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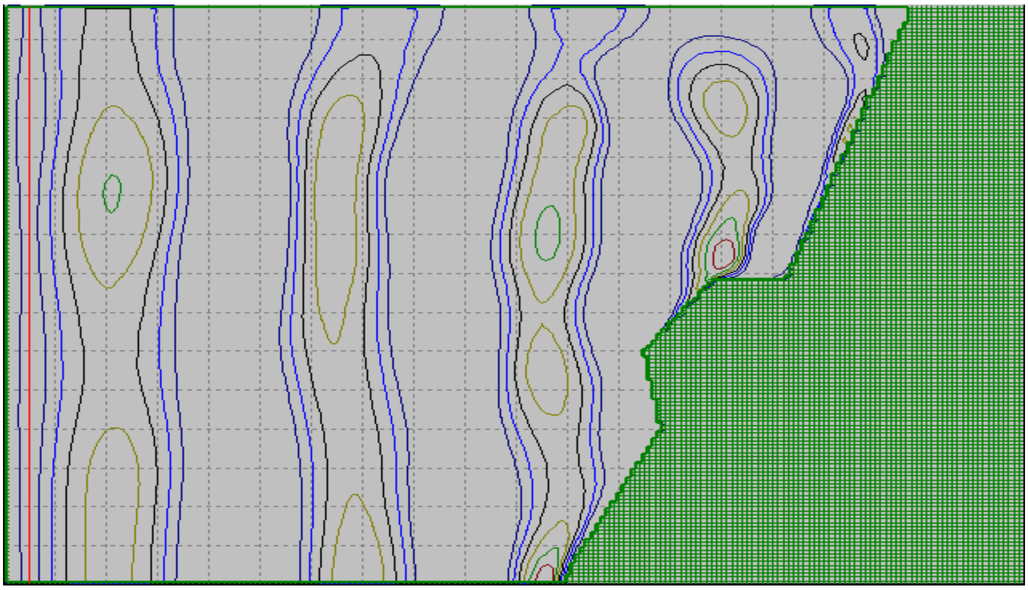

according to Co-operation Agreement (phase 2) between WAVEenergy (Norway) and Aalborg University, Dept. of Civil Engineering

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June, 2005

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Study of Wave Conditions at Kvitsøy Prototype Location of Seawave Slot-Cone Generator

by

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June, 2005

Preface

This report presents the results of a study of the wave conditions at the planned location of the prototype of the wave energy converter (WEC) Seawave Slot-Cone Generator (SSG). SSG is a WEC utilizing wave overtopping in multiple reservoirs.

A prototype of the SSG device is going to be installed on the west coast of the island Kvitsøy near Stavanger, Norway, and it is thus essential to obtain a good estimation of the wave conditions at this site. Therefore the Dept. of Civil Engineering, Aalborg University (AAU) has carried out a study of wave measurements and hindcasted waves in the region, as well as calculated the transformation of the offshore wave conditions to nearshore conditions at the considered site. This part of the work has been done using the computer model MildSim, developed within AAU.

The work has been carried out by Florent Guinot and Jens Peter Kofoed, AAU, in co-operation with Espen Osaland, WAVEenergy, Norway (WE), who has provided both measured and hindcasted wave data. The work has also been supervised by the developer of the MildSim code, Michael Brorsen (AAU). The report has been prepared by Jens Peter Kofoed (tlf.: +45 9635 8474, e-mail: i5jpk@civil.aau.dk).

The work has been carried out according to a Co-operation Agreement (phase 2) between WAVEenergy (Norway) and Aalborg University, Dept. of Civil Engineering.

Aalborg, June, 2005.

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1 Introduction

The purpose of the work described in the present report has been to determine the wave conditions at the location of the SSG prototype. In order to provide a realistic combination of wave conditions, transformation of waves from offshore to location has been done using the computer model MildSim developed at AAU.

The MildSim model is a model based on the Mild-Slope equation which is able to describe wave propagation in coastal regions of complex geometry. This model takes into account the different wave effects in coastal regions like refraction, diffraction, reflection, shoaling and breaking (see Andersen & Klindt, 1994, and Brorsen & Helm-Petersen, 1998).

A method of internal wave generation is applied instead of varying the surface elevation at the boundary of the computational domain. Thus the waves inside the boundaries are generated by perturbing the surface elevation in a line of points.

Sponge layers are used to model the reflection on the boundaries of the domain. For this study, coefficients corresponding to full absorption have been used for each sponge layer (for open boundaries as well as for the shore, see chapter 2-1 for more details).

The reduction in wave height due to wave breaking is modeled by extracting energy from the waves when the ratio between the wave height and the water depth reaches a critical value.

Before running the model, some analyses of available offshore wave data for the region have been performed, in order to select the most appropriate input for the model.

2 Setup of the numerical model

2.1 Discretization of the bathymetry

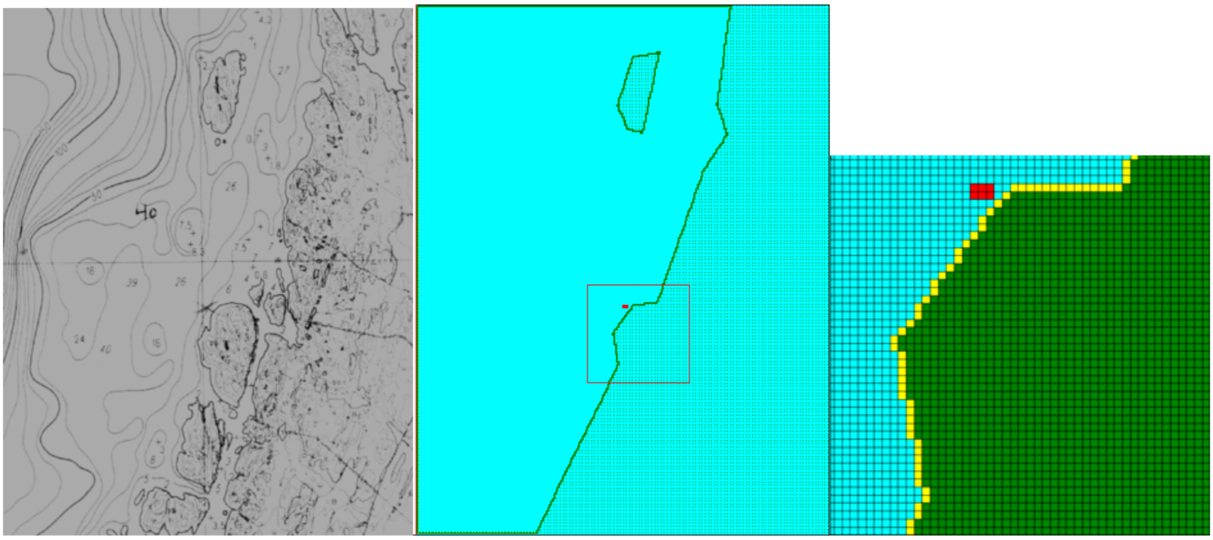

Figure 1. Left: Bathymetry near Kvitsøy. Middle: Discretization of bathymetry. Right: Zoom around the prototype location marked with a red rectangle.

In figure 1 the bathymetry around the approximate location of SSG near Kvitsøy is shown along with the discretization of this bathymetry.

The discretization has been done using cells with side lengths of 3 m and a time step equal to the 1/128 of the wave peak period, as this keeps the discretization error to a minimum (Andersen & Klindt, 1994, and Goda and Suzuki, 1976).

The yellow boxes near the land (green boxes) are sponge layers used to characterize the reflection on the boundaries. For this study, coefficients of sponge layers corresponding to full absorption have been used for each boundary because on the open boundaries, the goal is no reflection at all and on the shore as focus is on the energy production, just the incoming waves are interesting and not the reflected ones which come to the device from the back.

The sponge layers coefficients depends on all the parameters of the model (period of the waves, time step, box size, water depth in the box…). Thus to determinate these coefficients different flumes with each set of parameters have been modelled in order to find the value corresponding to full absorption for the different conditions.

2.2 Offshore conditions

Three different offshore wave data sets have been available for this study:

1. Measurements at Utsira during the period 1961-1990 (Vind- og temperaturstatistikk, DNMI, see Kofoed, 2005).
2. Hindcast data from DNMI during the period 1955-2005, grid point 1262.
3. Measurements from a buoy near Kvitsøy during the period 4/11/2004-11/3/2005.

Results of the analyses of these data are shown in table 1 to 3.

Wave cond.	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
Hs	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
Tp	3.5	6.1	7.9	9.3	10.6	11.7	12.7	13.7	14.6	15.4
Prob	12.9%	30.3%	26.5%	16.4%	8.3%	3.5%	1.5%	0.5%	0.1%	0.0%

Table 1. Probability of significant wave heights (Hs) within the given 1 m ranges and estimated wave peak period, based on Vind- og temperaturstatistikk, DNMI, for Utsira (Kofoed, 2005).

Tp Hs	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	pct
0-2	1.08	0	0	0	0	0	0	0	0	0	1.08
2-4	7.93	0	0	0	0	0	0	0	0	0	7.93
4-6	9.77	12.66	1.18	0	0	0	0	0	0	0	23.61
6-8	7.89	9.04	7.57	1.38	0.02	0	0	0	0	0	25.9
8-10	7.22	3.53	4.6	3.05	0.99	0.09	0	0	0	0	19.48
10-12	4.56	3.71	1.02	1.09	0.76	0.36	0.05	0	0	0	11.55
12-14	2.2	3.45	1.35	0.39	0.16	0.11	0.04	0.01	0	0	7.71
14-16	0.31	0.83	0.69	0.34	0.11	0.03	0.01	0.01	0	0	2.33
16-18	0.05	0.07	0.1	0.06	0.04	0.01	0	0	0	0	0.33
18-20	0.02	0.01	0	0.01	0	0	0	0	0	0	0.04
pct	41.03	33.3	16.51	6.32	2.08	0.6	0.1	0.02	0	0	99.96

Table 2. Probability of significant wave heights (Hs) and peak period (Tp) within the given 1 m ranges and 2 s ranges from hindcast data (grid point 1262). Yellow marks the most probable Tp within each 1 m Hs range.

Tp Hs	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	pct
0-2	0	0	0	0	0	0	0	0	0	0	0
2-4	0.85	0.02	0	0	0	0	0	0	0	0	0.87
4-6	1.8	2.33	0.15	0	0	0	0	0	0	0	4.28
6-8	4.47	13.36	5.02	0.77	0.05	0	0	0	0	0	23.67
8-10	5.37	8.43	10.58	6.6	2.4	0.4	0	0	0	0	33.78
10-12	4.22	7.08	3.47	3.5	4.02	1.97	0.22	0.08	0	0	24.56
12-14	1.08	3.58	2.55	0.77	0.43	0.37	0.2	0.28	0.07	0.02	9.35
14-16	0.1	1.03	0.45	0.25	0.08	0.02	0.02	0.1	0.1	0.12	2.27
16-18	0.02	0.2	0.17	0.08	0	0	0	0	0.02	0.03	0.52
18-20	0.08	0.05	0.28	0.25	0.02	0	0	0	0	0	0.68
pct	17.99	36.08	22.67	12.22	7	2.76	0.44	0.46	0.19	0.17	99.98

Table 3. Probability of significant wave heights (Hs) and peak period (Tp) within the given 1 m ranges and 2 s ranges from buoy data near Kvitsøy. Yellow marks the most probable Tp within each 1 m Hs range.

The data from the buoy near Kvitsøy are considered to represent the offshore conditions near the prototype location very well. However, these data only covers 4 months of measurements and can therefore not be taken as representative for the yearly average long term conditions.

Thus, the buoy data have been compared to the hindcast data during the 4 months during which the buoy measurements were performed. In table 4 results of this comparison are presented in terms of average peak periods from the buoy and hindcast data, respectively, within each of the considered 1 m significant wave height ranges. These results show relatively good correlation, and it is therefore justified to consider the hindcast data from grid point 1262 representative for the offshore conditions near the prototype locations.

Wave cond.	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
Hs	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
Tp, buoy	8.7	9.1	9.4	10.1	10.4	10.9	12.5	13.0	14.3
Tp, 1262	8.8	9.2	10.2	10.4	11.4	11.5	12.6	13.3	12.8

Table 4. Comparison between the average peak period for the hindcast data and buoy data for the 1 m significant wave height range during the period 4/11/2004 to 31/01/2005

Furthermore, a comparison between the estimated peak period for the Utsira data and the hindcast data was performed. The results hereof are shown in table 5. It can be seen from these results, that not all the Utsira values falls within the ranges from the hindcast data. However, the deviations are not considered to be large, and as the Utsira data set is based on actual long term wave measurements, this data set is considered the most reliable one. The Utsira data set is therefore used as input (offshore) for the modeling.

Wave cond.	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
Hs	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
Tp, utsira	3.5	6.1	7.9	9.3	10.6	11.7	12.7	13.7
Tp range, 1262	4-6	4-6	6-8	8-10	8-10	10-12	10-12	12-16

Table 5. Comparison between the estimated peak period for the Utsira data and the main 2s range of the peak period for the hindcast data for each wave conditions.

In order to provide some information about the incident wave directions the hindcast data is again considered. The available wave power, found as

$$P_{wave} = \frac{\rho g^2}{64\pi} T_e H_s^2$$

(Te = Tp/1.15 is used) multiplied by the probability of occurrence, is shown in table 6 for each 15° wave direction (θ) range, for each 1 m significant wave height range. As shown in this table, the far majority (90 %) of the incident wave energy is coming from 165° to 330° or roughly between South and North West. Thus, the wave offshore conditions shown in table 1 have been used in the model for 4 different directions of incoming waves determined by Table 5, North West, West, South West and South.

θ Hs	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	sum	pct
0	0.6	2.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.0
15	0.3	1.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0
30	0.3	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0
45	0.5	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0
60	0.9	1.7	0.9	0.0	0.0	0.0	0.0	0.0	0.0	3.5	0.0
75	2.3	7.1	3.4	0.0	1.3	0.0	0.0	0.0	0.0	14.1	0.1
90	3.1	13.3	6.8	0.0	0.0	0.0	0.0	0.0	0.0	23.2	0.2
105	0.7	1.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0
120	8.1	42.6	25.8	3.4	0.0	0.0	0.0	0.0	0.0	79.9	0.6
135	12.7	70.6	98.8	46.5	5.0	0.0	0.0	0.0	0.0	233.6	1.9
150	15.1	122.0	319.1	258.9	107.6	19.3	0.0	0.0	0.0	842.1	6.7
165	13.1	151.0	336.8	422.1	266.5	148.9	34.6	0.0	0.0	1373.1	11.0
S 180	31.7	200.8	389.6	416.8	276.4	115.0	27.0	0.0	5.4	1462.7	11.7
195	15.3	110.8	224.1	221.1	176.7	68.3	18.3	3.3	0.0	838.0	6.7
210	11.0	74.5	200.9	172.5	123.8	55.3	17.0	0.0	4.8	659.8	5.3
SW 225	4.0	48.4	108.0	113.6	68.7	41.7	0.0	0.0	0.0	384.4	3.1
240	6.5	82.0	185.7	193.7	146.8	67.4	25.2	19.6	0.0	726.8	5.8
255	11.9	134.6	292.8	329.1	231.0	144.0	43.5	25.6	5.5	1218.1	9.7
W 270	138.3	404.2	355.8	183.4	88.7	51.0	17.0	0.0	5.4	1243.9	9.9
285	8.4	46.7	86.1	66.3	44.8	28.6	11.4	8.9	0.0	301.2	2.4
300	8.1	58.4	118.2	130.8	90.5	44.9	14.1	4.3	0.0	469.3	3.7
NW 315	61.8	396.1	490.1	359.7	157.8	62.8	14.5	5.6	0.0	1548.4	12.4
330	121.2	402.2	302.3	113.0	33.9	5.4	0.0	0.0	0.0	978.0	7.8
345	29.2	62.1	24.4	5.2	0.0	0.0	0.0	0.0	0.0	120.8	1.0

Table 6. Available wave power multiplied by probability of occurrence, depending on direction and significant wave height.

As the probability of waves above 8 m is almost nil, no runs with these conditions have been done, as focus is on energy production rather than extreme events for structural design. Likewise, as the waves below 1 m are not interesting from an energy production point of view, no runs have been done in this range either.

For each directions (NW, W, S, SW) seven runs with the different waves conditions have been performed to determine the corresponding near shore wave conditions in terms of significant wave height, peak period and wave direction

For each run, irregular waves corresponding to the offshore wave conditions have been generated in the model during one hour and a half (a sensitivity analysis show stable results on comparison with 3 and 5 hours running time).

3 Results of numerical tests

For each run the following output of the MildSim model have been selected for further analyses:

- Overview of the wave heights contour.
- Zoom around the location of the wave heights contour.
- Wave time series in selected points with different depths at and in front of the prototype location.
- Real time surface elevations.

In the appendix some of the wave height contours around the prototype location is presented, to give an overview of the conditions near the prototype location.

These graphs disclosed some problems in modelling the largest waves (large periods and thus long wave lengths) in the area of interest. In these conditions, the mild slope assumption is not completely satisfied. Furthermore some local reflections on the slopes occur and the applied breaking criteria and numerical energy dissipation seems to react too slowly when the long waves shoal on the relatively steep slopes near shore. To avoid this problem a long plateau of 15 m water depth have been put instead of the land and the small peaks in the bathymetry with large gradients have been cut down for some of the runs with the largest conditions.

This problem was especially important for the west conditions where the waves meet a really steep slope close to the shore and therefore results as near shore significant wave heights of up 10 m for offshore significant wave heights of 6.5m in western direction have been found. Applying the above mentioned modifications gave results which are considered more appropriate, and these have been adopted in the overall results presented in table 7. However, the values for Western direction are a little uncertain and might be slightly overestimated.

The wave time series have been used to determinate more precisely the wave field close to the prototype location. Thus, for each offshore condition and direction the ratio between the significant wave height near shore at a water depth of 15 m (Hsloc) and the offshore significant wave height (Hso) has been calculated. These results are presented in table 2.

Offshore directions	1-2	2-3	3-4	4-5	5-6	6-7	7-8
NW-315	0.81	0.69	0.62	0.57	0.59	0.68	0.80
W-270	0.87	0.90	0.96	1.03	1.08	1.14	1.18
SW-225	0.52	0.68	0.84	0.92	0.96	1.00	1.03
S-180	0.37	0.39	0.33	0.72	0.77	0.84	0.94

Table 7. Ratio between wave height at prototype location and offshore wave height for each direction and condition (in terms of significant wave height 1 m range). Note that given the ratios are only valid for wave conditions with peak periods corresponding to the wave conditions as given in table 1.

Thus, based on this table the near shore wave conditions can for each of the given offshore conditions.

In table 8 the approximate direction of the waves close to the prototype location for each offshore direction and two different wave lengths. These results have been obtained from observation of the real time surface elevations.

Offshore directions	Short wave lengths (≈ 60-100m)	Long wave lengths (≈300m)
NW-315	315	300
W-270	270	285
SW-225	225	255
S-180	225	240

Table 8. Directions of waves close to the prototype location for different offshore wave directions and wave lengths.

In order to achieve the near shore wave conditions in terms of significant wave height, peak period, direction and probability of occurrence the tables 1, 6, 7 and 8 have been combined. From the model runs no significant changes in the peak periods have been seen, and these are therefore maintained unaltered from the Utsira data in table 1. The change in significant wave heights is given in table 7 for the considered four main directions (covering 45° each, 180° in total). The directions are derived from table 8 by simple interpolation. The probability of the individual wave conditions in each of the given directions are determined by distributing the probability of the wave conditions given in table 1 on the directions according to the distribution of probability between the 4 directions given in table 6.

Hs [m] Tp [s]		1-2 6.1	2-3 7.9	3-4 9.3	4-5 10.6	5-6 11.7	6-7 12.7	7-8 13.7	Sum
Hs [m]	NW-315	1.2	1.7	2.2	2.6	3.2	4.4	6	
Dir [deg.]		315	313	310	308	305	303	300	
Prob		9.9%	8.7%	5.4%	2.7%	1.1%	0.5%	0.2%	**28.5%**
Pwave [kW/m]		3.8	10.0	18.7	29.8	52.7	106.1	210.8	
Pwave*Prob		0.382	0.873	1.007	0.811	0.604	0.522	0.346	**4.5**
Hs [m]	W-270	1.3	2.3	3.4	4.6	5.9	7.4	8.9	
Dir [deg.]		270	273	275	278	280	283	285	
Prob		4.8%	4.2%	2.6%	1.3%	0.6%	0.2%	0.1%	**13.8%**
Pwave [kW/m]		4.4	17.1	44.9	97.3	176.5	298.1	458.7	
Pwave*Prob		0.213	0.716	1.164	1.277	0.976	0.707	0.363	**5.4**
Hs [m]	SW-225	0.8	1.7	2.9	4.1	5.3	6.5	7.7	
Dir [deg.]		225	230	235	240	245	250	255	
Prob		7.5%	6.5%	4.0%	2.0%	0.9%	0.4%	0.1%	**21.5%**
Pwave [kW/m]		1.6	9.8	34.4	77.7	139.4	229.4	349.5	
Pwave*Prob		0.119	0.638	1.390	1.590	1.204	0.849	0.431	**6.2**
Hs [m]	S-180	0.6	1.0	1.2	3.2	4.2	5.5	7.1	
Dir [deg.]		225	228	230	233	235	238	240	
Prob		8.1%	7.1%	4.4%	2.2%	0.9%	0.4%	0.1%	**23.3%**
Pwave [kW/m]		0.8	3.2	5.3	47.6	89.7	161.8	291.1	
Pwave*Prob		0.065	0.227	0.233	1.056	0.839	0.649	0.389	**3.5**
Sum									
Prob		**30.3%**	**26.5%**	**16.4%**	**8.3%**	**3.5%**	**1.5%**	**0.5%**	**87.0%**
Pwave*Prob		**0.8**	**2.5**	**3.8**	**4.7**	**3.6**	**2.7**	**1.5**	**19.6**

Table 9. Near shore wave conditions in terms of significant wave height, peak period, direction and probability of occurrence. The available wave power in the individual wave condition is also given, as well as the overall average.

From table it can be seen that the near shore overall average wave power is estimated to be 19.6 kW/m (when neglecting wave conditions with significant wave heights less than 1 m (12.9 %) and more than 8 m (0.1 %)).

4 Conclusion

After the analyses the following conclusions have been drawn:

- The approximate location of the device looks reasonable from a power production point of view because it is in a convergence zone for the waves which means that the wave energy will tend to focus in this area.
- The wave breaking seems not as important as initially thought, but these results must be taken with care in the calculation of the efficiency, as the device will probably be in the breaking zone where the numerical model has reduced accuracy and the energy loss therefore is hard to predict.
- The results indicate that the best orientation from a power capturing point of view for the device would be West. The results also show that bathymetry in front of the prototype location focus the wave directions towards the device, and reduces the incident angle space with a factor 0.45 to 0.67 depending on wave length.
- The presence of the relatively steep slope at the prototype location must also be taken into account for the orientation of the device so that the slope of the device is in the following of this natural slope. Thus, the exact location with in the area should probably be selected at the point where the normal to the slope is pointing due West. To enable this, a detailed bathymetry scan of the location is needed.
- Further studies about survivability must be adapted to take into account these waves breaking on the structure. This could include 3-D model testing of the location with the prototype in place. In such model tests both power capture (in terms of overtopping) and forces on the prototype structure (both global and local) should be measured.

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Appendix

For each direction, the following graphs from figure 1 to 12 represent the wave heights contour for 3 offshore conditions, 2-3, 4-5 and 6-7 in a zoom close to the location point. The red rectangle is the approximate location of the device and the lines represents the wave heights.

North West :

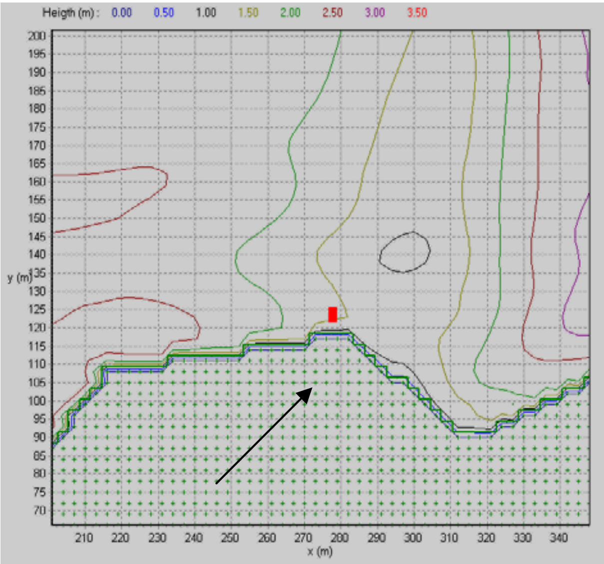

Figure 1, NW, 2-3

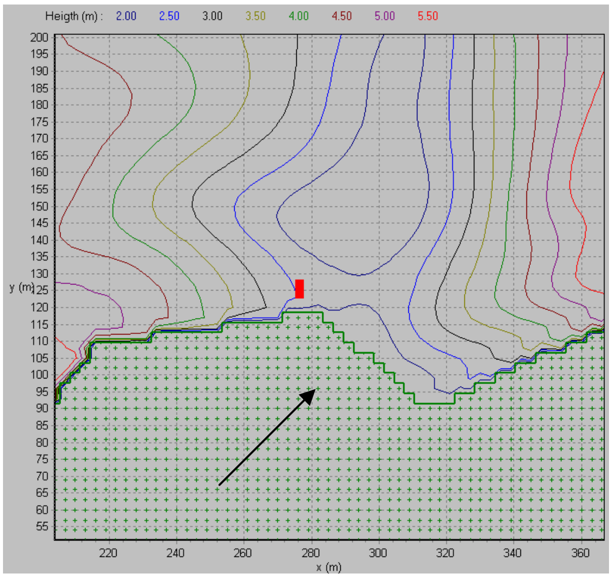

Figure 2, NW, 4-5

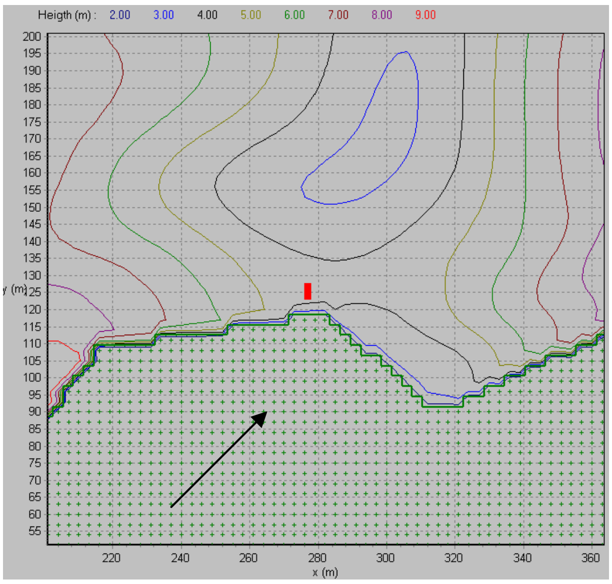

Figure 3, NW, 6-7

The arrow shows the North.

West :

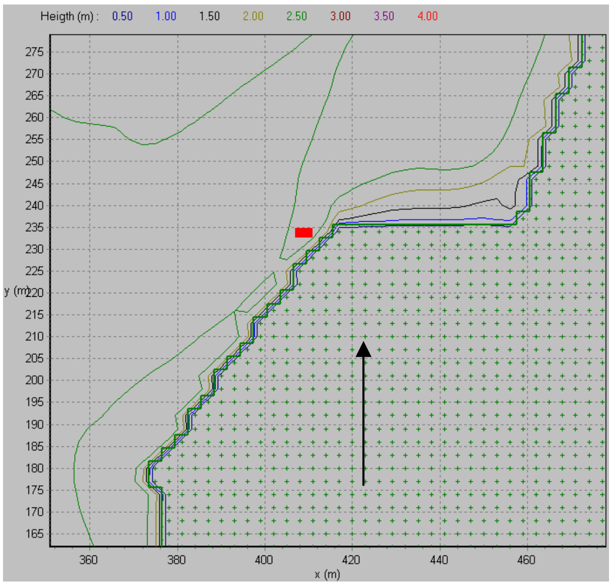

Figure 4, W, 2.5m

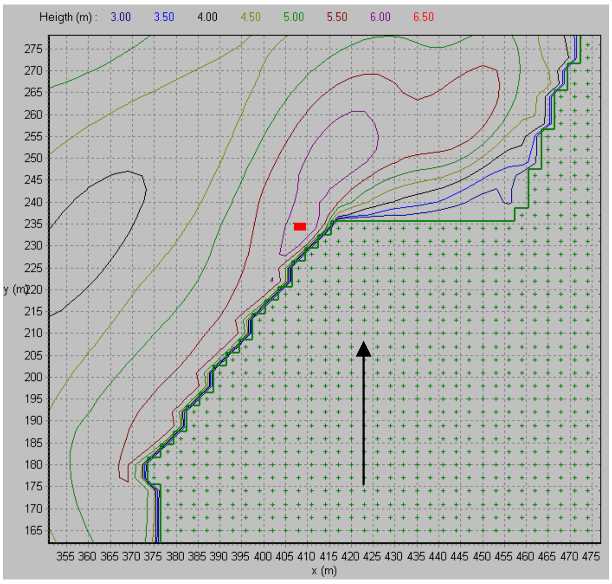

Figure 5, W, 4-5

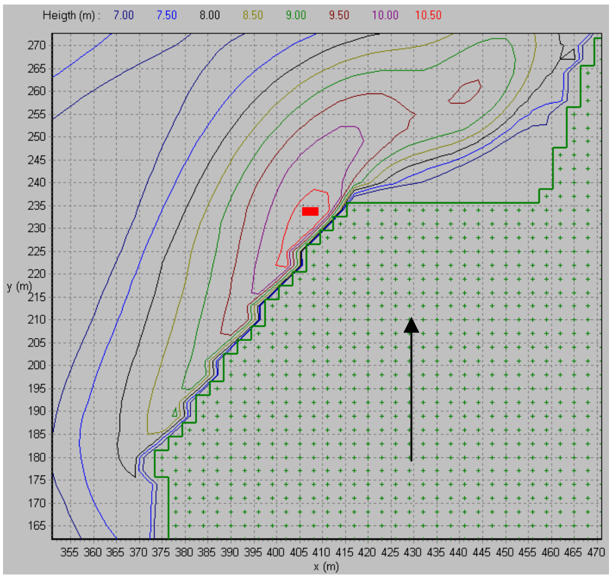

Figure 6, W, 6-7

The arrow shows the north.

South West :

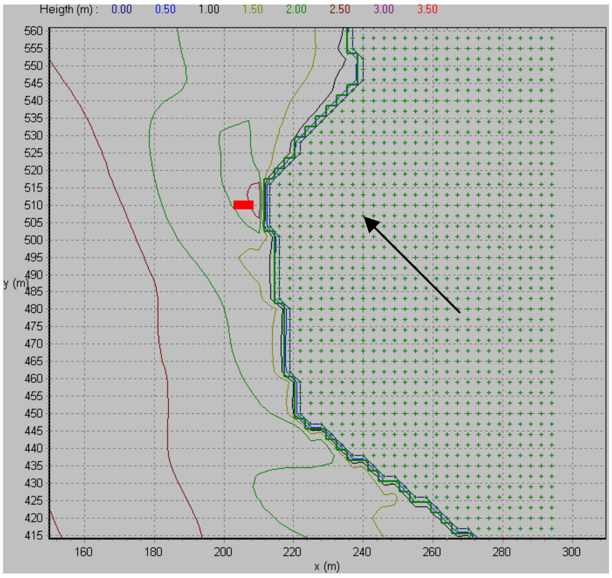

Figure 7, SW, 2-3

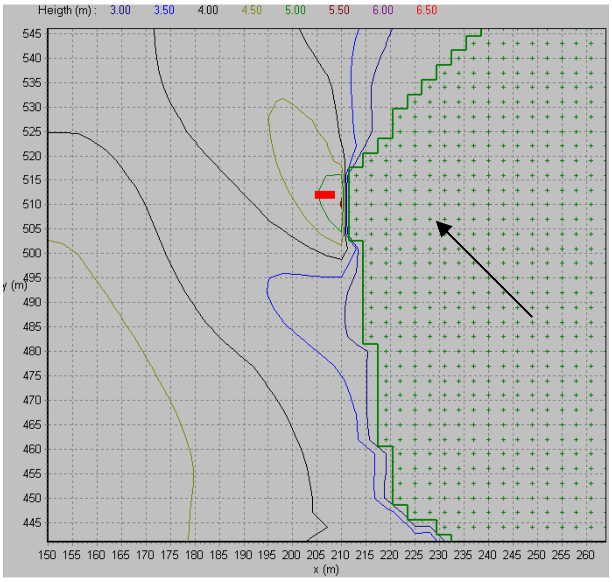

Figure 8, SW, 4-5

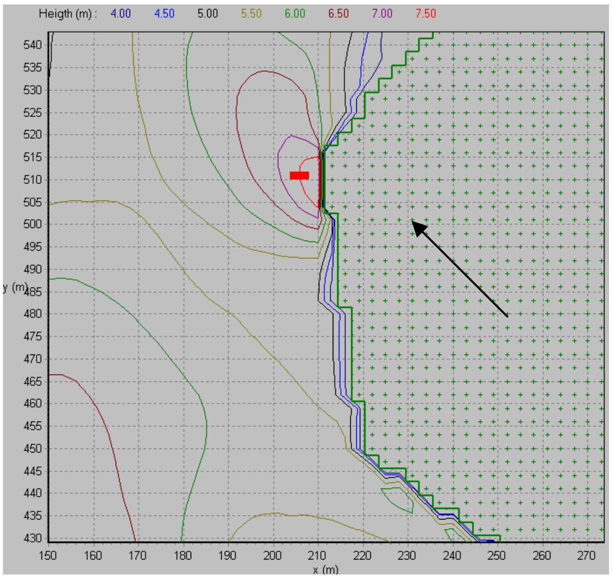

Figure 9, SW, 6-7

The arrow shows the North.

South :

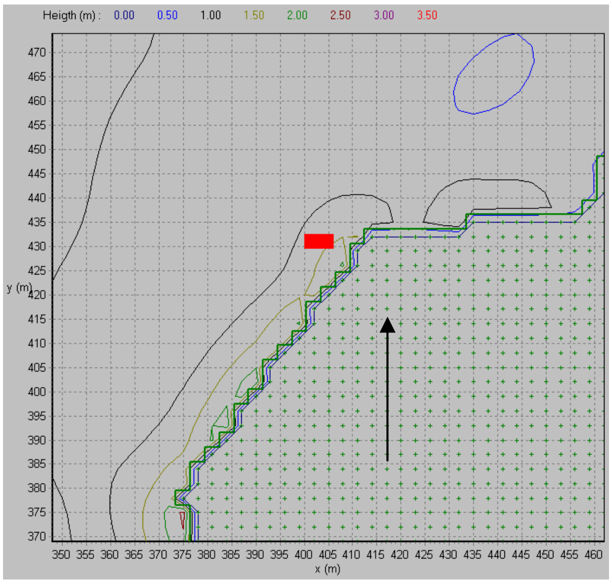

Figure 10, S, 2-3

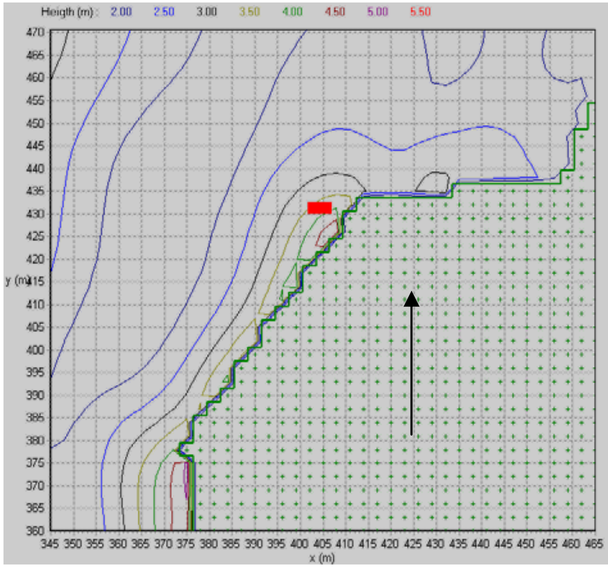

Figure 11, S, 4-5

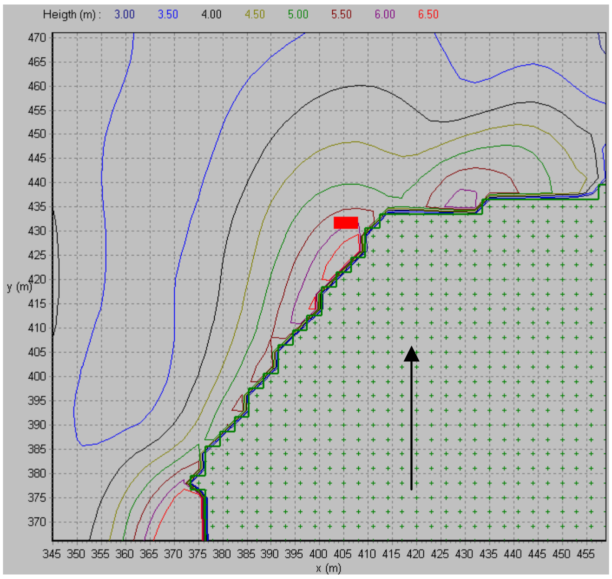

Figure 12, S, 6-7

The arrow shows the north.