Horns Rev II, 2D-Model Tests

Wave Run-Up on Pile

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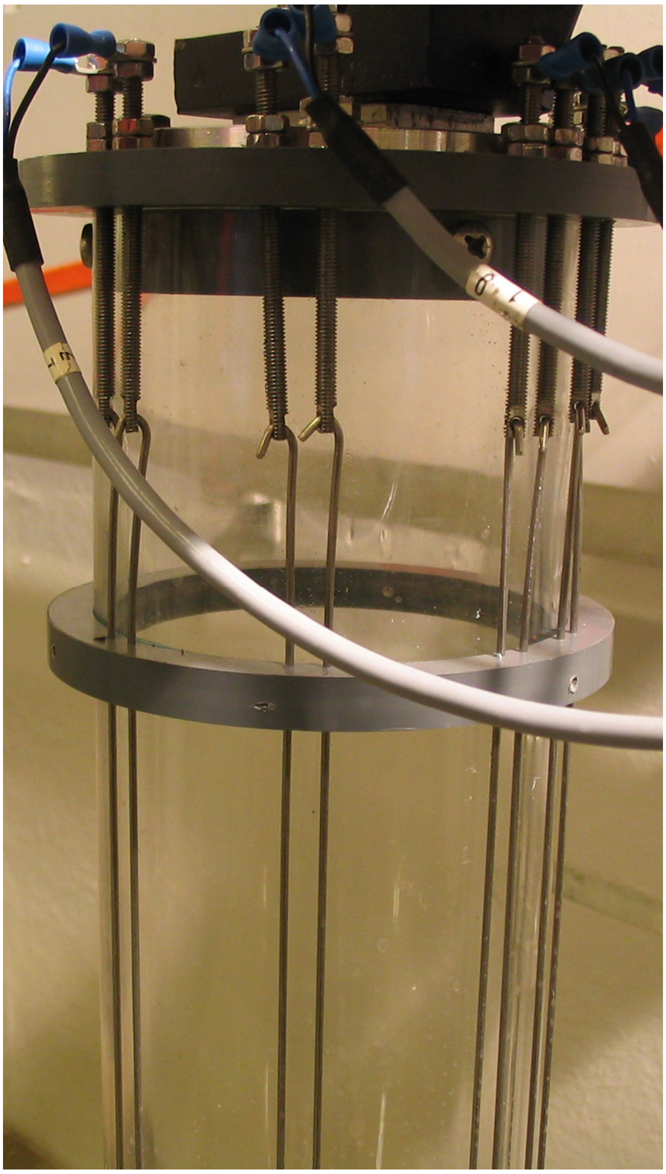

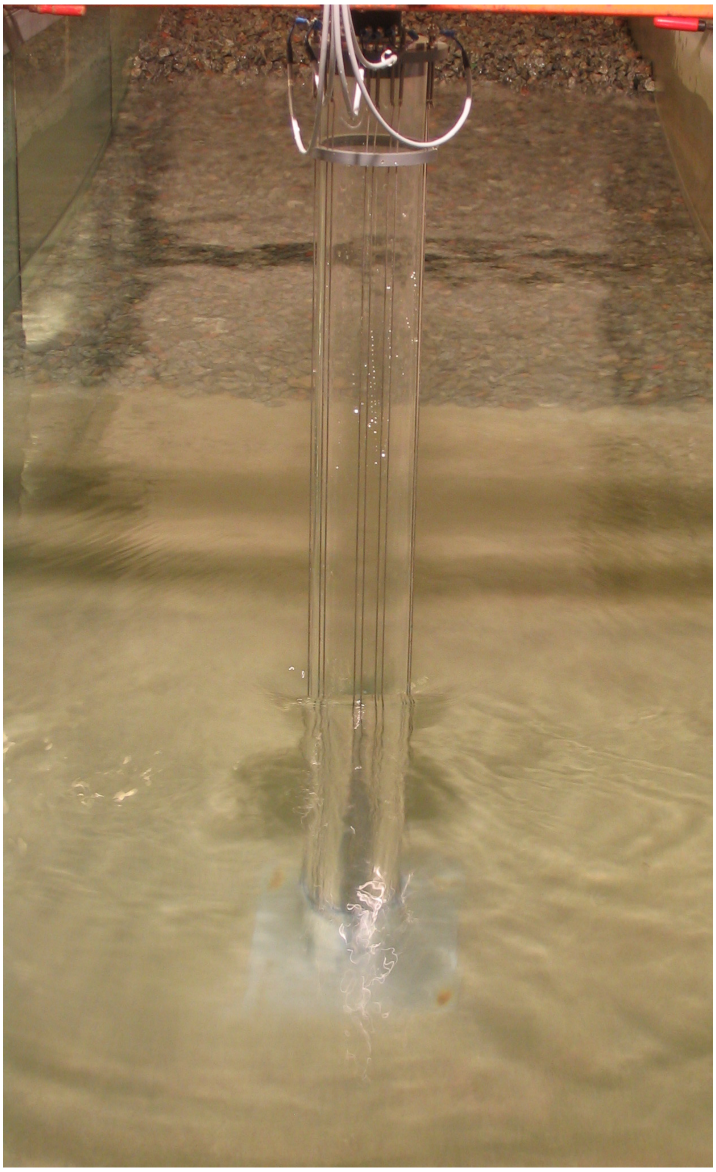

DCE Contract Report No. 3

AALBORG UNIVERSITY
Department of Civil Engineering

Aalborg University
Department of Civil Engineering
Water & Soil

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Horns Rev II, 2D-Model Tests

Wave Run-Up on Pile

by

Lykke Andersen, T.
Frigaard, P.

December 2006

Preface

This report present the results of 2D physical model tests carried out in the shallow wave flume at Dept. of Civil Engineering, Aalborg University (AAU) on behalf of Energi E2 A/S part of DONG Energy A/S, Denmark.

The objective of the tests was:

To investigate the combined influence of:
- *the pile diameter to water depth ratio and*
- *the wave height to water depth ratio*

on wave run-up of piles. The measurements should be used to design access platforms on piles.

The Model tests include:
- Calibration of regular and irregular sea states at the location of the pile (without structure in place).
- Measurement of wave run-up for the calibrated sea states on the front side of the pile (0 to 90 degrees).

These tests have been conducted at Aalborg University from 9. October, 2006 to 8. November, 2006. Unless otherwise mentioned, all values given in this report are in model scale. For further information please contact Thomas Lykke Andersen (tla@civil.aau.dk).

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1 Introduction

The assessment of impact forces generated by waves on the offshore windmill access platforms is discussed in the technical note by Gravesen, 2006. This technical note was established for design of the access platforms for the Horns Rev II windmill park. The idea is to determine the impact pressures in a three step procedure:

1) Calculate the expected maximum wave run-up height with no platform.
2) Use this run-up height to calculate the velocity at the level of the platform.
3) Use a slamming force model to get the maximum pressures.

The present report deals with model tests performed at Aalborg University to investigate step 1 and 2. Lykke Andersen and Brorsen, 2006 deals with the model tests performed for the third step.

Previously De Vos et. al., 2006 investigated step 1, where the run-up height is calculated from:

$$R_{u2\%} = \eta_{\max,2\%} + m \cdot \frac{u_{2\%}^2}{2g} \qquad (1)$$

where $\eta_{\max,2\%}$ is the crest level of the 2% highest wave and $u_{2\%}$ is the horizontal velocity in the top of the wave crest for the same wave. Both are calculated from the 2. order Stoke theory. De Vos et. al. gives m = 2.71 as the mean value for a monopole, but do not give a plot showing the scatter of the m-values.

Gravesen, 2006 performed a rough reanalysis the data of De Vos et. al., 2006 from one of the graphs in De Vos et. al., 2006. These preliminary investigations indicated of a lot of scatter on the m factor and a strong increase in m with Hs/h. The data of De Vos et. al., 2006 corresponds to $H_s/h < 0.42$ in all cases. The data indicated also an influence of h/D. This was the motivation for the present study, in which the influence of h/D and H_{m0}/h is studied.

In the present study the original data of De Vos et. al., 2006 was available and reanalysed. It was found that m was between 1.9 and 4.2 when the 2. order Stoke theory was used for the kinematics in the crest. Because, the stream function theory is considered more accurate for the kinematics in the crest, it was decided to work with this theory in the present project. Using the stream function theory on the data of De Vos et. al., 2006 gave an increase in the m values, as m was found then to be in the range from 2.7 to 4.9. Figure 1 shows the m values found by reanalysing the data of De Vos et. al., 2006 as function of h/D and Hs/h. It could be seen an increase in m with increasing wave height to water depth ratio. However, the very large m values (above six) for large values of Hs/h as indicated by Gravesen, 2006 was not found. This cannot be explained by using the stream function theory instead of the 2. order stoke theory as this gave an increase in the m-values.

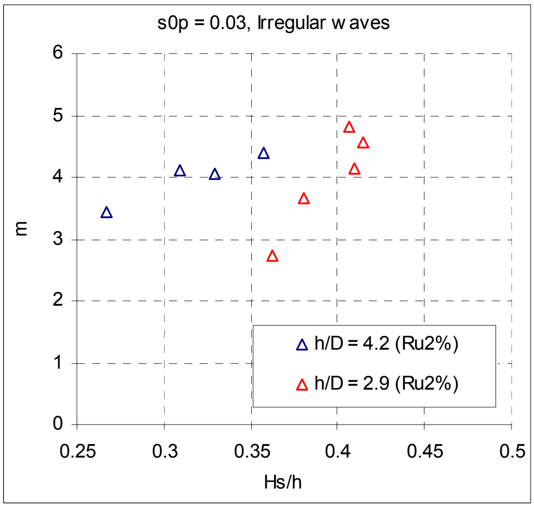

Figure 1: Run-up velocity head factor (m) for the results from De Vos et. al., 2006.
Data reanalyzed to use stream function theory. $\gamma \approx 3.3$.

2 Model Test Setup

The shallow water wave flume at Dept. of Civil Engineering, Aalborg University was used for the present tests. The flume configuration is shown in Fig. 2 and explained in the following. The bottom was horizontal on the first 6.5 m then a 3.5 cm step followed by a 1:98 slope with a length of 9 meters. The last part of the flume was horizontal and the model was placed 1.5 m into this horizontal part. The water depth at the wave maker was 12.5 cm larger than at the model. An absorbing rubble mound beach with a slope of 1:4 to 1:5 was created in the end of the flume for absorbing the main part of the incident energy. The waves were measured both at the location of the model and 1.7 m from the paddle. For the wave calibration tests the model was removed and the wave gauges were placed at the location of the pile (in the center of the flume) with the middle wave gauge placed at the center of the pile. For the run-up tests the wave gauges were moved so they instead were next to the model, but still with the middle wave gauge next to the center of the pile, cf. Fig. 2.

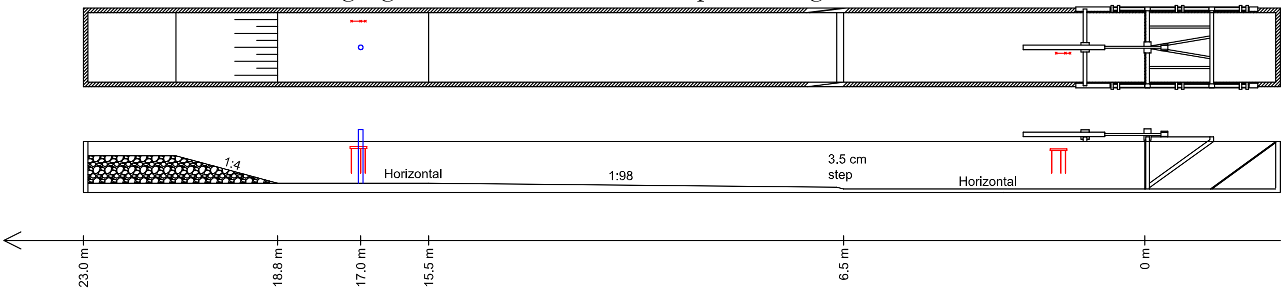

Figure 2: Layout in flume. Wave gauges shown in red and the run-up model in blue.

Wave run-up was measured using a run-up model similar to that used by De Vos et. al., 2006. Resistance type water surface gauges were attached to the model. These gauges consist of 2 wires with a diameter of 1 mm, placed approximately 2 mm from the surface of the cylinder and 7 mm between the centers of the two wires. Five pairs of wires were placed for measuring the run-up height at 0, 22.5, 45, 67.5 and 90 degrees from the front of the pile, cf. Fig. 3 and 4. The wires were prestressed using the system shown on the left picture in Fig. 3. Because the gauges placed in 0 and 22.5 degrees are very close to each other, it was feared that they would interact with each other. However, it was found that the interaction was small. Between the other gauges there was no interaction at all. Both the wave gauges and the run-up gauges were calibrated by filling the flume with water, due to non-linearities of the very long gauges. Because the conductivity depends on the water temperature cold water were filled in each day and the gauges were recalibrated if necessary.

Figure 3: Pictures of the run-up model.

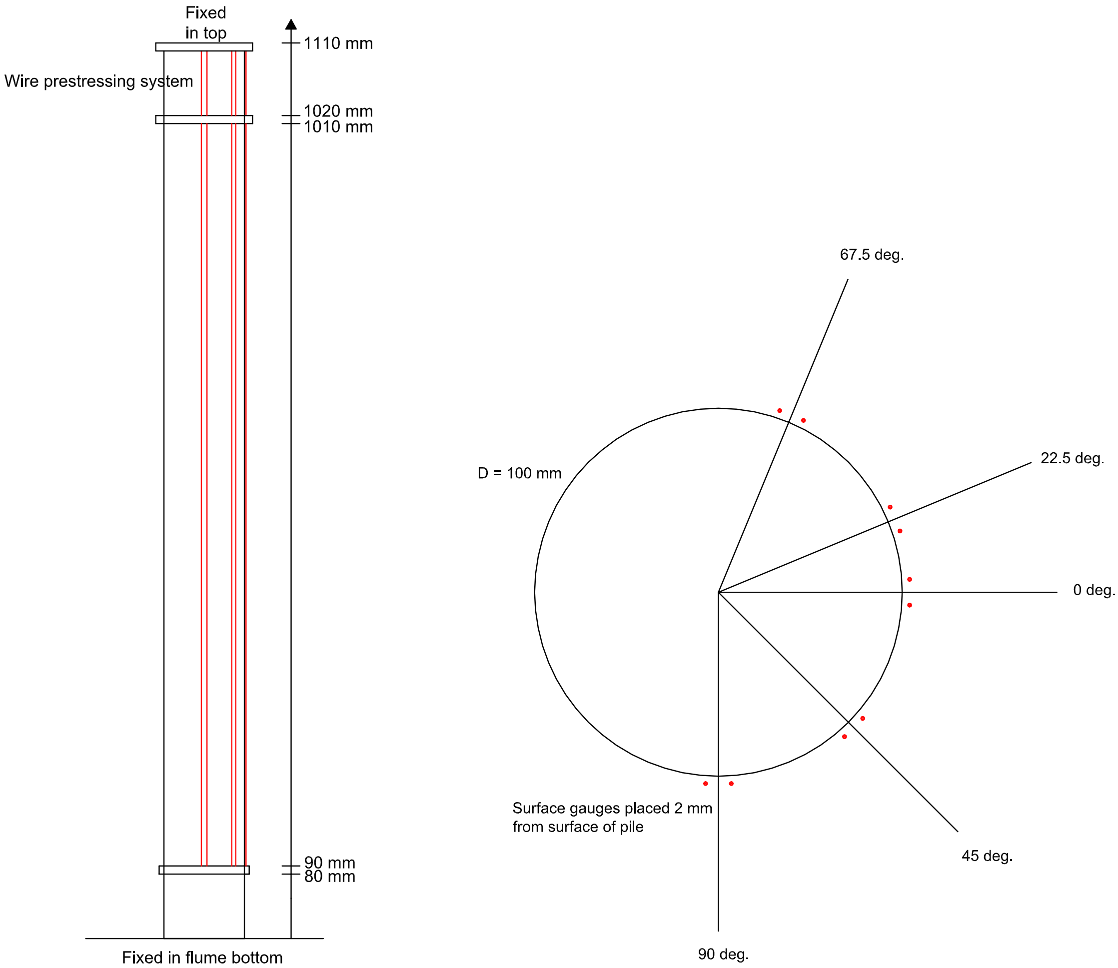

Figure 4: Run-up model.

3 Test Programme

The purpose of the wave calibration tests was to match the sea state at the location of the pile to the prespecified sea states. The range of H_{m0}/h from 0.35 to 0.50 was considered as the most relevant range for the present tests. However, it showed out that H_{m0}/h = 0.50 was impossible to generate in the flume. This was due to waves breaking just in front of the paddle due to limited water depth and due to wave breaking on the foreshore. Therefore, the initial test programme was modified so the four tested values of H_{m0}/h were 0.35, 0.40, 0.43 and 0.46. This was done for the three water depths (h) 0.20 m, 0.30 m and 0.40 m. The wave spectrums generated are JONSWAP spectrums with a peak enhancement factor (γ) of 1.5. The JONSWAP spectrum is defined according to ISO19901.

	D = 0.10 m, h = 0.20 m (h/D = 2)	**D = 0.10 m ; h = 0.30 m (h/D = 3)**	**D = 0.10 m; h = 0.40 m (h/D = 4)**
H_{m0}/h = 0.35	H_{m0} = 0.070 m	H_{m0} = 0.105 m	H_{m0} = 0.140 m
H_{m0}/h = 0.40	H_{m0} = 0.080 m	H_{m0} = 0.120 m	H_{m0} = 0.160 m
H_{m0}/h = 0.43	H_{m0} = 0.086 m	H_{m0} = 0.129 m	H_{m0} = 0.172 m
H_{m0}/h = 0.46	H_{m0} = 0.092 m	H_{m0} = 0.138 m	H_{m0} = 0.184 m

Table 1: Revised irregular test conditions.

The target sea states were reproduced at the pile verifying that both incident H_{m0} and T_p using the above given analysis method were correct. The entire wave spectrum shape was not reproduced. The same wave train could then be reproduces as the steering signal sent to the paddle was stored. In case of non-breaking waves (H_{m0}/h = 0.35) the peak period and the entire spectrum shape were both close to unchanged. However, in case of breaking waves the spectrum becomes wider and corresponds in the present case approximately to γ = 1.0 instead of the generated γ = 1.5.

The tests with H_{m0} = 0.184 m was impossible to generate due to heavy breaking both on the paddle and on the foreshore. In this case the wave height at the structure doesn't increase for a larger generated wave height. H_{m0}/h = 0.46 was possible for h = 0.20 m and 0.30 m, which is most probably due to less wave reflection than for h = 0.40 m.

In addition to the irregular tests the same number of regular wave sea states ware tested. The regular wave parameters were chosen so the wave heights were approximately equal to the incident $H_{2\%}$ found in the irregular tests. The wave period was equal to the peak period in the irregular tests.

4 Data Analysis

To minimize the influence of high frequent noise, the wave data has been filtered by an analog low-pass filter with a cut-off frequency of 8 Hz. The sample frequency was chosen to 20 Hz.

The incident wave spectrum and wave trains are determined by the WaveLab2 software package which utilizes the Mansard & Funke, 1980 method, which is a linear method. The method was used even though the generated waves in most cases are very non-linear and in some cases also breaking. The lower frequency boundary for the reflection analysis was set to the maximum of 0.1 Hz in model scale and 1/3 times the peak frequency (f_p). The upper boundary was 3 $\times$ f_p. The number of data points in each FFT block was selected to 512 with 20% tapering in each end and 20% overlap of the subseries. Wave reflection coefficients between 9% and 33% have been calculated.

It has been observed that there was some low frequency energy present in the wave spectrum which is expected to be due to bounded and free long waves that triggers the eigenmode of the flume. Correct reproduction of bounded long-waves were not performed as a linear white noise filtering method was used [Sand, 1982]. This is not taken into account in the wave analysis as this is mainly outside the band from 1/3 to 3 times f_p. Instead the low frequent energy could be treated as mean water level fluctuations. This was done for some few tests, but didn't changed the 2% run-up values significantly. Therefore, the values given in this report is without taking this into account.

From the initial analysis of the run-up data it was found that the run-up data contains no "real" energy above 8 Hz – only noise. Therefore, it was decided to use the 8 Hz analog low-pass filter also for the run-up signals. WaveLab2s component to compare signals has been used to find the time delay between the calibration test and the run-up test. This component utilizes a standard cross-correlation function. The delay has been calculated from the paddle displacement signal, which was also stored in the data file.

To derive the m factor in Eq. 1 it is necessary to estimate the crest elevation and the velocity. In the present case the stream function theory was utilized to perform these calculations. The number of terms in the Fourier series was set to N = 30. The current velocity (u) has been set equal to zero, corresponding to that the mean value of the velocities below the wave trough is zero. For the irregular waves the $H_{2\%}$, T_p values were used for the 2% run-up values and H_{max} , T_p for the maximum run-up values.

5 Results

In this chapter the following results of the run-up tests are given:

- m-values for irregular and regular waves. The m-vaules are calculated from Eq. 1 and using the stream function theory for the kinematics. The run-up height is taken as the highest measured from the five gauges. These results are also compared to those of De Vos et. al., 2006 given in Fig. 1.
- Predicted versus measured run-up heights for irregular and regular waves.
- Predicted versus measured run-up velocities for regular waves. The measured run-up velocity is found by numerical differentiation of the measured run-up time series. The predicted is found by $v(z) = \sqrt{2g \cdot (\mathrm{R}_u - z)}$

In appendix A and B the results of each of the tests are given.

5.1 Irregular Waves

From Fig. 5a and 5b it can be concluded that m is in the range from two to five. It can also be concluded that the long waves (s_{0p} = 0.02) result in larger m-values than the shorter waves (s_{0p} = 0.035). This can partly be due to wave reflections from the beach. No significant difference in m-values between 2% and maximum run-up values could be identified, but there is more scatter on the maximum values than on the 2% values.

The range of the m-values is in pretty good agreement with the data of De Vos et. al., 2006. However, the big influence of H_{m0}/h identified by De Vos et. al., 2006 was not identified. The influence of h/D seems also to be smaller than estimated from the De Vos et. al., 2006 data. This may partly be a consequence of the larger γ-value applied by De Vos et. al., 2006 .

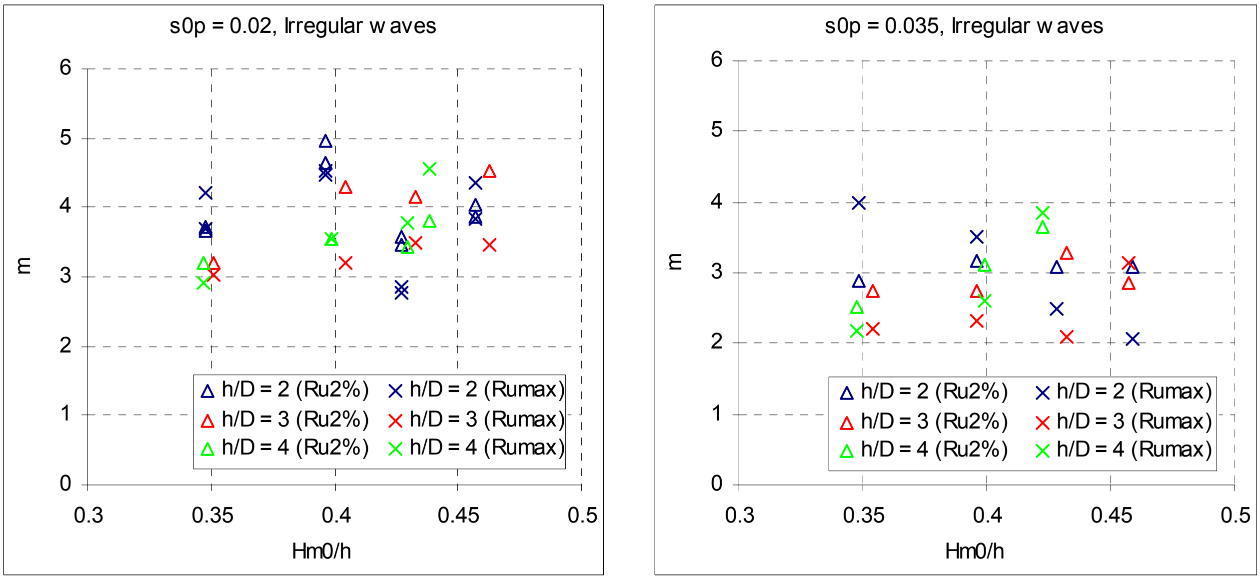

Figure 5a & 5b: m-values derived from measurements for 2% and maximum run-up for the two wave steepnesses tested. Wave kinematics are calculated from the stream function theory (using $H=H_{2\%}$ for $R_{u2\%}$ and $H=H_{max}$ for $R_{u,max}$, $T=T_p$ in both cases). $\gamma \approx 1.5$.

In Fig. 6 and 7 the measured and calculated 2% and maximum run-up heights are given when using m = 4 for s_{0p} = 0.02 and m = 3 for s_{0p} = 0.035. It can be seen that even though there was observed some scatter on the m-values the scatter on the run-up heights is much less, which is due to the velocity only being one of the two terms involved.

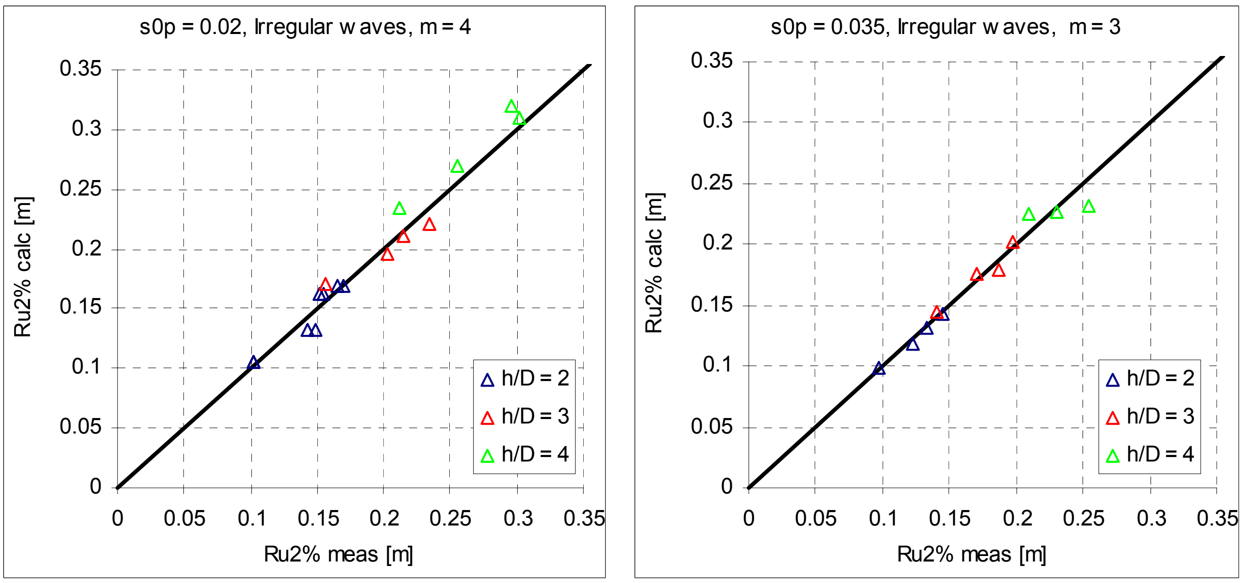

Figure 6a & 6b: Measured versus predicted 2% run-up heights when using m = 4 for s_{0p} = 0.02 and m=3 for s_{0p} = 0.035. Wave kinematics are calculated from the stream function theory using $H_{2\%}$ and T_p. $\gamma \approx 1.5$.

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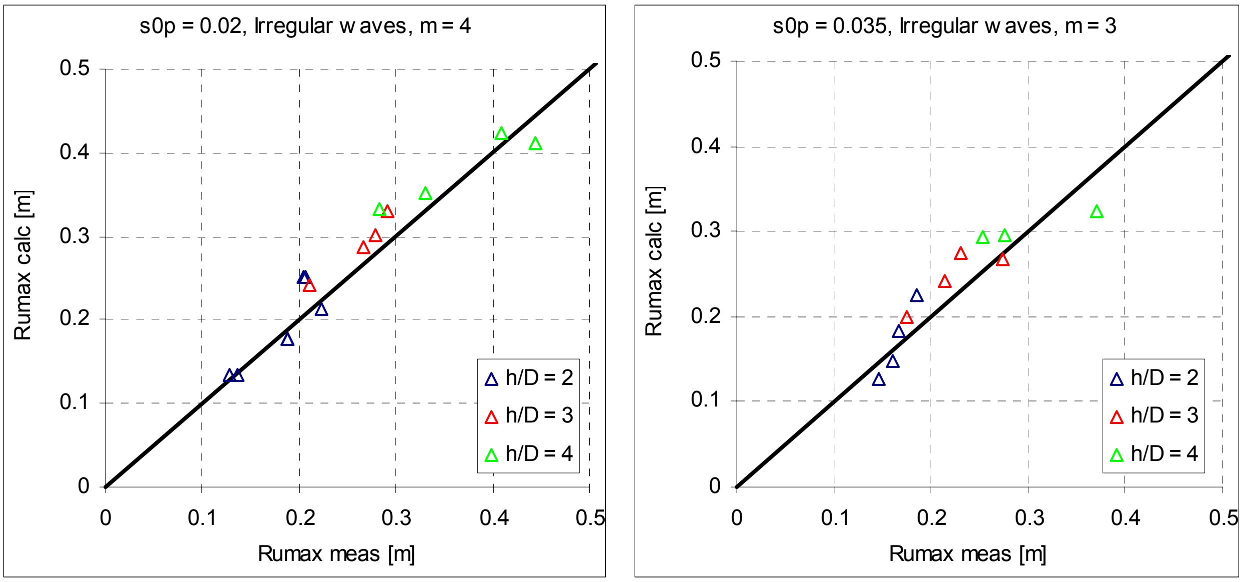

Figure 7a & 7b: Measured versus predicted maximum run-up heights when using m = 4 for s_{0p} = 0.02 and m=3 for s_{0p} = 0.035. Wave kinematics are calculated from the stream function theory using H_{max} and T_p. $\gamma \approx 1.5$.

The relative run-up around the pile is given in Fig. 8. The results are in pretty good agreement with those found by De Vos et. al., 2006. However, the run-up at 67.5 degrees some doubtful results have been obtained in some cases, as some very high values compared to the rest of the data and to the data of De Vos et. al., 2006 was obtained. This could maybe be caused by insufficient prestressing of this gauge.

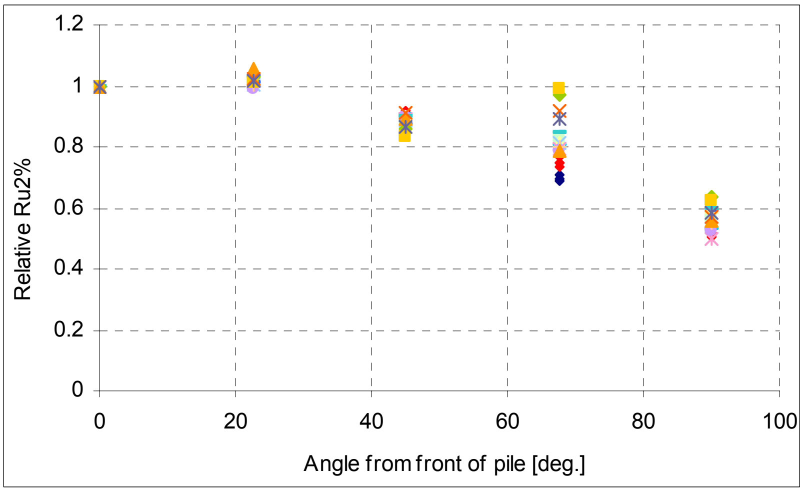

Figure 8: 2% run-up distribution along the pile (Ru,x_{deg} / $Ru,_{0\text{ deg}}$).

5.2 Regular Waves

From each of the irregular wave timeseries the incident $H_{2\%}$ was calculated. A regular wave train was generated with a wave height equal to this $H_{2\%}$ found from the irregular test and with a period equal to the peak period.

The incident wave train in the regular wave tests was calculated and a wave in the beginning of the wave train which matched the target wave height was selected. The m-factors from these single waves are given in Fig. 9. The H_{m0}/h and s_{0p} values refer to the irregular wave train from which the 2% wave for regular reproduction is selected. It can be seen that there is more scatter on the m-values for regular waves compared to the irregular waves. The distribution around the pile given in Fig. 11, is similar to that found for the irregular waves.

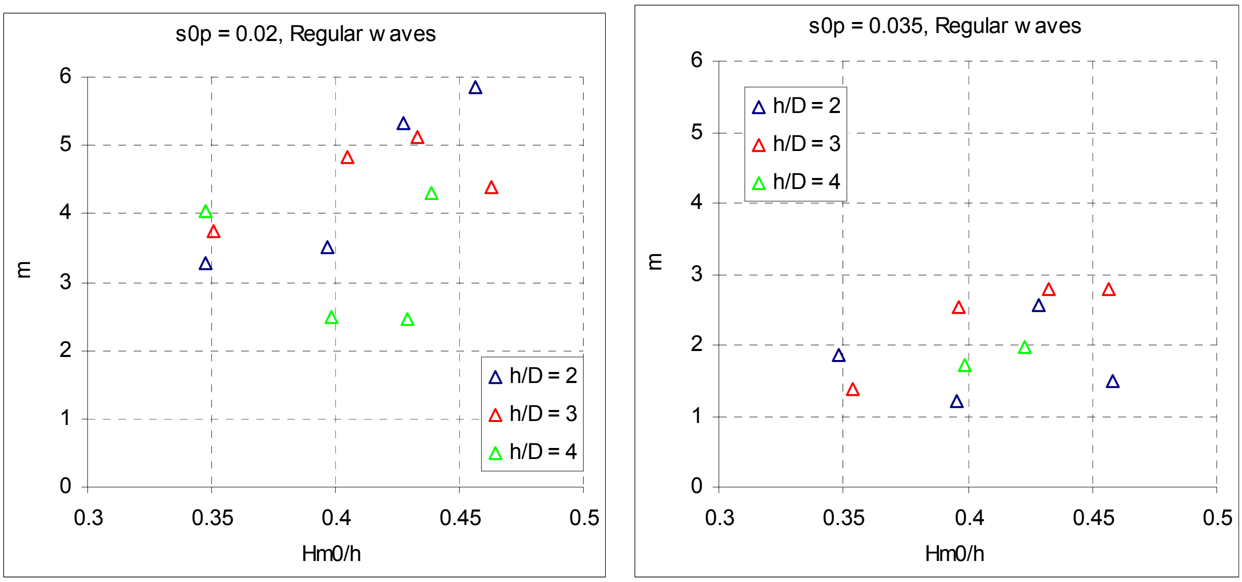

Figure 9a & 9b: m-values derived from measurements for single wave run-up for the two wave steepnesses tested. Wave kinematics are calculated from the stream function theory. The H_{m0}/h and s_{0p} values refer to the irregular wave train from which the 2% wave for regular reproduction is selected.

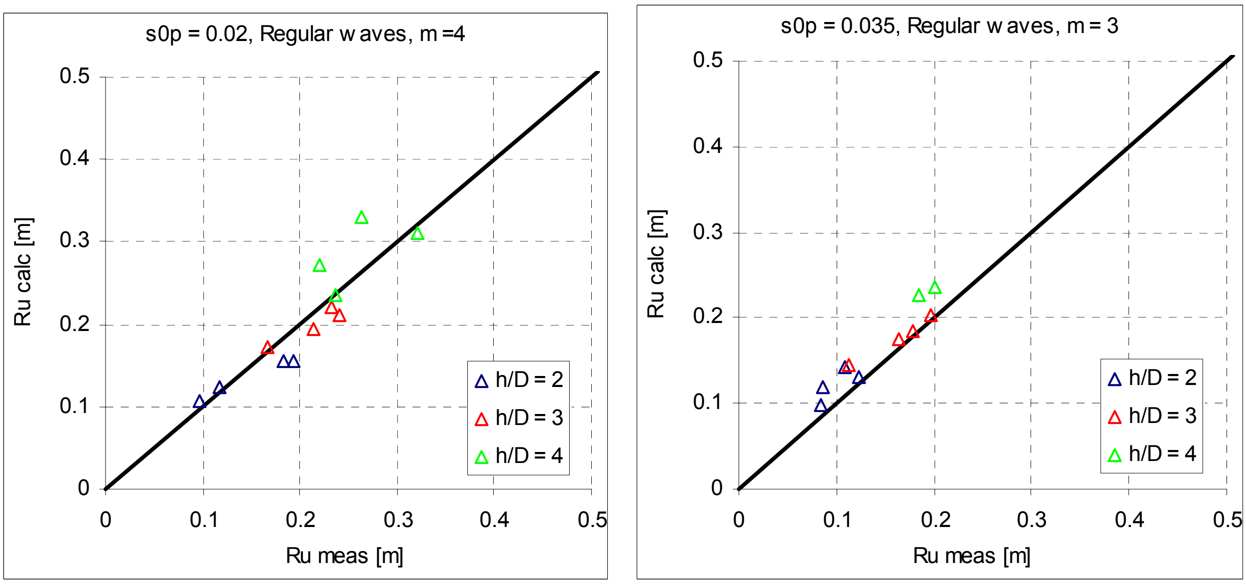

Figure 10a & 10b: Measured versus predicted maximum run-up heights when using m = 4 for s_{0p} = 0.02 and m=3 for s_{0p} = 0.035. Wave kinematics are calculated from the stream function theory.

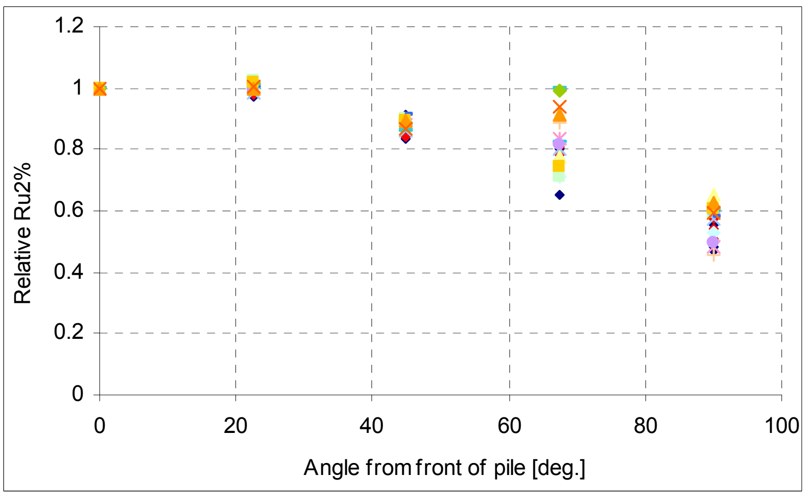

Figure 11: Run-up distribution along the pile.

In Fig. 12 the run-up velocities estimated by differentiation of the run-up time series are compared to those calculated by:

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

Reasonable agreement between the two estimates of the run-up velocities was found, but with some bias for large velocities.

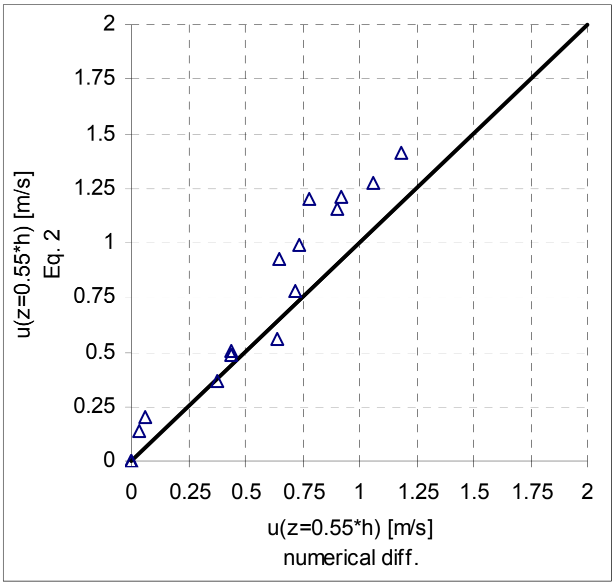

Figure 12: Comparison of run-up velocities predicted by two methods. The run-up velocities are compared at z=0.55·h, corresponding to the middle platform level tested by Lykke Andersen & Brorsen, 2006. The run-up velocity on the absisse axis is the maximum value of the five individual gauges and calculated by numerical differentiation of the run-up signal. The run-up velocity on the ordinate axis is calculated from Eq. 2

6 Model Effects

When measuring run-up with resistance type surface gauges the presence of air bubbles in the water makes the measurements less reliable.

Visually it has been observed small drops reaching very high levels during the run-up event, significant higher than measured by the gauges. However, these drops contain little energy due to the small mass and are therefore not expected to be a main contributor to the force on a platform.

The surface gauges mounted on the pile introduce a small roughness. However, the influence of this is expected to be very small.

7 Conclusions

Wave run-up on a pile has been measured for different situations of:

- Water depth to pile diameter ratio (h/D = 2,3 and 4).
- Wave height to water depth ratio (H_{m0} / h = 0.35, 0.40, 0.43 and 0.46).
- Wave steepness (s_{0p} = 0.02 and 0.035)

Both regular and irregular tests have been performed. The conclusion is that the water depth to pile diameter ratio and the wave height to water depth ratio has only a small influence on the run-up factor (m) which applies to the velocity head. However, the wave steepness has quite an influence as the run-up is clearly higher for the low steepness tests.

8 References

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Appendix A: Irregular Wave and Run-Up Data

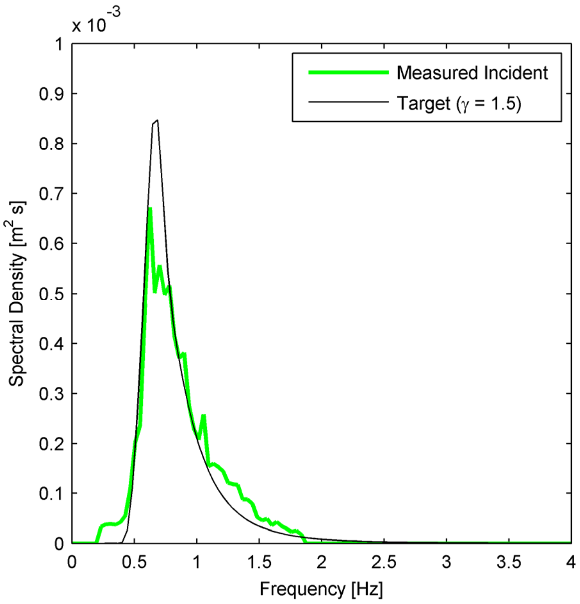
A.1 Test 1 ($h/D = 2$, $H_{m0}/h = 0.35$, $s_{0p} = 0.020$)

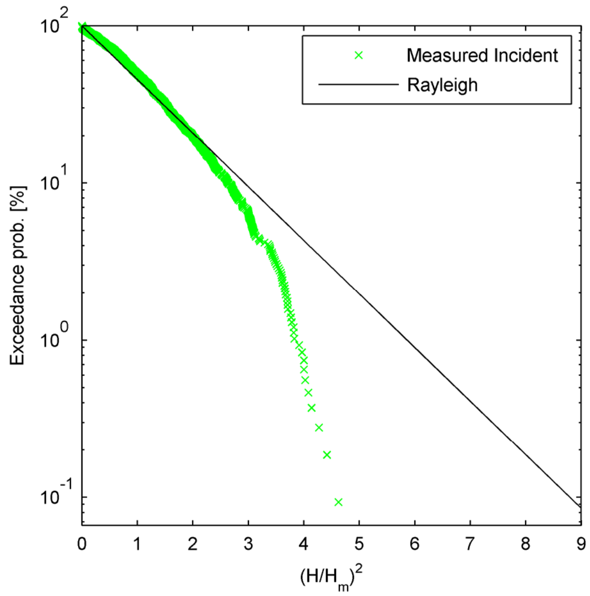
Incident wave parameters at structure determined from the calibration test:

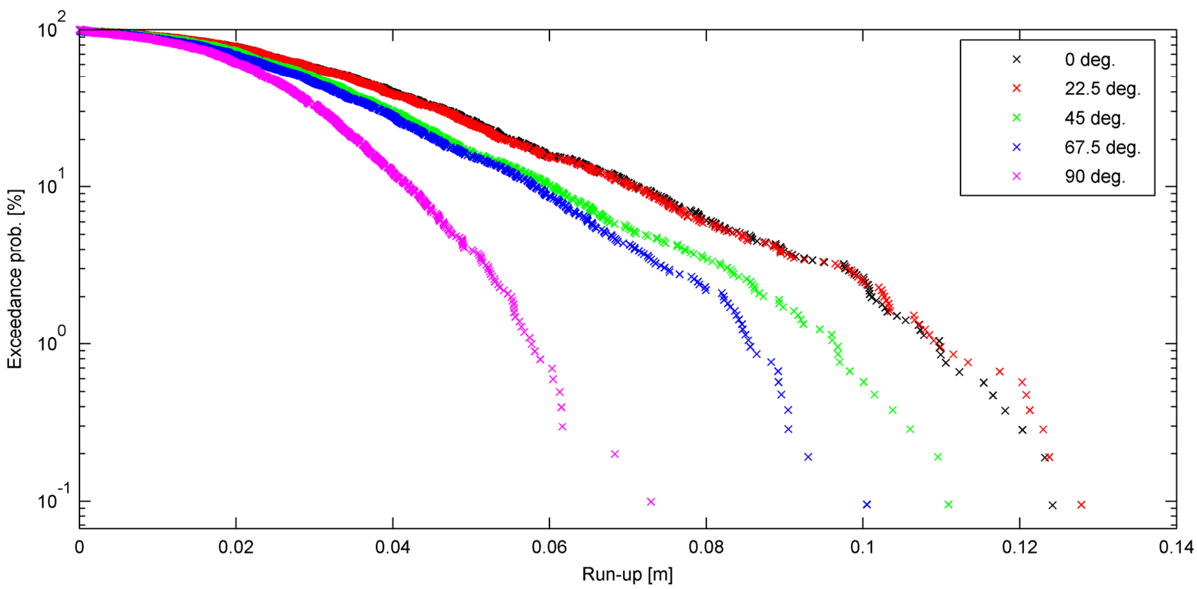
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test112.dat	RunUp_Test_001.dat	0.2	0.069	1.50	0.065	0.082	0.092	11.9%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.101		0.116		0.124	
22.5	0.103		0.121		0.128	
45	0.087		0.101		0.111	
67.5	0.082		0.089		0.101	
90	0.055		0.061		0.073	
Max	0.103	3.7	0.121	4.3	0.128	3.7







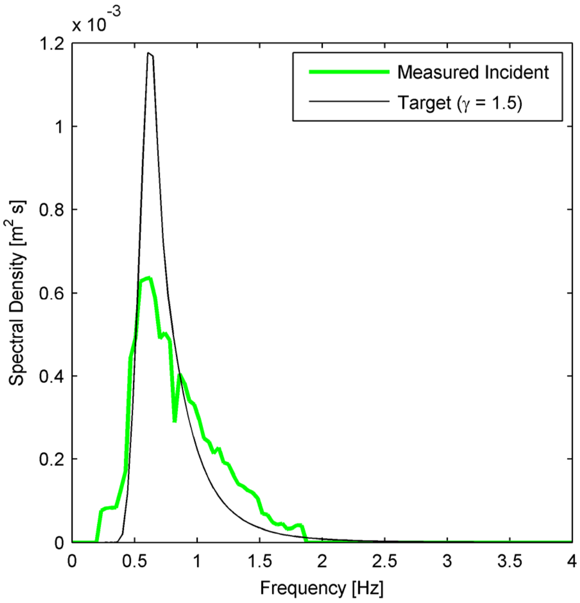
A.2 Test 2 (h/D = 2, H_{m0}/h = 0.40, s_{0p} = 0.020)

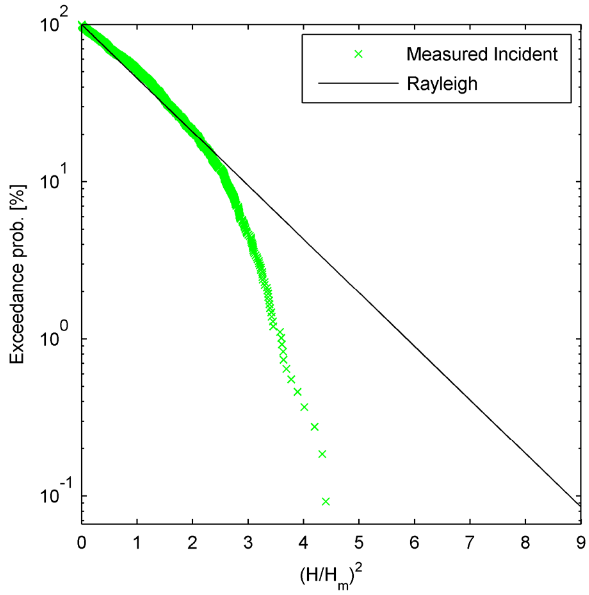
Incident wave parameters at structure determined from the calibration test:

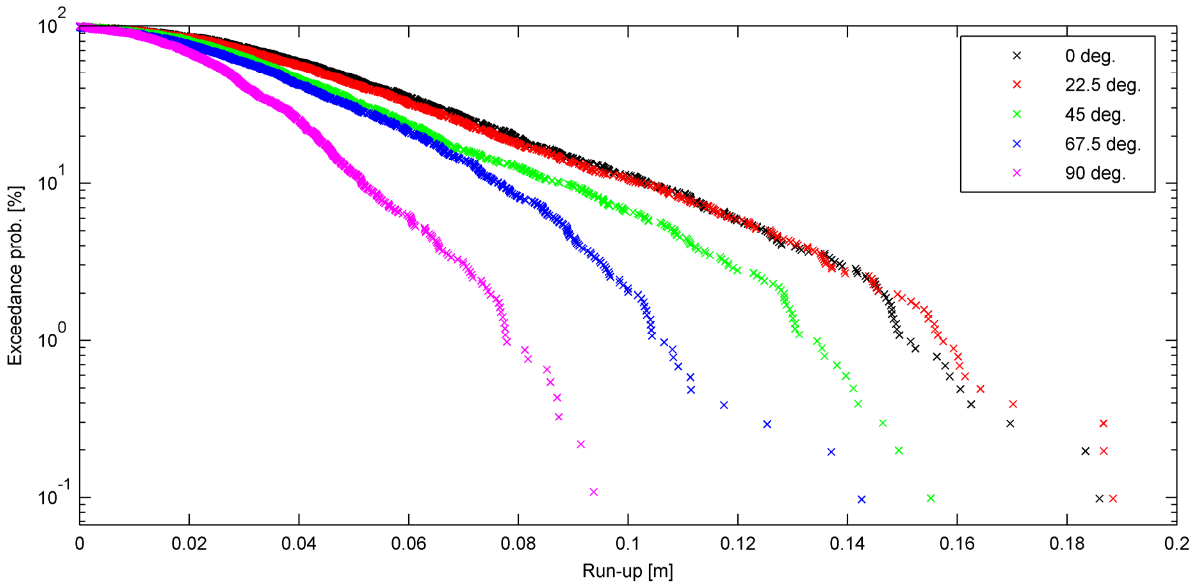
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test113.dat	RunUp_Test_002.dat	0.2	0.079	1.60	0.075	0.92	0.105	13.6%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.146		0.160		0.186	
22.5	0.148		0.164		0.188	
45	0.128		0.141		0.155	
67.5	0.101		0.111		0.143	
90	0.075		0.086		0.094	
Max	0.148	5.0	0.164	4.6	0.188	4.5







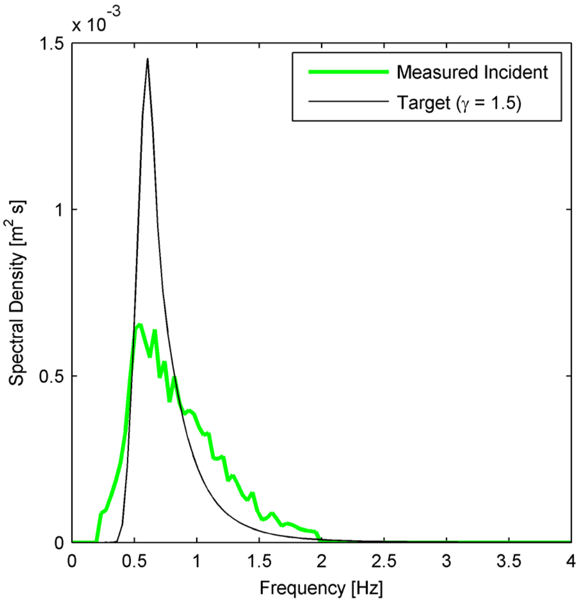
A.3 Test 3 ($h/D = 2$, $H_{m0}/h = 0.43$, $s_{0p} = 0.020$)

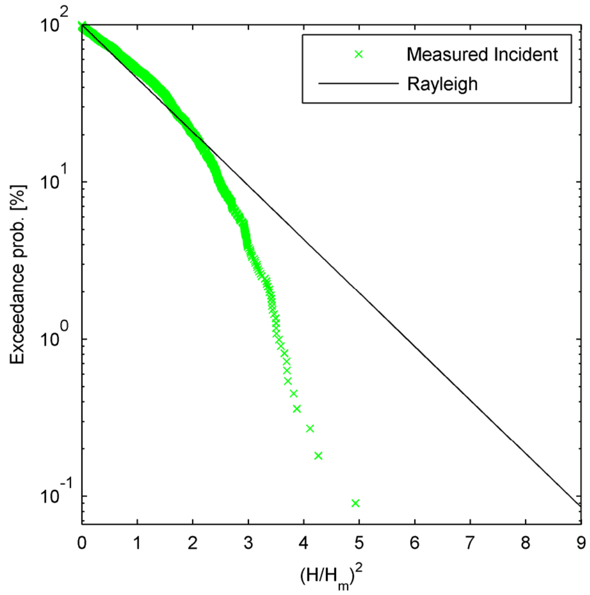
Incident wave parameters at structure determined from the calibration test:

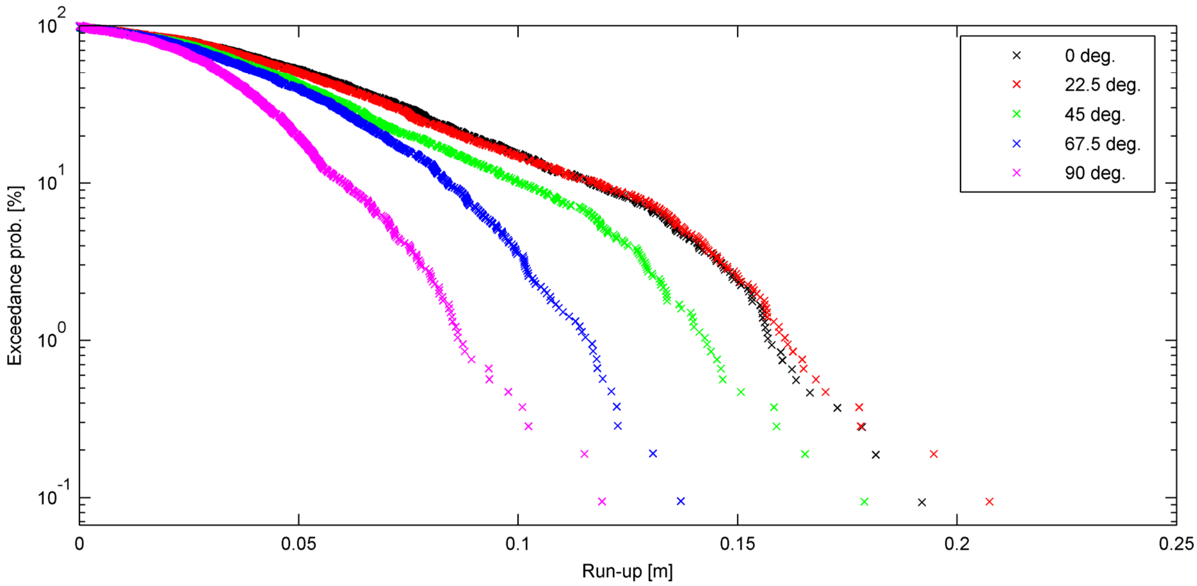
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test115.dat	RunUp_Test_003.dat	0.2	0.085	1.66	0.082	0.101	0.122	14.3%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.153		0.165		0.192	
22.5	0.154		0.169		0.207	
45	0.134		0.150		0.179	
67.5	0.107		0.121		0.137	
90	0.082		0.097		0.119	
Max	0.154	3.6	0.169	3.5	0.207	2.9







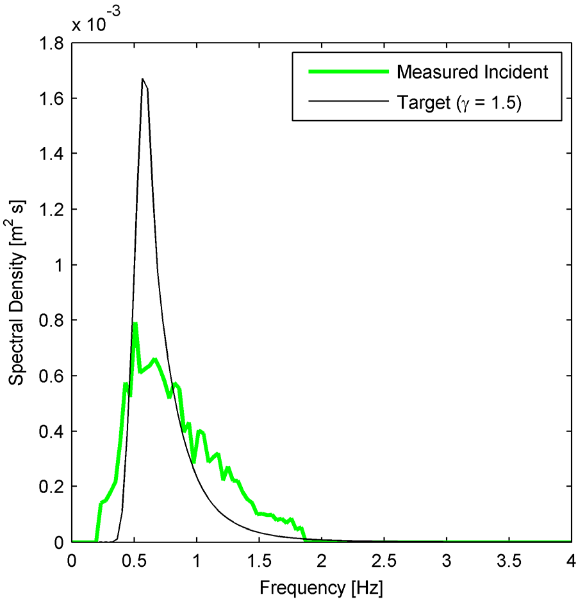
A.4 Test 4 (h/D = 2, H_{m0}/h = 0.46, s_{0p} = 0.020)

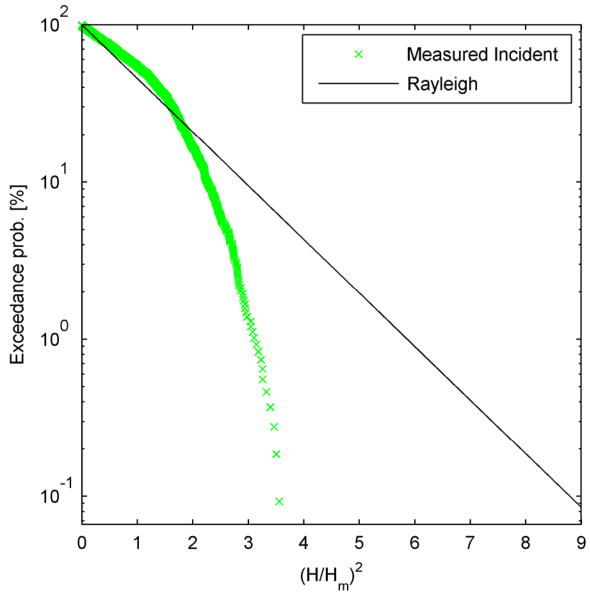
Incident wave parameters at structure determined from the calibration test:

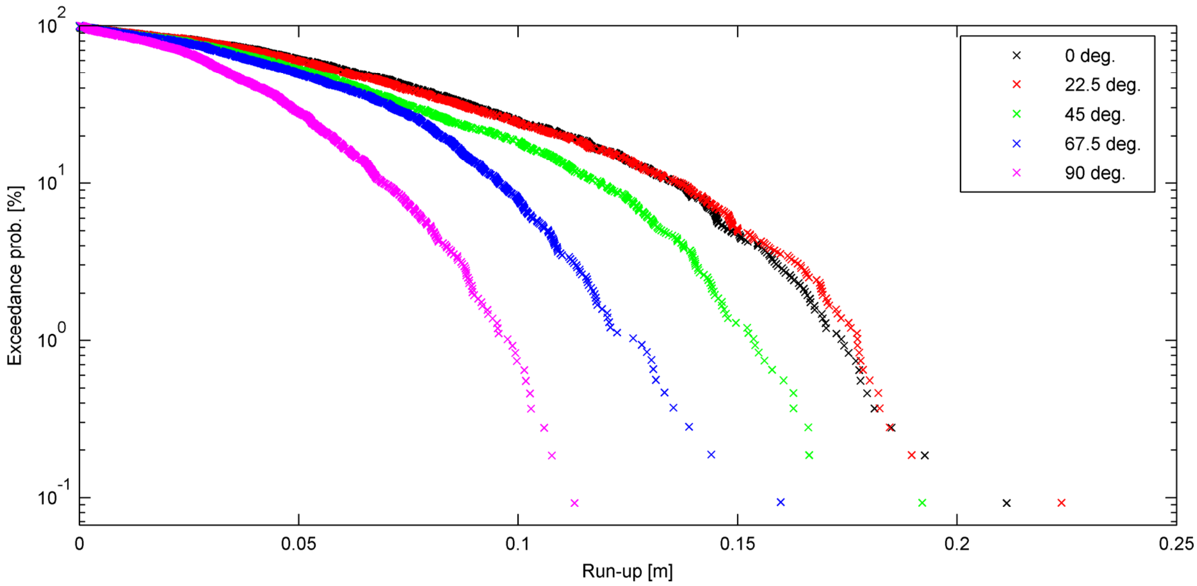
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test116.dat	RunUp_Test_004.dat	0.2	0.091	1.72	0.087	0.102	0.114	15.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.166		0.179		0.211	
22.5	0.169		0.181		0.224	
45	0.145		0.162		0.192	
67.5	0.117		0.133		0.160	
90	0.090		0.102		0.113	
Max	0.169	4.0	0.181	3.5	0.224	4.4







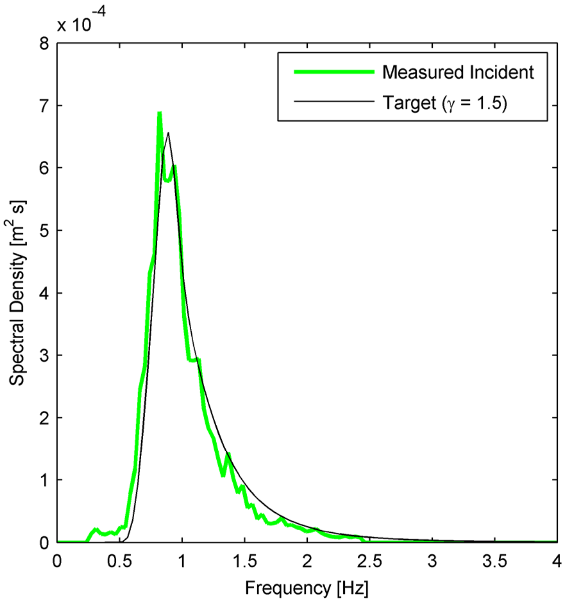
A.5 Test 5 ($h/D = 2$, $H_{m0}/h = 0.35$, $s_{0p} = 0.035$)

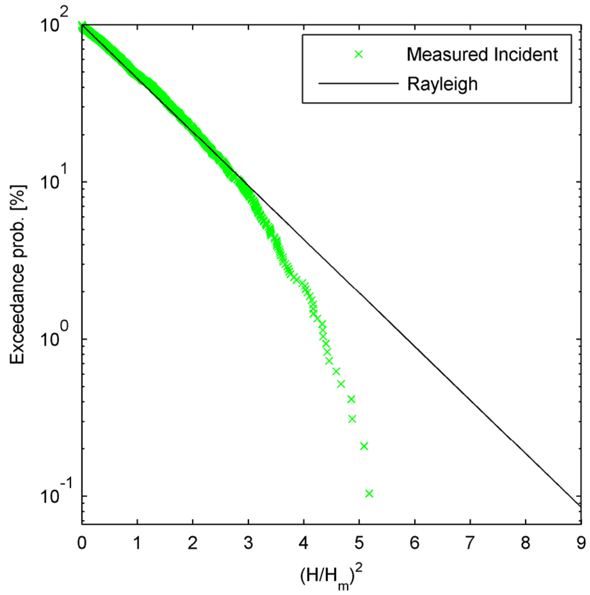
Incident wave parameters at structure determined from the calibration test:

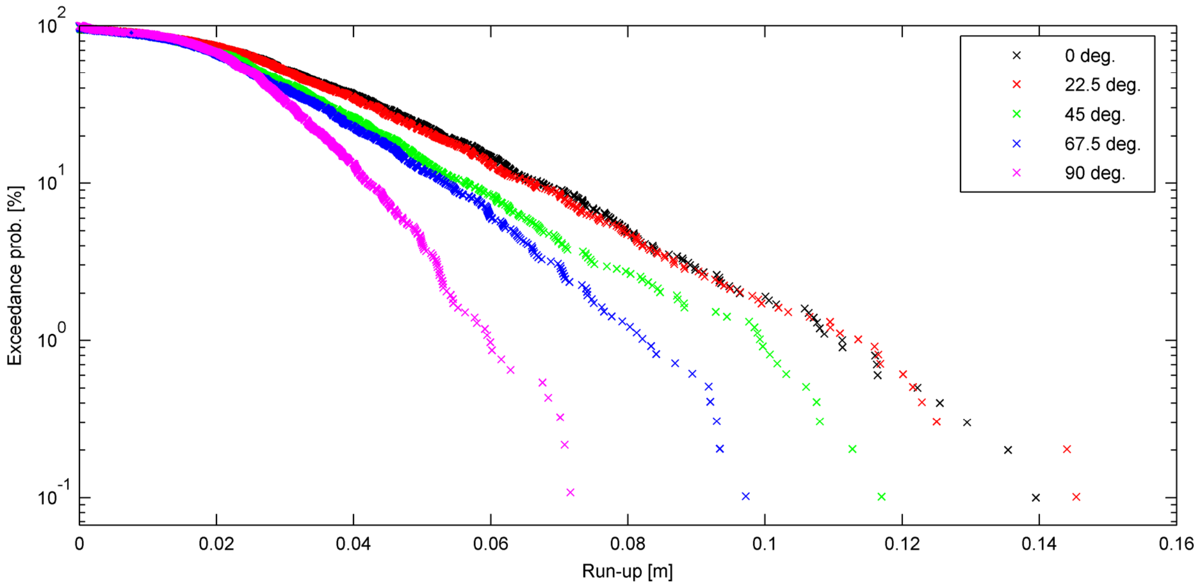
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test117.dat	RunUp_Test_005.dat	0.2	0.070	1.13	0.067	0.087	0.098	9.2%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.097		0.122		0.140	
22.5	0.097		0.122		0.145	
45	0.086		0.106		0.117	
67.5	0.074		0.092		0.097	
90	0.054		0.068		0.072	
Max	0.097	2.9	0.122	3.5	0.145	4.0







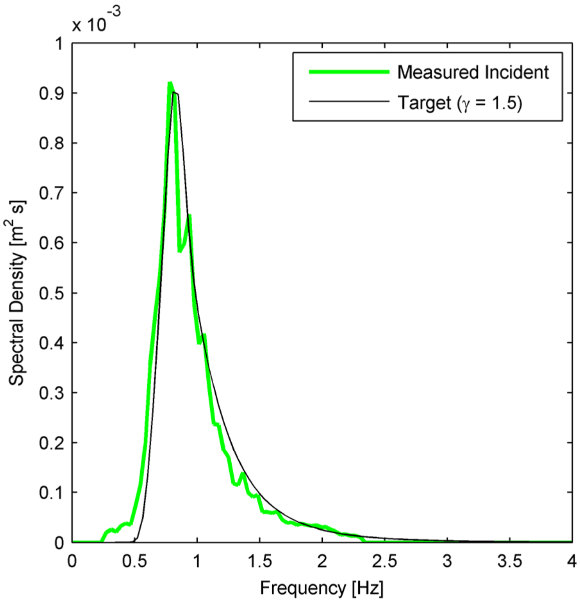
A.6 Test 6 ($h/D = 2$, $H_{m0}/h = 0.40$, $s_{0p} = 0.035$)

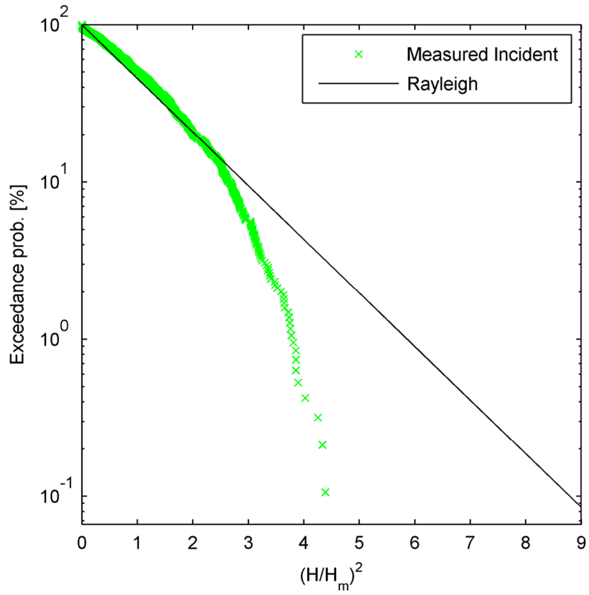
Incident wave parameters at structure determined from the calibration test:

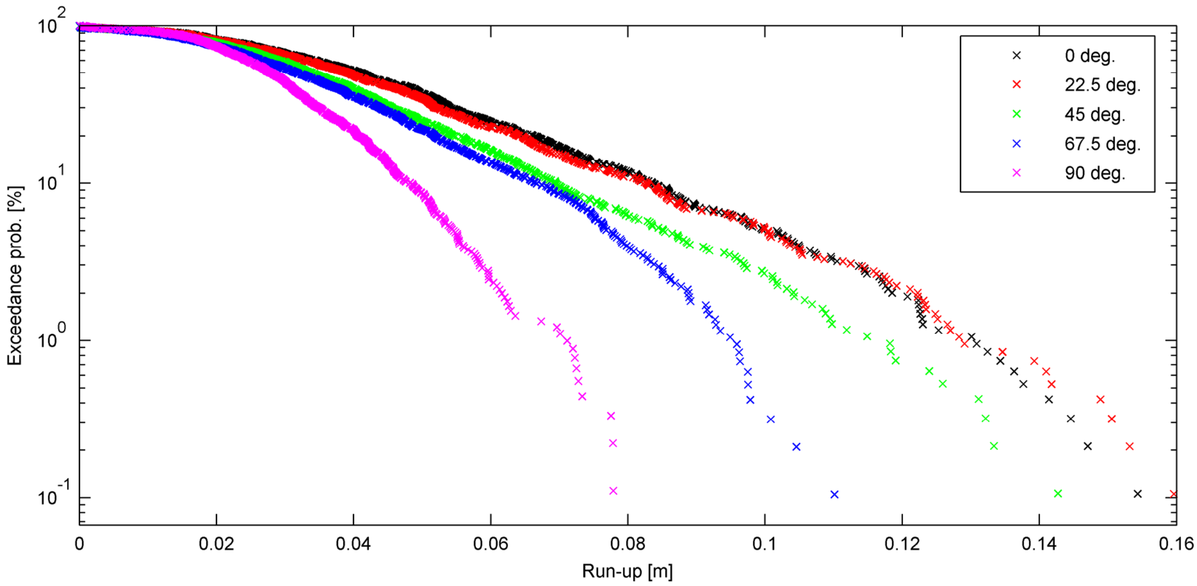
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test118.dat	RunUp_Test_006.dat	0.2	0.079	1.21	0.076	0.095	0.105	10.0%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.119		0.139		0.154	
22.5	0.122		0.144		0.168	
45	0.104		0.128		0.143	
67.5	0.089		0.098		0.110	
90	0.062		0.073		0.078	
Max	0.122	3.2	0.144	3.6	0.168	2.5







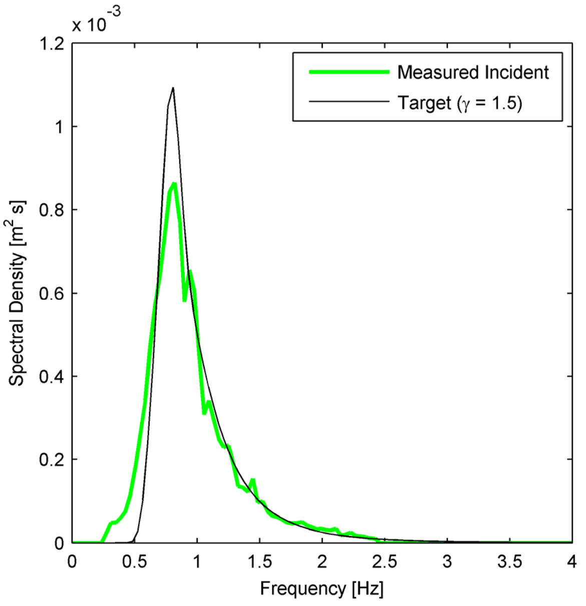
A.7 Test 7 (h/D = 2, H_{m0}/h = 0.43, s_{0p} = 0.035)

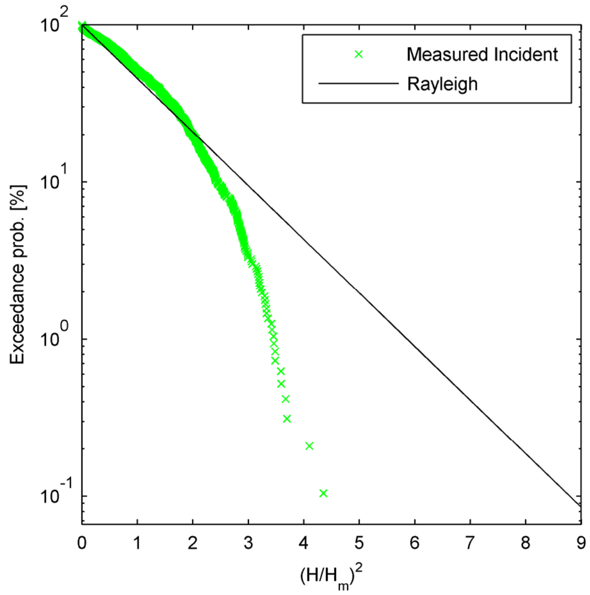
Incident wave parameters at structure determined from the calibration test:

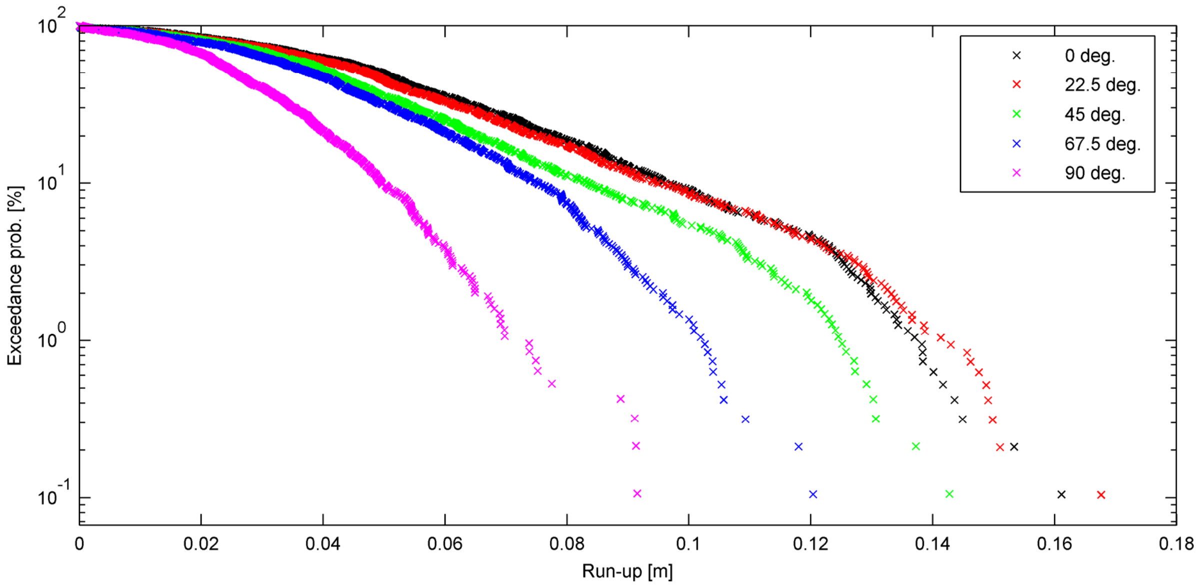
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test119.dat	RunUp_Test_007.dat	0.2	0.086	1.25	0.082	0.100	0.115	10.6%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.130		0.142		0.161	
22.5	0.133		0.149		0.168	
45	0.119		0.129		0.143	
67.5	0.096		0.105		0.120	
90	0.065		0.081		0.092	
Max	0.133	3.1	0.149	3.1	0.168	2.5







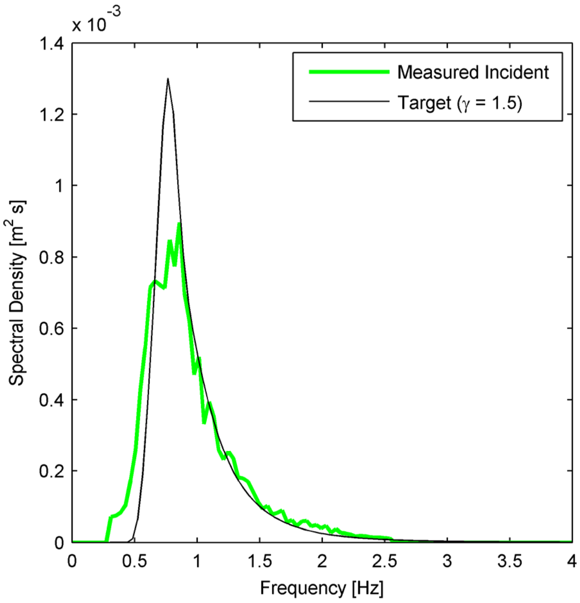
A.8 Test 8 (h/D = 2, H_{m0}/h = 0.46, s_{0p} = 0.035)

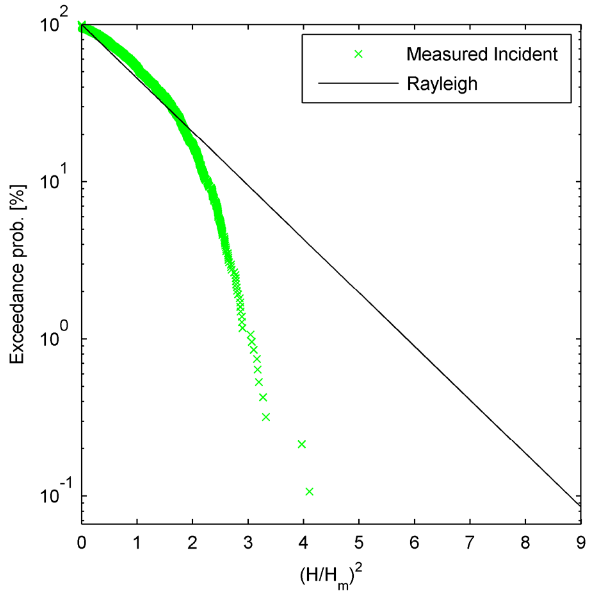
Incident wave parameters at structure determined from the calibration test:

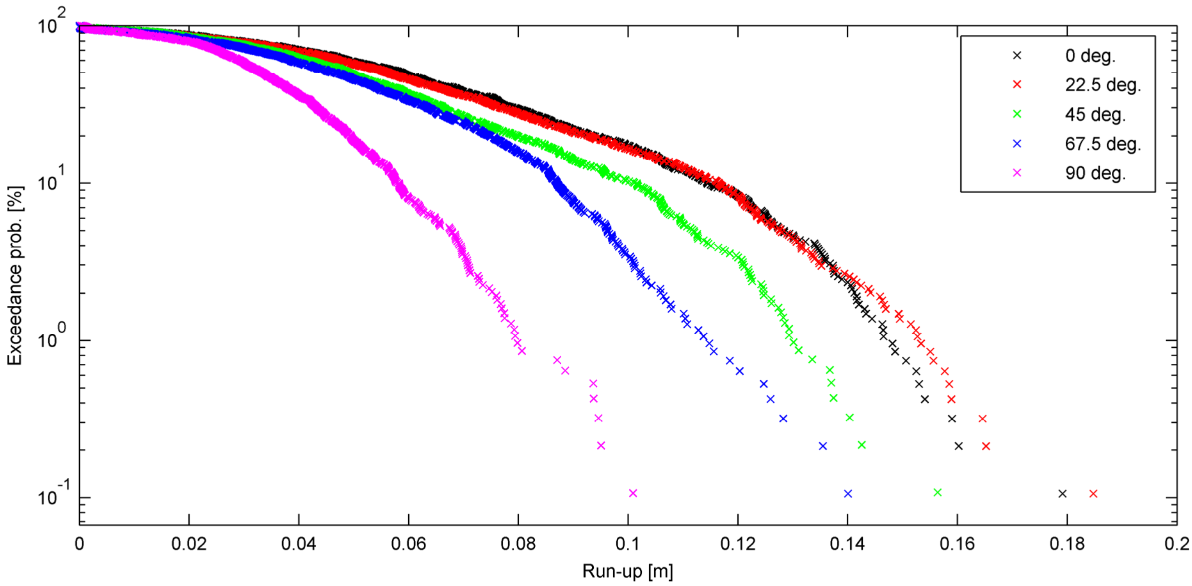
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test120.dat	RunUp_Test_008.dat	0.2	0.092	1.30	0.089	0.103	0.125	11.7%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.141		0.153		0.179	
22.5	0.144		0.159		0.185	
45	0.125		0.137		0.156	
67.5	0.106		0.125		0.140	
90	0.075		0.094		0.101	
Max	0.144	3.1	0.159	2.7	0.185	2.1







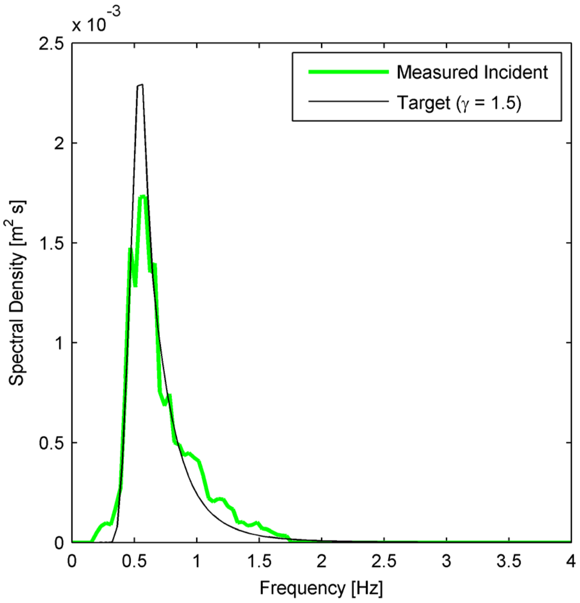
A.9 Test 9 ($h/D = 3$, $H_{m0}/h = 0.35$, $s_{0p} = 0.020$)

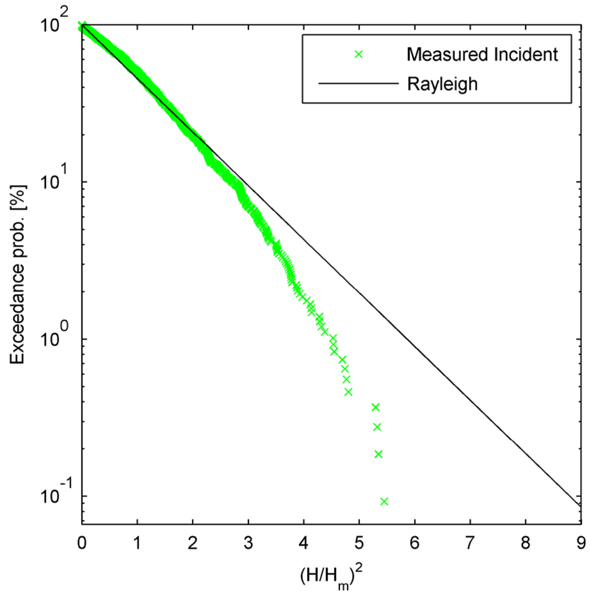
Incident wave parameters at structure determined from the calibration test:

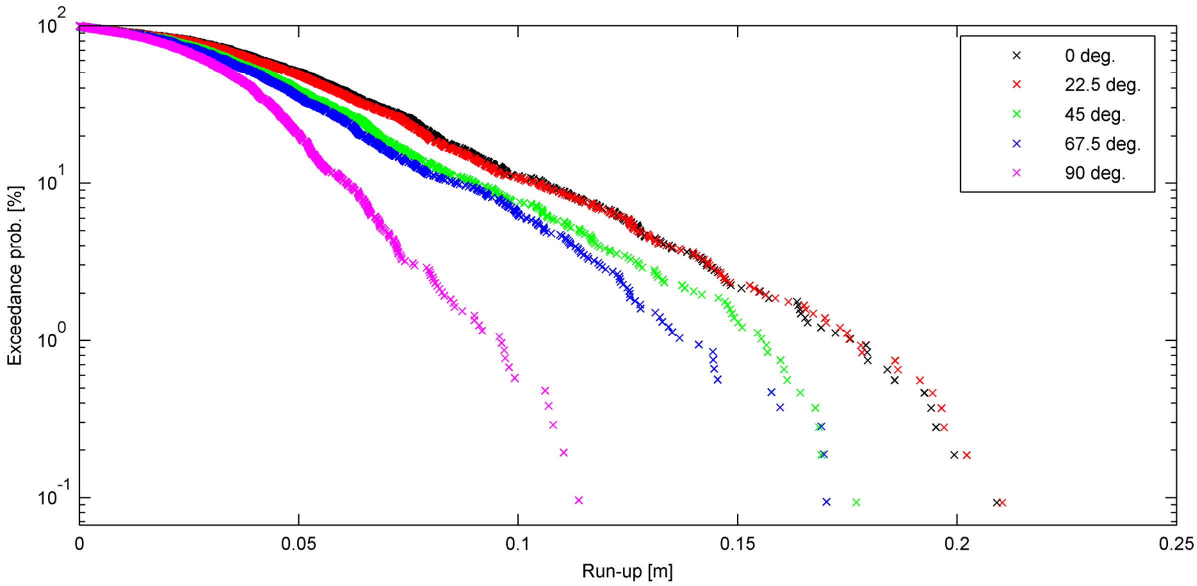
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test122.dat	RunUp_Test_009.dat	0.3	0.105	1.83	0.100	0.129	0.152	11.3%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.156		0.190		0.209	
22.5	0.156		0.193		0.210	
45	0.141		0.163		0.177	
67.5	0.125		0.154		0.170	
90	0.083		0.105		0.114	
Max	0.156	3.2	0.193	3.4	0.210	3.0







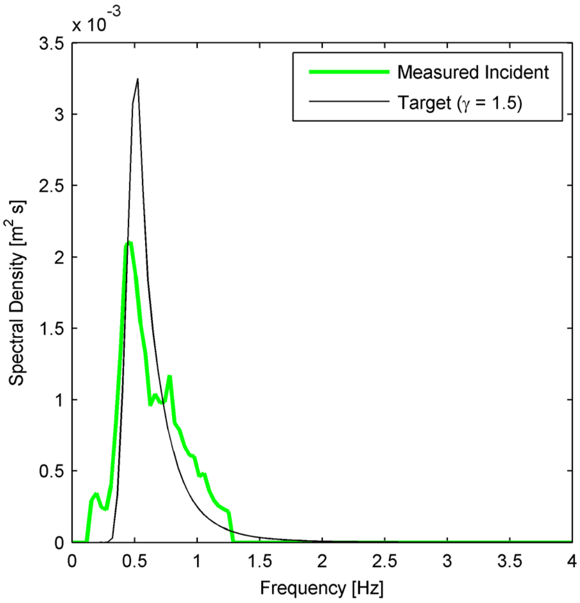
A.10 Test 10 (h/D = 3, H_{m0}/h = 0.40, s_{0p} = 0.020)

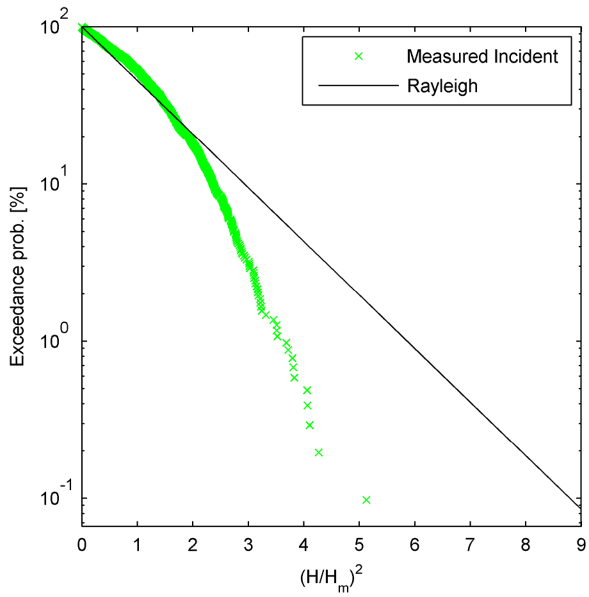
Incident wave parameters at structure determined from the calibration test:

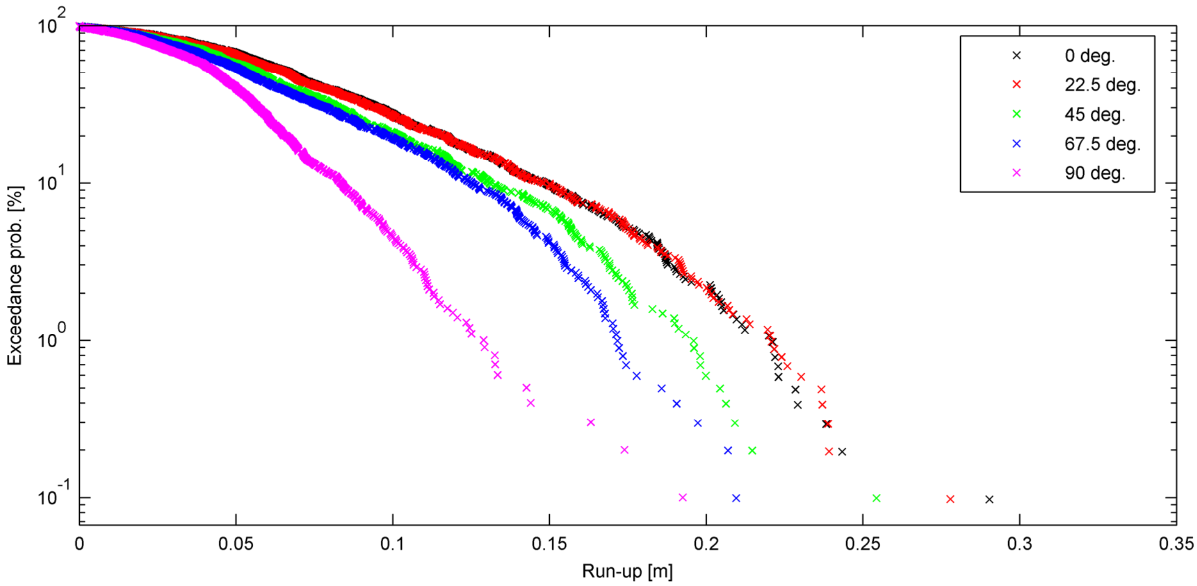
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test125.dat	RunUp_Test_010.dat	0.3	0.121	1.96	0.112	0.136	0.173	19.6%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.203		0.228		0.290	
22.5	0.201		0.236		0.278	
45	0.176		0.204		0.254	
67.5	0.165		0.186		0.210	
90	0.113		0.143		0.193	
Max	0.203	4.3	0.236	3.6	0.290	3.2







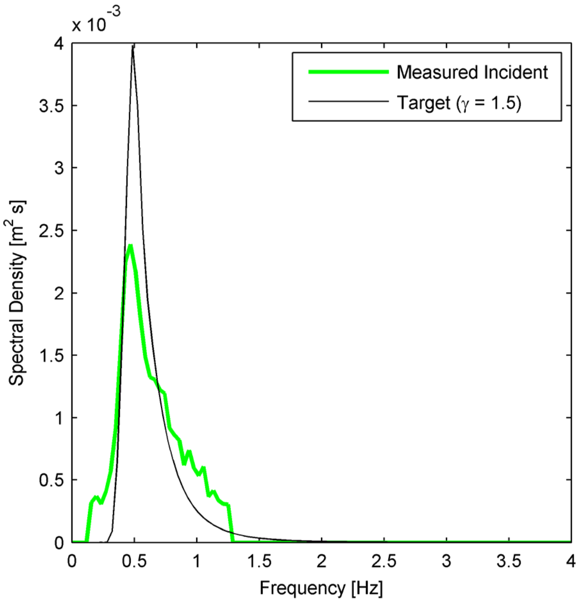
A.11 Test 11 (h/D = 3, H_{m0}/h = 0.43, s_{0p} = 0.020)

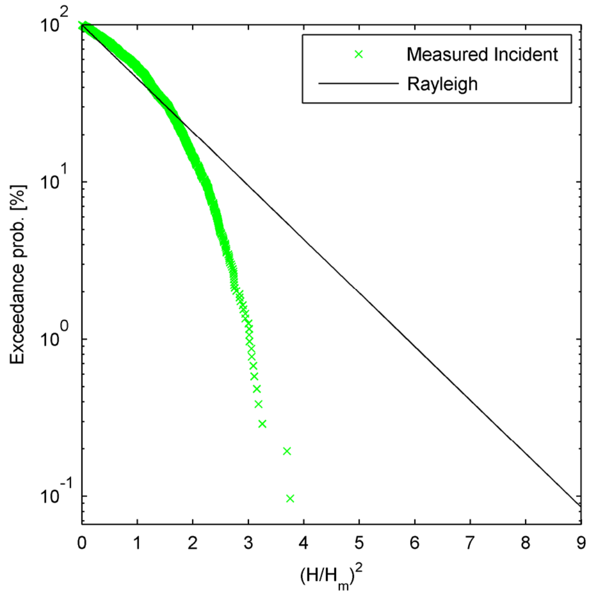
Incident wave parameters at structure determined from the calibration test:

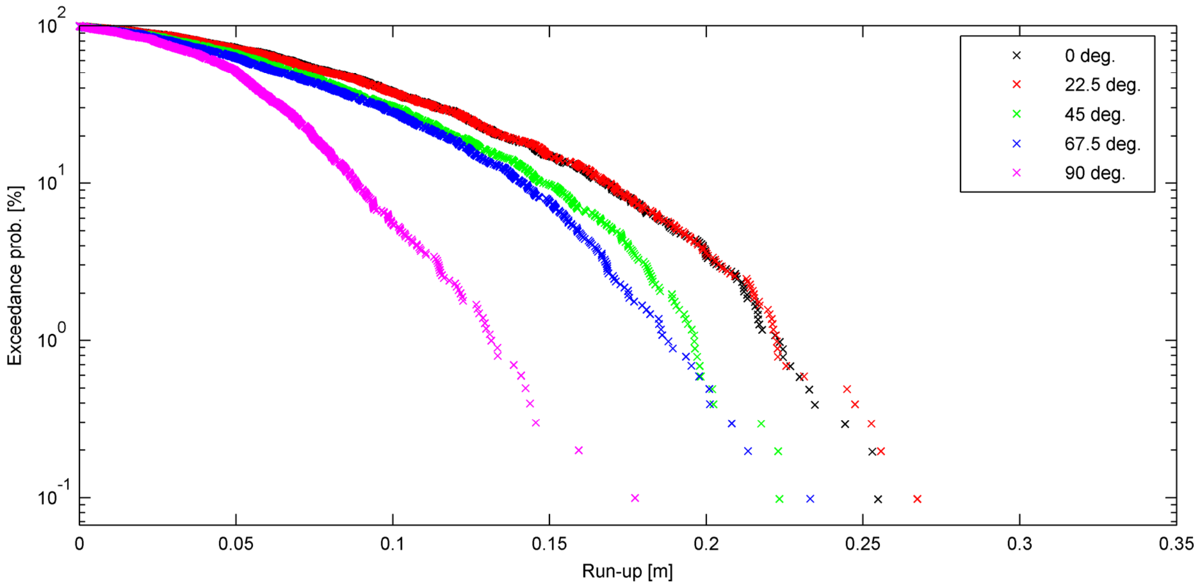
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test127.dat	RunUp_Test_011.dat	0.3	0.130	2.03	0.119	0.141	0.163	22.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.213		0.233		0.255	
22.5	0.215		0.244		0.267	
45	0.188		0.202		0.223	
67.5	0.175		0.201		0.233	
90	0.122		0.142		0.177	
Max	0.215	4.1	0.244	4.2	0.267	3.5







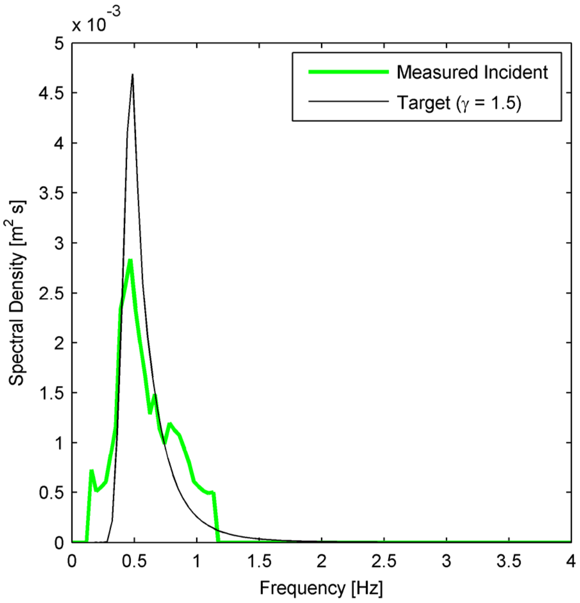
A.12 Test 12 (h/D = 3, H_{m0}/h = 0.46, s_{0p} = 0.020)

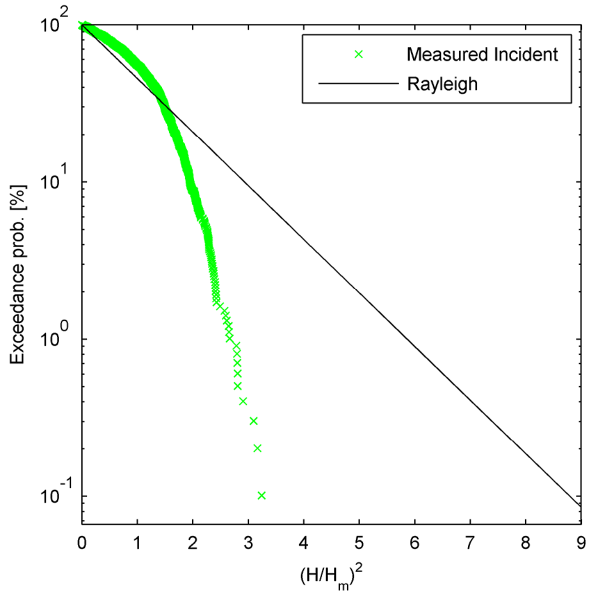
Incident wave parameters at structure determined from the calibration test:

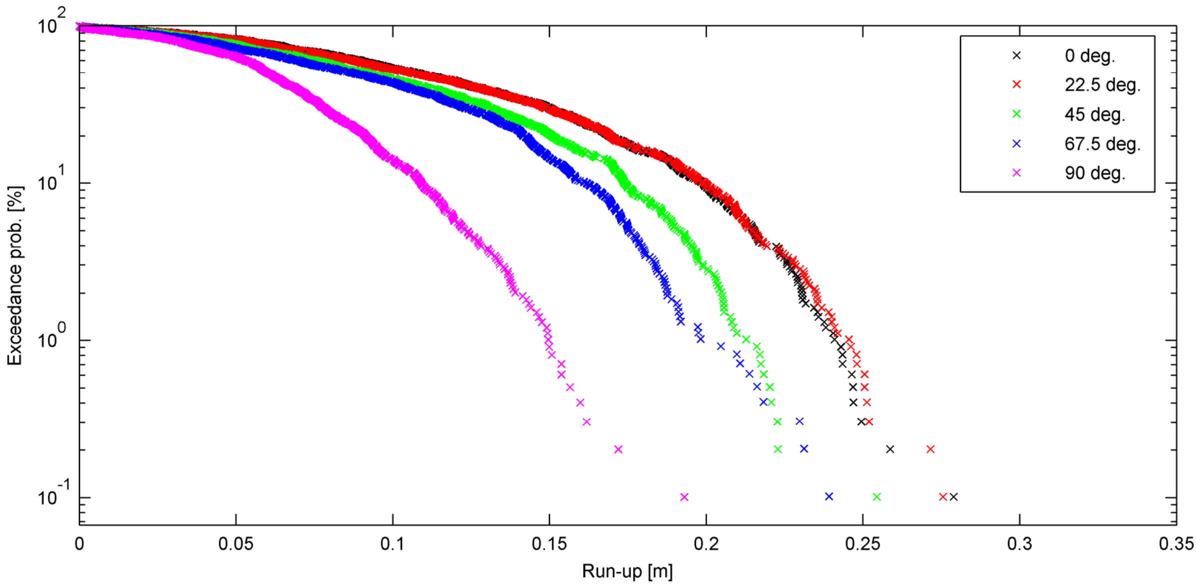
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test128.dat	RunUp_Test_012.dat	0.3	0.139	2.10	0.125	0.143	0.166	26.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.231		0.247		0.279	
22.5	0.235		0.251		0.276	
45	0.205		0.220		0.254	
67.5	0.188		0.216		0.239	
90	0.140		0.157		0.193	
Max	0.235	4.5	0.251	3.8	0.279	3.5







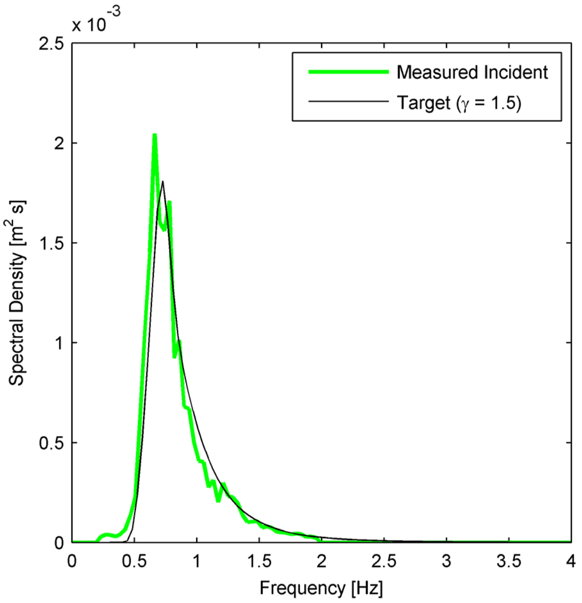
A.13 Test 13 (h/D = 3, H_{m0}/h = 0.35, s_{0p} = 0.035)

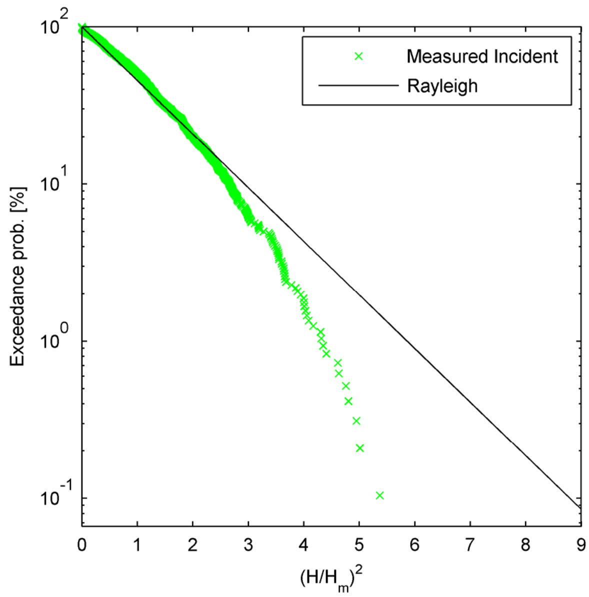
Incident wave parameters at structure determined from the calibration test:

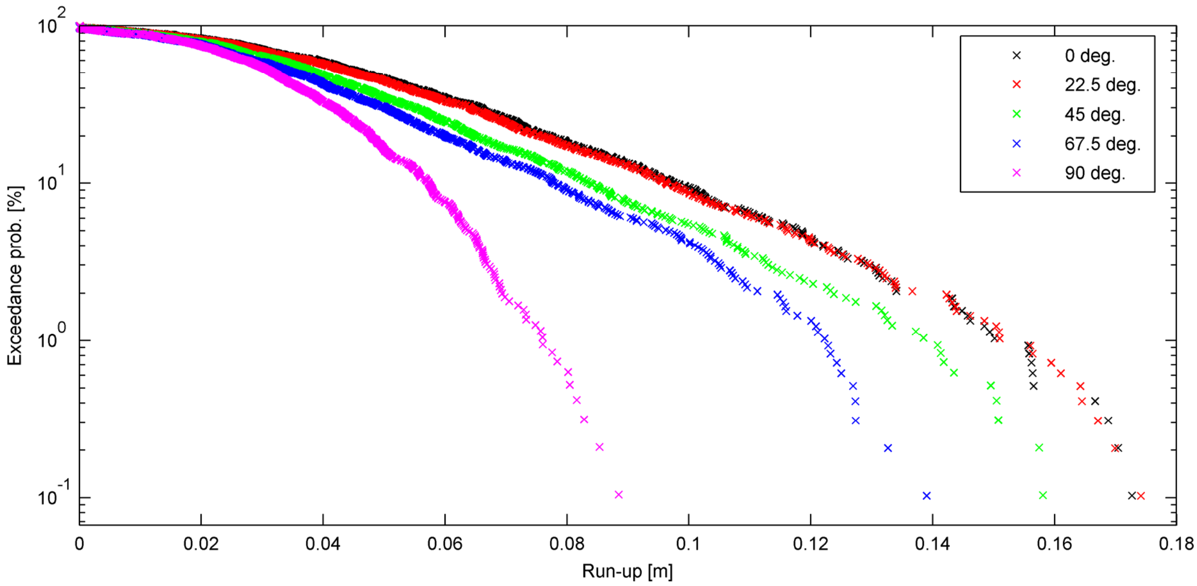
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test130.dat	RunUp_Test_013.dat	0.3	0.106	1.39	0.099	0.129	0.151	11.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.139		0.158		0.173	
22.5	0.140		0.164		0.174	
45	0.124		0.150		0.158	
67.5	0.113		0.127		0.139	
90	0.069		0.081		0.089	
Max	0.140	2.7	0.164	2.6	0.174	2.2







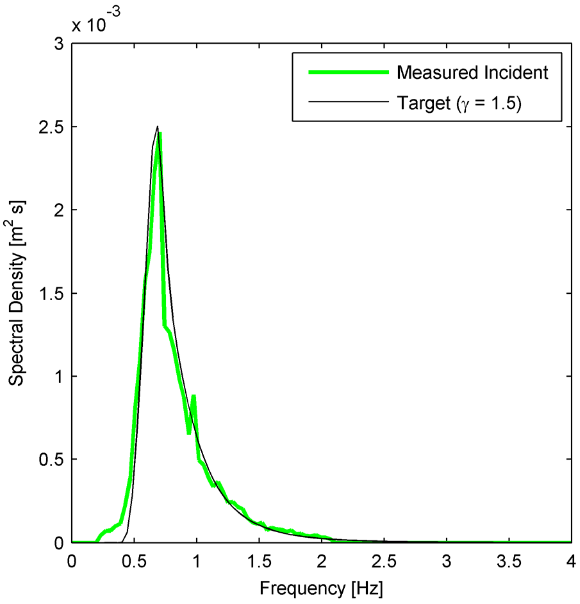
A.14 Test 14 ($h/D = 3$, $H_{m0}/h = 0.40$, $s_{0p} = 0.035$)

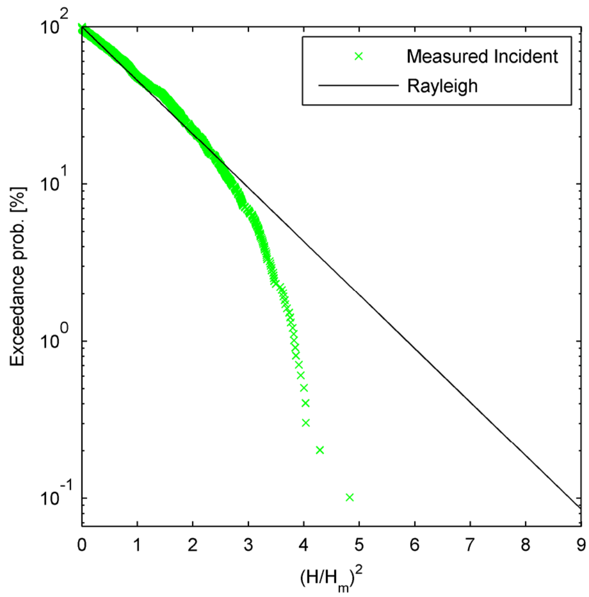
Incident wave parameters at structure determined from the calibration test:

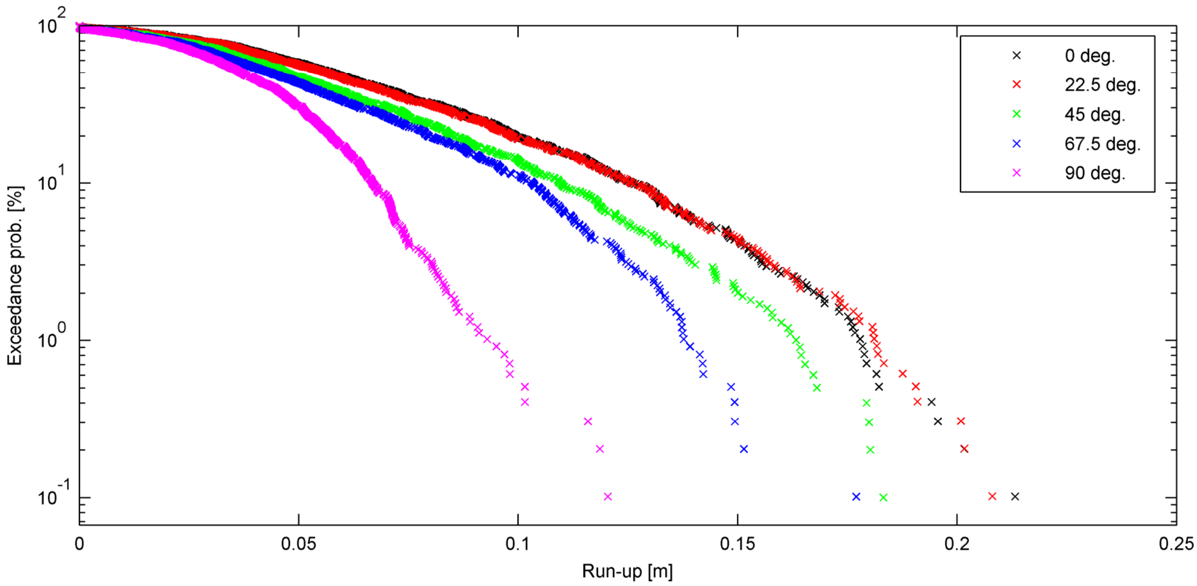
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test131.dat	RunUp_Test_014.dat	0.3	0.119	1.48	0.115	0.142	0.164	13.3%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.168		0.183		0.213	
22.5	0.170		0.191		0.208	
45	0.150		0.168		0.183	
67.5	0.133		0.149		0.177	
90	0.084		0.102		0.120	
Max	0.170	2.8	0.191	2.8	0.213	2.3







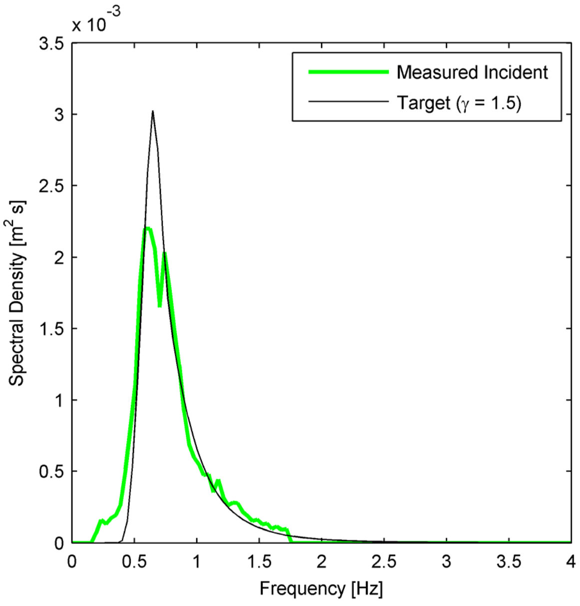
A.15 Test 15 (h/D = 3, H_{m0}/h = 0.43, s_{0p} = 0.035)

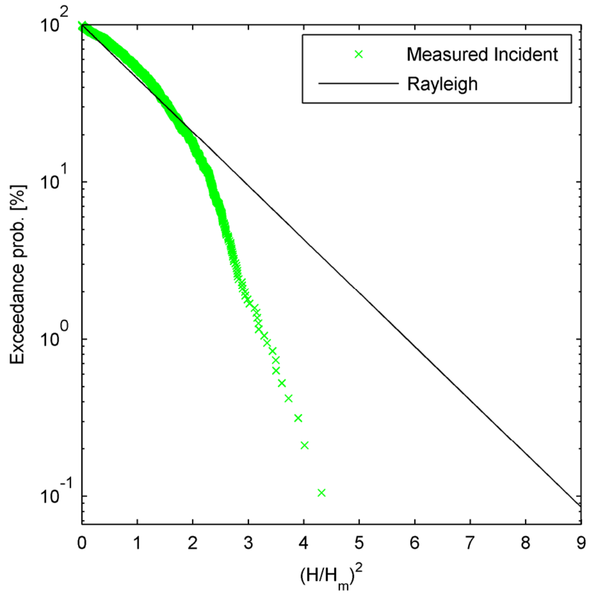
Incident wave parameters at structure determined from the calibration test:

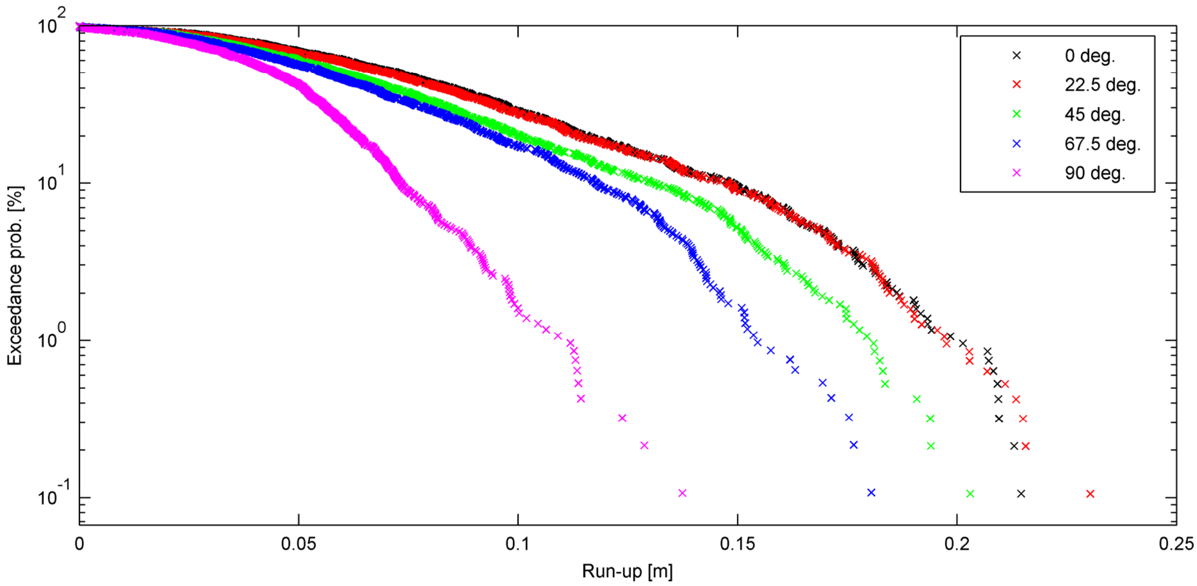
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test132.dat	RunUp_Test_015.dat	0.3	0.130	1.54	0.120	0.143	0.173	15.9%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.186		0.209		0.215	
22.5	0.185		0.212		0.230	
45	0.168		0.186		0.203	
67.5	0.146		0.170		0.181	
90	0.098		0.114		0.137	
Max	0.186	3.3	0.212	2.7	0.230	2.1







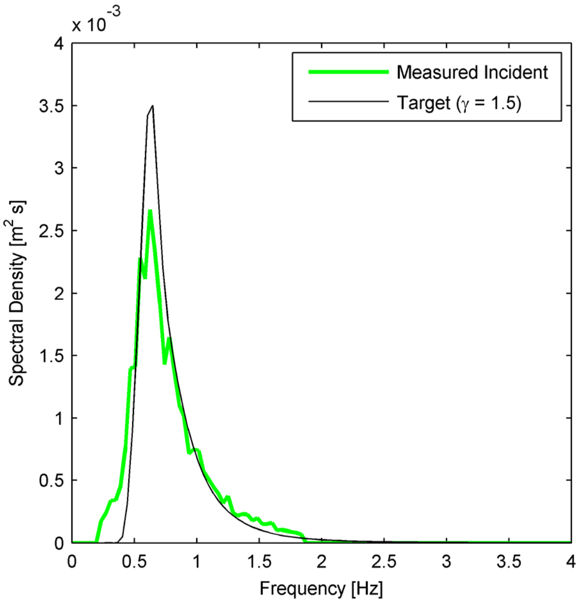
A.16 Test 16 ($h/D = 3$, $H_{m0}/h = 0.46$, $s_{0p} = 0.035$)

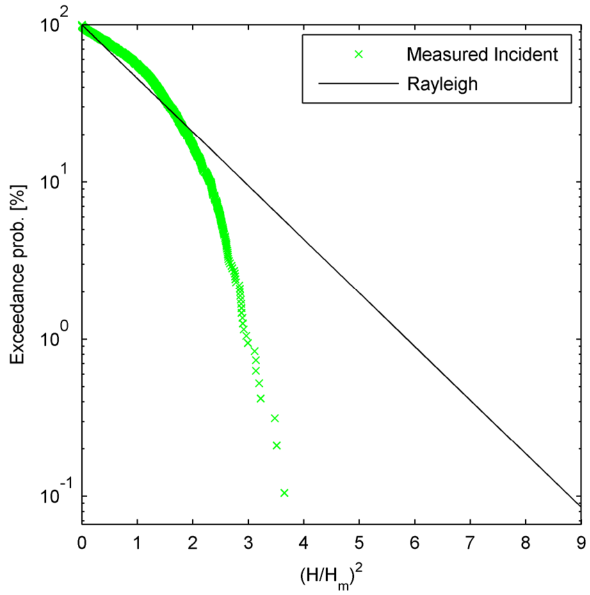
Incident wave parameters at structure determined from the calibration test:

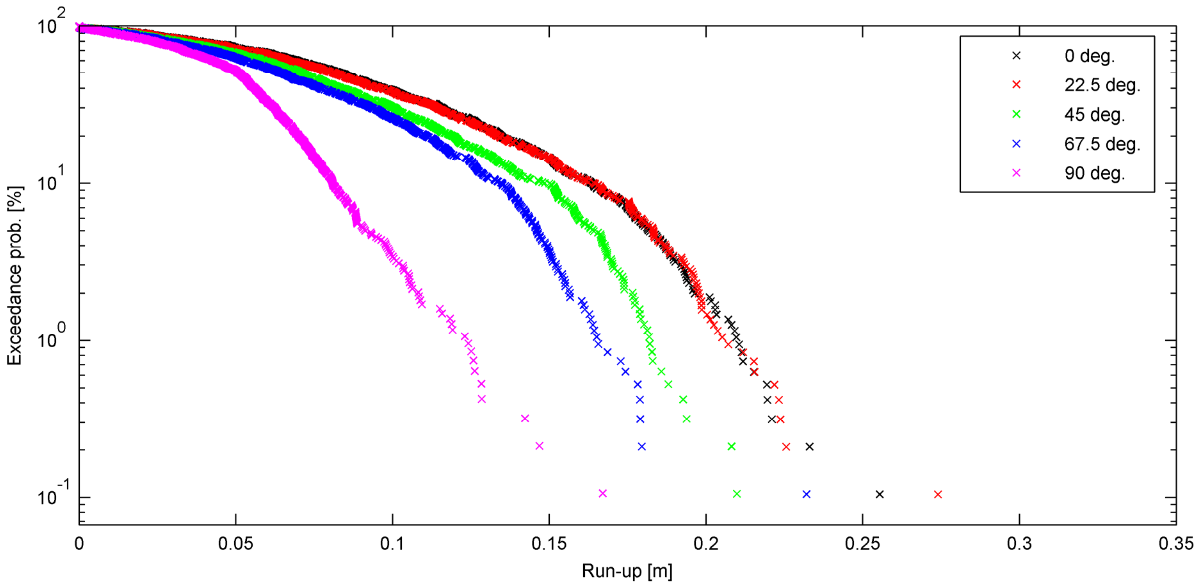
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test133.dat	RunUp_Test_016.dat	0.3	0.137	1.59	0.129	0.151	0.171	16.9%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.196		0.219		0.255	
22.5	0.198		0.222		0.274	
45	0.177		0.189		0.210	
67.5	0.157		0.178		0.232	
90	0.108		0.128		0.167	
Max	0.198	2.9	0.222	2.8	0.274	3.2







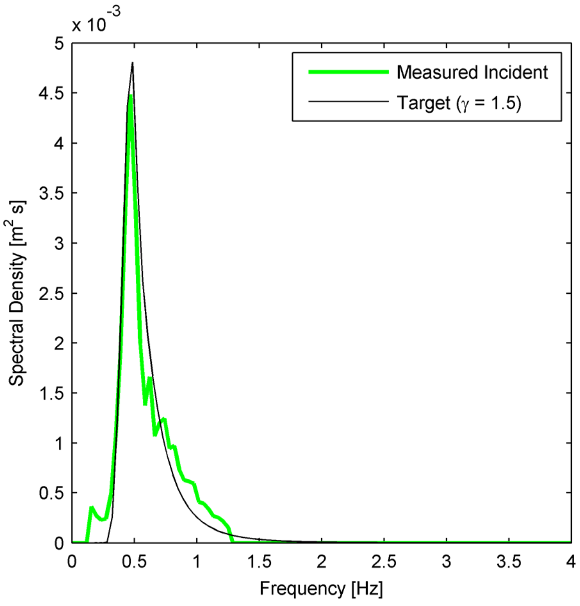
A.17 Test 17 (h/D = 4, H_{m0}/h = 0.35, s_{0p} = 0.020)

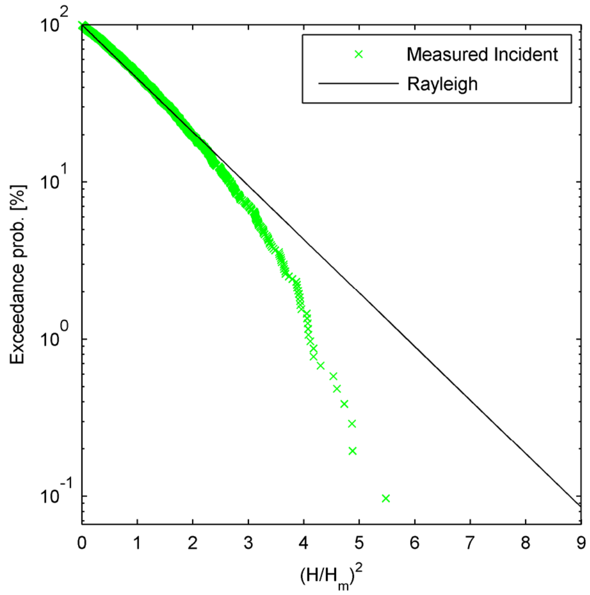
Incident wave parameters at structure determined from the calibration test:

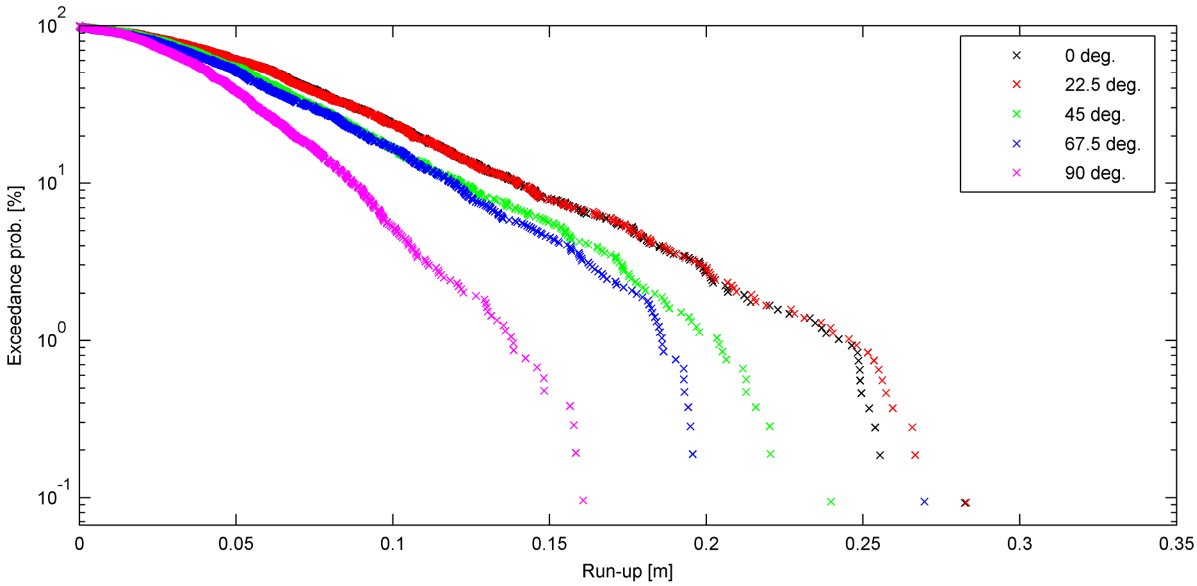
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test098.dat	RunUp_Test_017.dat	0.4	0.139	2.12	0.134	0.173	0.205	24.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.209		0.249		0.282	
22.5	0.212		0.257		0.283	
45	0.183		0.213		0.240	
67.5	0.178		0.193		0.270	
90	0.123		0.148		0.161	
Max	0.212	3.2	0.257	3.5	0.283	2.9







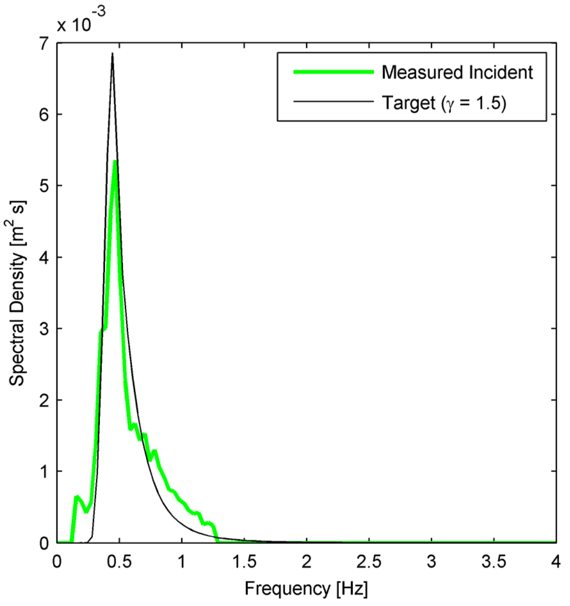
A.18 Test 18 (h/D = 4, H_{m0}/h = 0.40, s_{0p} = 0.020)

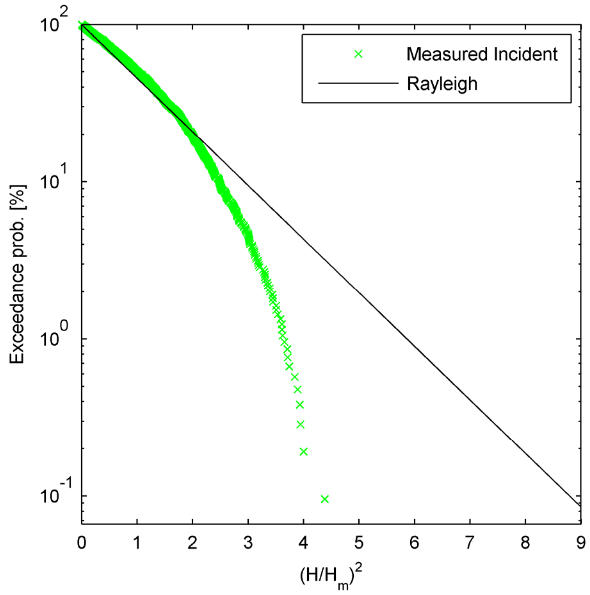
Incident wave parameters at structure determined from the calibration test:

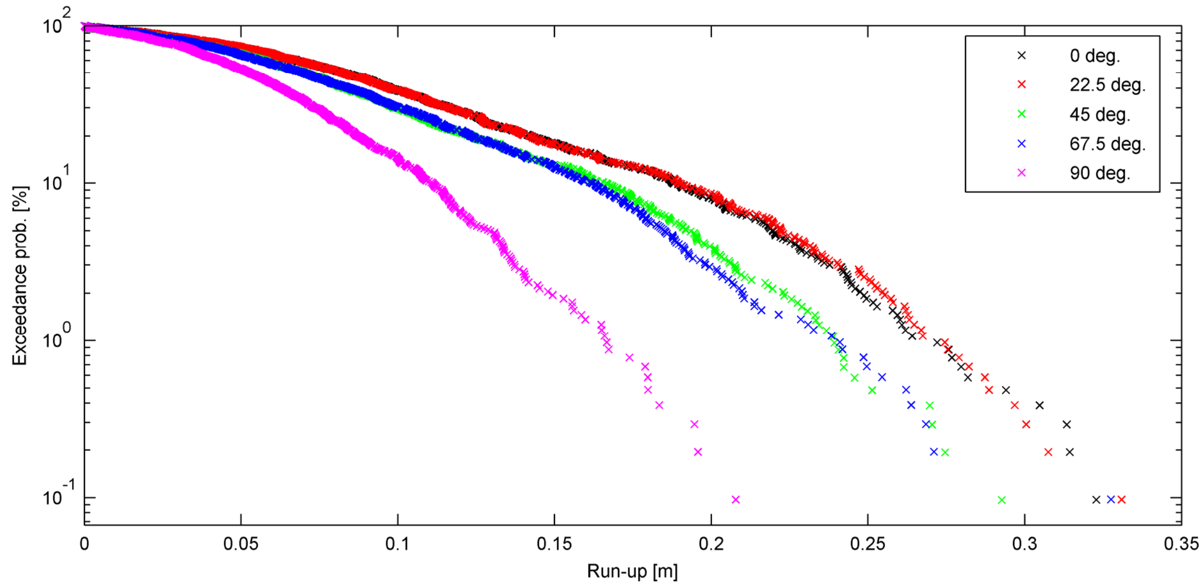
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test099.dat	RunUp_Test_018.dat	0.4	0.159	2.26	0.150	0.185	0.210	25.0%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.248		0.292		0.323	
22.5	0.255		0.288		0.331	
45	0.223		0.250		0.293	
67.5	0.210		0.261		0.328	
90	0.149		0.180		0.208	
Max	0.255	3.5	0.292	3.6	0.331	3.5







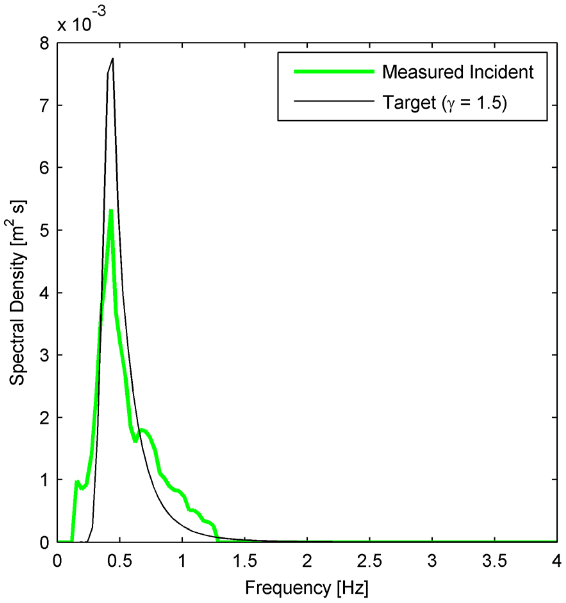
A.19 Test 19 (h/D = 4, H_{m0}/h = 0.43, s_{0p} = 0.020)

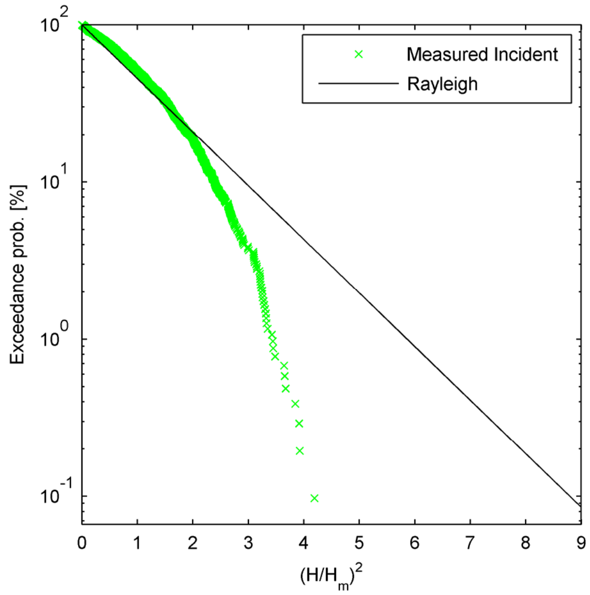
Incident wave parameters at structure determined from the calibration test:

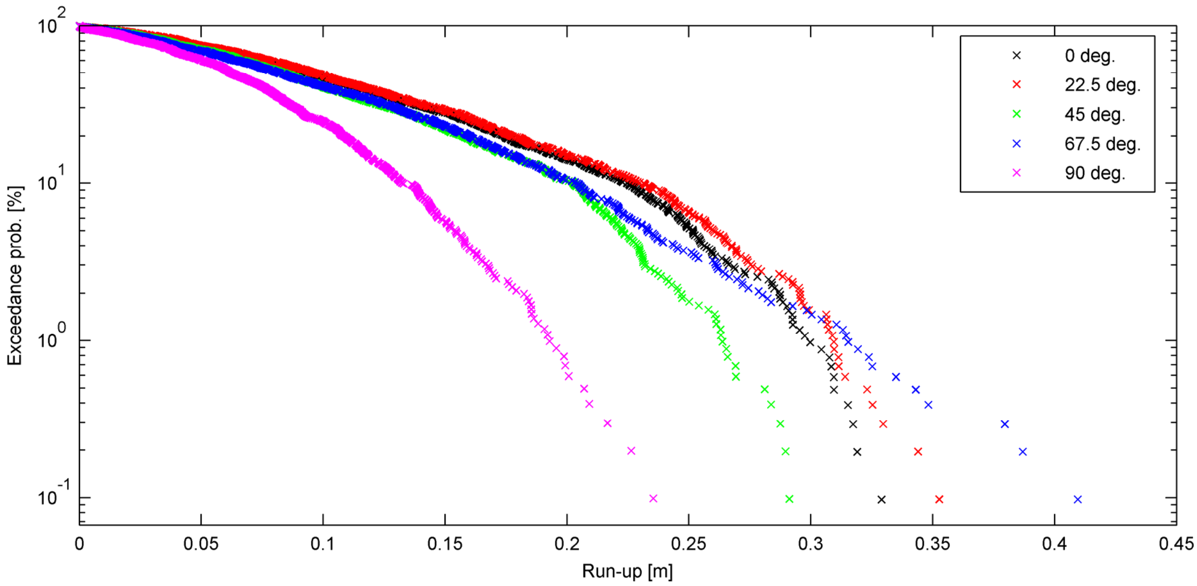
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test100.dat	RunUp_Test_019.dat	0.4	0.172	2.35	0.163	0.200	0.227	31.1%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.287		0.309		0.329	
22.5	0.296		0.322		0.353	
45	0.247		0.280		0.291	
67.5	0.279		0.342		0.409	
90	0.182		0.207		0.235	
Max	0.296	3.4	0.342	3.6	0.409	3.8







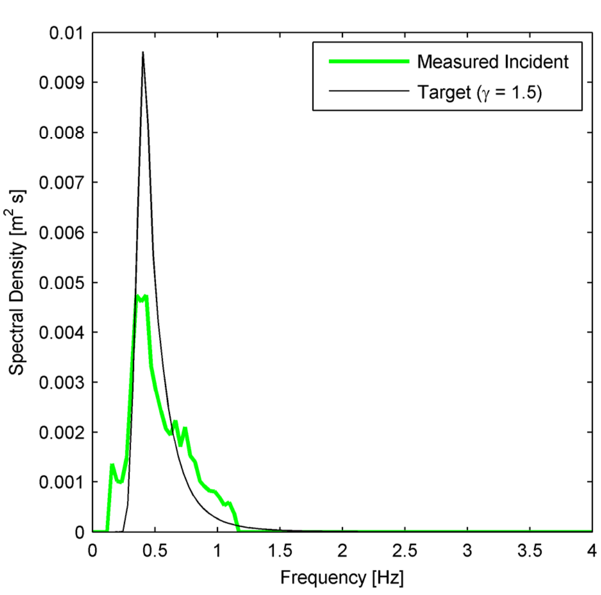
A.20 Test 20 ($h/D = 4$, $H_{m0}/h = 0.44$, $s_{0p} = 0.020$)

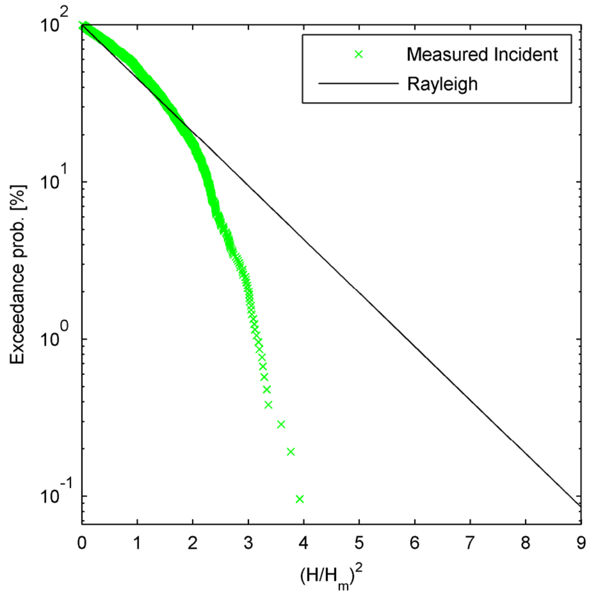
Incident wave parameters at structure determined from the calibration test:

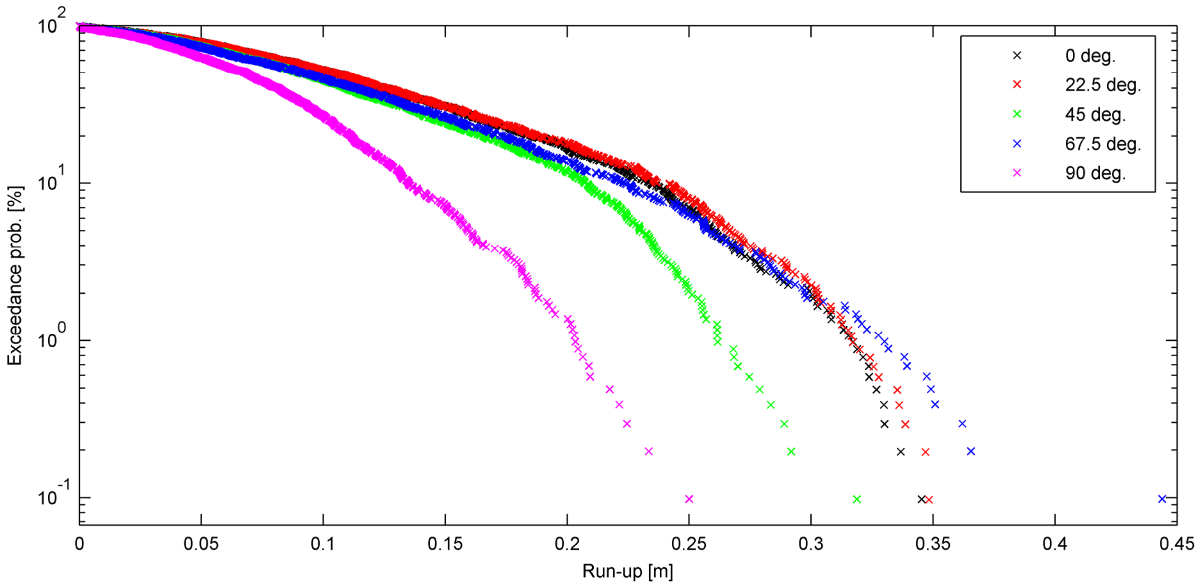
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test101.dat	RunUp_Test_020.dat	0.4	0.176	2.43	0.162	0.196	0.224	28.5%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.300		0.326		0.345	
22.5	0.302		0.334		0.348	
45	0.251		0.278		0.319	
67.5	0.297		0.349		0.444	
90	0.187		0.217		0.25	
Max	0.302	3.8	0.349	4.1	0.444	4.6







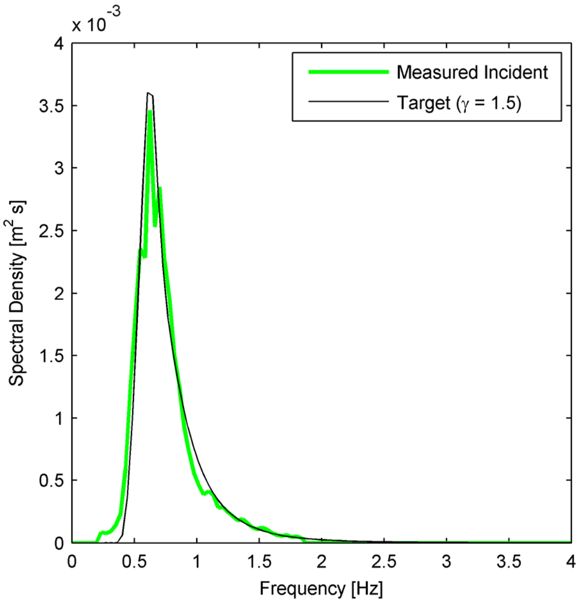
A.21 Test 21 (h/D = 4, H_{m0}/h = 0.35, s_{0p} = 0.035)

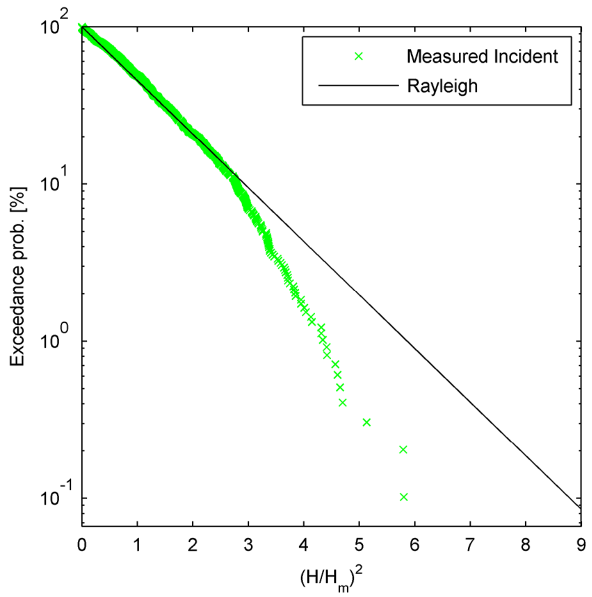
Incident wave parameters at structure determined from the calibration test:

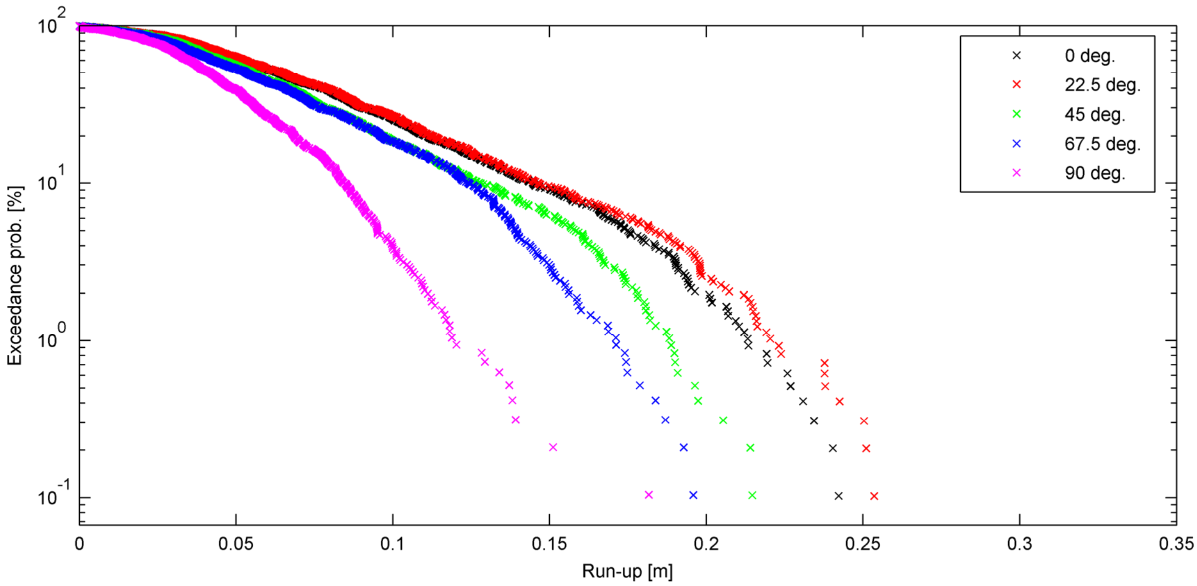
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test105.dat	RunUp_Test_021.dat	0.4	0.139	1.60	0.134	0.171	0.210	13.6%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.199		0.227		0.242	
22.5	0.210		0.239		0.254	
45	0.178		0.197		0.215	
67.5	0.156		0.180		0.196	
90	0.111		0.137		0.182	
Max	0.210	2.5	0.239	3.2	0.254	2.2







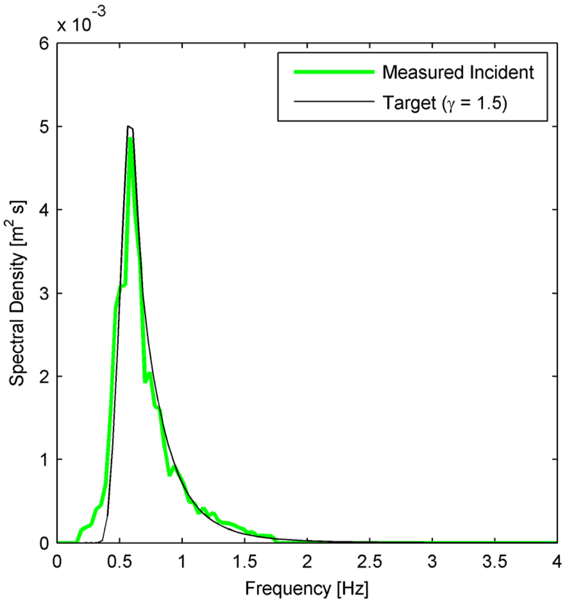
A.22 Test 22 (h/D = 4, H_{m0}/h = 0.40, s_{0p} = 0.035)

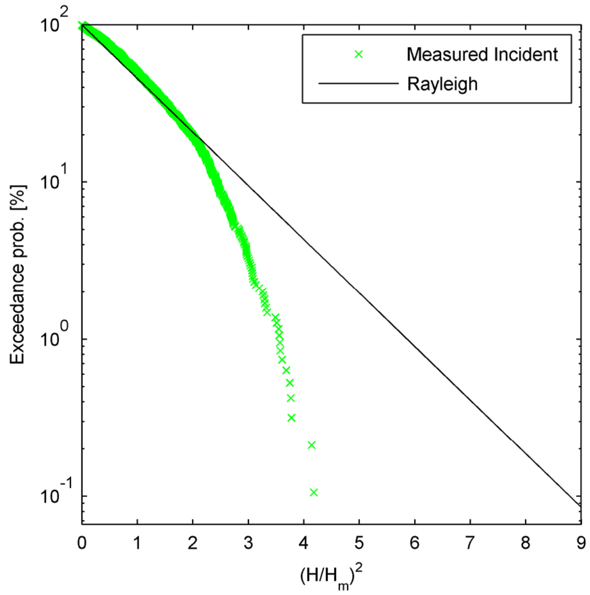
Incident wave parameters at structure determined from the calibration test:

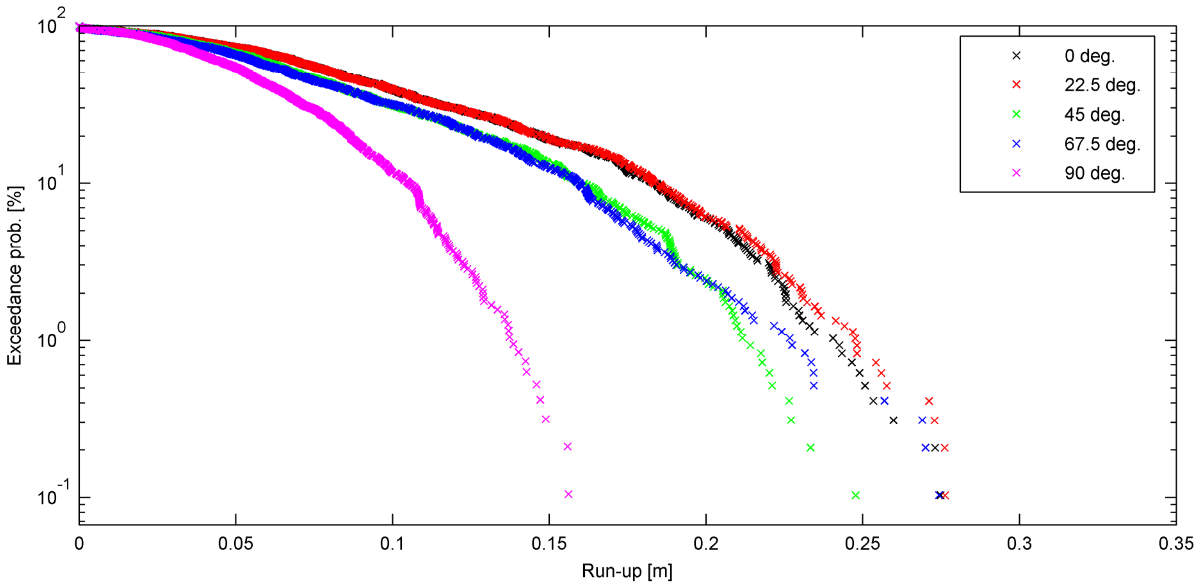
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test108.dat	RunUp_Test_022.dat	0.4	0.160	1.71	0.152	0.186	0.211	17.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.225		0.251		0.275	
22.5	0.231		0.260		0.276	
45	0.205		0.222		0.248	
67.5	0.207		0.238		0.274	
90	0.129		0.146		0.156	
Max	0.231	3.1	0.260	2.9	0.276	2.6







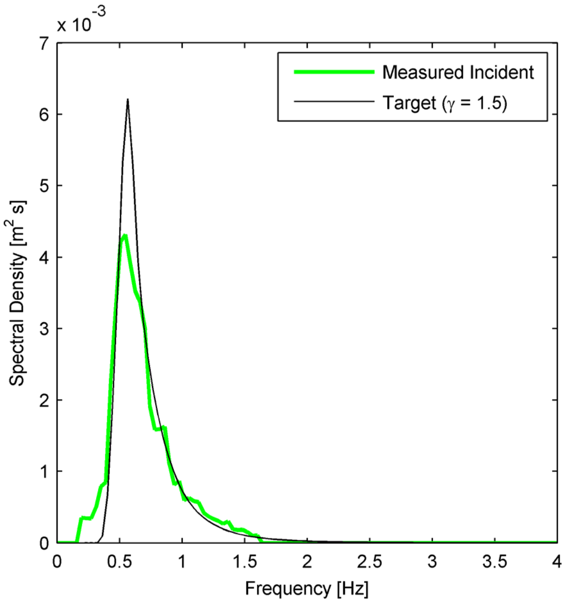
A.23 Test 23 (h/D = 4, H_{m0}/h = 0.42, s_{0p} = 0.035)

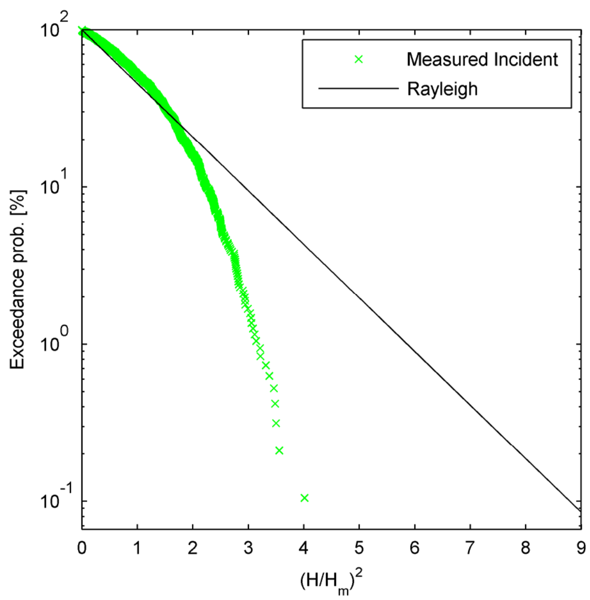
Incident wave parameters at structure determined from the calibration test:

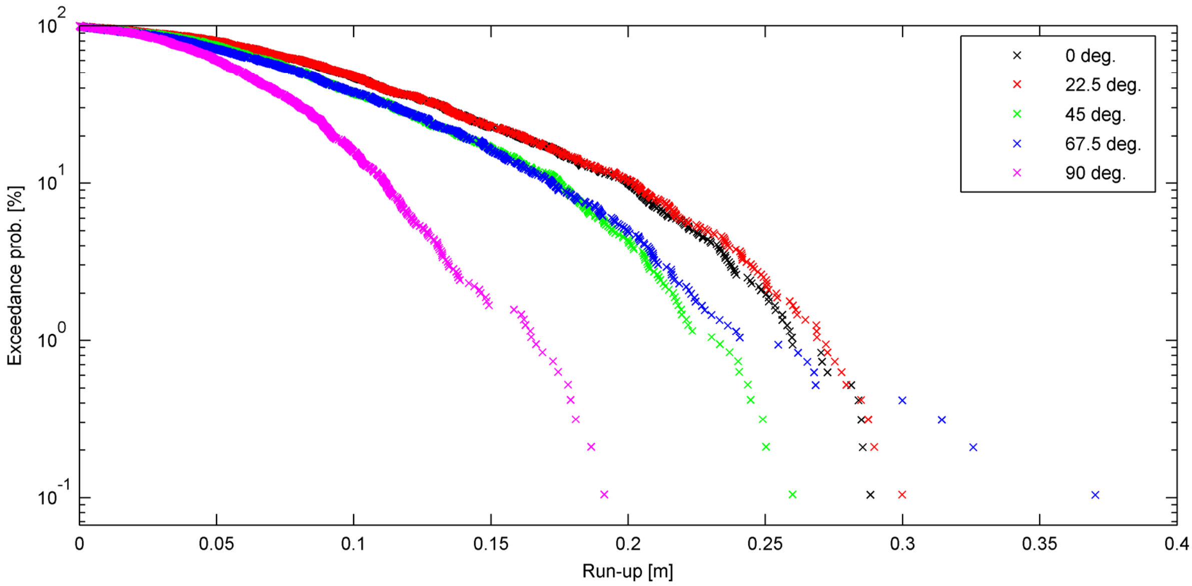
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test110.dat	RunUp_Test_023.dat	0.4	0.169	1.77	0.156	0.187	0.219	19.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.250		0.282		0.288	
22.5	0.254		0.281		0.300	
45	0.216		0.244		0.260	
67.5	0.223		0.275		0.370	
90	0.146		0.178		0.191	
Max	0.254	3.7	0.282	3.2	0.370	4.8







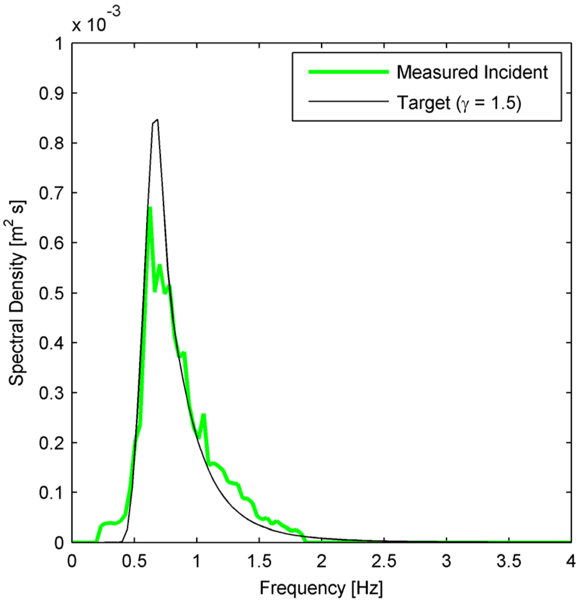
A.24 Test 50 (Replay of Test 1)

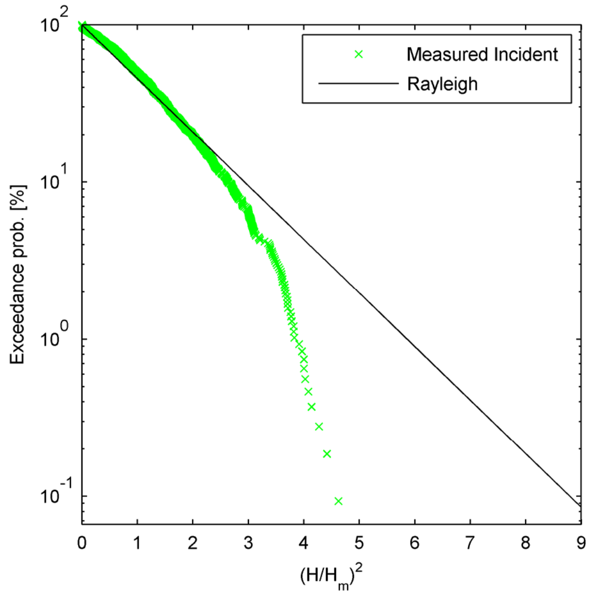
Incident wave parameters at structure determined from the calibration test:

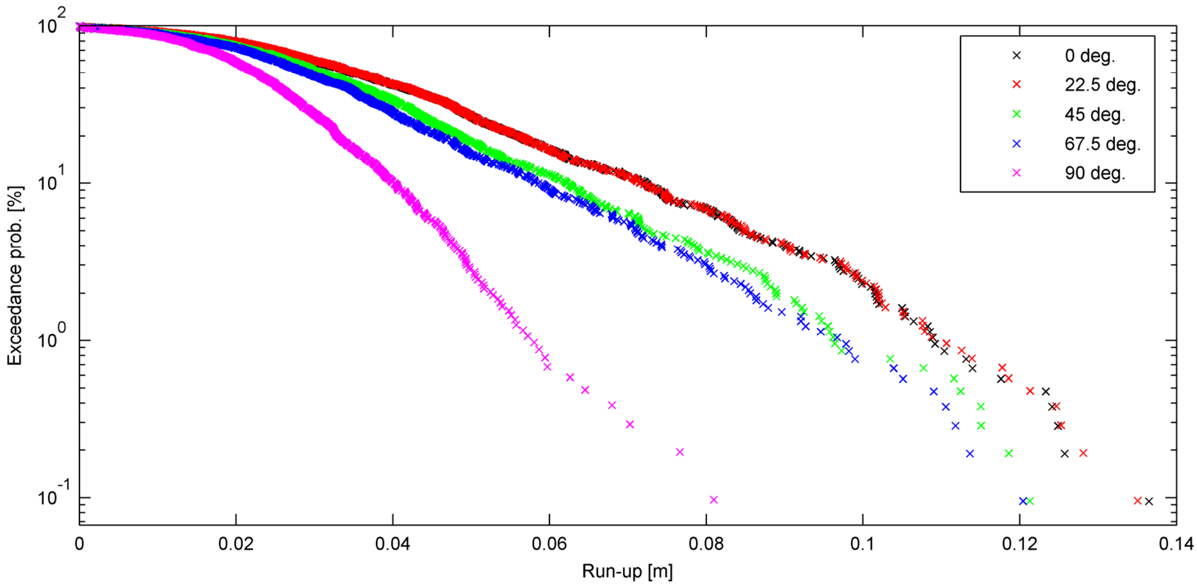
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test112.dat	RunUp_Test_050.dat	0.2	0.069	1.50	0.065	0.082	0.092	11.9%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.102		0.122		0.137	
22.5	0.102		0.121		0.135	
45	0.089		0.112		0.121	
67.5	0.086		0.108		0.120	
90	0.053		0.064		0.081	
Max	0.102	3.7	0.122	4.4	0.137	4.2







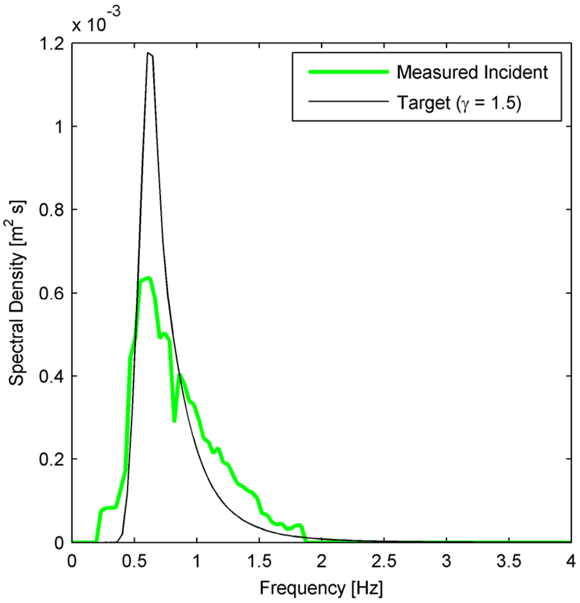
A.25 Test 51 (Replay of Test 2)

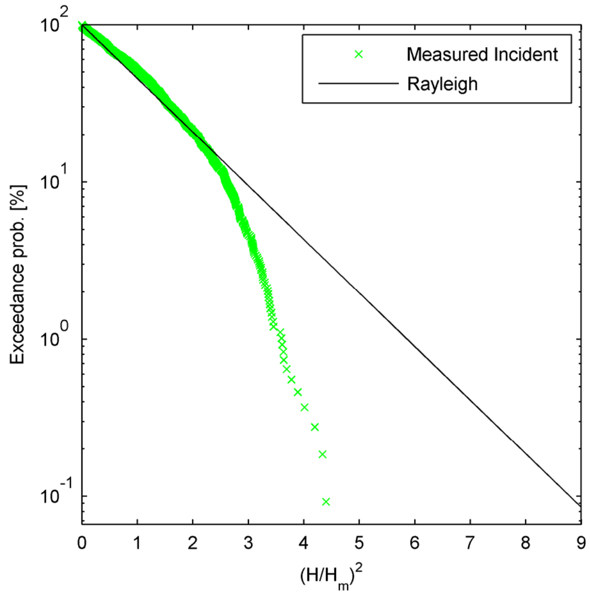
Incident wave parameters at structure determined from the calibration test:

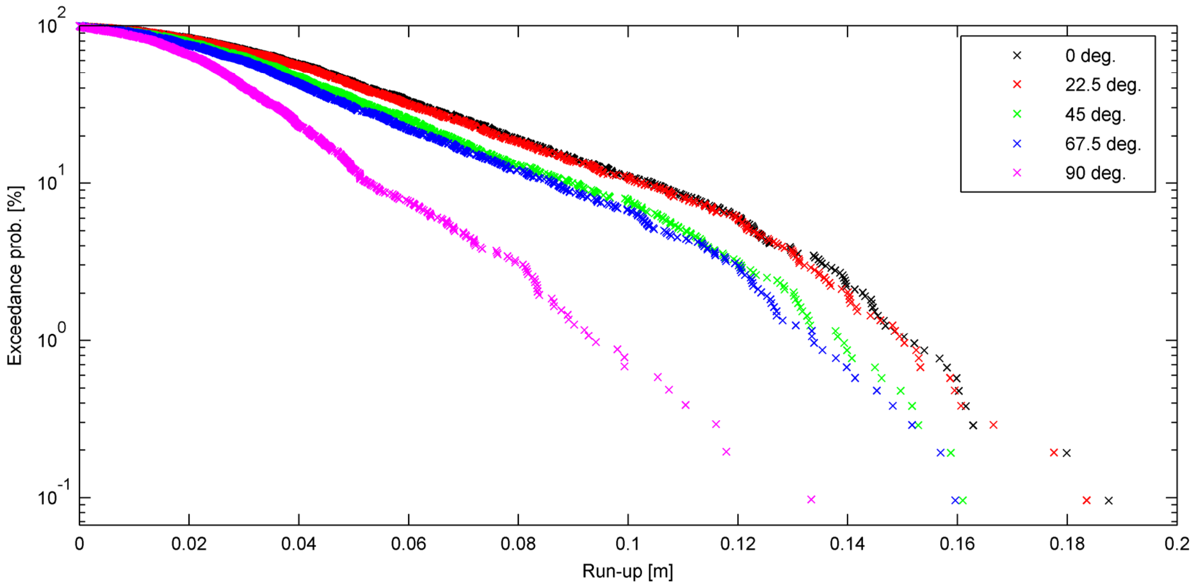
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test113.dat	RunUp_Test_051.dat	0.2	0.079	1.60	0.075	0.92	0.105	13.6%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.143		0.160		0.188	
22.5	0.140		0.159		0.184	
45	0.130		0.149		0.161	
67.5	0.125		0.145		0.160	
90	0.084		0.107		0.133	
Max	0.143	4.6	0.160	4.4	0.188	4.5







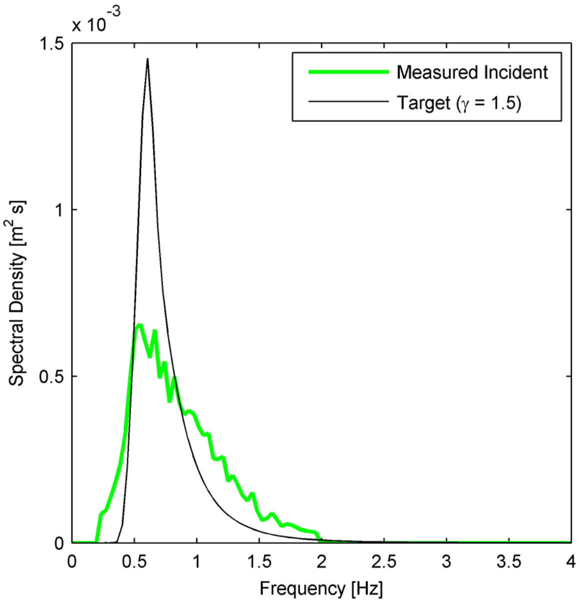
A.26 Test 52 (Replay of Test 3)

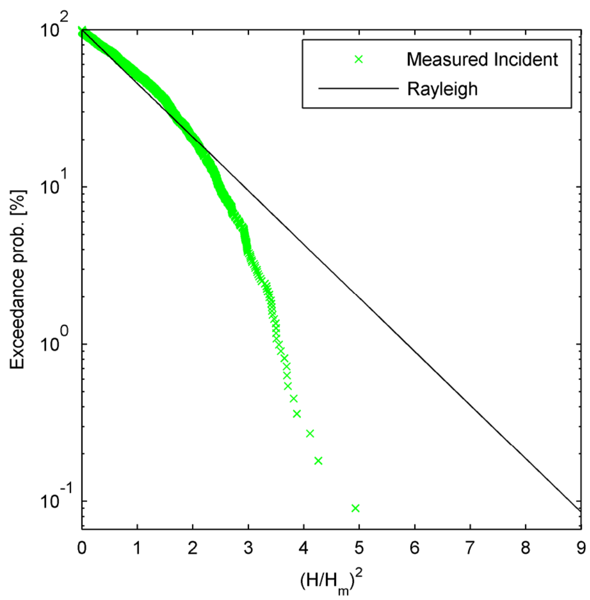
Incident wave parameters at structure determined from the calibration test:

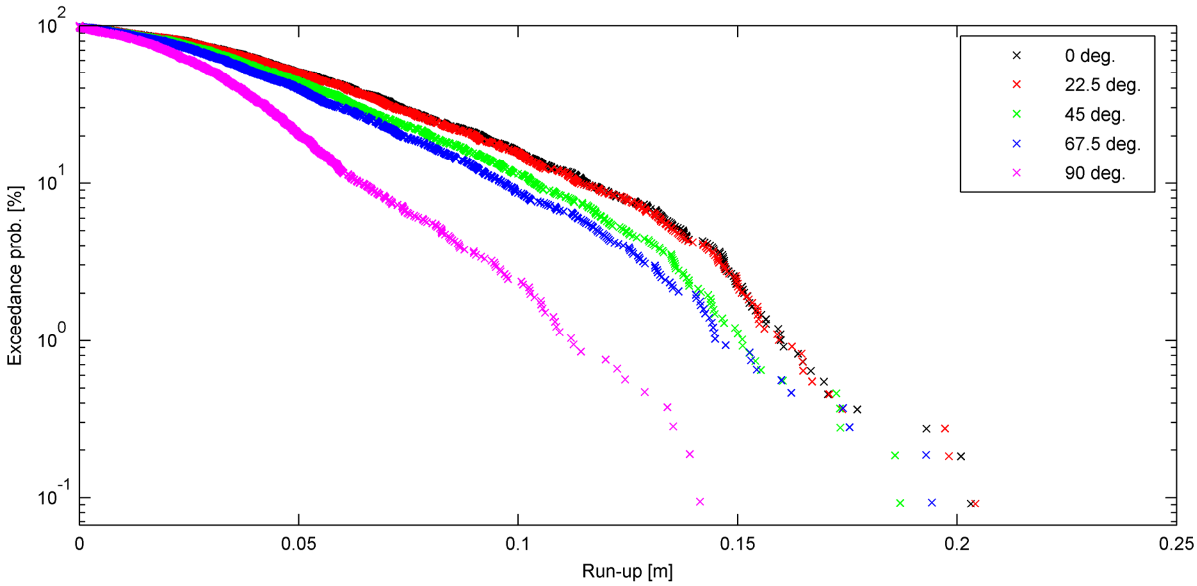
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test115.dat	RunUp_Test_052.dat	0.2	0.085	1.66	0.082	0.101	0.122	14.3%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.152		0.170		0.203	
22.5	0.151		0.169		0.204	
45	0.142		0.168		0.187	
67.5	0.139		0.161		0.194	
90	0.103		0.128		0.141	
Max	0.152	3.5	0.170	3.5	0.204	2.8







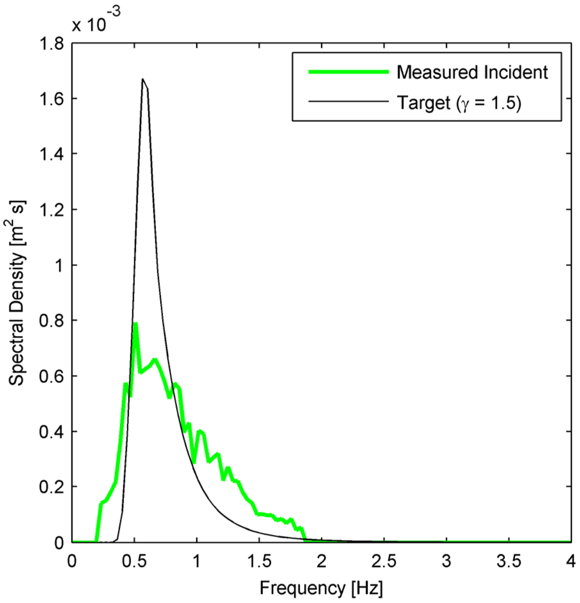
A.27 Test 53 (Replay of Test 4)

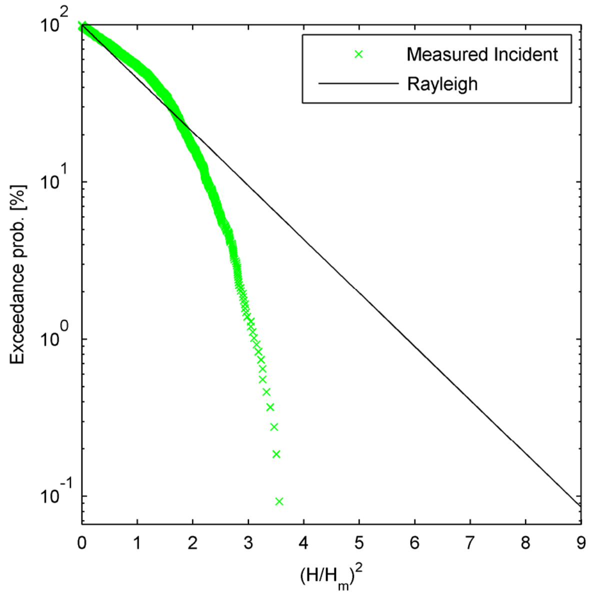
Incident wave parameters at structure determined from the calibration test:

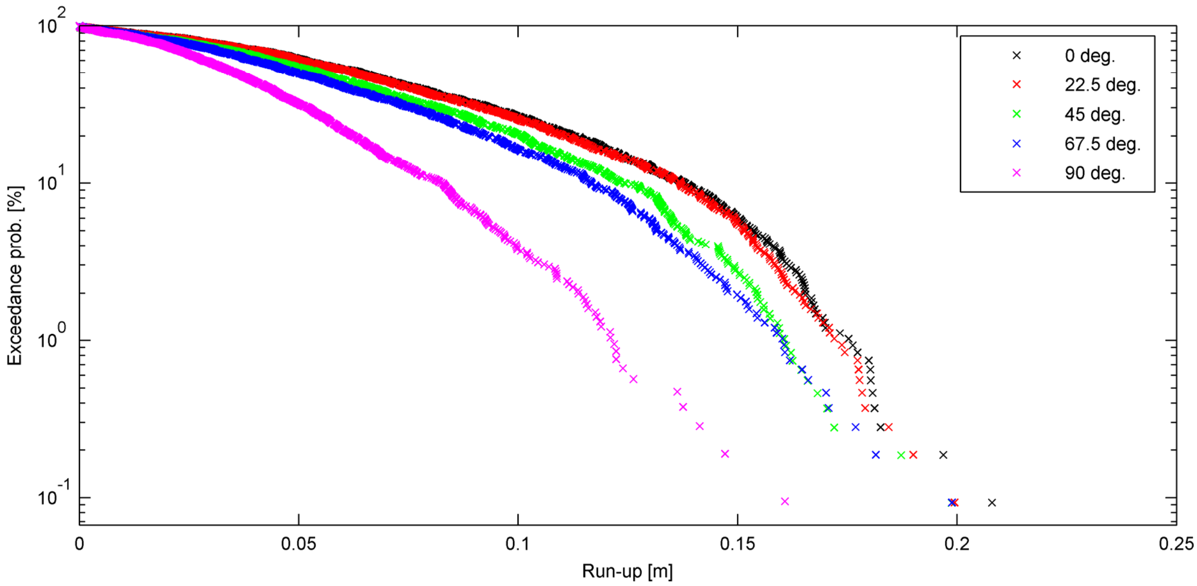
Wave data	Run-up data	h [m]	H_{m0} [m]	T_p [s]	H_s [m]	$H_{2\%}$ [m]	H_{max} [m]	Refl. coef.
test116.dat	RunUp_Test_053.dat	0.2	0.091	1.72	0.087	0.102	0.114	15.4%

Run-up data with m values (wave kinematics calculated from stream function theory):

Angle [deg.]	$R_{u,2\%}$ [m]	m (2% run-up)	$R_{u,0.5\%}$ [m]	m (0.5% run-up)	$R_{u,max}$ [m]	m (max run-up)
0	0.165		0.181		0.208	
22.5	0.164		0.178		0.199	
45	0.154		0.167		0.199	
67.5	0.149		0.169		0.199	
90	0.114		0.134		0.161	
Max	0.165	3.9	0.181	3.5	0.208	3.8







Appendix B: Regular Wave and Run-Up Data

Wave data	Run-up data	h [m]	H [m]	T [s]	R_u 0 deg [m]	R_u 22.5 deg [m]	R_u 45 deg [m]	R_u 67.5 deg [m]	R_u 90 deg [m]	m
testR006.dat	RunUp_Test_025.dat	0.4	0.185	2.26	0.218	0.221	0.187	0.217	0.132	2.5
testR009.dat	RunUp_Test_026.dat	0.4	0.203	2.35	0.26	0.264	0.230	0.258	0.160	2.5
testR012.dat	RunUp_Test_027.dat	0.4	0.196	2.43	0.316	0.322	0.283	0.234	0.192	4.3
testR061.dat	RunUp_Test_029.dat	0.4	0.186	1.71	0.185	0.185	0.165	0.169	0.116	1.7
testR063.dat	RunUp_Test_030.dat	0.4	0.189	1.77	0.199	0.200	0.173	0.187	0.118	2.0
testR039.dat	RunUp_Test_031.dat	0.3	0.129	1.83	0.167	0.167	0.147	0.137	0.100	3.7
testR042.dat	RunUp_Test_032.dat	0.3	0.136	1.96	0.213	0.215	0.188	0.152	0.113	4.8
testR043.dat	RunUp_Test_033.dat	0.3	0.141	2.03	0.234	0.240	0.211	0.167	0.139	5.1
testR045.dat	RunUp_Test_034.dat	0.3	0.144	2.10	0.231	0.233	0.203	0.180	0.151	4.4
testR048.dat	RunUp_Test_035.dat	0.3	0.129	1.39	0.113	0.111	0.097	0.091	0.065	1.4
testR052.dat	RunUp_Test_036.dat	0.3	0.141	1.48	0.162	0.163	0.143	0.135	0.078	2.5
testR054.dat	RunUp_Test_037.dat	0.3	0.145	1.54	0.178	0.176	0.159	0.145	0.088	2.8
testR056.dat	RunUp_Test_038.dat	0.3	0.151	1.59	0.194	0.196	0.172	0.172	0.088	2.8
testR017.dat	RunUp_Test_039.dat	0.2	0.082	1.50	0.097	0.096	0.081	0.078	0.054	3.3
testR018.dat	RunUp_Test_040.dat	0.2	0.089	1.60	0.117	0.114	0.100	0.094	0.068	3.5
testR021.dat	RunUp_Test_041.dat	0.2	0.099	1.66	0.182	0.183	0.166	0.119	0.086	5.3
testR025.dat	RunUp_Test_042.dat	0.2	0.098	1.72	0.193	0.193	0.175	0.149	0.093	5.8
testR028.dat	RunUp_Test_043.dat	0.2	0.087	1.13	0.083	0.081	0.070	0.065	0.044	1.9
testR030.dat	RunUp_Test_044.dat	0.2	0.095	1.21	0.087	0.086	0.078	0.071	0.044	1.2
testR032.dat	RunUp_Test_045.dat	0.2	0.099	1.25	0.122	0.120	0.106	0.099	0.070	2.6
testR037.dat	RunUp_Test_046.dat	0.2	0.104	1.30	0.109	0.107	0.092	0.086	0.059	1.5
testR002.dat	RunUp_Test_054.dat	0.4	0.174	2.12	0.235	0.236	0.215	0.233	0.136	4.1