the physical model tests conducted at DHI, as part of this PSO-project, are also used in the analyses and interpretation.

The model tests measured the influence of the shape of the platform. The pressure on a conical shape as well as a horizontal platform was measured. In addition the influence of the solid plating or grating for the construction of the platform was tested.

The result showed that a conical platform could reduce the loads significantly compared to a horizontal platform. Finally, the tests showed that the use of grating instead of solid plates can reduce the load on the platform by up to a factor of five.





## **2.5 Guidelines for Wave Run-up on Monopiles**

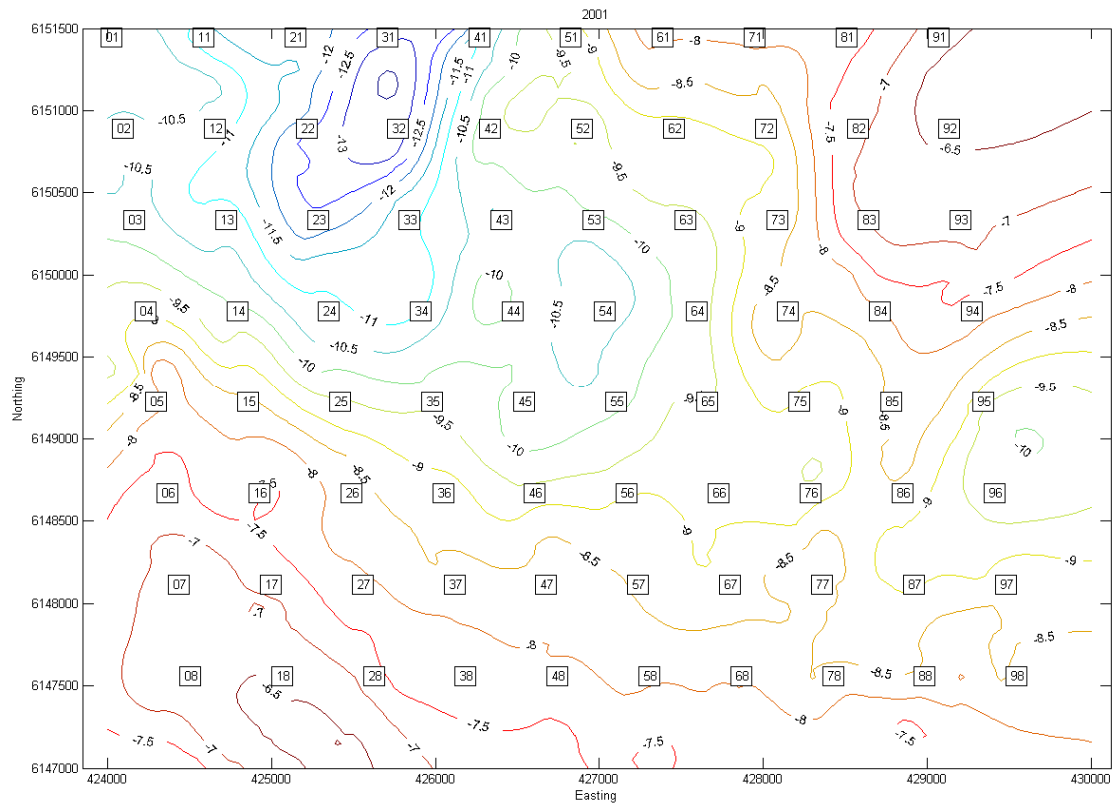
Based on the results of the project the following guidelines for wave run-up can be outlined:

- Wave run-up shall mainly be considered in areas with breaking waves.
- The maximum wave run-up is estimated to more than twice the local water depth.
- The speed of the front of the wave run-up can be estimated to approximately 20 m/s.

These guidelines can be used in connection with the design of offshore wind turbines foundations of the monopile type. However, it is recommended to verify the design in a physical or numerical model because of the local hydrographical conditions and actual detailed construction.

### 3 FINAL REPORT

The Horns Rev I Wind Farm is located in the North Sea off the Danish west coast. It is located on relatively shallow water (6.5-13 m water depth), see Fig 3.1. The wind farm is exposed to severe waves including breaking waves and strong currents.



*Fig 3.1 Bathymetry in the Horns Rev I Wind Farm in 2001 (before installation of the turbines). Water levels are relative to mean sea level (MSL). The numbers in the squared boxes represent the turbines.*

The wave run-up on the Horns Rev I wind turbine foundations has been heavily underestimated. This has caused damages to ladders and external platform leading to significant extra costs. The main objective of the project was to obtain a better understanding and knowledge about the wave run-up so that future offshore wind farms can be designed correctly for wave run-up. It has been reported that the turbines on the shallowest part of the wind farm have suffered the worst damages.

Wave run-up was not considered in the original design of the external platforms. It was, in the original design, assumed that the platforms were located in so high elevation that they would not be influenced by any hydrodynamic loading.



The project consists of four parts:

- Part 1 – Analysis of the Horns Rev Run-up
- Part 2 – Physical Model Tests of Run-up
- Part 3 – Numerical Model Tests of Run-up
- Part 4 – Test of Deprecating Structure

Each part is described in the next sections.

### **3.1 Part 1 – Analysis of the Horns Rev Run-up**

The aim of this part of the project was to make an analysis of the videos of the wave run-up on the Horns Rev I wind turbines, see Fig 3.2 After the installation of the Horns Rev I Wind Farm damages were observed on many of the boat landings and access platforms at the foundations. Video recordings from the wind farm showed that the damages most likely were caused by unexpectedly large wave run-up. In order to determine the potential of damages caused by wave run-ups the number of severe run-ups was counted. A severe wave run-up was defined as a run-up large enough to reach the access platform located 9 m above mean sea level (MSL).

The wave conditions and water levels for the two events are found by numerical simulations. The results are listed in Table 3.1.

*Table 3.1 Wave conditions and water level for the two videos.*

Event (date)	$H_s$ [m]	$T_p$ [s]	Water level relative to MSL [m]
12 Dec 2004 - 10 to 11	3.8	8.9	1.1
19 Jan 2005 – 15 to 16	2.0	9.0	0.6

This work is described in Section 3.4.



*Fig 3.2 Example of severe run-up at a Horns Rev wind turbine. Photo by courtesy of Vattenfall and DONG Energy*

### **3.2 Part 2 – Physical Model Tests of Run-up**

The aim of this part was to reproduce the wave run-up observed at Horns Rev I Wind Farm by use of a physical model, see Fig 3.3. Several conditions were tested. Different wave steepnesses, influence of the scour protection, and the effect of wave approaching from multiple directions. This work is described in Section 3.4.



*Fig 3.3 Run-up in the physical model. A plywood base with the envelope of a typical scour protection is applied to study the effect of the scour protection.*

### **3.3 Part 3 – Numerical Model Tests of Run-up**

The aim of this part was to develop a numerical model capable of simulating the wave run-up on a pile in a domain of the same size as the actual size of the physical model test area. The experimental results from the physical model tests are used for comparison. This work is described in Section 3.5.

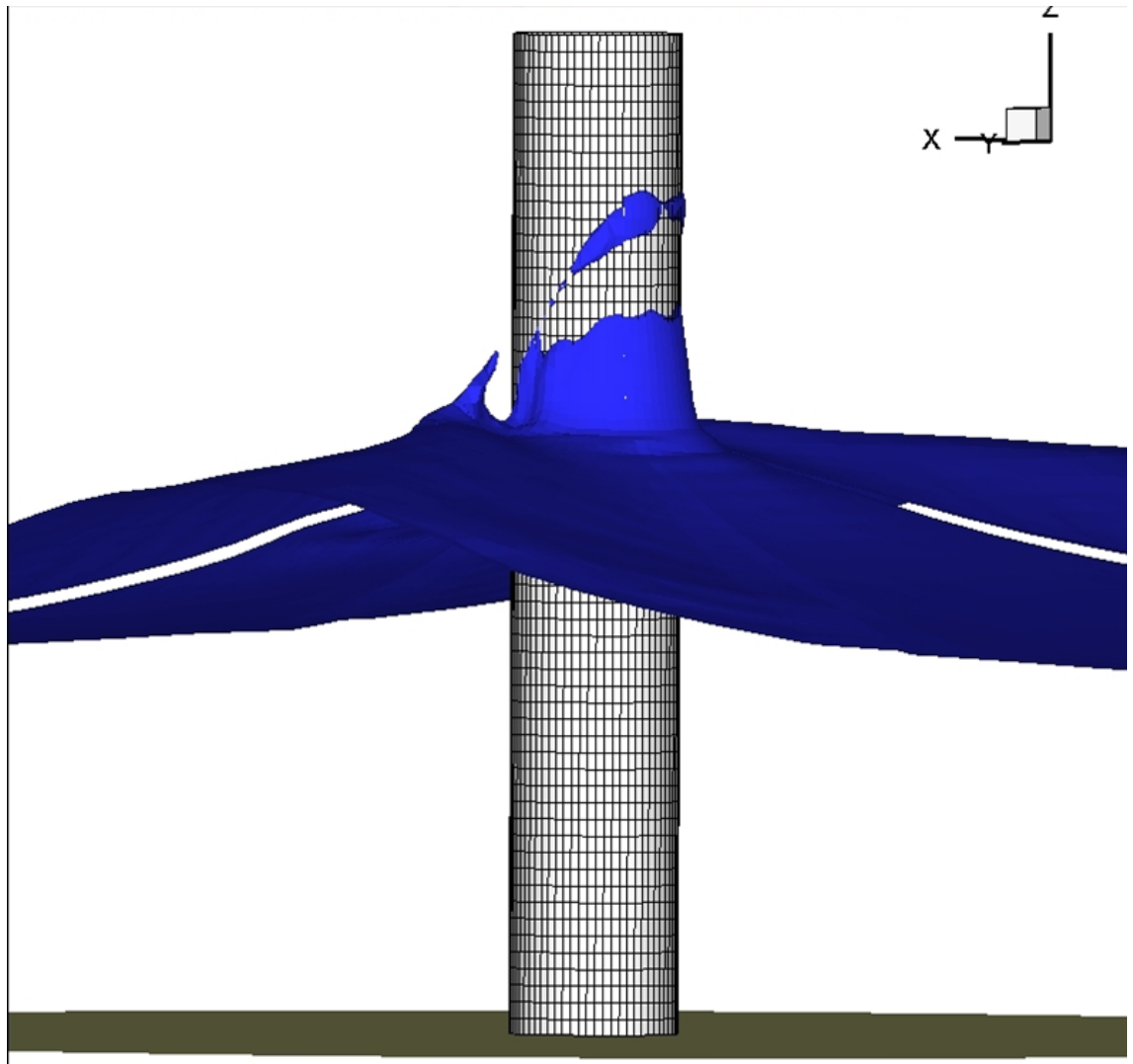


Fig 3.4 Run-up in the numerical CFD simulation.

### 3.4 Part 4 – Test of Degrading Structures

The aim of this part was to investigate possible ways to reduce the loads on the platform. Two different ways were investigated: To use a conical shaped platform instead of the plane platform and to see the effect of using grating for the platform deck instead of solid plating. A picture of the model of the platform is shown in Fig 3.5. The work is described in Section 3.7.



*Fig 3.5 The conical shaped platform tested by DONG Energy and Aalborg University.*



**3.5 “Wave Run-up on a Wind Turbine Foundation” – Paper from EOW 2007**



# Wave Run-up on a Wind Turbine Foundation

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## Summary:

After the installation of the offshore wind farm Horns Rev I in the North Sea, 20 km from the west coast of Denmark, the access platforms have suffered damage during severe wave conditions. The damage appears to be due to wave run-up on the foundation pile leading to excessive slamming forces on the access platform. In recent years intensive work has been carried out to understand and to quantify the run-up phenomenon. In this paper the results of 3D physical model tests are presented and compared with video recordings of wave run-up on the Horns Rev I Wind Turbines.

## Abstract:

The paper presents the results of an investigation of the wave run-up on offshore wind turbine monopile foundations. The paper includes the results of an analysis of the wave run-up at the offshore wind farm "Horns Rev I" situated on the west coast of Denmark. The number of large run-ups is determined during two short periods (approximately 20 minutes) in a seastate with a return period around 1 to 5 years. The vertical run-up velocity is estimated from the videos.

3D physical model tests of the wave run-up on a monopile foundation have been conducted to reproduce the run-ups seen on the Horns Rev I. The effect of wave breaking and three-dimensional waves has been the main subject for the project.

Results of the investigations show that the wave run-up at Horns Rev I is a relatively common phenomenon and it must be taken into account. The model tests show that the run-up may reach as high as 1.8 times the water depth.

**Keywords:** wave run-up, high speed video measurements, 3D waves.

## 1 Introduction

During the last years, the interest of developing offshore wind turbines has increased significantly as the wind turbines have increased in size and numbers and it has become more difficult to find

new good locations onshore. The offshore wind turbines are located at relatively shallow waters, where the foundations are often exposed to large breaking and near breaking waves.

After the installation of the Horns Rev I, one of the first offshore wind farms exposed to a harsh environment like the North Sea, the wave run-up showed to be of major importance. Major damages to the access platforms and ladders have been caused by wave impacts. Videos from the area have shown that the wave run-up may reach the access platform located 9 m above MSL, and that wave run-up of this size is relatively common during a normal storm.

To obtain a better understanding of the wave run-up a series of model tests was conducted. These model tests showed that the wave run-up may reach 1.8 times the local water depth, which corresponds with the observations from Horns Rev I.

## 2 Wave Run-up on the Horns Rev Wind Turbines

The wind turbines at Horns Rev are monitored by video cameras. Two short videos have been analysed with relation to wave run-up. The videos are taken 22-12-2004 (approx. 20 minutes) and 19-01-2005 (approx. 25 minutes).

The videos are taken during periods with harsh weather, but the exact environmental conditions are not known. However, the seastate can be estimated on the basis of the videos. In both cases the significant wave height is around 2 to 3 m and the peak period is 5 to 7 s. The waves on 19-01-2005 seem to be a little higher and with longer periods than the waves on 22-12-2004. The water level at the 22-12-2004 event is estimated to be around MSL, while it was approximately 0.5 to 1 m lower at the 19-01-2005 event. For comparison the 10 year wave condition for the area is around  $H_s = 5.0$  m and  $T_p = 8.0$  s.

An example of a severe run-up is shown in Figure 1. The number of run-ups hitting the first wind turbine in the row has been found from reviewing the two videos. Only run-ups large enough to hit the platform (+9 m MSL) are counted. The wind turbine was hit by such a

large run-up 4 times during the 20 minutes video from the 22-12-2004 event and 7 times during the 25 minutes video from the 19-01-2005 event. Based on the above observations it can be concluded that large run-ups are common at locations like Horns Rev and that larger run-ups shall be anticipated several times for each foundation during a typical storm situation.



Figure 1: Example of severe run-up at a Horns Rev wind turbine, Vattenfall and DONG Energy.

The videos from Horns Rev I confirm that the wave breaking played a major role for the wave run-up as reported by e.g. H Mase et al. [1]. All the major wave run-ups were caused by breaking or almost breaking waves, while the non-breaking waves cause no or only very limited run-up. The videos show that the non-breaking waves either pass the foundation more or less undisturbed or reflect on the foundation, depending on the wave steepness. Waves with a low steepness will pass undisturbed, while steeper waves will have a relatively high reflection on the surface of the foundation.

### 3 Physical Model Tests with the Wave Run-up on Wind Turbines

The model tests were designed to give a better understanding of the wave run-up phenomena and were not directly related to any prototype case. However, the foundation diameter, wave heights, wave periods, etc. are comparable with the Horns Rev I in the scale 1:25. Bathymetry was kept horizontal all over the test area.

#### 3.1 The Test Set-up

The tests were conducted in a 3D shallow water basin equipped with a 3D wavemaker. The bottom of the basin was horizontal and the water

level was kept constant at 0.4 m. Phase and directional focused waves were used for the experiments. The waves were measured by wave gauges around the foundation and at the front of the foundation. The foundation was a plastic cylinder with an external diameter of 0.164 m. The foundation was marked with horizontal strips for every 1 cm, see figure 3.

The horizontal forces on the foundation were measured by a 2D force transducer. Tests with and without scour protection were carried out. The scour protection was made of a plywood block with the shape comparable to the envelope of a typical scour protection.

The wave field around the foundation was measured by conductivity wave gauges. The wave gauges were set up in a close pattern around the foundation as illustrated in figure 2. Since the waves are symmetric around the mean direction the wave gauges were concentrated along the symmetry line and on one side of the symmetry line.

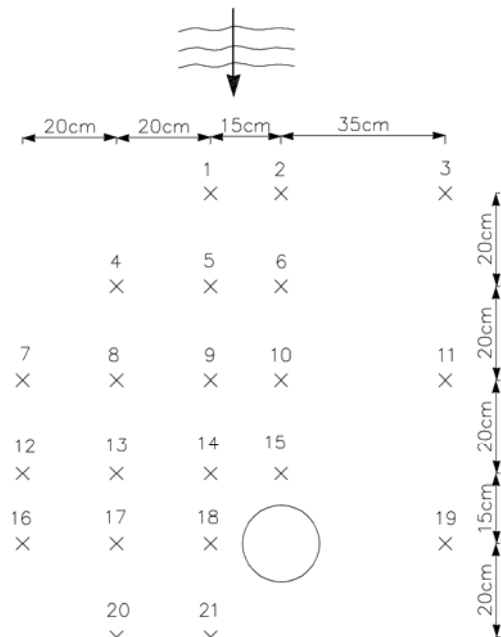


Figure 2: The positions of the wave gauges relative to the foundation. Wave gauges 15 and 18 were only used for the reference measurements (without foundation tower). The mean wave direction is indicated as well.

#### 3.1.1 High Speed Camera

To obtain a detailed picture of the wave run-up at the foundation a high speed video camera was used. The camera was an Olympus i-SPEED high speed camera, recording 600 fps. This record frequency is sufficient to get sharp

undisturbed frames.

### 3.1.2 Support of the Foundation Tower

The foundation tower was hung off a supporting structure. The supporting structure was placed approximately 0.5 m behind the foundation. This distance was sufficient to eliminate reflections from the support structure in the measuring period. A two component force transducer was applied between the support structure and the foundation. A gap of 1 to 2 mm between the foundation and the bottom/scour protection was maintained. The set-up without scour protection is shown in figure 3.

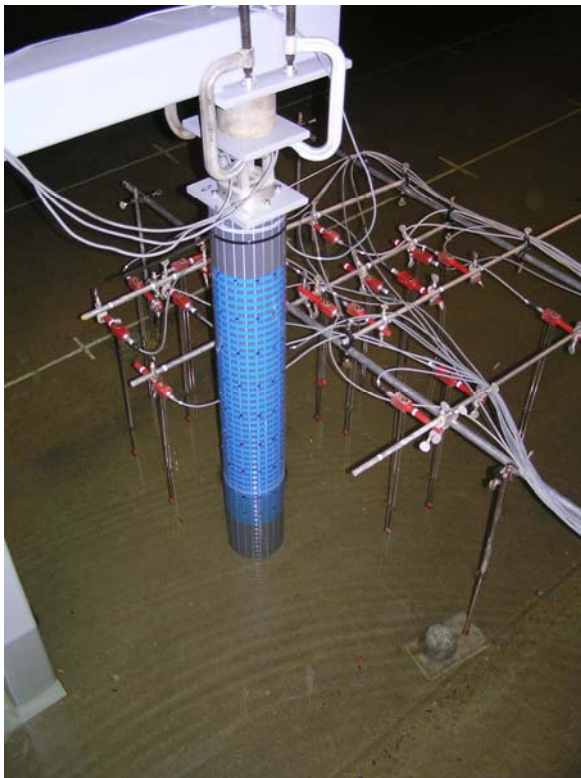


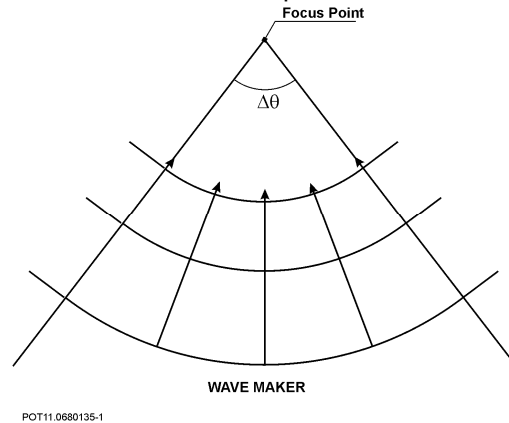
Figure 3: The foundation, wave gauges, and part of the support

### 3.2 The Phase and Directional Focused Waves

A focused wave is characterised by moving towards one point where the wave becomes very high. Each part of a wave front moves towards the same point (directional focusing) and the wave front behind moves faster than the wave ahead, so they also meet in the focus point (phase focusing). See also figure 4.

Although this kind of waves is not found in nature, it is very convenient and well suited for the purpose: It allows good control of the breaking point on a horizontal bottom, includes some 3D effects and the use of single events, which reduces problems with reflected waves and other disturbances.

The focused waves are characterised by: Maximum wave height,  $kh$  for the highest wave, the focus point (distance to the foundation) and the angle,  $\Delta\theta$ , between the ends of the waves, see figure 4, where  $k$  is the wave number and  $h$  is the water depth. The different wave components in the focused wave are chosen to fit a usual JONSWAP spectrum



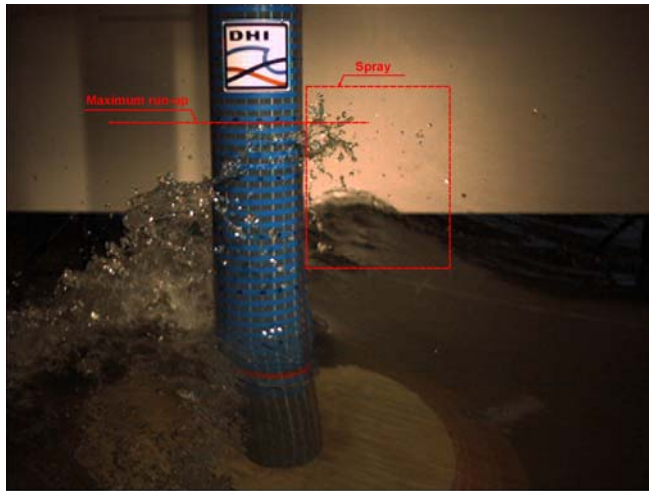
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Figure 4: Definition of the phase and directional focused waves used for the physical modelling.

### 3.3 Measuring Wave Run-up

The wave run-up is characterised by being a very fast event. In the laboratory it takes place in the order of 0.1 s. The high speed in the run-up combined with thin layers of water and disturbances like high turbulence, air entrainment, and water spray make exact measurements of the run-up difficult. In the present study two methods have been used: A high speed camera, see Section 3.1.1, and a conductive wave gauge at the front of the foundation. The wave gauge at the front of the foundation was measuring too small run-up due to the low conductivity in the thin layer of water in the run-up. The analysis of the high speed videos has to be done manually leading to some subjectivity in the results. However, the method is regarded as rather exact, around  $\pm 2$  cm.

The high speed videos were analysed for the highest run-up. The run-up is defined as the highest point of the water which is part of a continuous water sheet in full contact with the pile starting at the actual water surface. Small individual water spots in contact with the pile, free droplets, etc. are not regarded as run-up. Run-up and spray is defined in figure 5. This definition of run-up corresponds to the definition used in other tests e.g. [2].



Plot7.07.80135-3.sdr

Figure 5: Definition of run-up and spray.

### 3.4 Calibration of the Wave Gauge at the Front of the Pile

The conductivity wave gauge is a widely used wave gauge. But in the case of wave run-up the thin layer of water at the tongue of the wave run-up will provide smaller electrical conductivity

compared to larger volumes of water, as for example a usual non-breaking wave. For this reason the wave gauge at the front of the pile shall not be calibrated linearly as other wave gauges. If the run-up gauge is calibrated linearly the run-up gauge will measure too small run-ups. Figure 6 shows the run-up measured from the high speed videos as a function of the run-up measured by the wave gauge. The full-drawn line is the parabolic calibration curve, while the dashed curve is the traditional linear calibration curve. For small waves a linear calibration is used as run-ups for these small waves do often not exist or are very small compared to the wave height. Therefore the measurements for these small waves are not affected by a thin water layer in the run-up.

The difference between the linear calibration curve and the parabolic curve is in the present results up to approximately 20 cm or 35% for the highest waves. This is a significant difference and it is very important to account for this effect in model tests.

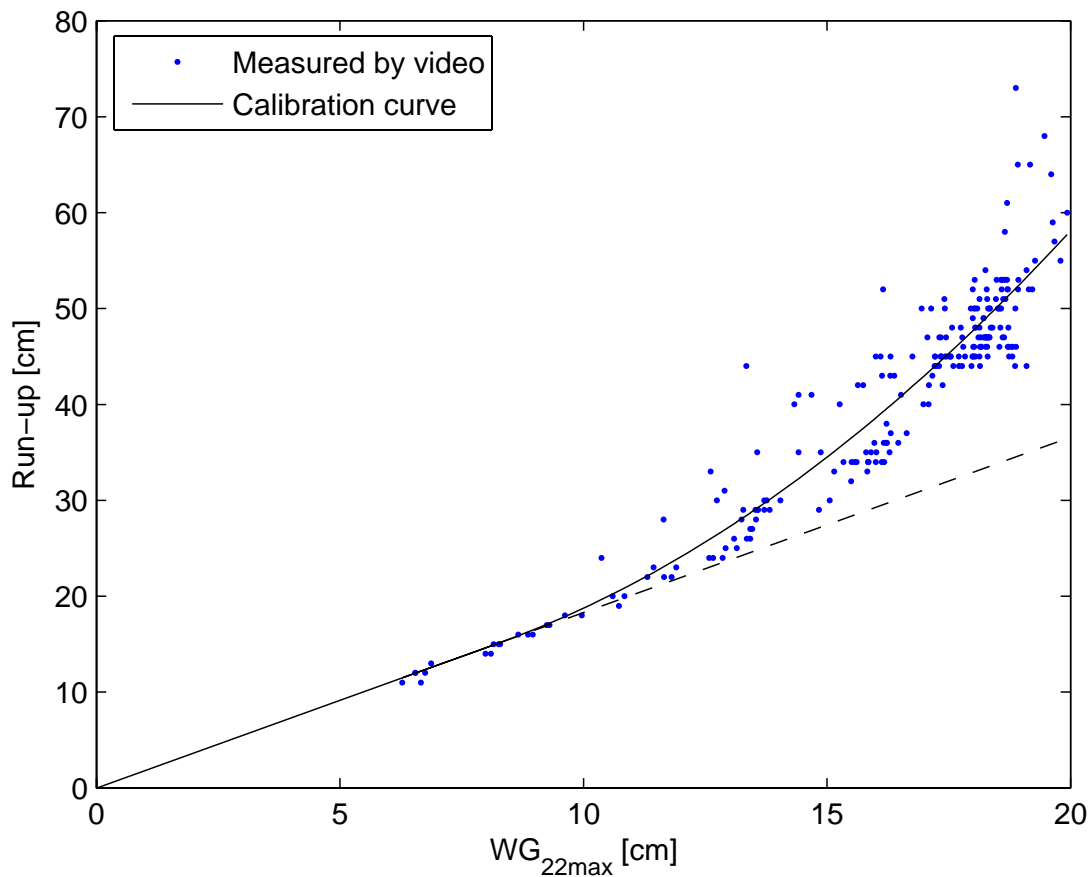


Figure 6: The parabolic calibration curve compared with the linear calibration curve (dashed).

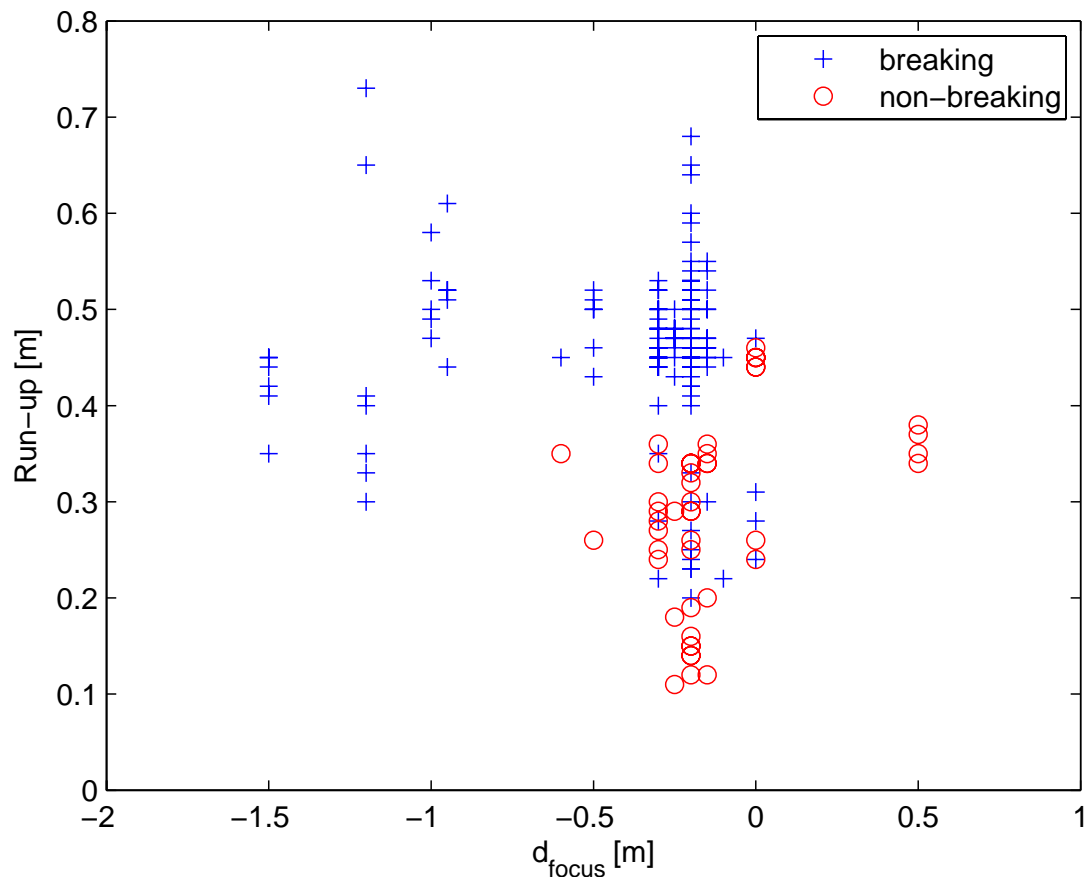


Figure 7: Run-up height versus distance from foundation to the focus point. The foundation is located at 0 m. The waves are progressing in the positive direction.

### 3.5 Results

The aim of the model tests was to obtain a better understanding of the influence of 3D waves and to determine the maximum run-up. During the tests the following parameters were varied: Angle between the outermost waves,  $\Delta\theta$ , the wave number,  $k$ , the maximum wave height,  $H$ , and the distance from the focus point to the foundation. The maximum wave height was in most of the tests kept constant in order to let the wave break near the focus point. A small wave would not break and a large wave would break at the wave generator. As the maximum wave height is kept constant for almost all the tests with breaking waves the distance between the focus point and breaking point will be almost constant for most of the tests and changes in the distance between the focus point and the foundation can then be taken equal to the changes in the distance from the breaking point and to the foundation.

Figure 7 shows the run-up height for different focus distances relative to the foundation. It is determined by visual inspection whether the waves are breaking or not. From the figure it is

seen that the run-up becomes significantly higher if the wave is breaking. The exact breaking point is of less importance, as long as the wave still contains enough energy.

#### 3.5.1 Influence of the Scour Protection

Numerical simulations have shown that the scour protection might have an influence on the run-up, mainly for small waves, while the effect is small for larger waves.

The result of the tests with and without scour protection is shown on figure 8. The figure shows that the run-up is more or less the same for the two situations as expected on the basis of the numerical simulations. However, there is a small tendency to have a larger run-up without scour protection. It might be explained by reflections of energy at the scour protection. However, the higher run-up is not very significant and might also be caused by uncertainties and the random nature of the run-up. It shall be noted that the scour protection was included as a solid structure with a shape of the envelope of a typical scour protection.

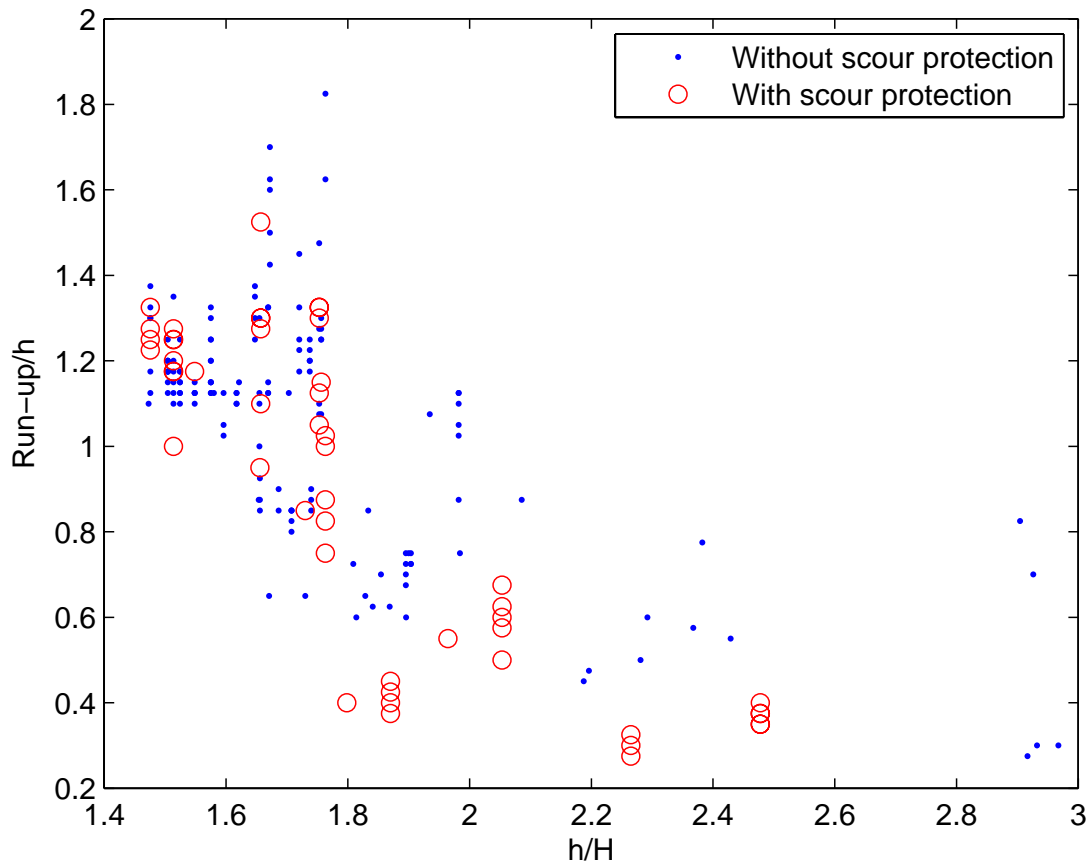


Figure 8: Run-up on the foundation with and without scour protection.

### 3.5.2 Velocities of the Run-up

The vertical velocity of the wave run-up has been determined on the basis of the run-ups measured by the wave gauge mounted on the foundation. Figure 9 shows the run-up as a function of the maximum vertical velocity in the power of two together with a curve representing a “free fall”. A free fall assuming that the mass of the moving body is constant and that the body is not losing or gaining any energy. The maximum run-up assuming free fall is expressed as:

$$r = wt - \frac{1}{2}gt^2$$

By differentiation the maximum run-up is found as:

$$r_{max} = \frac{1}{2} \frac{w^2}{g}$$

Figure 9 shows that the run-up almost follows the “free fall” for small run-ups while the run-up becomes much smaller for higher velocities than predicted by the free fall approach. There seems to be two explanations for that: The friction between the water and foundation will increase with increasing velocity and the loss of energy

and mass because of spray is much more important for the higher run-ups.

The videos from Horns Rev show that the run-ups have a vertical velocity of approximately 20 m/s. If it is assumed that a Froude scaling is valid for the actual case and that the model tests are carried out in a scale 1:25 of the Horns Rev Wind Farm, the model tests and the full-scale wind turbine can be compared. 20 m/s in full scale is equal to 4 m/s in model scale. Using figure 9 the run-up above maximum wave elevation in model scale is then between 0.3 m and 0.4 m or 7.5 m to 10.0 m in full scale. The maximum wave elevation seen on the video is approximately 2 m above MSL. Even though the water has to pass through the grating in the access platform it reaches a level approximately 2 m above the platform. The platform is placed 9 m above MSL, so the run-up above maximum wave elevation is 9 m. However, if the platform has not blocked the run-up it would probably have been more than 10 m. Taking the uncertainties of these results into account the conclusion is that the model tests are in good correlation with the full-scale situation.

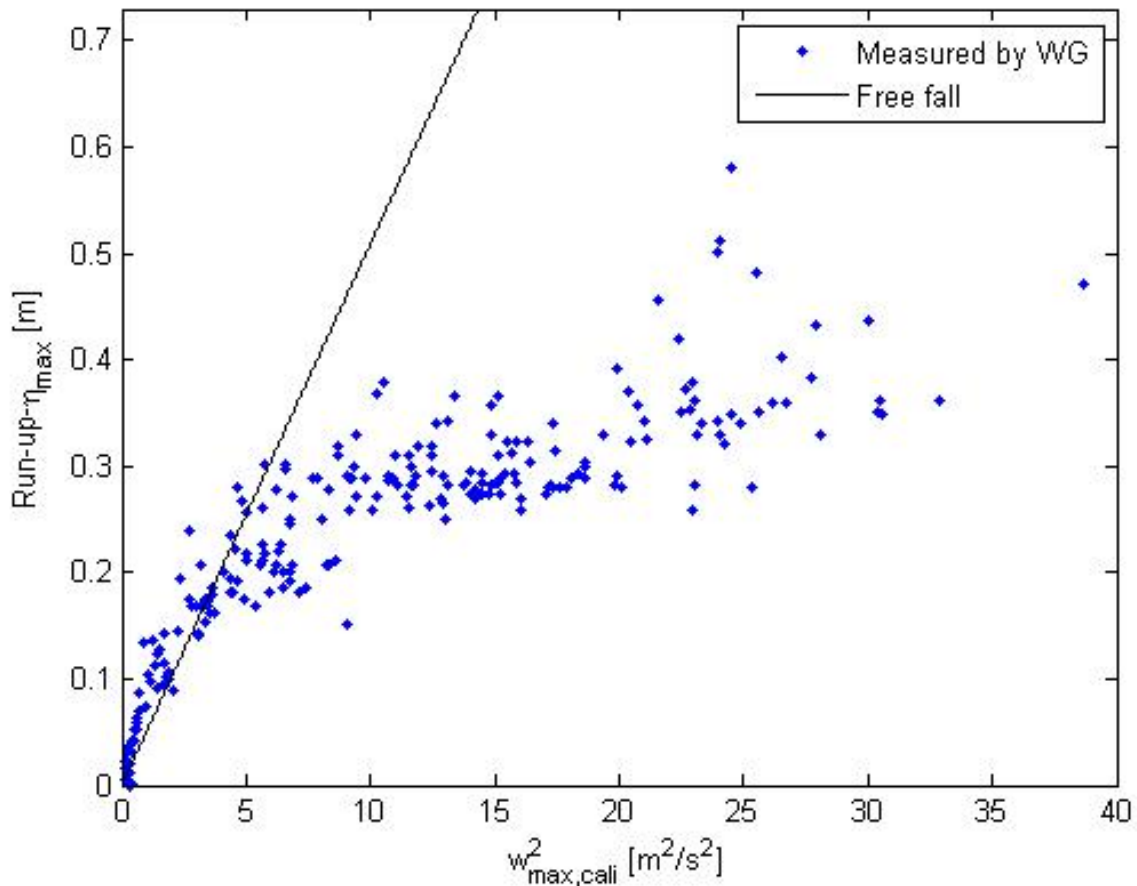


Figure 9: Run-up versus the maximum vertical velocity in the power of two.

### 3.5.3 Comparison with 2D Results

A set of comparable physical model tests was conducted by Aalborg University (AAU) for DONG Energy [3]. The tests were carried out in a wave flume with a sloping bottom using irregular waves (JONSWAP spectrum).

The foundation was placed on a horizontal bottom 12.7 cm above the level of the wavemaker. The wavemaker level and the foundation level were connected by a 1:98 slope. The wave run-up was measured by conductivity wave gauges similar to the one used in the above 3D model tests. However, the wave gauges were calibrated using a traditional linear calibration, which does not take the effect of the thin layer of water into account. It should be mentioned that the effect of the underestimation of the run-up was of minor importance for the original purpose of the tests.

Figure 10 shows the results of the DHI tests measured from high speed video and measured by use of linear calibrated wave gauge together with the results from AAU. As expected the run-up measured by video is much larger than the AAU data measured by wave gauge. Of more interest is that the run-up measured by DHI using linear calibrated wave gauge and the similar result from AAU is fully comparable.

By comparing the results in figure 10 with the 2D results presented in [1] it is seen that the run-ups measured by high speed video fit very well with these results. The run-ups obtained by AAU fit well for small run-ups (values of  $h/H$  larger than approximately 3).

The conclusion of this is that the effect of 3D waves appears to be small for the magnitude of the run-up.

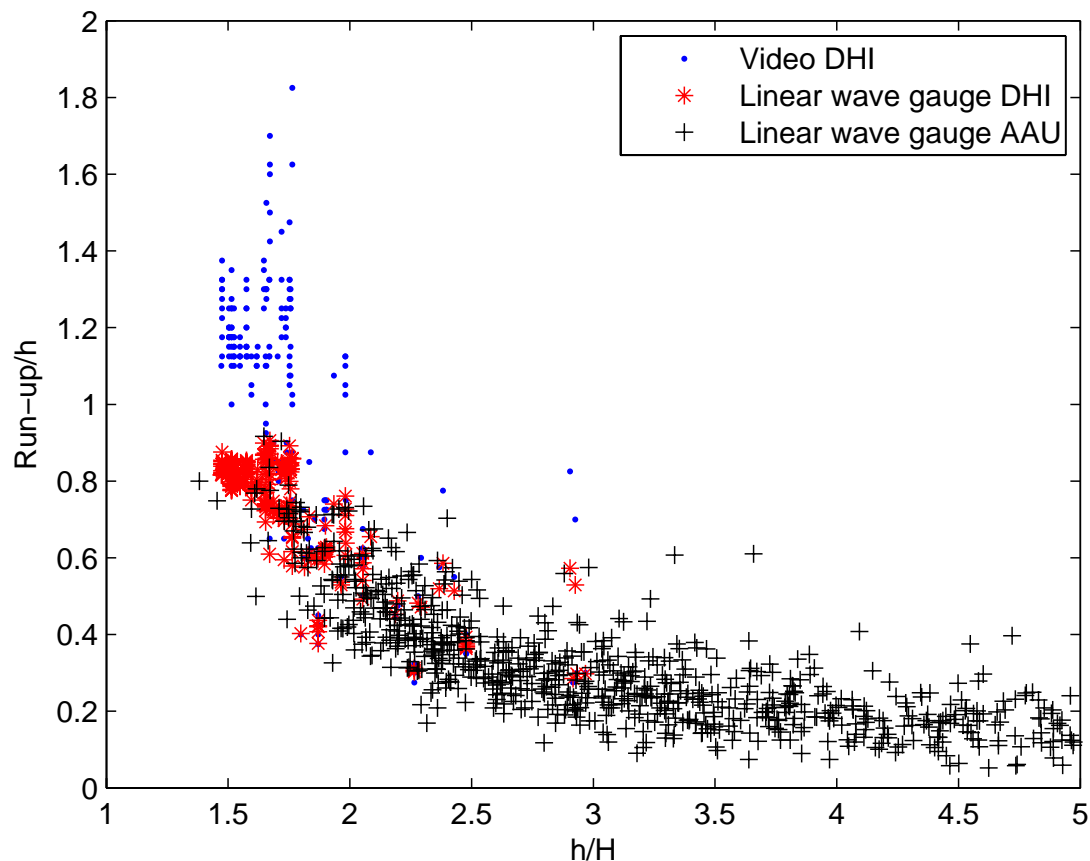


Figure 10: The measured run-up heights for the DHI tests (measured from the high speed video and by linear calibrated wave gauge) and comparable tests conducted at Aalborg University. The foundation used by AAU was 0.1 m in diameter and the local water depth was 0.2 m giving  $h/D=2.0$  for the AAU tests.  $h/D=2.4$  was used for the DHI tests. Irregular waves with  $T_p=1.60$  s and  $H_s=0.075$  m were used for the AAU tests.

## 4 Conclusion

From videos recorded at the Horn Rev I wind farm it is seen that wave run-up high enough to reach the access platform located 9 m above MSL is a common phenomenon. The run-up can be expected to reach the platform several times a year for each foundation.

The physical model tests have been designed in order to find the effect of: the extreme run-up, 3D waves, scour protection. Based on these physical model test results, it can be concluded that:

- The maximum run-up was approximately 1.8 times the water depth
- 3D waves appear not to influence the run-up compared with 2D waves
- Scour protection seems to have no effect on the run-up caused by large waves
- Run-up heights and vertical velocities in the model and full scale are comparable

## Acknowledgements

The financial support (1.0 mio. DKK) of the Danish Public Service Program (PSO) for PSO-R&D-project no. 2006-1-6426 is gratefully acknowledged.

The provision of on-site video records from Horns Rev I by Vattenfall and DONG Energy is gratefully acknowledged.

The provision of 2D model tests results by DONG Energy and Aalborg University is gratefully acknowledged.

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**3.6 “Numerical Modelling of Wave Run-up on a Wind Turbine Foundation” – Paper from OMAE 2008**

OMAE2008-57224

## NUMERICAL MODELLING OF WAVE RUN-UP ON A WIND TURBINE FOUNDATION

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### ABSTRACT

This paper presents the results of a CFD model of the wave run-up on a monopile. The monopile is widely used as the foundation unit for offshore wind turbines. The aim for the calculations is to make a detailed investigation of the effect of three-dimensional (3D) waves on the run-up and to determine the maximum wave run-up. The CFD results are compared with the results of physical model tests conducted under the same conditions. The model tests were conducted under idealized conditions: The tests were carried out on a horizontal bottom using phase and directional focused waves to obtain a 3D effect and at the same time being able to control the breaking. The key objective of this part of the numerical analysis is to develop a model capable of reproducing the results of the physical model tests.

### INTRODUCTION

During recent years, the interest of developing offshore wind turbines has increased significantly. The wind conditions offshore are favourable, and the turbines have increased in size and numbers and it has become more difficult to find new good locations onshore. The offshore wind turbines are often located in relatively shallow waters. Here, however, the foundations are often exposed to breaking and near-breaking waves and strong currents.

One of the major hydrodynamic challenges for the offshore wind turbines has turned out to be large breaking waves. These large breaking waves are now known to cause severe damages to the external access platforms and to boat-landings. It has been reported that access platforms located 9m above mean sea level have been hit and damaged by wave run-up under

conditions even where the air gap (wave crest elevation to platform distance) is very large, see Figure 1. It has been reported that grating at the access platform have been removed by the wave run-up and access ladders have been deformed at the Horns Rev Wind Turbines. A better understanding of the run-up is therefore necessary to be able to make a reliable and cost-effective design of the platforms and ladders. The important parameters for the design are the maximum run-up height and the associated forces on the structure. This paper is concentrated on the run-up height.

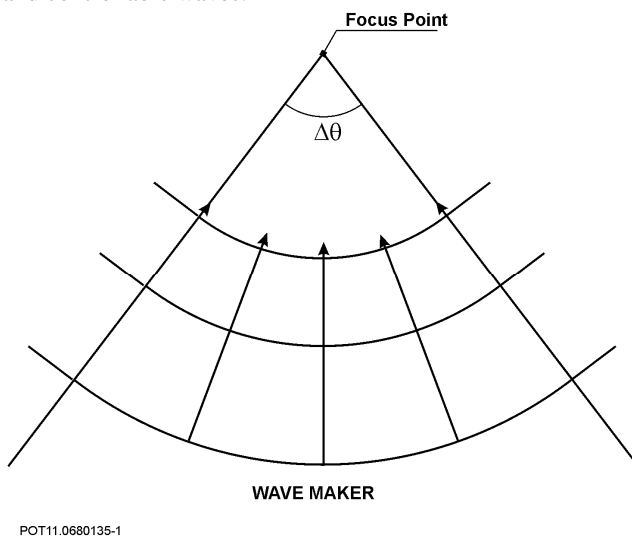


**Figure 1** Example of severe run-up at a Horns Rev wind turbine, Vattenfall and DONG Energy.

## TEST SET-UP

The test set-ups for the numerical and the physical tests were as similar as possible. The bathymetry was in both cases kept horizontal. The water depths were 40cm and the diameter of the foundations was 16.4cm.

In order to obtain a breaking wave on the horizontal bottom, a phase and directional focused wave was used. Figure 2 shows the principle of the phase and directional focused wave. Due to the curvature of the wave fronts, the energy in every single wave will be concentrated over a very short wave front at the focus point. The wave field consists of waves with different celerities. The celerity of each wave component is determined to ensure that all the waves reach the focus point at the same time. This makes it possible to generate large, steep and controllable waves.



**Figure 2** Definition of the phase and directional focused waves used for the modelling.

The following parameters were applied for the physical and numerical tests:

- Angle between the outermost waves:  $\Delta\theta=45^\circ$
- Theoretical wave at the focus point: 30cm
- The distance from the focus point to the centre of the foundation was different for the two tests. The distance was 0.2m in the physical model test, while it was 1.2m in the numerical model test, both in front of the foundation.

The reasons for the relative large difference in focus distance can be: The wave breaking in the numerical model is very sensitive to the grid spacing. Both a focus distance of 0.2m and 1.2m have been used in the physical model tests and it is found that the wave with focus point 0.2m in front of the cylinder fitted very well with the numerical simulation with focus point 1.2m in front of the foundation. Just in front of the breaking point of the wave with focus distance 1.2m, the

difference in wave height was approximately 2cm. For comparison, the vertical grid spacing in the numerical model is 1.58cm. In Figure 6 it is seen that the wave height in general is slightly under-predicted by the numerical model.

The boundary conditions were different for the physical and numerical model tests: the physical model tests used a piston type wavemaker with a first order Navier-Stokes signal, while the numerical model test used a first order Navier-Stokes signal with depth variations.

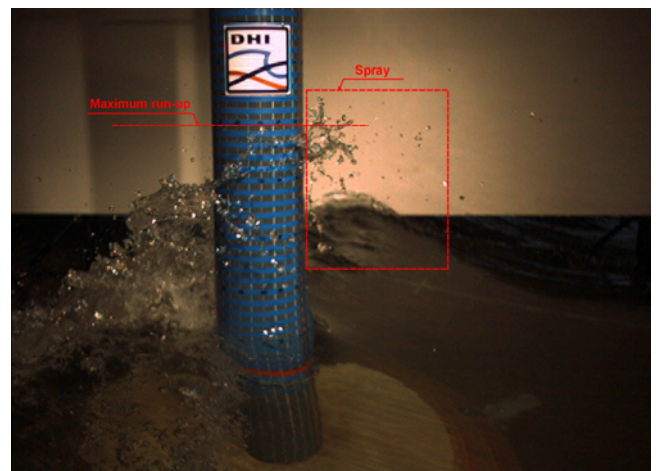
The cut off frequency was 2.0Hz and 0.91Hz for the physical model and the numerical model tests, respectively. However, the effect of this is minor as only a small amount of energy is present between 0.91Hz and 2.0Hz in the physical model tests, see Numerical Model Set-up. The total amount of energy was the same in the physical and numerical tests.

## MEASURING THE RUN-UP

The wave run-up is characterised by being a very fast event. In the present model tests, it takes place within approximately 0.1s. The high speed in the run-up combined with thin layers of water and disturbances like high turbulence, air entrainment, and water spray make exact measurements of the run-up difficult, especially in the physical model.

In the present study, a high speed video camera was used to capture the run-up and determine it manually. The manually measuring of the run-up heights lead to some subjectivity in the results. The method is regarded, however, as rather exact, around  $\pm 2$ cm.

The high speed videos were analysed for the highest run-up. The run-up is defined as the highest point of the water, which is part of a continuous water sheet in full contact with the pile starting at the actual water surface. Small individual detached water spots in contact with the pile, free droplets, etc, are not regarded as run-up. Run-up and spray are defined in Figure 3. The run-up height is relative to still water level. This definition of run-up corresponds to the definition used in other tests, eg Vos et al (2007).

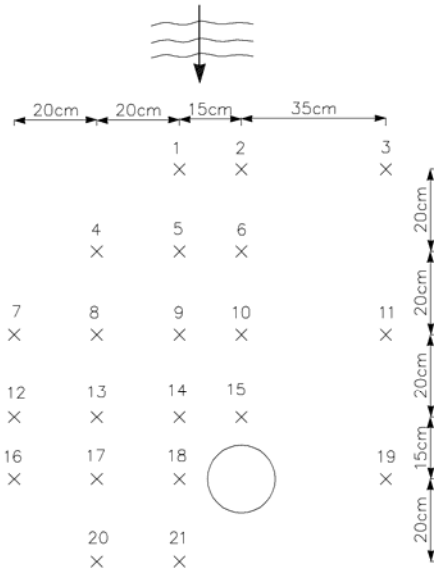


**Figure 3** Definition of run-up and spray.

## PHYSICAL MODEL SET-UP

The waves in the physical model tests were generated by an 18m long piston type wavemaker located 13m in front of the foundation. The wavemaker consists of 36 pistons which allow the generation of 3D (short-crested) waves.

The wave field in the area around the foundation was measured by conductivity wave gauges. The wave gauges were set up in a close pattern around the foundation as illustrated in Figure 4. Since the waves are symmetric around the mean direction, the wave gauges were concentrated along the symmetry line and on one side of the symmetry line. In the present study, only the wave gauges in front of the pile were used (wave gauges 2, 6 and 10 in Figure 4).



**Figure 4** Positions of the wave gauges relative to the foundation. Wave gauges 15 and 18 were only used for the reference measurements (without foundation tower). The mean wave direction is indicated as well.

The wave run-up at the foundation was measured by a high speed video camera and by a traditional conductivity wave gauge mounted directly on the foundation towards the mean wave direction.

The camera was an Olympus i-SPEED high speed camera, recording 600fps. This recording frequency is sufficient to achieve sharp, undisturbed frames. The run-up at the front of the foundation was manually recorded from the videos. These measurements have a precision of around  $\pm 2\text{cm}$ , which is a good precision compared to the fast and severe run-up. The run-up in the numerical model is compared with the run-up heights measured by video. Further details about the physical model tests can be found in Nielsen and Jacobsen (2007).

## NUMERICAL MODEL

The CFD model, NS3, is previously described in H. Bredmose et al (2006). The model consists of a fully non-linear 3D Navier-Stokes solver with a Volume of Fluid (VOF) treatment of the free surface. The viscous forces and compressibility effects are neglected reducing the Navier-Stokes equations to the Euler equations, which are given below.

$$\frac{\partial u_i}{\partial x_i} = 0 \quad [1]$$

$$\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial u_i u_j}{\partial x_j} = \rho g_i - \frac{\partial p}{\partial x_i} \quad [2]$$

Here  $u_i$  are the three velocity components,  $g_i$  is the gravity vector,  $p$  is the pressure, and  $\rho$  is the fluid density. The free surface motion is governed by the kinematic boundary condition where a particle on the free surface follows the fluid velocity. The kinematic boundary condition is included by extrapolation of the velocities within the fluid domain to the surface and through the use of the Volume of Fluid method. The dynamic boundary condition in the case of an inviscid fluid is given as

$$p_{surf} = p_{atm} \quad [3]$$

where the atmospheric pressure is set to zero in the computations. In the computations, hydrostatic pressure corresponding to the still water is subtracted from the pressure field, such that the computational pressure variable is the excess pressure. This approach improves the numerical accuracy and removes the gravity term in [2]. In terms of excess pressure, the dynamic surface condition for the free surface [3] becomes

$$\tilde{p}_{surf} = \rho g_i r_i \quad [4]$$

Where  $r_i$  is the position vector of the free surface relative to a fixed reference point on the still water level. The free surface is resolved using a Volume-of-Fluid description. A scalar function  $F$  is assigned a value of 1 within the fluid domain and 0 in the void domain. The present method was first described in Hirt and Nichols (1981) and with an improved scheme for the advection of the conserved quantity  $F$ , cf. Ubbink (1997). The grid is fixed, while  $F$  moves with the fluid.  $F = 0.5$  determines the position of the surface. The spatial discretisation is based on the finite-volume approach on a multi-block grid. The time-integration of the equations is performed by application of the fractional step method. The CFD-code solving the Navier-Stokes equations as sketched above has been used and validated in Mayer et al (1998), Nielsen & Mayer (2001), Christensen (2006) and Bredmose et al (2006).

## NUMERICAL MODEL SET-UP

The waves in the numerical model were generated over an 18m long boundary using a 3D Boussinesq wave formulation at the same distance from the cylinder as for the physical model tests. From the free surface elevation time-series (used as boundary in the physical model tests), time-series for the depth-averaged velocities  $U$ ,  $V$  and their derivatives  $U_x$ ,  $U_{xx}$ ,  $U_{xy}$ ,  $V$ ,  $V_y$ ,  $V_{yy}$  and  $V_{xy}$  were constructed. This allows a reconstruction of the horizontal velocity profile with a parabolic shape and a linearly shaped profile of the vertical velocity. The accuracy for this theory decays for increasing frequency, thus the incident wave field has been truncated at a frequency of 0.91Hz (corresponding to a  $kh=1.5$ ).

The computational domain was 18m wide and 22m long with a cylindrical shaft (the monopile) having a diameter of 9cm located at a distance of 13m from the wave generation line. The domain walls and the monopile were modeled using impermeable walls. The horizontal bed boundary was also represented by an impermeable wall. The presence of air is neglected.

The lower and upper boundary was set to  $\pm 0.4$ m. Two numerical simulations were carried out to investigate the cell resolution requirement close to the cylinder in order to model the proper magnitude of the wave run-up. The number of cells for the simulations was 1612800 for the first simulation and 1489920 for the second simulation, both distributed between 12 blocks. Close to the cylinder the cell volume were  $0.67 \times 0.78 \times 1.58 \text{cm}^3$  and  $1.37 \times 0.78 \times 1.58 \text{cm}^3$  respectively for the two simulations. Downstream of the structure, a sponge layer was applied to damp out the waves once propagating past the cylinder. The grid used for the numerical model tests is seen in Figure 5.

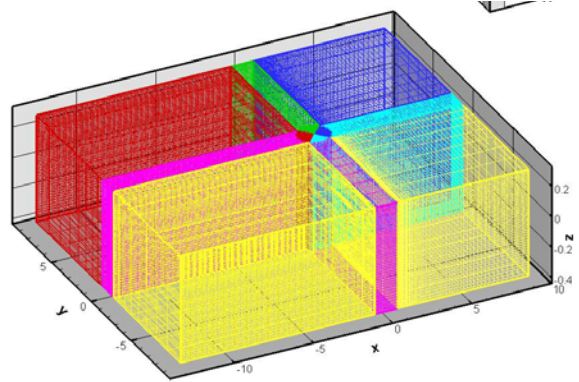
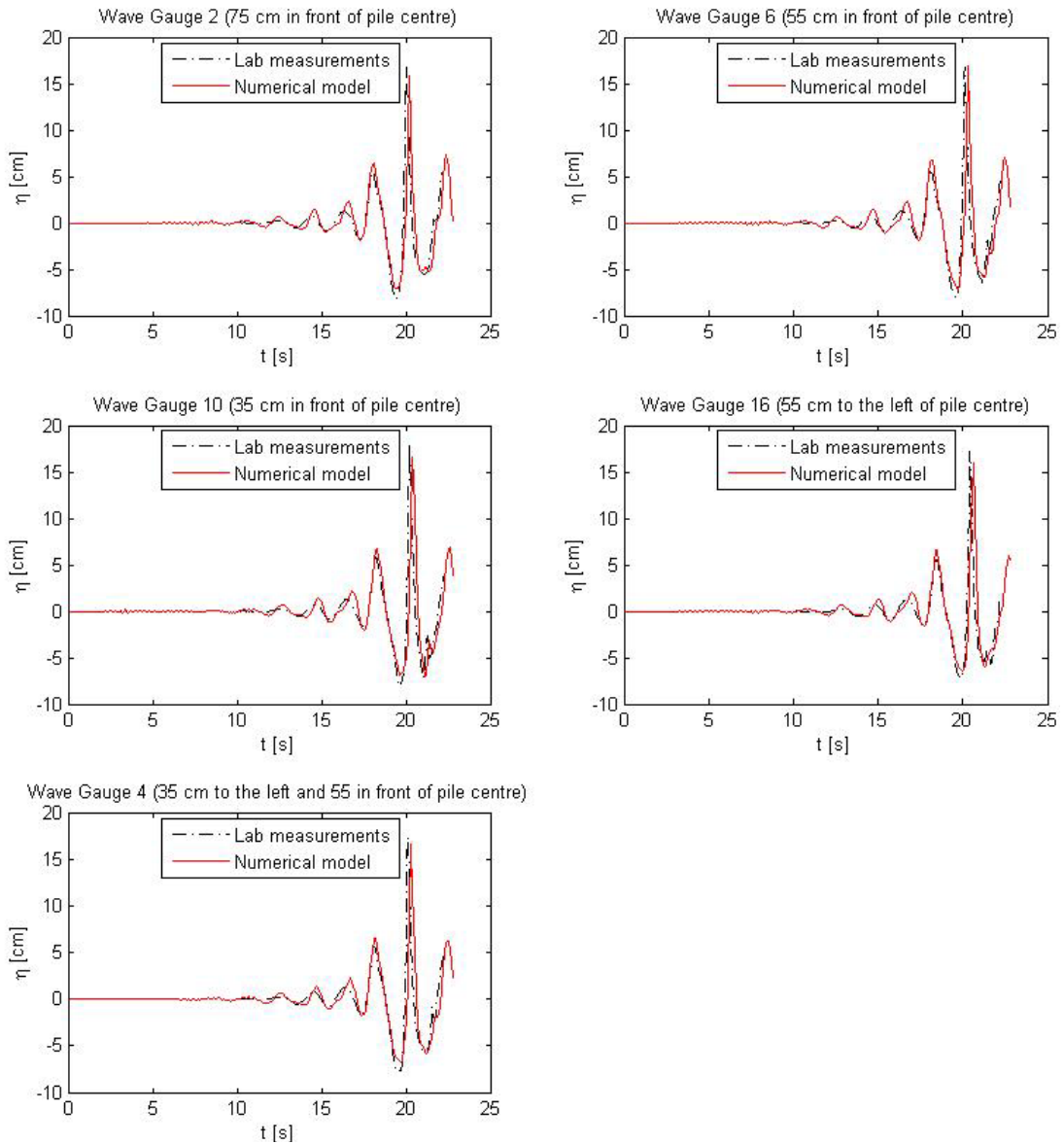


Figure 5 Grid used for the numerical simulation.

## RESULTS

The two numerical simulations were carried out on an HPxw4600 WorkStation with an Intel Quad-Core 2.4GHz processor with 4GB RAM. The computational run-time for each simulation was 15 hours and 11 minutes for modeling 23.0s of real-time. Given the small wave periods and the sharp crested nature of the propagating 3D waves, a very fine cell resolution was required in the entire domain in front of the cylinder in order to model the combined phase and directional wave focusing correctly. The fine resolution was also required to prevent a significant under-estimation of the surface elevation near the focus point in front of the cylinder and an associated under-prediction of the resulting wave run-up on the cylinder. It was found that an average cell size of  $4.8 \times 13.9 \times 1.58 \text{cm}$  ( $x, y, z$ ) in the far field in front of the structure was required in order to capture the 3D focusing effects sufficiently and ensure a proper prediction of the surface elevation in the close proximity of the cylinder.



**Figure 6** Surface elevation comparison for five selected wave gauges compared with numerical computed values.



**Figure 7** Wave run-up for two different grid resolutions. The figure to the left shows the run-up for a grid resolution of 0.60x0.78x1.58cm, while the figure to the right shows the run-up for a grid resolution of 1.37x0.78x1.58cm

In Figure 6, the surface elevation time series measured by wave gauges 2, 4, 6, 10 and 16, see Figure 4, is compared with the corresponding computed values by the numerical model. From this, it can be concluded that there exists a very satisfactory agreement between measurements and the numerical model predictions of the surface elevation for all five wave gauge locations.

**Table 1** Grid used for the numerical simulation.

Condition	Maximum Run-up on cylinder [cm]
Laboratory test	50
Numerical Model, cell volume at cylinder: (0.67 cm x 0.78 cm x 1.58 cm)	37.7
Numerical Model, cell volume at cylinder: (1.37 cm x 0.78 cm x 1.58 cm)	32.7

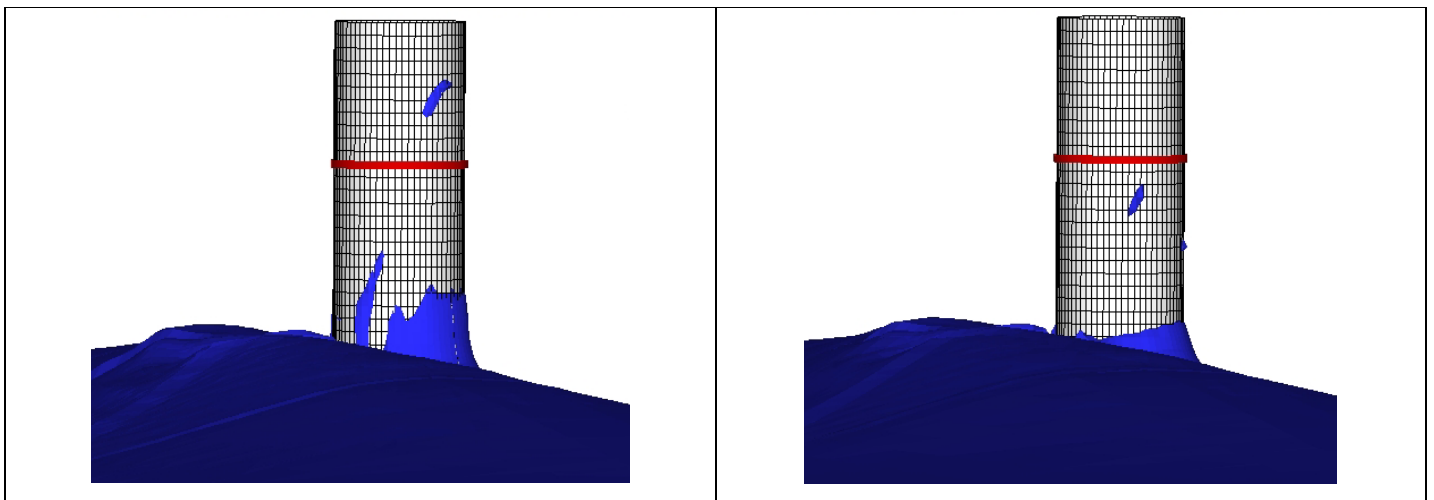
In Table 1, the maximum run-up height as measured in the laboratory has been compared to the run-up given by the two numerical simulation runs. The occurrence of the maximum

run-up for the two numerical simulations has also been visualized in Figure 7.

From the comparison, it can be concluded that both numerical simulations under-estimate the wave run-up height (in comparison with the laboratory measurements). It is also evident that the numerically predicted run-up height is very dependent on the cell resolution in the close proximity of the cylinder. It is observed that just by changing the width of the cells (in the direction normal to the cylinder surface) from 1.37cm to 0.67cm, the predicted run-up is increased by 13.3%.

Figure 8 contains a visualization of the wave run-up 0.1s after the maximum run-up has occurred in the two numerical simulations. For both simulations, a detached body of water located respectively 48.0cm and 34.1cm above the SWL is noticed. As per the definition given earlier in this paper, detached bodies of water do not count in the run-up estimations, but in this case it could serve as an indication that the cell resolution close to the cylinder is not sufficiently fine.

From the physical model tests, it is known that the frontal part of the run-up is thicker than the lower part of the run-up, see Figure 9. It is therefore speculated that the detached water seen on Figure 10 constitutes the actual front of the run-up. In this case, the actual wave run-up calculated by the numerical model (fine resolution) becomes 48.0cm or almost the same as for the physical model (50cm).



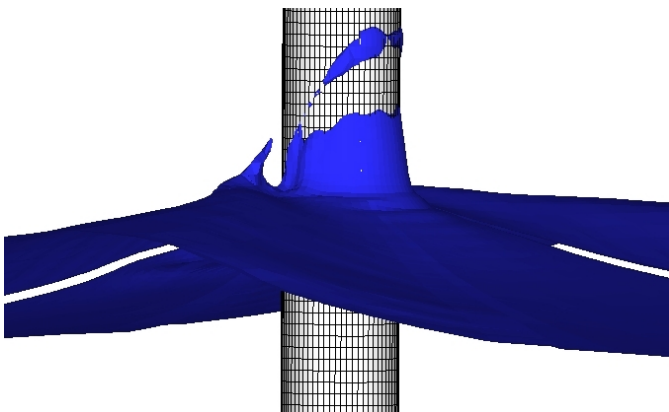
**Figure 8** Wave run-up at  $t=20.67s$  for two different grid resolutions. The figure to the left shows the run-up for a grid resolution of  $0.67 \times 0.78 \times 1.58cm$ , while the figure to the right shows the run-up for a grid resolution of  $1.37 \times 0.78 \times 1.58cm$





**Figure 9** Wave run-up on a pile. It is seen that the front of the run-up is thicker than the rest of the run-up. The front is approximately 40cm above SWL (red line) (the blue/grey lines are 1cm each and there are 10cm between the blue lines with black dots).

A further analysis of increased cell resolution in the area close to the cylinder is therefore warranted.



**Figure 10** The run-up when the detached water body reaches the maximum height. The detached water body has the same shape as the front of the run-up seen in Figure 9.

## CONCLUSION

The analysis has shown that NS3 is fully capable to calculate the 3D wave field around a vertical pile, including the effect of very steep near-breaking waves.

The wave run-up is underestimated by the numerical model. This is likely to be due in part to the use of a too coarse resolution of the grid near the pile surface. However, the run-up acts overall as expected from the physical model tests: The frontal part of the run-up is thicker than the lower part of the run-up, which is the reason for the break up of the run-up. If the detached water in the numerical calculation is accepted as the front of the run-up, the run-up height will be 48.0cm or almost as high as the physical model test indicating 50cm.

## ACKNOWLEDGMENTS

The financial support (1.0 mio DKK) of the Danish Public Service Program (PSO) for PSO-R&D-project No 2006-1-6426 is gratefully acknowledged.

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**3.7 “Design Loads on Platforms on Offshore Wind Turbine Foundations with Respect to Vertical Wave Run-up” – Paper from EOW 2007**

# Design loads on platforms on offshore wind turbine foundations with respect to vertical wave run-up

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## Abstract:

Experiences have shown that the vertical run-up generated by waves meeting the offshore wind turbine foundations, can result in rather vigorous loads on appurtenances and platform structures. This study aims to provide a qualitative method of determining run-up height and the following loads depending on the wave parameters in the area in question. This is approached by a three step calculation routine supported by model tests. Supplementary tests have been made to determine the reduction in loads, when grated platforms are used in preference to a closed surface. This leads to an appreciable reduction in the loads by up to 75%.

Furthermore it is indicated, that the fact that offshore wind turbines often are placed on limited water depths thereby increasing the amount of (nearly) breaking waves, seems to increase the run-up height and thereby the pressures on the structure.

**Keywords:** design loads, waves, secondary structures.

## 1 Experiences with wave run-up

In offshore wind farms the effects of vertical wave run-up has appeared evident as little or no attention has been paid to this phenomenon during the traditional design process. This has resulted in extensive damages to platform structures and appurtenances, as seen at the Horns Reef offshore wind farm. An illustration of the phenomenon is shown in figure 1.



Figure 1: Example of wave run-up; Horns Reef

## 2 Model tests

As the run-up is governed by complex hydrodynamics the initial step is to investigate the phenomenon through a model test program. This is initiated in cooperation with Aalborg University (AAU), and the test runs are carried out in the wave flume in Aalborg. The aim of the model test runs are partly to investigate the nature of vertical wave run-up and to detect the governing influences, partly to set up a calculation model in preparation for design purposes. The model tests at AAU are supported by the PSO project with participants from DONG Energy, Danish Hydraulic Institute (DHI) and Vestas.

The PSO project only examines the run-up height, but do so through more complicated wave patterns in a 3D wave basin at DHI. The two independent test series are compared for verification of results.

### 2.1 Calculation model approach

As the main goal is the ability to include the loads from wave run-up in the design process, a calculation model is suggested and then attempted calibrated through the test results.

A three step calculation routine is suggested:

- 1) Determine run-up height based on wave parameters and water depth
- 2) Determine vertical velocity at the level of the structure in question
- 3) Determine the pressure induced by the water masses impact on the structure

The run-up height is expected to be described as a sum of the elevation and a factor,  $m$ , times the velocity head

$$R_u = \eta + m \frac{u^2}{2g} \quad (1)$$

The vertical velocity at the level,  $z$ , above SWL is then suggested calculated by the expression

$$v(z) = \sqrt{2g(R_u - z)} \quad (2)$$

Finally the load is calculated as a slamming force

$$\frac{F}{A} = \frac{1}{2} C_s \rho (v(z))^2 \quad (3)$$

The factors  $m$  and  $C_s$  are then investigated based on the test results from AAU. Furthermore the expression for  $v(z)$  is checked against the measurements. The wave parameters  $\eta$ , crest elevation, and  $u$ , maximum horizontal particle velocity, are calculated using stream function theory.

## 2.2 Test series in wave flume

A number of parameters are investigated as variables in the test program. Both wave steepness,  $s_{op}$ , normalized depth,  $h/D$ , and normalized wave height,  $H_{m0}/h$ , are included in the study. Table 1 lists the cases, each case is run with  $s_{op} = 0.020$  and  $s_{op} = 0.035$ , hence 24 different wave series are run.

$H_{m0}/h$	$h/D = 2$	$h/D = 3$	$h/D = 4$
0.35	$H_{m0}=0.070$ m	$H_{m0}=0.105$ m	$H_{m0}=0.140$ m
0.40	$H_{m0}=0.080$ m	$H_{m0}=0.120$ m	$H_{m0}=0.160$ m
0.43	$H_{m0}=0.086$ m	$H_{m0}=0.129$ m	$H_{m0}=0.172$ m
0.46	$H_{m0}=0.092$ m	$H_{m0}=0.138$ m	$H_{m0}=0.184$ m

Table 1: Test conditions for irregular wave trains

The geometry of the wave flume is shown in figure 2.

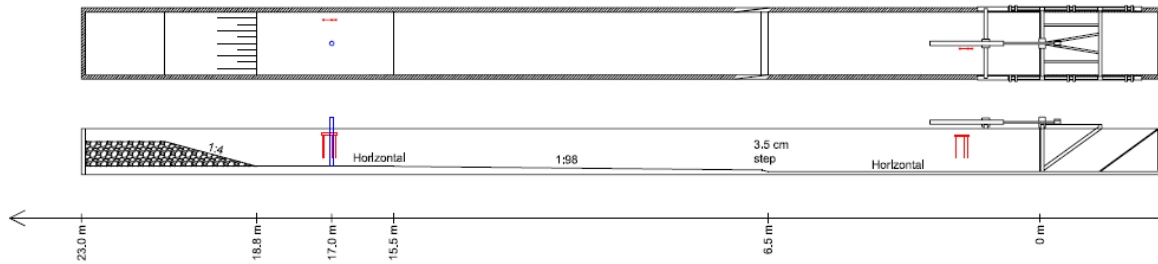


Figure 2: Layout in flume. Wave gauges are shown in red, run-up model in blue

The modeled structure to generate the run-up is a monopile with the diameter,  $D = 10$  cm. The cylinder is equipped with surface wave gauges per  $22.5^\circ$  asymmetrically.  $0.0^\circ$  indicates the impact point for the wave front.

An air gap of approximately 2 mm between the wires and the cylinder wall minimize the risk of water standing between the surfaces and thereby inducing errors on the measurements.

Figure 3 show pictures of the model set-up, whereas figure 4 presents a principle sketch of the wave gauge layout.

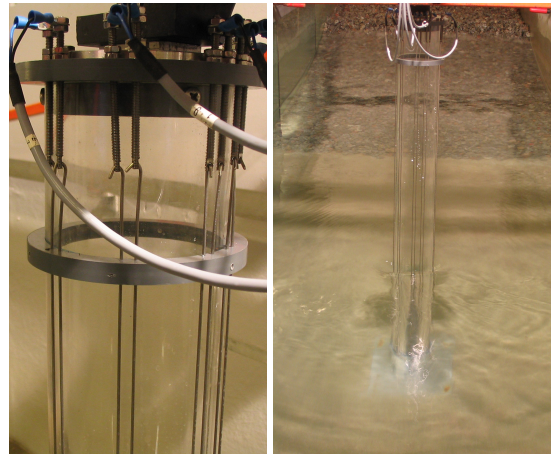


Figure 3: Pictures of the run-up model

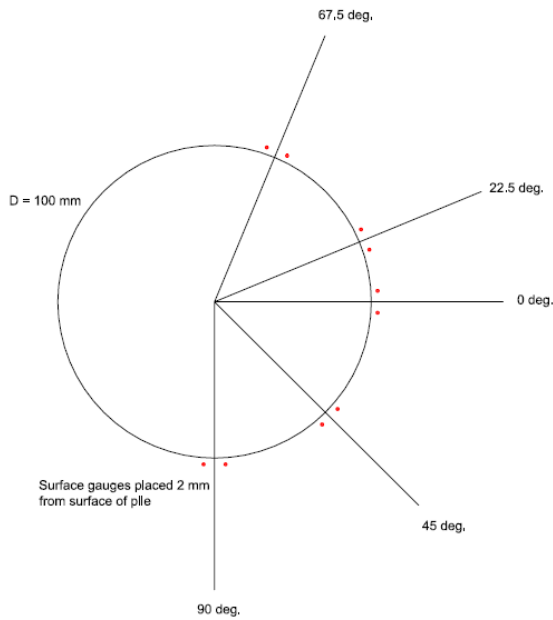


Figure 4: Run-up model with orientation of surface gauges indicated; waves are approaching from the right.

After completing the tests measuring the run-up heights the model monopile is equipped with a horizontal and then a cone shaped platform before running the same wave series once again. The platform models are mounted with a number of pressure cells logging at 1000 Hz. The models are illustrated in figure 5 and 6.

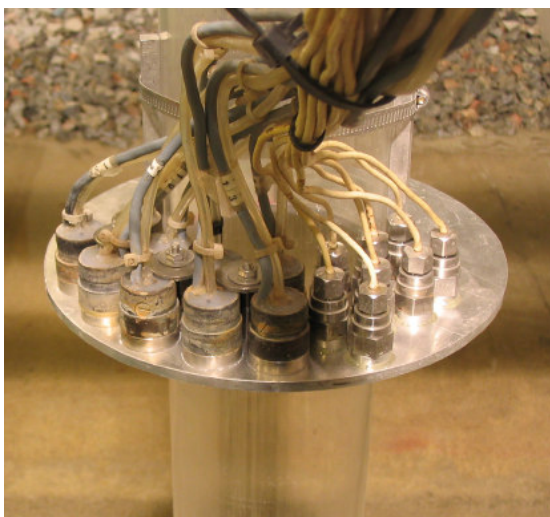


Figure 5: Model of horizontal platform with pressure cells

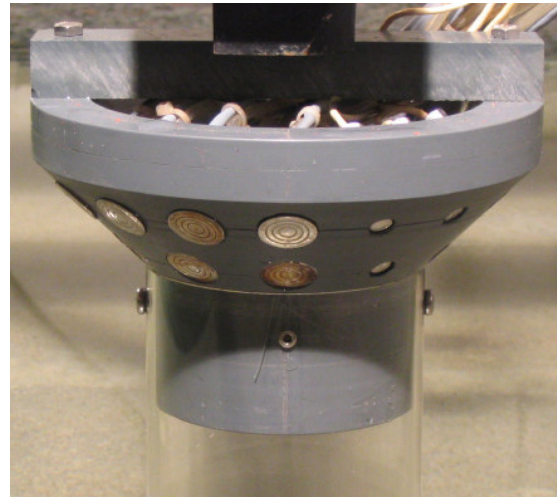


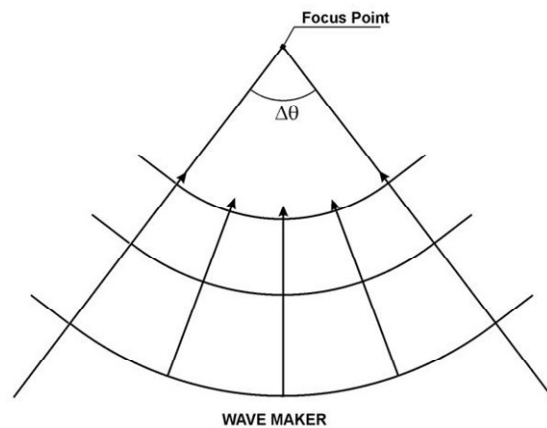
Figure 6: Model of cone platform

The run-up tests serve to describe the m-factor on the velocity head in expression (1), whereas the test series with the platform models should lead to the estimation of the introduced slamming coefficient,  $C_s$ , in expression (3).

### 2.3 Test series in 3D wave basin

The wave tests at AAU are carried out in a 2D wave flume. To elaborate further on this subject DONG Energy entered into a Public Service Obligation project in cooperation with Vestas and Danish Hydraulic Institute (DHI), concerning the run-up height. Those model test series was carried out in a 3D wave basin at DHI, and focus mainly on the influence of 3D-effects on the run-up height.

Looking at figure 7, the wave parameters are illustrated.



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Figure 7: Wave parameters in DHI tests

The variable parameters in this study are:

- 1) Incoming angle,  $\Delta\theta$
- 2) Location of focus point with regard to pile centre
- 3) Wave height at focus point

The modeled monopile is shown in figure 8.

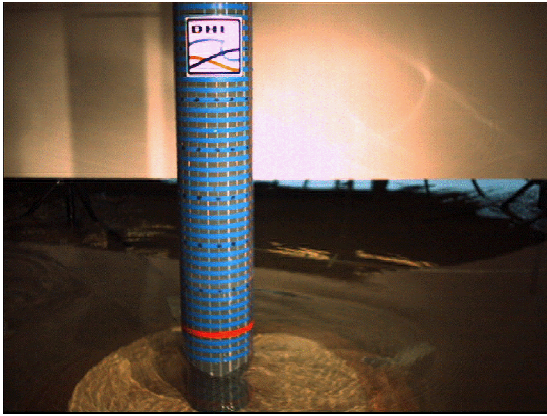


Figure 8: Model set-up for wave run-up tests at DHI

The run-up is registered both by wave gauges and by high speed camera – hence the blue horizontal lines on the pile.

### 3 Results from model tests

The test results are analyzed with respect to the suggested calculation model, and the results from the AAU test series and the DHI test series are also compared to each other in order to get some verification of the results.

#### 3.1 Run-up tests at AAU

The conclusion is, that the water depth to pile diameter ratio and the wave height to water depth ratio is of little significance to the wave run-up height. The wave steepness however seems to have quite an influence, as the m-factor on the velocity head seems to decrease with increasing wave steepness.

Figure 9 and 10 show the comparison of the result found by the calculation model using the apparent m-factors, and the measured results.

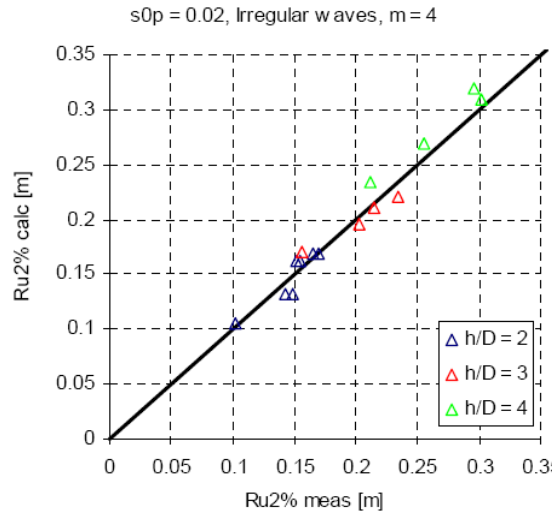


Figure 9: Measured versus predicted values of run-up height using  $m = 4$  for  $s_{0P} = 0.020$ ; wave kinematics calculated by stream function theory

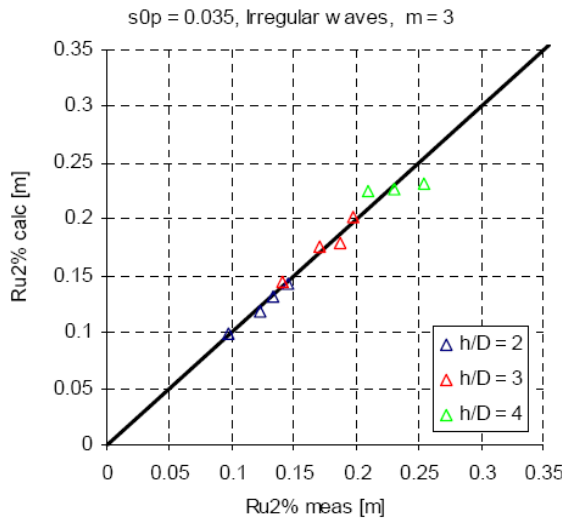


Figure 10: Measured versus predicted values of run-up height using  $m = 3$  for  $s_{0P} = 0.035$ ; wave kinematics calculated by stream function theory

The run-up tests are also used to verify the suggested expression for the vertical velocity of the water at a given level,  $z$ , as presented in expression (2).

There is found a reasonable agreement between the velocities found based on the measurements, through differentiation, and the velocities calculated accordingly using expression (2). The result is shown in figure 11.

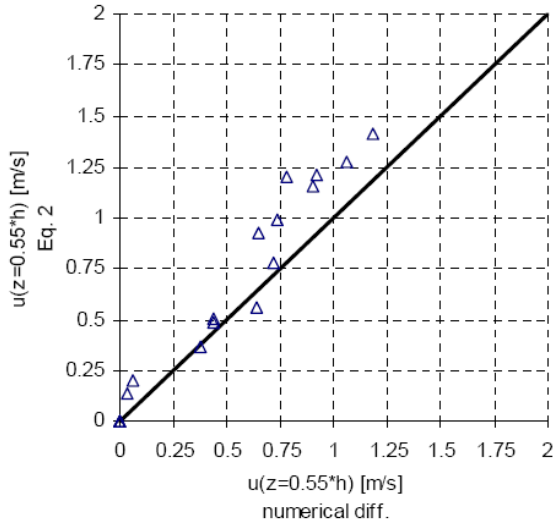


Figure 11: Comparison of vertical velocities of run-up water found based on measurements and based on the calculation model

### 3.2 Impact pressure tests at AAU

The slamming coefficient is calculated based on comparing the run-up tests with the pressure measurements on the platform models.

Figure 12 and 13 show plots of the maximum measured pressures with lines to indicate a number of slamming coefficients for the horizontal and the cone platform. The slamming coefficient describes the maximum local pressure, affecting an area of  $0.5 \text{ m}^2$ .

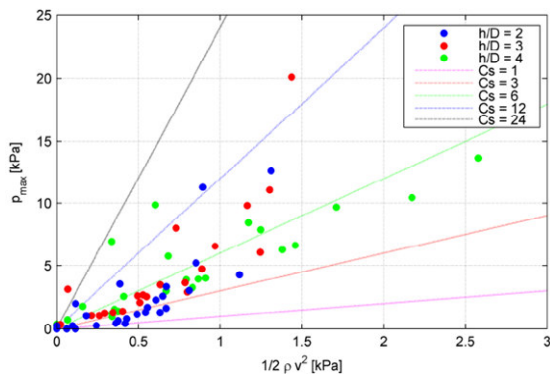


Figure 12: Measured pressures for the horizontal platform indicating the slamming coefficient for the maximum local load according to expression (2)

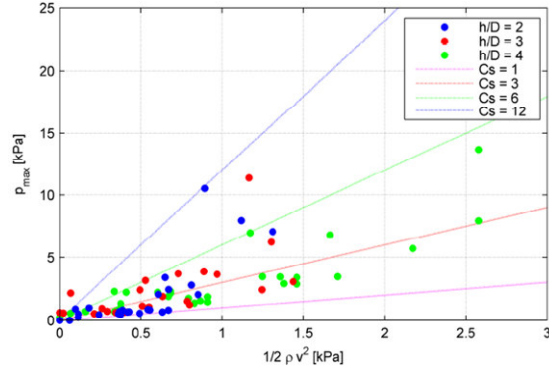


Figure 13: Measured pressures for the cone platform indicating the slamming coefficient for the maximum local load according to expression (2)

As expected it is seen from figure 12 and 13, that the loads on a horizontal platform are significantly larger than those on a cone platform.

The measurements indicate that the loads on a horizontal platform are twice as high as those on a cone platform with the bottom slope of  $45^\circ$ .

### 3.3 Run-up tests at DHI

Analyzing the results lead to the initial conclusions that both  $kh$  and 3D effects are of little influence to the run-up height. Meanwhile the wave steepness are of some influence, as the AAU results also showed, and one of the main results from the test series was that decreasing energy level, i.e. breaking waves, leads to an increase in run-up height. However the tests in the 3D wave basin only showed a very limited influence of the location of the focus point; and thereby the breaking point, relative to the center of the pile.

As an overall result, the maximum run-up height appears to be in the order of

$$Ru_{\max} = 1.75 h \quad (4)$$

Comparing the run-up height registered by the wave gauges with the high speed camera recordings it is evident, that the wave gauges underestimate the run-up height. This is illustrated in figure 14.



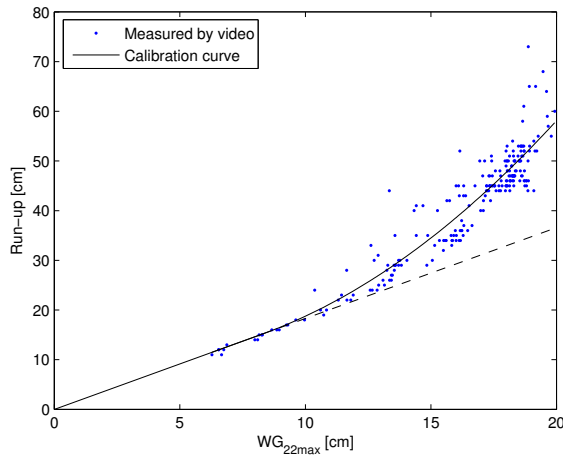


Figure 14: Run-up height measured by video plotted against the run-up measured by the wave gauges

The underestimation is assumed to be caused by air mixed into the water which disturbs the resistance over the wave gauges.

Furthermore there is not established any discrepancy between the DHI and the AAU results, which is serving as an initial verification of the results.

#### 4 Evaluating the calculation model and test results

The test results has provided the factors used in the calculation model and the run-up height is assumed rather well described through the 2D and 3D wave tests. However especially the slamming coefficient is somewhat higher than seen in earlier studies on wave impacts; hence the calculation model leads to rather high values for the loads.

The time series from the pressure cells are studied closer. A typical pressure peak according to one run-up event is shown in figure 15.

There appears to be two indications to the pressure measurements being on the conservative side.

- a) The duration of the run-up induced load is very short; in the order of 0.01 s to 0.05 s (prototype scale). This leaves little time for the structure to respond to the full load impact

- b) The transient peak drops below zero indicating a sort of dynamic overshoot governed by the dynamics of the pressure cell.

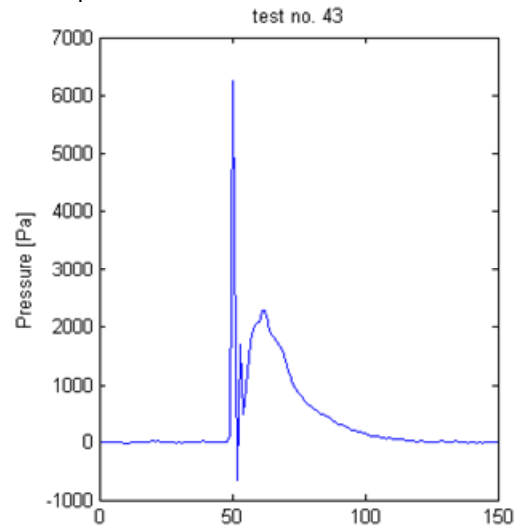


Figure 15: Section of time series during a run-up event

It is assumed that further studies on the loads will give a significant optimization on the design loads, but at this stage it is too early to describe a well defined reduction.

#### 5 Grate platforms

As a way to reduce the loads on the platform structure the effect of using gratings instead of a closed surface is studied by a series of tests at AAU.

The test set-up is illustrated in figure 16.



Figure 16: Test set-up for test with grates

The tests are carried out for four different types of gratings with different porosity, wall geometry and opening sizes, and for a closed surface as reference.

The main result is that the sole governing variable is the porosity, and not the size or shape of the holes or the geometry of the walls. The porosity for the gratings used in the test cases lies from 0.70 to 0.87, and the minimum reduction in load is by approximately 70% compared to the closed surface.

Figure 17 show the forces measured for different angles of attack between 48° to and 90° to the grate of the type Fiberline 40, with the porosity of 0.70.

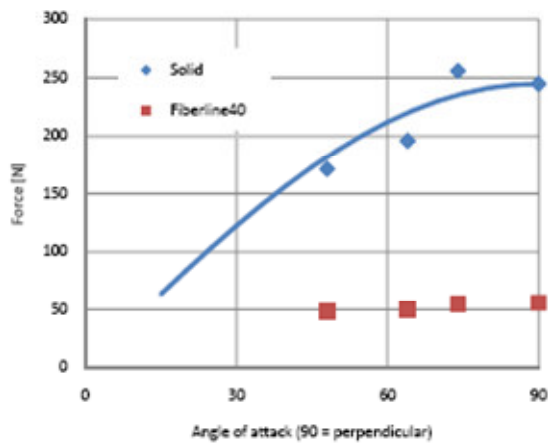


Figure 17: Plot of measured forces at different angles of attack

This indicates that grate platforms could be a way of reducing the design loads due to wave run-up, but previous experiences has shown that there can be some difficulties in the fastening systems, which should be taken into account when choosing the platform design.

## 6 Conclusion

The calculation model described in section 2.1 provides an initial method for designing with regards to loads induced by vertical wave run-up. Expression (1) is replaced by expression (5), taking the underestimation of the run-up measured by wave gauges into account. This is only a linear adjustment, and further studies are needed to incorporate the full non-linear underestimation.

$$Ru = 1.2 \left( \eta + m \frac{u^2}{2g} \right) \quad (5)$$

Also the loads can be determined based on the calculation model, however some conservatism is expected at this point, and a more optimized design can be achieved by carrying out elaborating studies on this subject.



## 4 CONCLUSION

The project has shown that the wave run-up is a common phenomenon at the Horns Rev I Wind Farm. The wave run-up is related to breaking waves and it can be concluded that no significant run-up will take place in cases without breaking waves. In other words, most cases of wave run-up will be related to shallow water areas. However, wave breaking leading to wave run-up can be assumed to take place in areas with larger water depths, for example in case of a strong current (in opposite direction of the waves).

The physical model tests showed that a wave run-up of at least 1.8 times the local water depth can be expected. However, it is recommended to do a detailed analysis of the run-up in relation to run-up height and forces on structures in case of breaking waves.

In the case of Horns Rev I Wind Farm the speed of the run-up is estimated to be 20 m/s. It is not determined to what extent this velocity depends on factors like the pile diameter, local bathymetry, etc. The run-up velocity estimated from the videos from Horns Rev is comparable with the velocities measured in the physical model.

It can also be concluded that it is possible to calculate the wave run-up using an existing CFD code (NS3). The CFD program is able to calculate the front of the wave run-up correctly, but the water sheet behind the front of the wave run-up is not modelled correctly due to its small thickness.

Test of the predicating structures showed that the shape of the platform is important for the loads on the platform. A conical shaped platform can reduce the vertical load on the platform significantly.