SUND & BÆLT

ANALYSES OF NEW ISLAND HARBOUR AT TÅRS

WAVE TRANSFORMATION AND TRANQUILLITY STUDIES

ADDRESS COWI A/S
Parallelvej 2
2800 Kongens Lyngby
Denmark

TEL +45 56 40 00 00
FAX +45 56 40 99 99
WWW cowi.com

SUND & BÆLT

ANALYSES OF NEW ISLAND HARBOUR AT TÅRS

WAVE TRANSFORMATION AND TRANQUILLITY STUDIES

PROJECT NO.	DOCUMENT NO.
A258774	A258774-HAV-RAP-01

VERSION	DATE OF ISSUE	DESCRIPTION	PREPARED	CHECKED	APPROVED
1.0	04-02-2025	Wave studies	SYBS; ABRV; HGLN	HGLN; ADKE	JJU

CONTENTS

APPENDICES

1 Project Location

The project site is located near Tårs (DK) in Langslandsbælt. The objective is to establish an offshore ferry harbour on an artificial island approximately 3.5 km from Lolland, out in the Langslandsbælt, which can reduce the travelling time all year round on the Spodsbjerg-Tårs crossing.

The proposed harbour location and its area is shown in Figure 1-1.

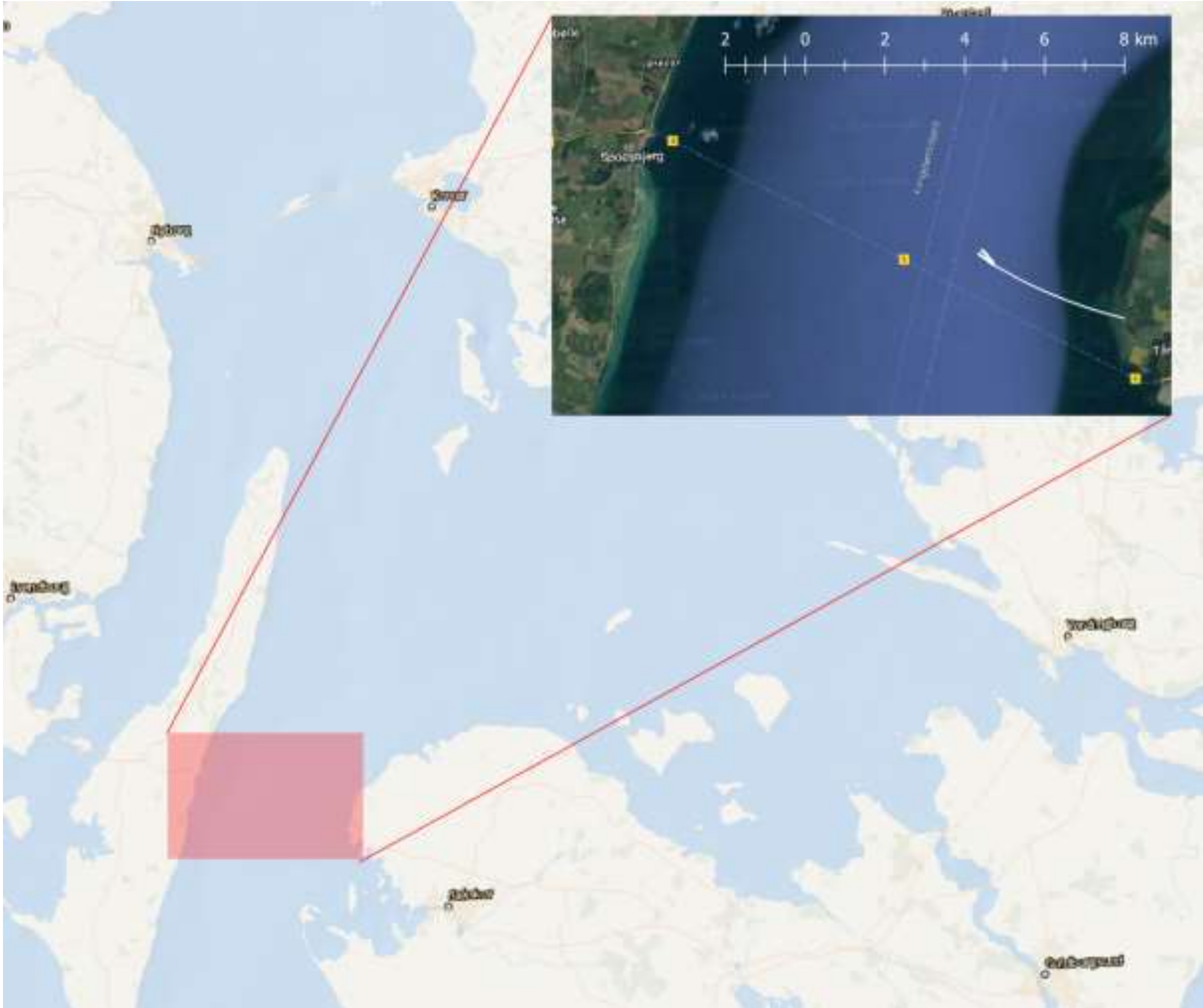


Figure 1-1 Location of Tårs Ferry Harbour in Langslandsbæltet.

2 Scope of study

The purpose of this study is to establish wave conditions outside the future harbour to be used for hydraulic design of marine structures (e.g. breakwaters). The wave conditions outside the harbour were established with a spectral wave model (MIKE 21 SW). Wave tranquillity modelling was subsequently performed to transfer the waves into the harbour basin. Wave conditions inside the harbour were established with a Boussinesq type wave model (MIKE 21 BW).

Three harbour layout options were studied as shown in

Figure 2-1.

The expected operational downtime was calculated as presented in section 5 of the report. The downtime enters into the process of selecting a preferred harbour layout together with environmental aspects, cost assessments, navigation assessments etc.

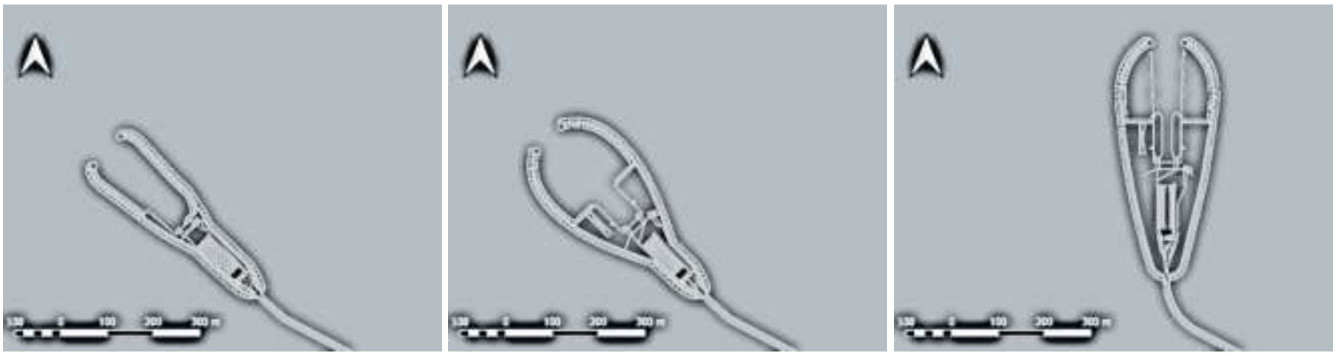


Figure 2-1 Layouts analysed in this report, Left – Layout 1, Mid – Layout 2, Right – Layout 3.

3 Wave Transformation Modelling Study

An existing spectral wave model (MIKE 21 SW) was used and modified to derive the wave conditions outside the harbour. The results from the model were subsequently used to establish extreme waves for design of breakwaters and marine structures. Moreover, the wave conditions outside the harbour were transferred into the harbour basin using the tranquillity model (MIKE 21 BW), see section 4.

The following section describes the wave transformation modelling study (MIKE 21 SW).

3.1 Model Description

Numerical modelling of the wave conditions was performed using the Spectral Wave (SW) module of the comprehensive 2-dimensional MIKE 21 modelling suite from DHI, Denmark. The model is based on a flexible mesh, and hence very fine resolution bathymetries, where necessary, can be incorporated with this model.

MIKE 21 SW is a third-generation time-dependent spectral wind-wave model based on unstructured meshes. It simulates the growth, propagation, decay, and transformation of wind generated waves and swells in offshore and coastal areas. The model includes wave growth by action of wind, interaction between waves with different frequencies and dissipation due to white capping. Furthermore, the model includes shallow water effects like refraction and shoaling due to varying depth and dissipation due to depth limited wave breaking and bottom friction.

The applied MIKE 21 SW model requires the following main inputs;

› Bathymetry of the area.

› Wind condition (wind speed and direction, or wind velocity components).

› Bottom friction parameters.

› Wave breaking parameters.

› Water level conditions.

MIKE 21 SW includes two different formulations:

› Fully Spectral – This can be used for wind-wave generation and propagation over long fetches and complex bathymetries where both wind-sea and swell are important.

› Directionally Decoupled – This can be used for wind wave generation and propagation in small fetches and regular bathymetries.

3.2 Modelling Methodology

Following approach was adopted for the wave transformation study.

- An existing wave model developed in 2014 was modified to add fine elements in the proposed project site.

- Wind, water level and wave boundary conditions from the existing wave model was used without any change.

- The wave model with modified mesh resolution near the project site was simulated for a period of 11 years from 2003 to 2013.

3.3 Model Bathymetry

The existing mesh and bathymetry were updated to add fine elements at the project area. The modified mesh is shown in Figure 3-1 and the model bathymetry is shown in Figure 3-2.

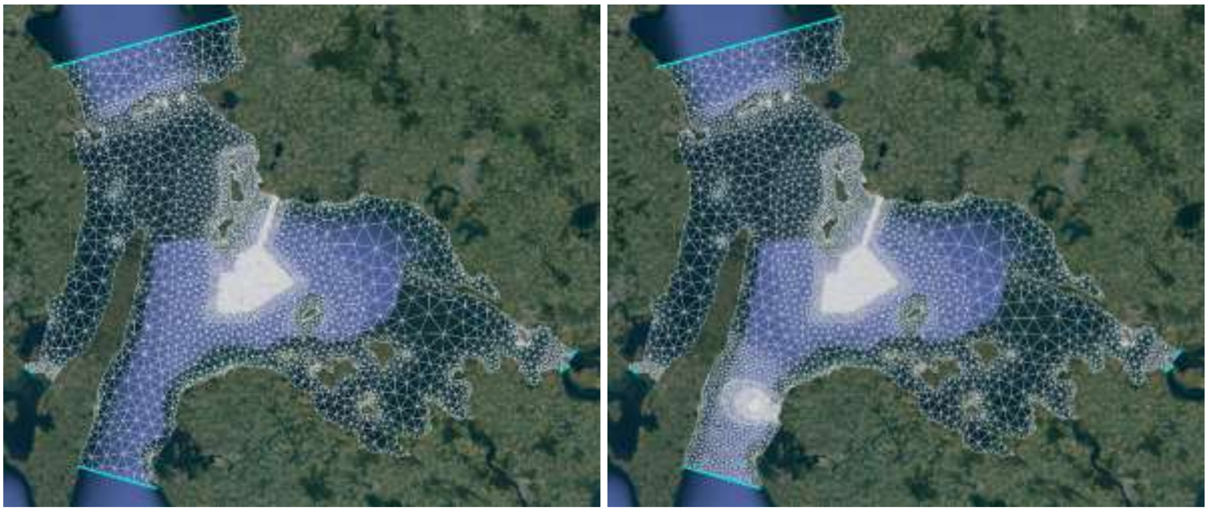


Figure 3-1 Model mesh. Left: Existing model. Right: With fine elements added at project site. Open boundaries shown as cyan lines.

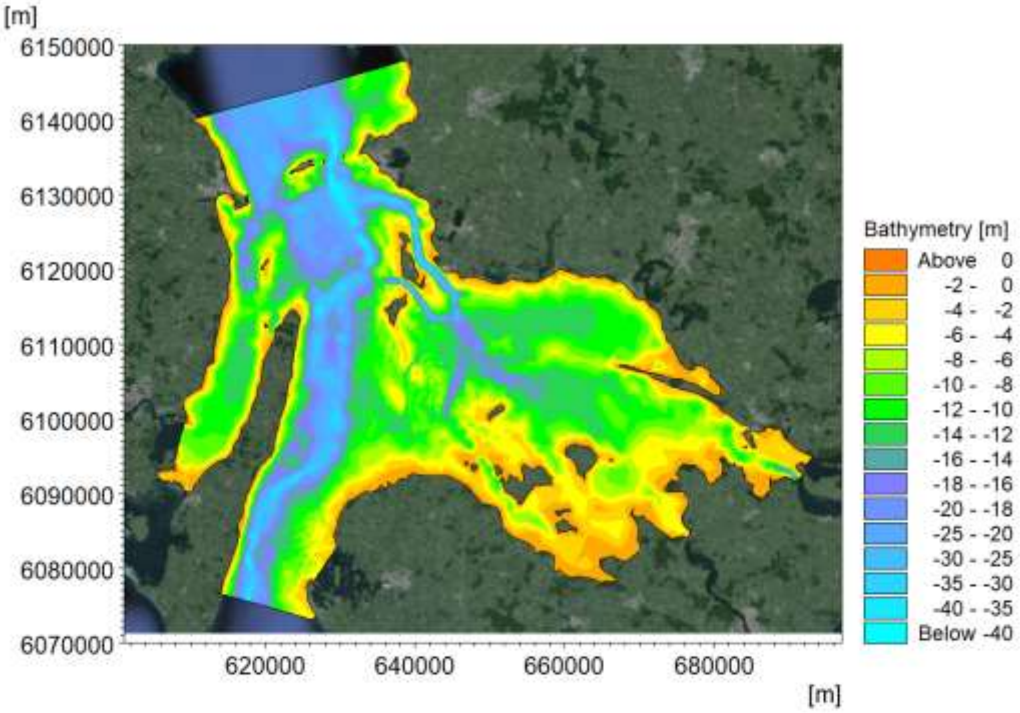


Figure 3-2 Bathymetry (m CD) used for the wave study.

3.4 Model Verification

COWI's existing wave model from 2014, had been extensively validated against ADCP wave measurements performed in Nov 2013 to Jan 2014 as shown in Figure 3-3.

The wave measurements from Now 2013-Jan 2014 are not available for the present project, therefore the 2014-wave model is used as an alternative means of verification of the new/updated wave model.

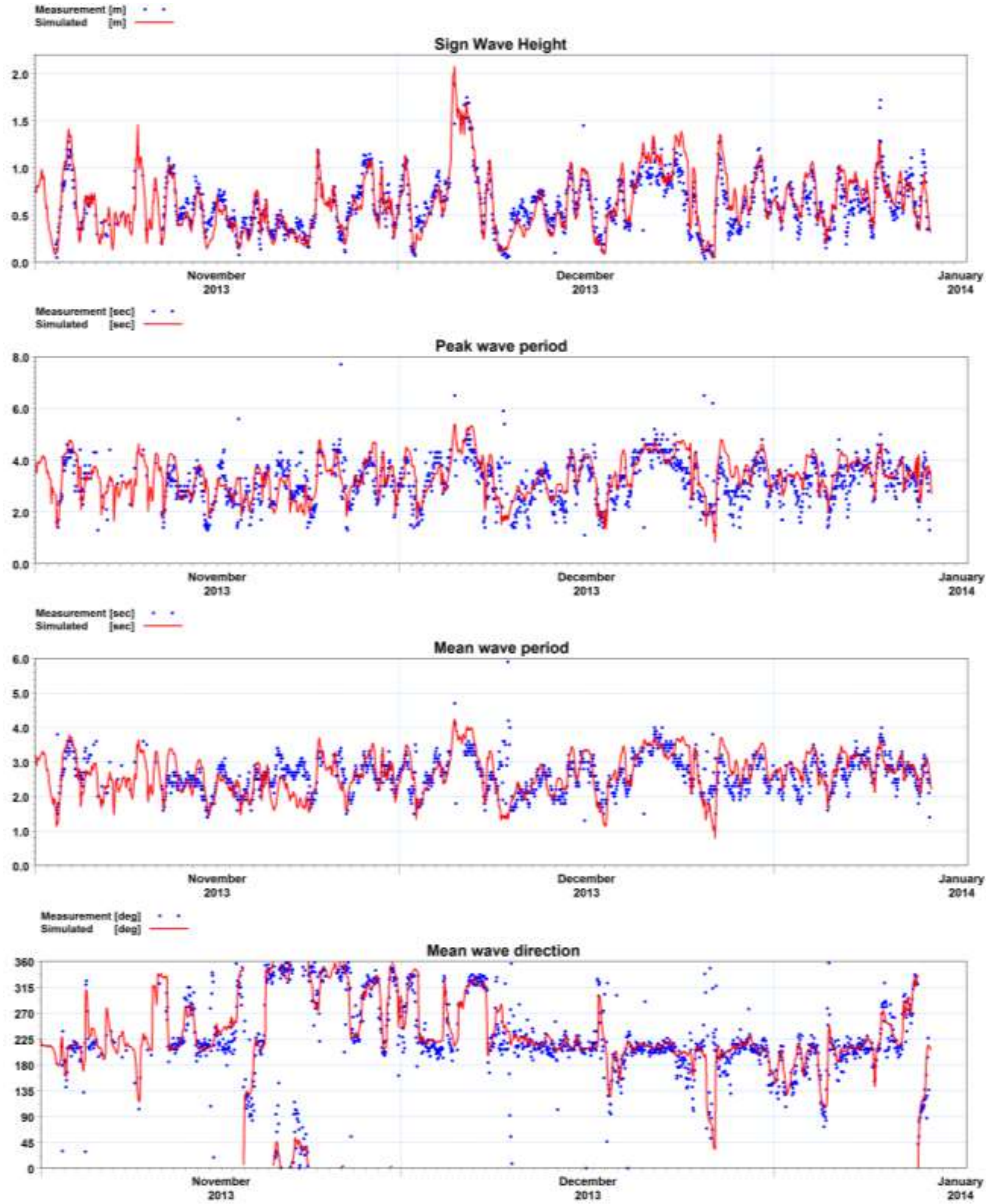


Figure 3-3 *Comparison of H_{m0} (Top), T_p (Second from Top), T_m (Third from top) and MWD (Bottom) between ADCP measurement and the 2014-wave model.*

The updated wave model was simulated for a period of 11 years (2003-2013) to generate long term wave climate at the site. For model verification, wave parameters were extracted at 2 locations namely, 'Deep' (depth = 14m) and 'Shallow' (depth = 5m), as shown in Figure 3-4.

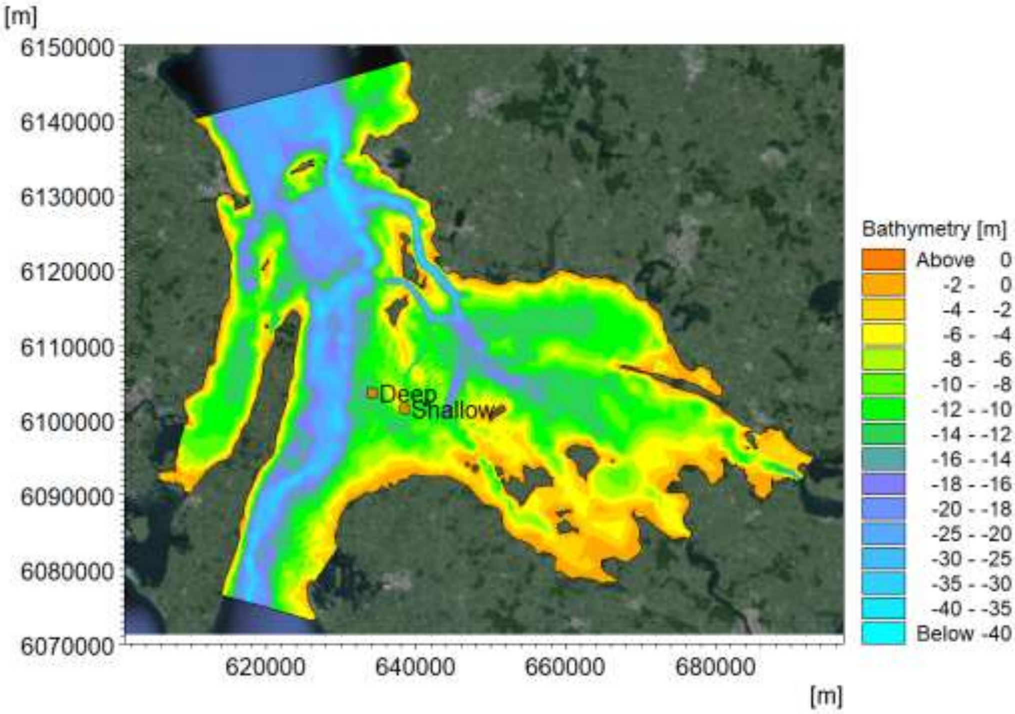


Figure 3-4 *Extraction locations for model verification.*

Time series comparison plots are shown in Figure 3-5 and Figure 3-6 for locations shown in Figure 3-4.

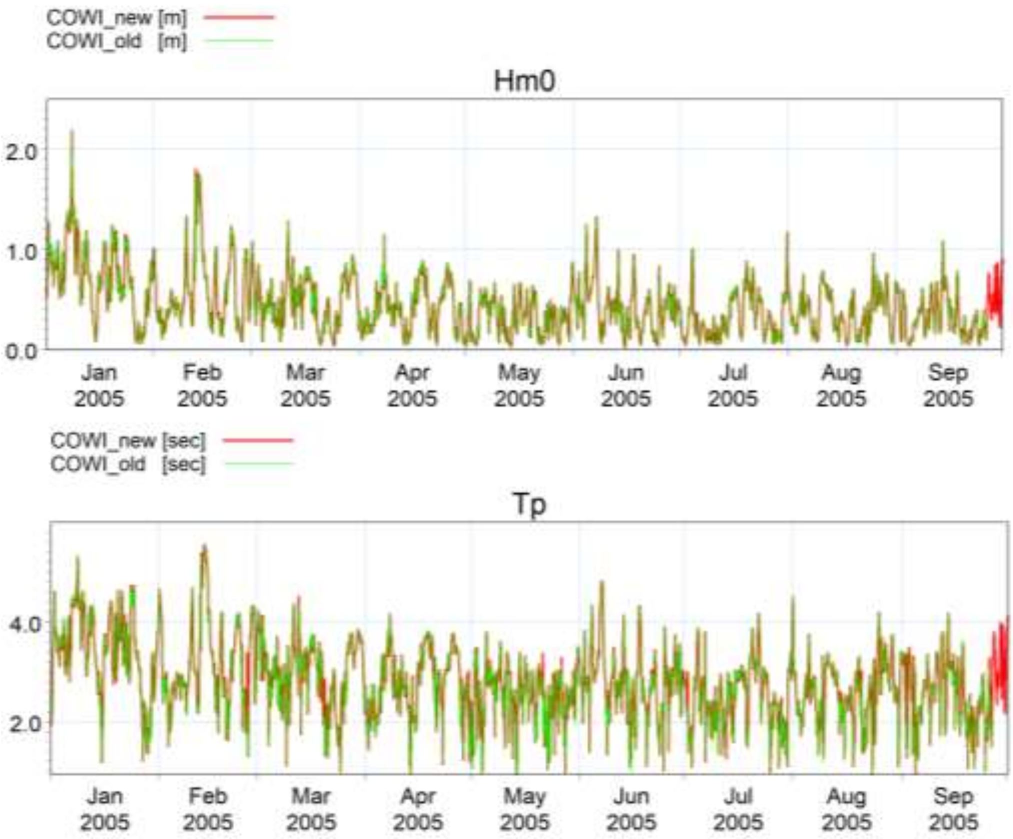


Figure 3-5 *Comparison between old (2014) and new (2024) simulated H_{m0} and T_p at location 'Deep'.*

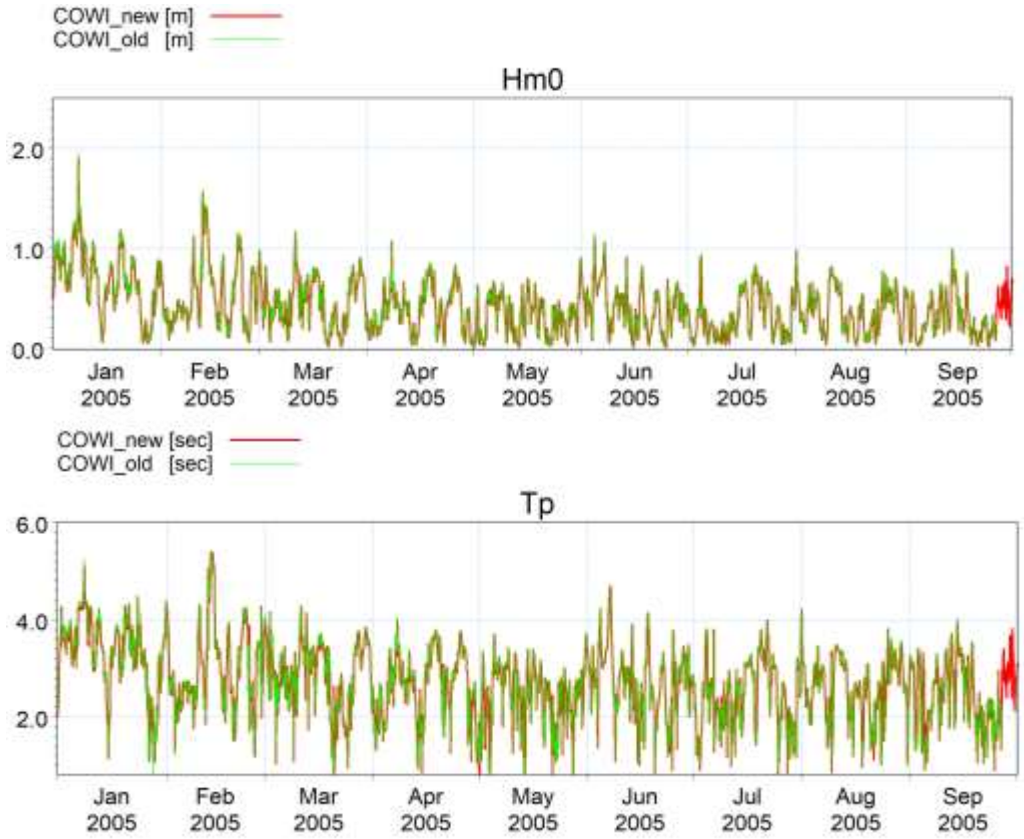


Figure 3-6 Comparison between old (2014) and new (2024) simulated H_{m0} and T_p at location 'Shallow'.

The comparisons show that the updated model is in full agreement with the calibrated 2014-model. Hence, that changes in mesh resolution near the project site and software update from version 2013 to version 2024 of MIKE 21, do not affect the model results. The updated model is thus considered to be well calibrated.

3.5 Wave Inputs to Tranquillity Study

Wave data was extracted at point 'P1', which is at a depth of 11 m (see Figure 3-7). In this section the conditions at P1 are presented as wave roses, exceedance plots, scatter tables and scatter plots of peak wave period, mean wave direction, and significant wave height.

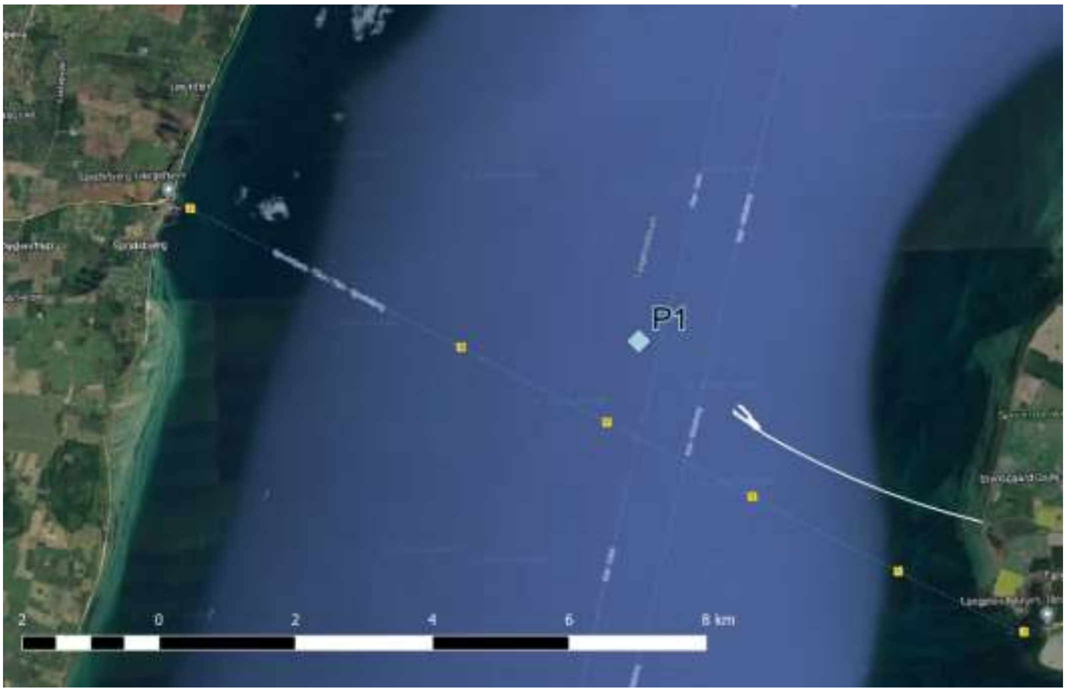


Figure 3-7 Wave data extraction location for establishing boundary conditions for the BW model.

Figure 3-8 shows the rose plots for the significant wave height, H_{m0}, and peak wave period, T_p, at P1. Scatter tables and scatter plots of H_{m0} vs. T_p, T_p vs. MWD (mean wave direction) and H_{m0} vs. MWD at P1 are shown in Table 3-1 to Table 3-3 and Figure 3-9 to Figure 3-11.

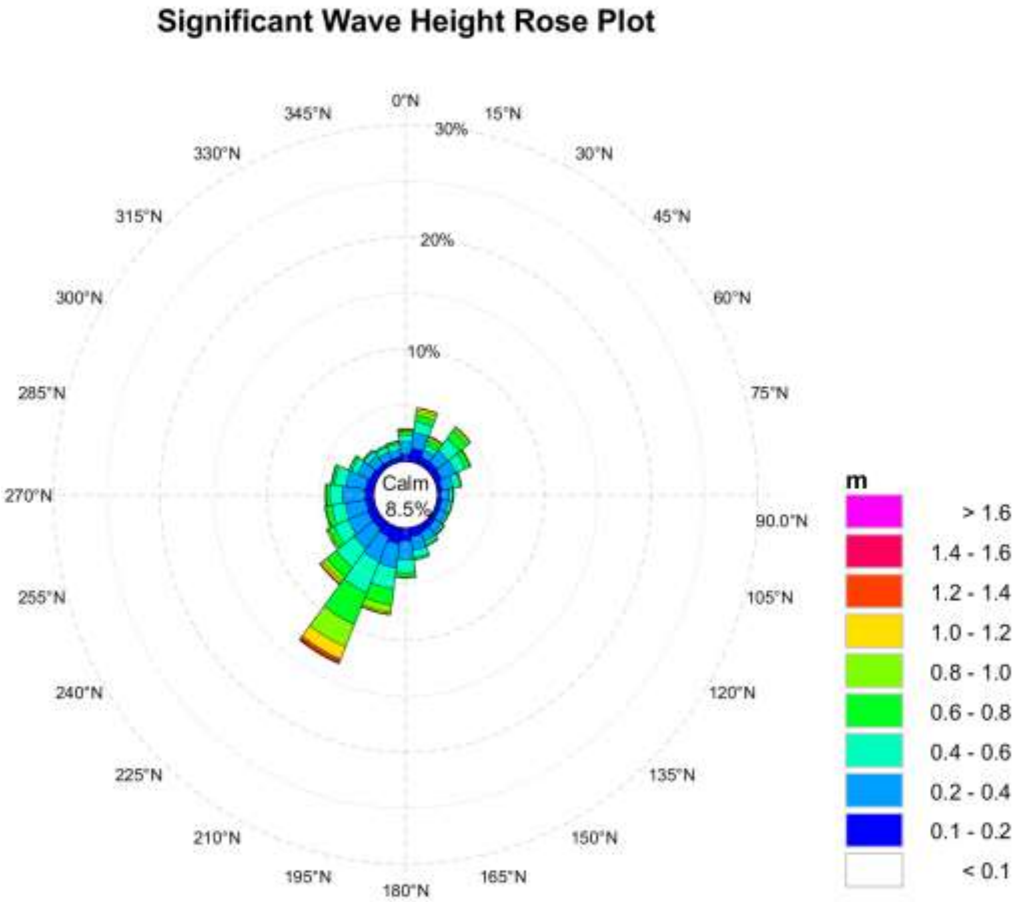


Figure 3-8 *Significant wave height rose plot at location P1, for the period 2003-2013.*

Table 3-1 *Joint occurrence of peak wave period, T_p, and significant wave height, H_{m0}, at location P1, for the period 2003-2013.*

Joint Occurrence Table of Peak Wave Period and Significant Wave Height

Peak Wave Period (s)	Significant Wave Height (m)											
	0.0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	> 2.0	Total
0.0 - 1.0	<0.1%											0.1%
1.0 - 2.0	13.9%	4.2%										18.1%
2.0 - 3.0	9.8%	22.5%	11.1%	1.4%	<0.1%							44.8%
3.0 - 4.0	1.3%	5.2%	10.4%	8.7%	2.0%	0.2%	<0.1%					27.9%
4.0 - 5.0	<0.1%	0.3%	0.9%	1.6%	3.2%	2.1%	0.5%	<0.1%				8.7%
5.0 - 6.0				<0.1%	<0.1%	<0.1%	0.2%	0.1%	<0.1%			0.4%
6.0 - 7.0												0.0%
> 7.0												0.0%
Total	25.2%	32.1%	22.4%	11.8%	5.3%	2.3%	0.7%	0.2%	0.0%	0.0%	0.0%	100%

Table 3-2 *Joint occurrence of significant wave height, H_{m0}, and mean wave direction, MWD, at location P1, for the period 2003-2013.*

Joint Occurrence Table of Significant Wave Height and Mean Wave Direction

Significant Wave Height (m)	Mean Wave Direction												
	0°N	30°N	60°N	90°N	120°N	150°N	180°N	210°N	240°N	270°N	300°N	330°N	Total
0.0 - 0.2	2.4%	2.7%	1.7%	1.0%	1.0%	1.7%	4.3%	3.7%	2.0%	1.9%	1.5%	1.1%	25.2%
0.2 - 0.4	2.3%	1.8%	2.9%	1.6%	1.4%	1.8%	3.5%	4.6%	4.0%	4.2%	2.6%	1.5%	32.1%
0.4 - 0.6	1.6%	1.4%	2.1%	0.7%	0.5%	0.8%	2.3%	5.3%	3.0%	2.4%	1.3%	1.0%	22.4%
0.6 - 0.8	0.7%	1.1%	1.0%	0.2%	0.1%	0.3%	0.9%	4.7%	1.2%	0.7%	0.5%	0.3%	11.8%
0.8 - 1.0	0.4%	0.6%	0.2%	<0.1%	<0.1%	<0.1%	0.3%	3.0%	0.4%	0.1%	<0.1%	<0.1%	5.3%
1.0 - 1.2	0.2%	0.3%	<0.1%				<0.1%	1.6%	0.1%	<0.1%	<0.1%	<0.1%	2.3%
1.2 - 1.4	<0.1%	<0.1%						0.4%	<0.1%	<0.1%			0.7%
1.4 - 1.6								0.1%	<0.1%				0.2%
1.6 - 1.8								<0.1%					0.0%
1.8 - 2.0								<0.1%					0.0%
> 2.0													0.0%
Total	7.6%	8.0%	8.0%	3.5%	3.1%	4.6%	11.4%	23.6%	10.8%	9.5%	5.9%	4.0%	100%

Table 3-3 *Joint occurrence of peak wave period, T_p, and mean wave direction, MWD, at location P1, for the period 2003-2013.0*

Joint Occurrence Table of Peak Wave Period and Mean Wave Direction

Peak Wave Period (s)	Mean Wave Direction												
	0°N	30°N	60°N	90°N	120°N	150°N	180°N	210°N	240°N	270°N	300°N	330°N	Total
0.0 - 1.0						<0.1%							0.1%
1.0 - 2.0	0.8%	1.5%	0.9%	0.9%	1.2%	1.3%	1.8%	1.6%	2.0%	2.9%	2.1%	1.3%	18.1%
2.0 - 3.0	3.0%	3.0%	3.0%	1.7%	1.4%	2.7%	5.6%	6.4%	6.3%	6.0%	3.4%	2.4%	44.8%
3.0 - 4.0	2.7%	2.9%	3.8%	0.9%	0.4%	0.5%	3.4%	9.8%	2.2%	0.6%	0.3%	0.4%	27.9%
4.0 - 5.0	1.1%	0.7%	0.2%	0.2%	<0.1%	<0.1%	0.6%	5.4%	0.3%	<0.1%		<0.1%	8.7%
5.0 - 6.0	<0.1%							0.3%	<0.1%				0.4%
6.0 - 7.0													0.0%
> 7.0													0.0%
Total	7.6%	8.0%	8.0%	3.5%	3.1%	4.6%	11.4%	23.6%	10.8%	9.5%	5.9%	4.0%	100%

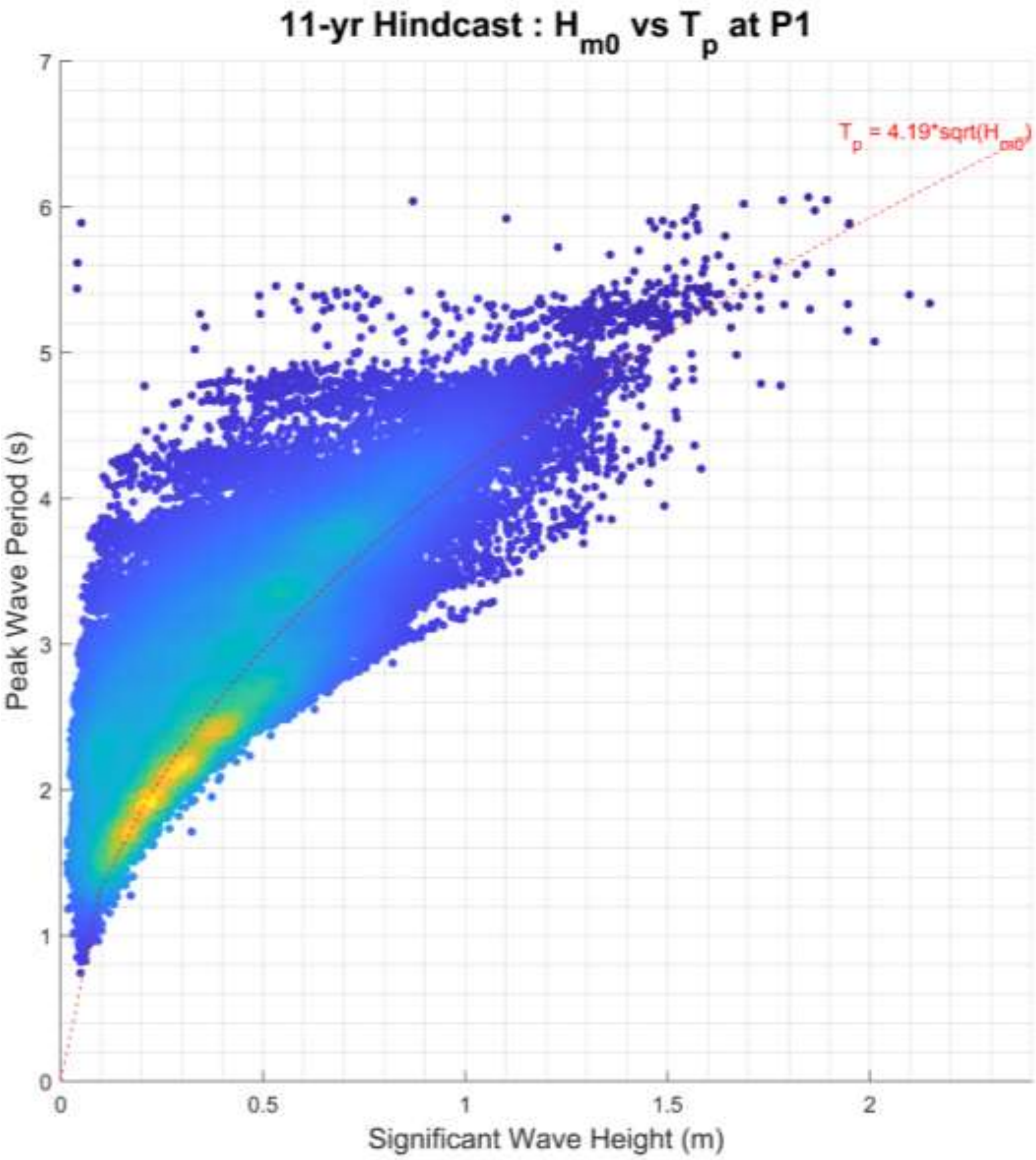


Figure 3-9 *Scatter plot of significant wave height, H_{m0}, and peak wave period, T_p, at location P1, for the period 2003-2013.*

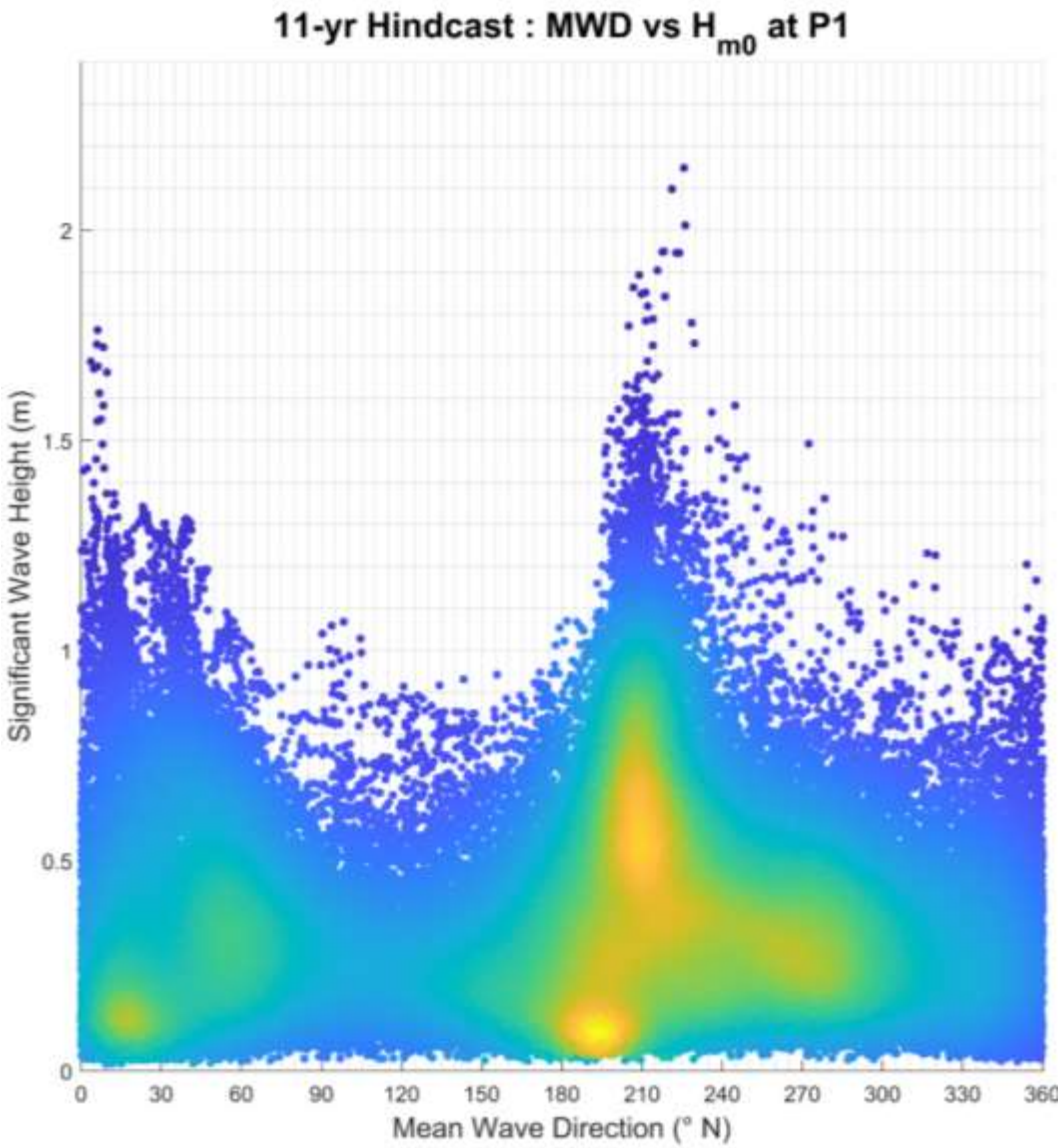


Figure 3-10 *Scatter plot of mean wave direction and significant wave height at location P1, for the period 2003-2013.*

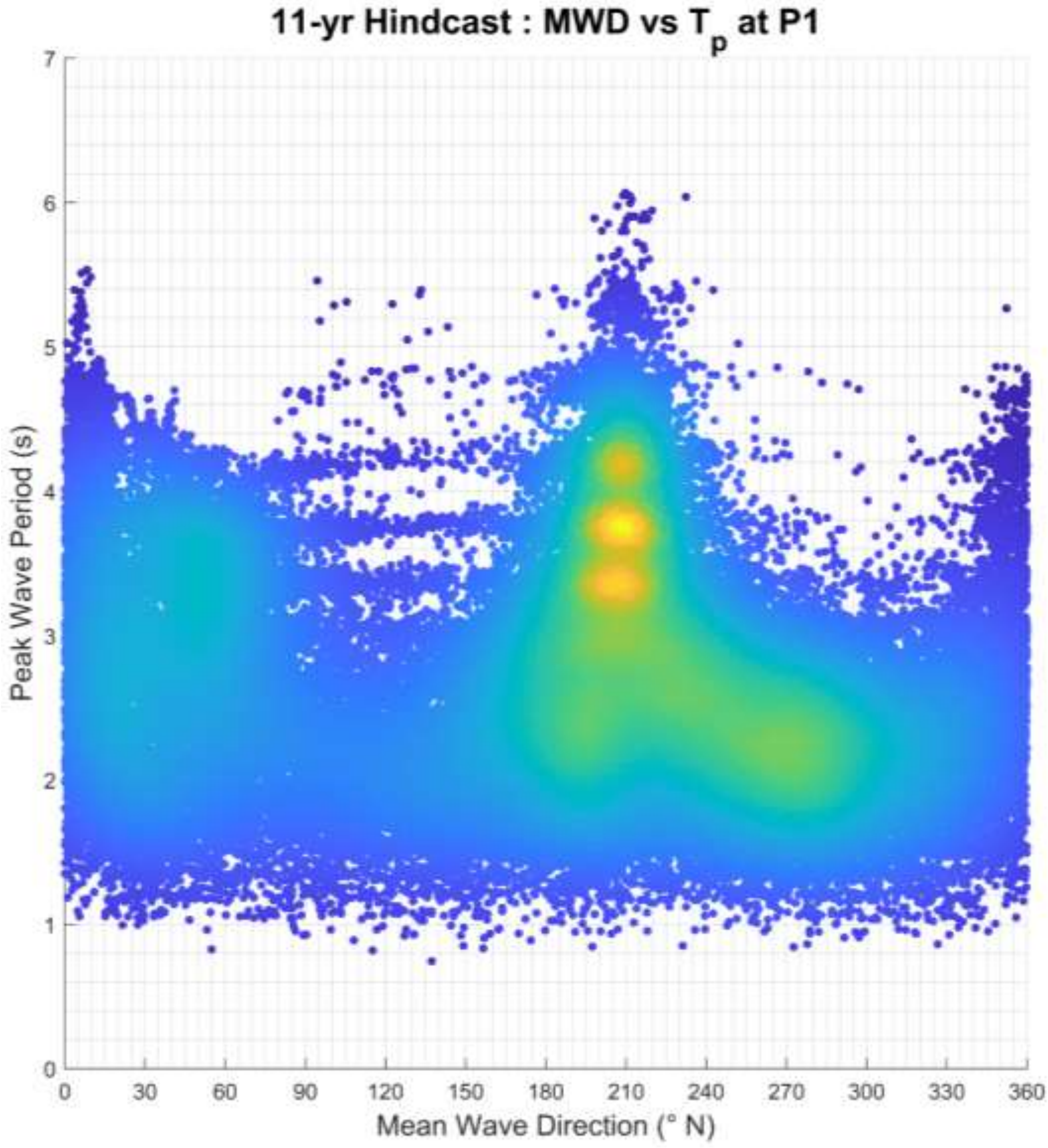


Figure 3-11 *Scatter plot of mean wave direction and peak wave period at location P1, for the period 2003-2013.*

An exceedance analysis is performed as shown in Figure 3-12. The exceedance analysis shows the likelihood (percent of time) of significant wave heights, H_{m0}, exceeding various levels from various directions within the period 2003-2013.

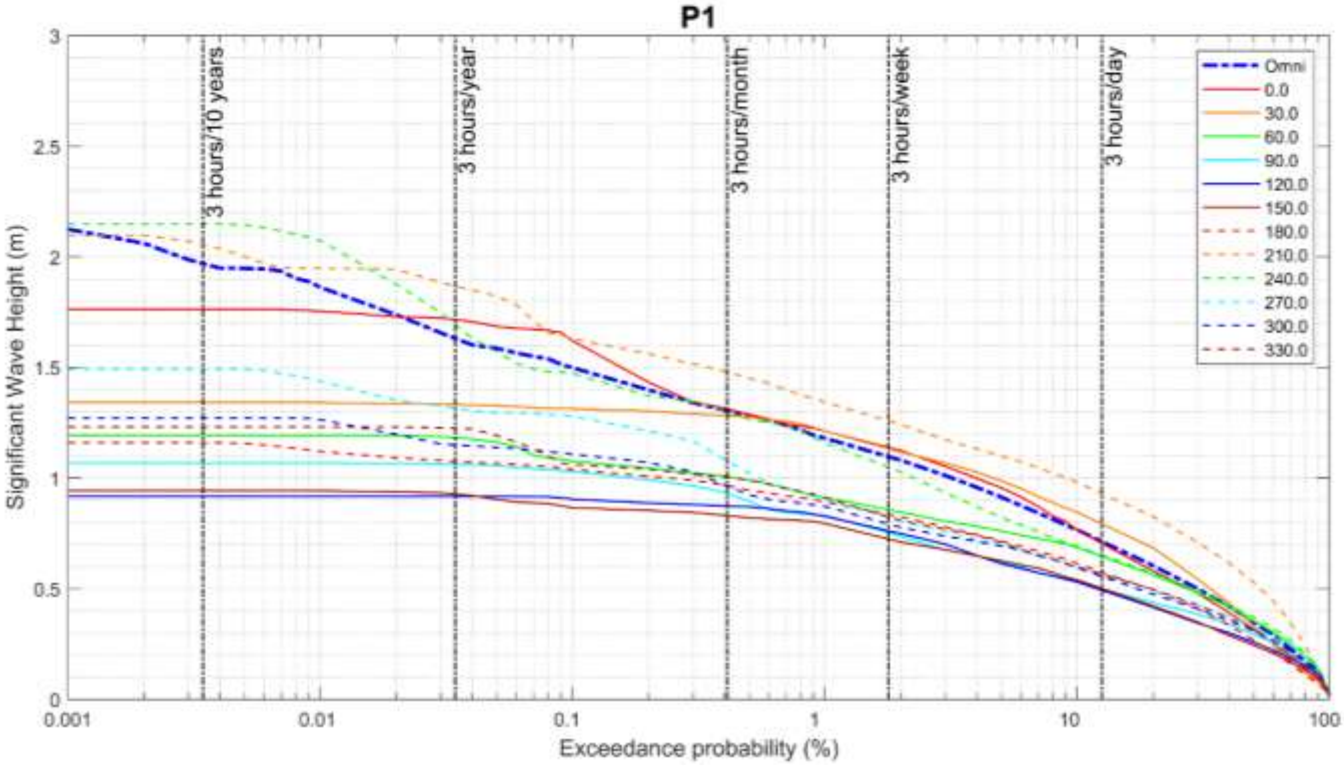


Figure 3-12 Directional exceedance plot showing the likelihood (percentage of time) of exceeding various levels of H_{m0} at point P1.

Wave condition at P1 outside the harbour may be described as follows:

- Higher waves are generally from SSW (210-240°N) and from NNE (0-30°N) directions aligned with the orientation of the Great Belt and the longer wind-fetch. The significant wave height can reach the order of 1.8m from NNE and 2.1m from SSW during storm.

- The most frequent wave-direction is from S (180°) to W (270°). Waves come from these directions more than 50% of the time (55.3%). Waves from N (0°) to NNE (60°) occur 21% of the time.

- Waves from NW (300-330°) occur only ~10% of the time and they rarely exceed H_{m0} = 1m, which is why this orientation of the ferry harbour is considered optimal considering waves only.

- T_p is generally less than 5 s and are mostly 2-4 s. During storms the peak wave period, T_p, can reach the order of 5.5s from NNE and 6.0s from SSW.

3.6 Extreme wave conditions

The extreme wave conditions were calculated in the extraction point P1. The conditions were determined via an extreme value analysis (EVA) where the 11-year dataset was fitted to a Weibull 3-parameter distribution and extrapolated to 1-, 5-, 10-, 25-, 50-, 100-, and 200-year return periods. The analysis was based on dataset of storm peaks found using a POT-threshold corresponding to 2 events per year, which resulted in the best fit. It shall be noted that extrapolating 11-years of data to a return period of more than 50-

year comes with a significant statistical uncertainty. The 100- and 200-year conditions shall thus be applied with caution.

The wave period associated to the extreme wave height was calculated based on the following relationship:

$$T_p = a \cdot H_{m0}^{0.5}$$

The variable *a* was fitted to the dataset in Figure 3-9 and a value of a=4.19 was found to fit the dataset fairly well at P1. The associated wave period of each extreme wave height was calculated using the above expression and rounded to nearest 0.5s.

Table 3-4 Extreme significant wave height, H_{m0}, and associated peak wave period, T_p, at P1 in brackets. Both the extreme fit and upper confidence level including 1 standard deviation are presented.

H_{m0} [m] (T_p [s])	1 year		5 year		10 year		25 year		50 year		100 year		200 year	
	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std
Omni	1.6 (5.5)	1.7 (5.5)	1.9 (6.0)	2.0 (6.0)	2.1 (6.0)	2.2 (6.0)	2.2 (6.0)	2.4 (6.5)	2.3 (6.5)	2.7 (7.0)	2.5 (6.5)	2.9 (7.0)	2.6 (6.5)	3.1 (7.5)
0°	1.2 (4.5)	1.2 (4.5)	1.5 (5.0)	1.6 (5.5)	1.6 (5.5)	1.8 (5.5)	1.8 (5.5)	2.1 (6.0)	2.0 (6.0)	2.4 (6.5)	2.1 (6.0)	2.7 (7.0)	2.3 (6.5)	3.0 (7.0)
30°	1.2 (4.5)	1.2 (4.5)	1.3 (5.0)	1.3 (5.0)	1.3 (5.0)	1.4 (5.0)	1.4 (5.0)	1.5 (5.0)	1.4 (5.0)	1.5 (5.0)	1.5 (5.0)	1.6 (5.5)	1.5 (5.0)	1.7 (5.5)
60°	0.9 (4.0)	0.9 (4.0)	1.1 (4.5)	1.1 (4.5)	1.1 (4.5)	1.2 (4.5)	1.2 (4.5)	1.3 (5.0)	1.3 (4.5)	1.4 (5.0)	1.3 (5.0)	1.5 (5.0)	1.4 (5.0)	1.6 (5.5)
90°	0.7 (3.5)	0.7 (3.5)	0.8 (4.0)	0.9 (4.0)	0.9 (4.0)	1.0 (4.5)	1.1 (4.5)	1.2 (4.5)	1.2 (4.5)	1.4 (5.0)	1.3 (4.5)	1.6 (5.5)	1.4 (5.0)	1.8 (5.5)
120°	0.7 (3.5)	0.8 (3.5)	0.9 (4.0)	0.9 (4.0)	0.9 (4.0)	1.0 (4.0)	1.0 (4.0)	1.1 (4.5)	1.0 (4.0)	1.1 (4.5)	1.1 (4.5)	1.2 (4.5)	1.1 (4.5)	1.2 (4.5)
150°	0.8 (3.5)	0.8 (4.0)	0.9 (4.0)	0.9 (4.0)	0.9 (4.0)	1.0 (4.0)	1.0 (4.0)	1.0 (4.0)	1.0 (4.0)	1.0 (4.5)	1.0 (4.0)	1.1 (4.5)	1.0 (4.0)	1.1 (4.5)
180°	1.0 (4.0)	1.0 (4.0)	1.1 (4.5)	1.1 (4.5)	1.1 (4.5)	1.2 (4.5)	1.2 (4.5)	1.2 (4.5)	1.2 (4.5)	1.3 (4.5)	1.2 (4.5)	1.3 (5.0)	1.2 (4.5)	1.3 (5.0)
210° *	1.6 (5.5)	1.7 (5.5)	1.9 (6.0)	2.0 (6.0)	2.1 (6.0)	2.2 (6.0)	2.2 (6.0)	2.4 (6.5)	2.3 (6.5)	2.7 (7.0)	2.5 (6.5)	2.9 (7.0)	2.6 (6.5)	3.1 (7.5)
240°	1.3 (5.0)	1.4 (5.0)	1.7 (5.5)	1.9 (5.5)	1.9 (6.0)	2.2 (6.0)	2.2 (6.0)	2.4 (6.5)	2.3 (6.5)	2.7 (7.0)	2.5 (6.5)	2.9 (7.0)	2.6 (6.5)	3.1 (7.5)
270°	1.1 (4.5)	1.1 (4.5)	1.3 (5.0)	1.4 (5.0)	1.4 (5.0)	1.5 (5.0)	1.5 (5.0)	1.7 (5.5)	1.6 (5.5)	1.9 (5.5)	1.7 (5.5)	2.0 (6.0)	1.8 (5.5)	2.2 (6.0)
300°	0.9 (4.0)	1.0 (4.0)	1.1 (4.5)	1.2 (4.5)	1.2 (4.5)	1.3 (5.0)	1.3 (5.0)	1.4 (5.0)	1.4 (5.0)	1.6 (5.0)	1.5 (5.0)	1.7 (5.5)	1.5 (5.0)	1.8 (5.5)
330°	0.9 4.0)	0.9 4.0)	1.1 (4.5)	1.1 (4.5)	1.1 (4.5)	1.2 (4.5)	1.2 (4.5)	1.3 (5.0)	1.3 (4.5)	1.4 (5.0)	1.3 (5.0)	1.5 (5.0)	1.4 (5.0)	1.6 (5.5)

**/ Values increased to match omni.*

Results of the extreme value analysis are presented in Table 3-4. The table contains both the best fit to the data and an upper confidence level corresponding to the central fit plus one standard deviation. The upper confidence level covers some of the statistical uncertainty introduces by having only 11-years of data. It is thus advised to use this upper confidence level for design of marine structures.

3.7 Extreme wind conditions

The extreme wind conditions are calculated in a point of the NORA3 wind dataset near the project site. The conditions are determined by an extreme value analysis (EVA) where a 30-year dataset is fitted to a Weibull 3-parameter distribution and extrapolated to 1-, 5-, 10-, 25-, 50-, 100-, and 200-year return periods. The analysis is based on a POT-threshold corresponding to 2 events per year, which result in the best fit. Results are presented in Table 3-5 and Table 3-6.

Table 3-5 *Extreme wind speed (directionally), U_{10}, in the NORA3 dataset. Both the extreme fit and upper confidence level including 1 standard deviation are presented. Data from 1993-01-01 to 2023-11-29.*

Wind Speed (m/s)	1 year		5 year		10 year		25 year		50 year		100 year		200 year	
	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std
Omni	20.0	20.3	24.0	24.8	25.9	27.1	28.5	30.6	30.5	33.5	32.6	36.7	34.8	40.2
0°	15.5	15.9	17.7	18.8	18.7	20.2	20.0	22.3	21.0	23.9	22.1	25.7	23.1	-
30°	15.6	16.0	17.2	17.9	17.8	18.7	18.6	19.8	19.2	20.6	19.7	21.4	20.2	-
60°	15.9	16.5	18.6	19.9	19.8	21.6	21.3	24.0	22.5	25.9	23.7	27.9	24.9	-
90°	16.9	17.5	19.7	21.1	21.0	22.9	22.6	25.3	23.8	27.2	25.0	29.2	26.2	-
120°	17.4	18.1	20.3	21.7	21.5	23.4	23.1	25.7	24.3	27.5	25.5	29.4	26.6	-
150°	20.0	20.3	22.7	23.8	23.6	25.0	24.8	26.6	25.6	27.7	26.4	28.9	27.2	-
180°	20.0	20.3	24.0	24.8	25.9	27.1	28.5	30.6	30.5	33.5	32.6	36.7	34.8	-
210°	20.0	20.3	24.0	24.8	25.9	27.1	28.5	30.6	30.5	33.5	32.6	36.7	34.8	-
240°	19.6	20.1	21.9	23.1	22.9	24.4	24.1	26.2	25.1	27.6	26.0	29.0	26.9	-
270°	17.4	17.8	19.4	20.4	20.3	21.6	21.5	23.4	22.4	24.8	23.2	26.3	24.1	-
300°	14.8	15.0	15.5	15.8	15.8	16.2	16.1	16.6	16.3	16.9	16.5	17.2	16.8	-
330°	14.3	14.7	15.8	16.5	16.4	17.3	17.2	18.4	17.7	19.2	18.3	20.0	18.8	-

Table 3-6 *Extreme wind speed (monthly), U_{10}, in the NORA3 dataset. Both the extreme fit and upper confidence level including 1 standard deviation are presented.*
Data from 1993-01-01 to 2023-11-29.

Wind Speed (m/s)	1 year		5 year		10 year		25 year		50 year		100 year		200 year	
	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std	Extreme	+ 1std
Yearly	20.0	20.4	24.0	24.8	25.9	27.1	28.4	30.5	30.4	33.3	32.4	36.3	34.5	-
January	16.3	16.7	21.2	22.1	23.4	24.8	26.3	28.5	28.5	31.5	30.7	34.7	32.9	-
February	15.8	16.2	19.7	20.4	21.3	22.3	23.3	24.9	24.8	26.9	26.3	29.0	27.8	-
March	14.8	15.1	18.1	18.7	19.4	20.2	20.9	22.1	22.0	23.4	23.1	24.8	24.1	-
April	13.7	14.0	16.5	17.0	17.6	18.3	19.0	20.0	19.9	21.2	20.9	22.5	21.8	-
May	13.0	13.2	15.3	15.7	16.2	16.7	17.2	18.1	18.0	19.1	18.8	20.0	19.5	-
June	13.1	13.3	15.9	16.4	17.1	17.9	18.7	20.0	19.9	21.6	21.2	23.4	22.4	-
July	13.2	13.4	15.2	15.6	16.0	16.4	16.8	17.4	17.4	18.2	18.0	18.9	18.5	-
August	13.3	13.6	15.7	16.1	16.5	17.0	17.5	18.2	18.2	19.0	18.8	19.9	19.4	-
September	14.1	14.4	17.0	17.6	18.2	18.9	19.6	20.7	20.7	22.0	21.7	23.4	22.7	-
October	15.1	15.4	19.0	19.8	20.8	22.0	23.3	25.3	25.2	27.9	27.2	30.7	29.1	-
November	15.4	15.7	18.7	19.3	19.9	20.8	21.5	22.8	22.7	24.3	23.8	25.8	24.9	-
December	15.8	16.2	20.4	21.4	22.5	23.9	25.4	27.7	27.6	30.7	29.8	33.9	32.1	-

4 Wave Tranquillity Study

To assess wave tranquillity inside the harbour to ensure safe manoeuvring and berthing operations, a wave tranquillity modelling is carried out to establish wave disturbance coefficients inside the harbour layout area.

The wave disturbance in the harbour is an important aspect for the safety and operational activities of vessels. Boussinesq type models can calculate wave climate and long-period wave motions in the harbours. In the present study, the wave disturbance in the harbour due to short period waves is assessed using the MIKE 21 BW and the results are presented in the subsequent sections.

4.1 Numerical Model (MIKE 21 BW)

The numerical model applied for modelling of the wave propagation into the harbour was the Boussinesq Wave Module of DHI's MIKE 21 numerical model (MIKE 21 BW).

MIKE 21 BW is a Boussinesq type non-linear wave model, which simulates in the time domain the properties of propagation of irregular, directional waves into the harbour considering all important effects like shoaling, depth refraction, diffraction, bottom friction, non-linear wave-wave interaction, frequency and directional dispersion, partial and full reflection, and transmission through porous structures. Wave breaking is not included in the model.

The model requires the following input:

› Basic model parameters describing the extent of the model area, the grid spacing of the computational model grid, the time step and the duration of the simulation.

› A digitised bathymetry

› Incident wave conditions described by flux time series on the boundaries of the model area. Prior to simulation, these time series are generated on basis of specified wave spectra.

› Porosities ('reflection and transmission coefficients') to describe the reflection characteristics for all structures and natural obstructions (breakwaters, quay walls, cliffs, beaches etc) in the model area. The reflection is described by specification of the porosity of the nearest grid points to the reflective object. For impermeable objects, the porosity layer describing the reflection characteristics of a structure is backed by an impermeable land point.

› Description of so-called sponge layers, which are areas absorbing all wave energy propagating into the area (i.e., no reflection). Sponge layers are used to ensure that no unwanted and unnatural reflections occur in the model area (e.g., from the boundaries of the model).

The model set up, the investigated layouts and the various input parameters applied in the simulations are described in the sections below.

4.1.1 Restrictions of MIKE 21 BW

Depending on whether the deep-water correction terms are included in the solution of the Boussinesq-equations, the numerical model MIKE 21 BW is subject to the different restrictions, as shown in Table 4-1.

Table 4-1 Restrictions of MIKE 21 BW when excluding and including the deep-water correction terms in the computations.

Deepwater terms *excluded*	Deepwater terms *included*
$\frac{h_{max}}{L_0} \le 0.22$	$\frac{h_{max}}{L_0} \le 0.60$
$\frac{L_{min}}{\Delta x} \ge 7$	$\frac{L_{min}}{\Delta x} \ge 7$
$\frac{T_{min}}{\Delta t} \ge 7$	$\frac{T_{min}}{\Delta t} \ge 32$
$\Delta t \le \frac{\Delta x}{\sqrt{gh_{max}}}$	$\Delta t \le \frac{\Delta x}{\sqrt{gh_{max}}}$

h_{max} : maximum water depth in the model area (m)

h_{min} : minimum water depth in the model area (m)

L_0 : deep-water wavelength (m)

T_{min} : minimum wave period (s)

L_{min} : minimum wavelength (m) determined from T_{min} and h_{min}

Δx : grid spacing (m) in both x- and y-direction

Δt : time step (s)

g : gravitational acceleration (m/s^2)

Although the harbour is in relatively shallow water depths, the prevalent waves in this area have very short period. Hence, the simulations performed in this study were carried out with an h_{max}/L_0-ratio up to 0.50 for the shortest wave period. Hence, it was necessary to include the deep-water correction terms in the computations.

4.2 Layouts

The layouts considered in the present study is shown in Figure 4-1, Figure 4-2, and Figure 4-3.

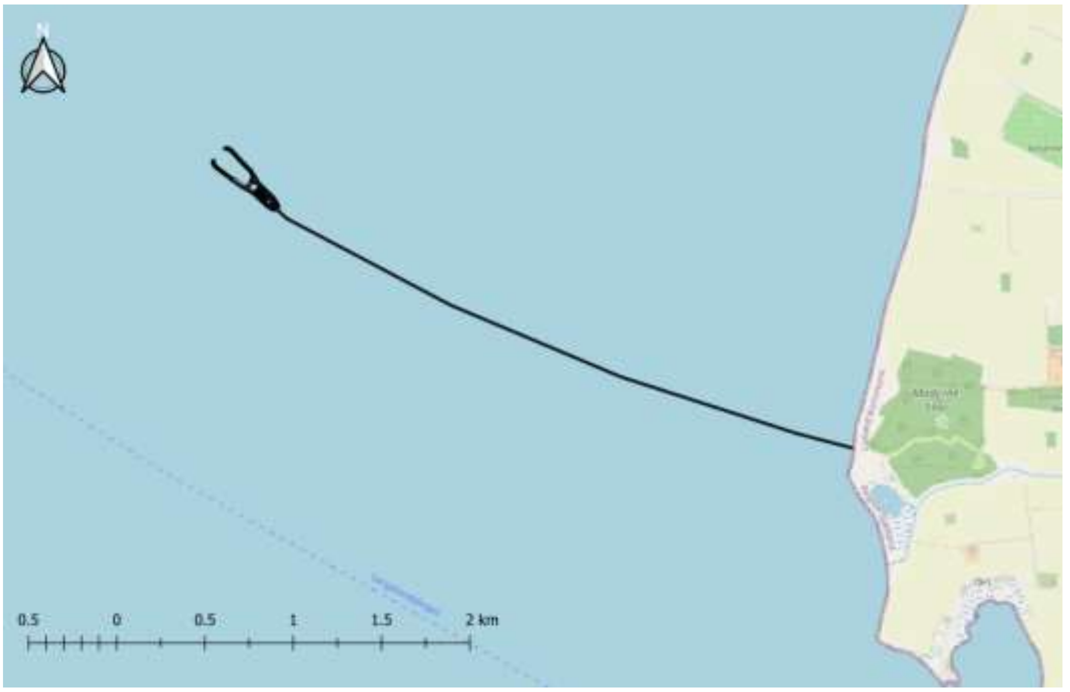


Figure 4-1 Project site showing the harbour layout 1.

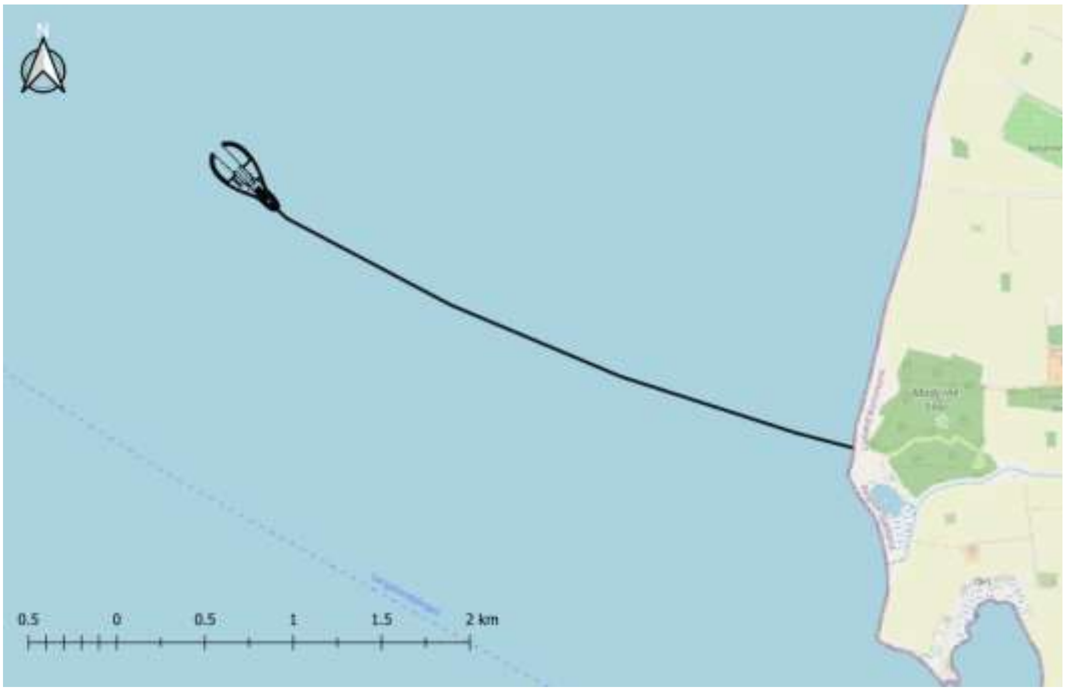


Figure 4-2 Project site showing the harbour Layout 2.

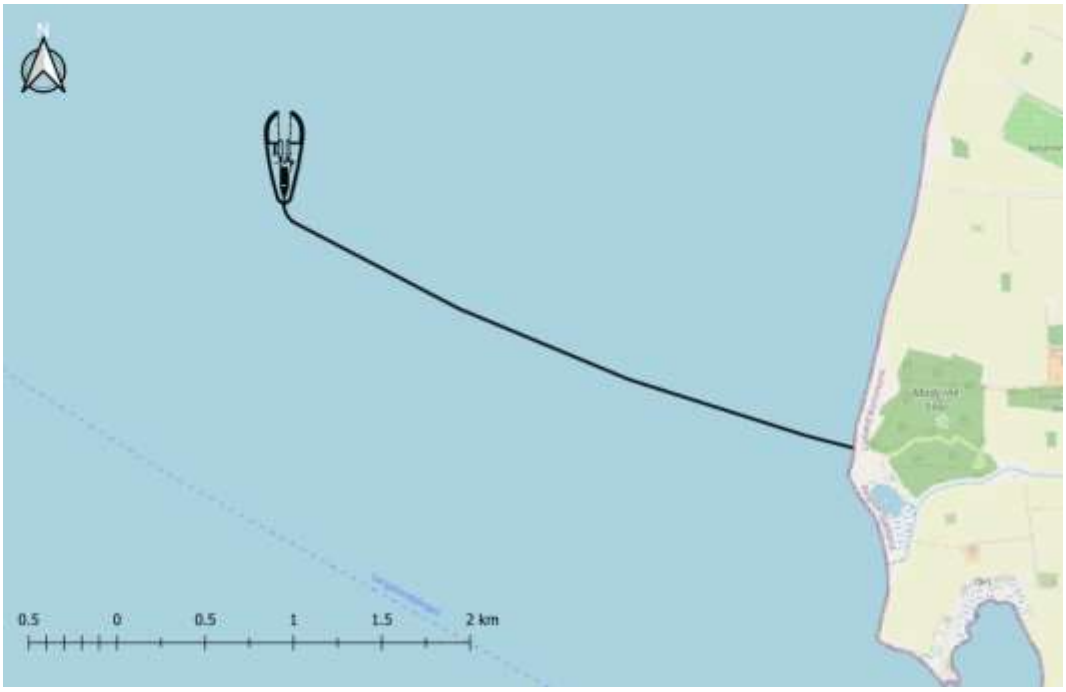


Figure 4-3 *Project site showing the harbour Layout 3.*

4.3 Simulation Matrix

The modelling has been performed with an incoming significant wave height of $H_{m0, incoming}$=1 m. A simulation matrix was prepared including nine directions and four wave periods as presented in Table 4-2 and Table 4-3.

Table 4-2 *Test matrix used for layouts 1 and 2 for the wave disturbance simulations at the model boundary.*

Model orientation	Wave Direction	Sign. Wave Height (m)	Peak Wave Period (sec)
0°N	255	1.0	3.5s, 5s
	270		3.5s, 5s
	285		3.5s, 5s
	345		3.5s, 5s
	0		3.5s, 5s
315°N	210	1.0	4.5s, 6s
	225		4.5s, 6s
	240		4.5s, 6s
	300		3.5s, 5s
	315		3.5s, 5s
	330		3.5s, 5s

Table 4-3 Test matrix used for Layout 3 for the wave disturbance simulations at the model boundary.

Model orientation	Wave Direction	Sign. Wave Height (m)	Peak Wave Period (sec)
0°N	285	1.0	3.5s, 5s
	345		3.5s, 5s
	0		3.5s, 5s
	15		3.5s, 5s
	75		3.5s, 5s
315°N	300	1.0	3.5s
	315		3.5s
	330		3.5s, 5s
	30		3.5s, 5s
	45		3.5s, 5s
	60		3.5s, 5s

4.4 Model Domain and Bathymetry

Considering the percentage occurrence of waves at 11 m water depth (refer Table 3-3), for layouts 1 and 2, wave directions at every 15° between 210°N and 0°N are considered for the present study. For Layout 3, every 15° between 285°N and 75°N are considered. Since the wave directions are varied, two model bathymetries were developed with orientation towards 0°N and 315°N. The purpose of having two bathymetries was to reduce the required extent of the model (hence to save computation time) and to make sure that the wave propagation in the model was generally as perpendicular to the grid orientation as possible.

The bathymetry generated with the grid orientation of 0°N is used for the wave directions of 255°N, 270°N, 285°N, 345°N, 0°N, 15°N and 75°N where the oblique mean wave direction relative to the model axes are ±10°-30° on either side. The bathymetry generated with an orientation of 315°N is used for simulating 210°N, 225°N, 240°N, 300°N, 315°N, 330°N, 30°N, 45°N, and 60°N. See Figure 4-4 and Figure 4-5 for the model domains used and Figure 4-6 shows the bathymetry within the model domains.

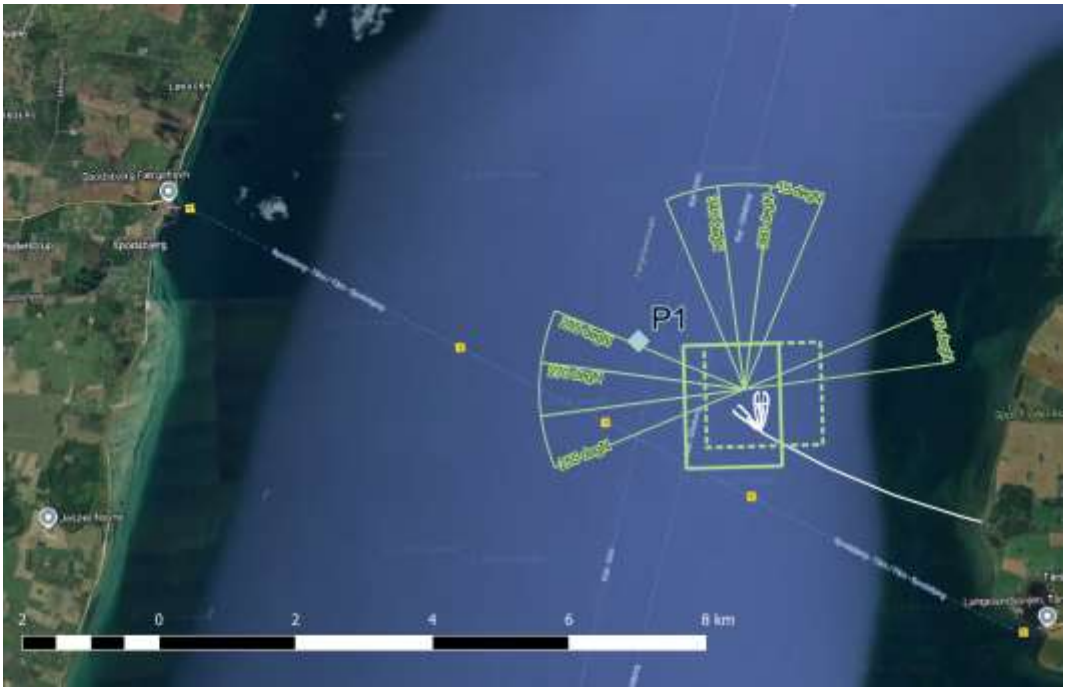


Figure 4-4 *BW model domain used for incoming wave directions of 255°N, 270°N, 285°N, 345°N, 0°N, 15°N and 75°N. Solid line for layouts 1 and 2, dashed line for Layout 3.*

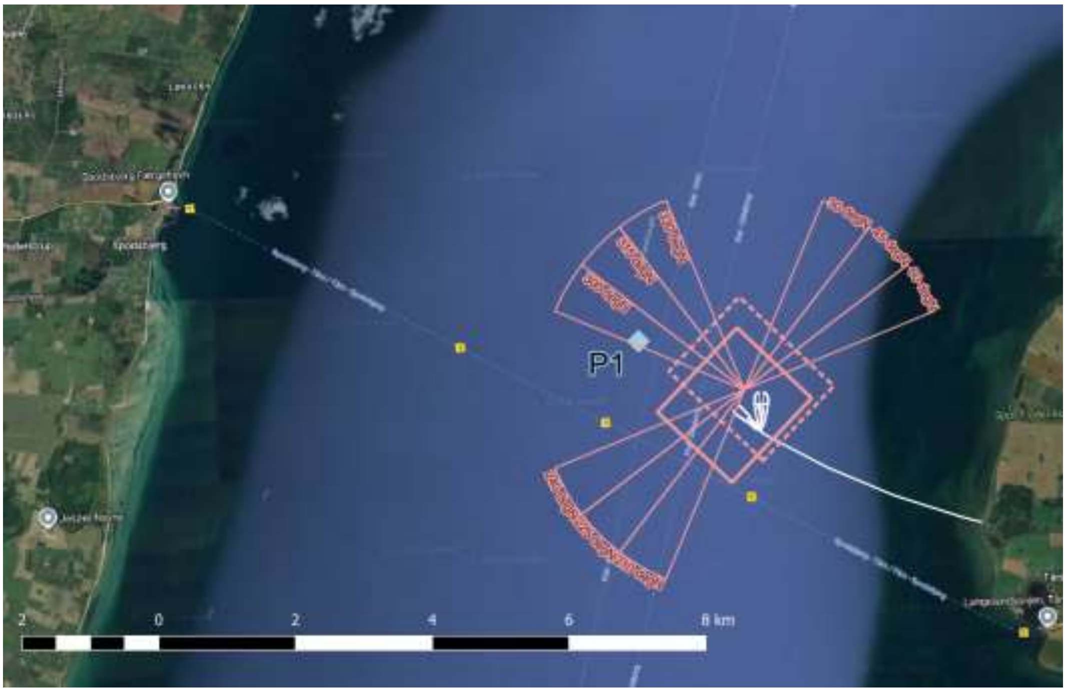


Figure 4-5 *BW model domain used for incoming wave directions of 210°N, 225°N, 240°N, 300°N, 315°N, 330°N, 30°N, 45°N, and 60°N. Solid line for layouts 1 and 2, dashed line for Layout 3.*

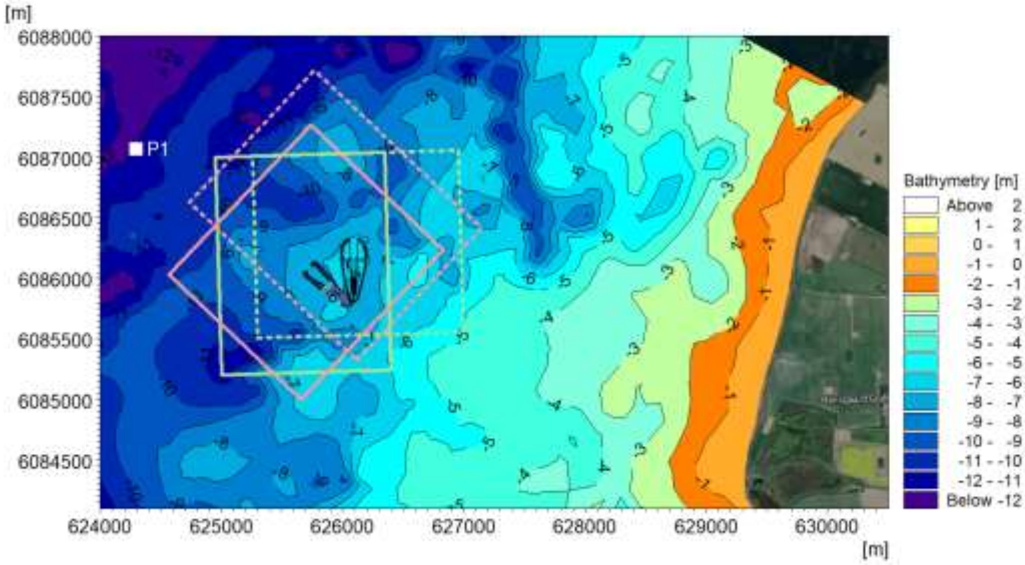


Figure 4-6 Bathymetry (m CD) within the BW model domains.

As an example, the model bathymetry for layouts 1 and 2 for model direction of 270°N is presented in Figure 4-7. In the model bathymetry, the horizontal datum is WGS1984/UTM 32N. A grid spacing of 2 m x 2 m has been used for the model bathymetry.

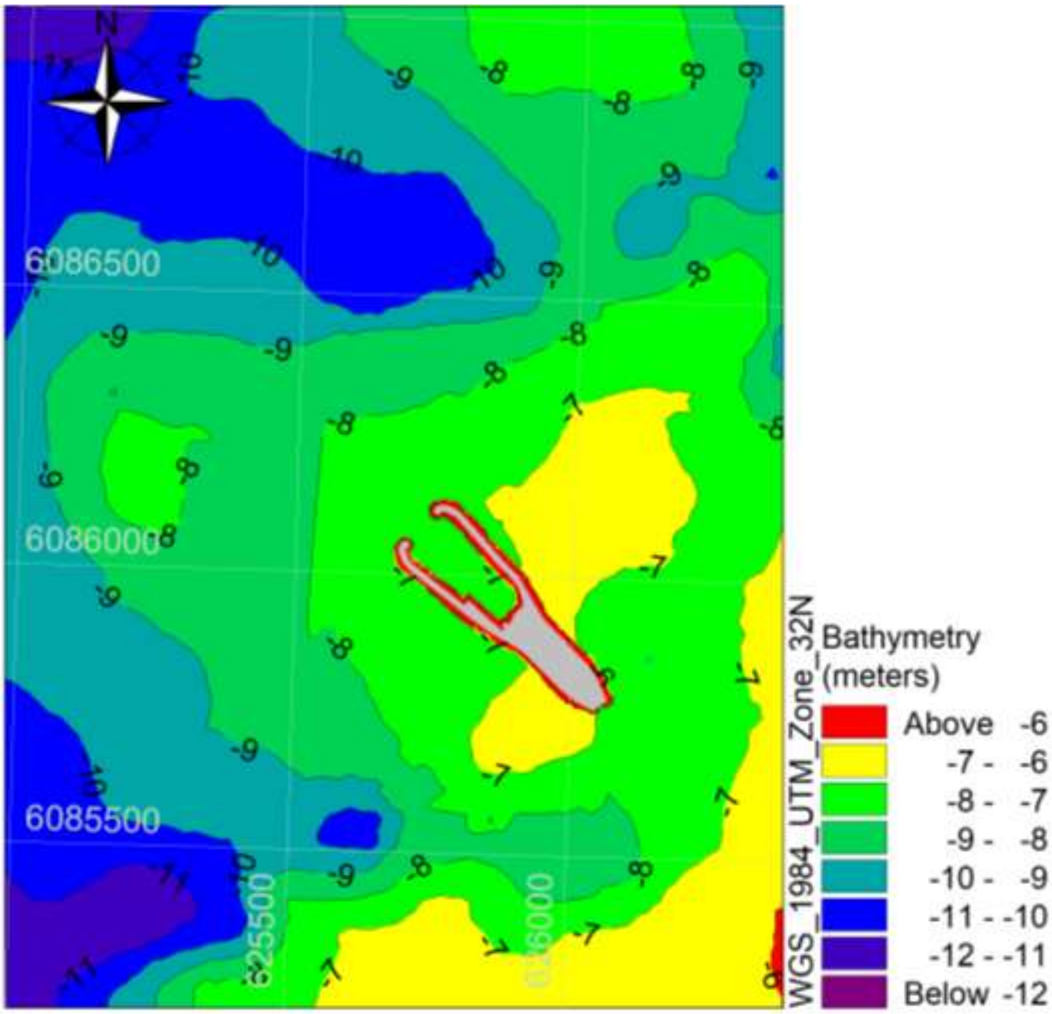


Figure 4-7 Bathymetry (m CD) for model direction = 270°N

4.5 Water Level

All numerical simulations were carried out with a water level of 0 m DVR90.

4.6 Minimum and Maximum Water Depths

To meet the restrictions of MIKE 21 BW (see Table 4-1), the maximum water depth was set to h_{max}= 11 m in simulations where the minimum wave period would be T_{min} = 3.7 s, hence simulations with peak wave periods of T_p =4.5 s, 5 s, and 6 s. For simulations with wave periods down to T_{min} = 2.8 s (T_p =3.5 s), a maximum water depth of h_{max} = 6 m was used. In all the simulations, depths larger than h_{max} were reduced to h_{max}.

This simplification of the bathymetry only has a very minor influence on the wave propagation and refraction due to the wavelength (L) to water depth (h_{max}) ratio.

4.7 Simulation Duration and Time Step

To ensure fully developed wave patterns in the basin and reliable wave height statistics, the duration of each simulation generally corresponded to 30 minutes. The last 20 minutes of each simulation were used for statistical analysis, i.e. determination of the significant wave height (H_{m0}) throughout the model area.

The time step (Δt) applied in the simulations was 0.05s.

4.8 Partial Reflection and Transmission

The reflective characteristics of various coastal structures in the model domain, such as rubble mounds, vertical walls, etc., is defined by porosity layers. The location of partial reflective and almost fully reflective structures is defined as shown in Figure 4-8 to Figure 4-13. These are specified by the porosity values corresponding to the reflection characteristics of these structures. The assumed reflection characteristics are given in Table 4-4.

Table 4-4 Reflection coefficients specified in the model.

Feature / Structure	Reflection Coefficient
Revetment	0.40
Vertical Wall	0.95
Wooden Plank (Breakwater heads made as a “Tømmerkiste”, a caisson-type structure with vertical wooden planks and filled with rocks inside)	0.80

The porosity values applied in the model are calculated for these reflection coefficients considering actual water depths, wave height and period in front of the structure.

Figure 4-8 *Location of almost fully reflecting vertical walls, wooden planks, and partially reflecting revetments for layout 1.*

Figure 4-9 *Location of almost fully reflecting vertical walls, wooden planks, and partially reflecting revetments for Layout 2a.*

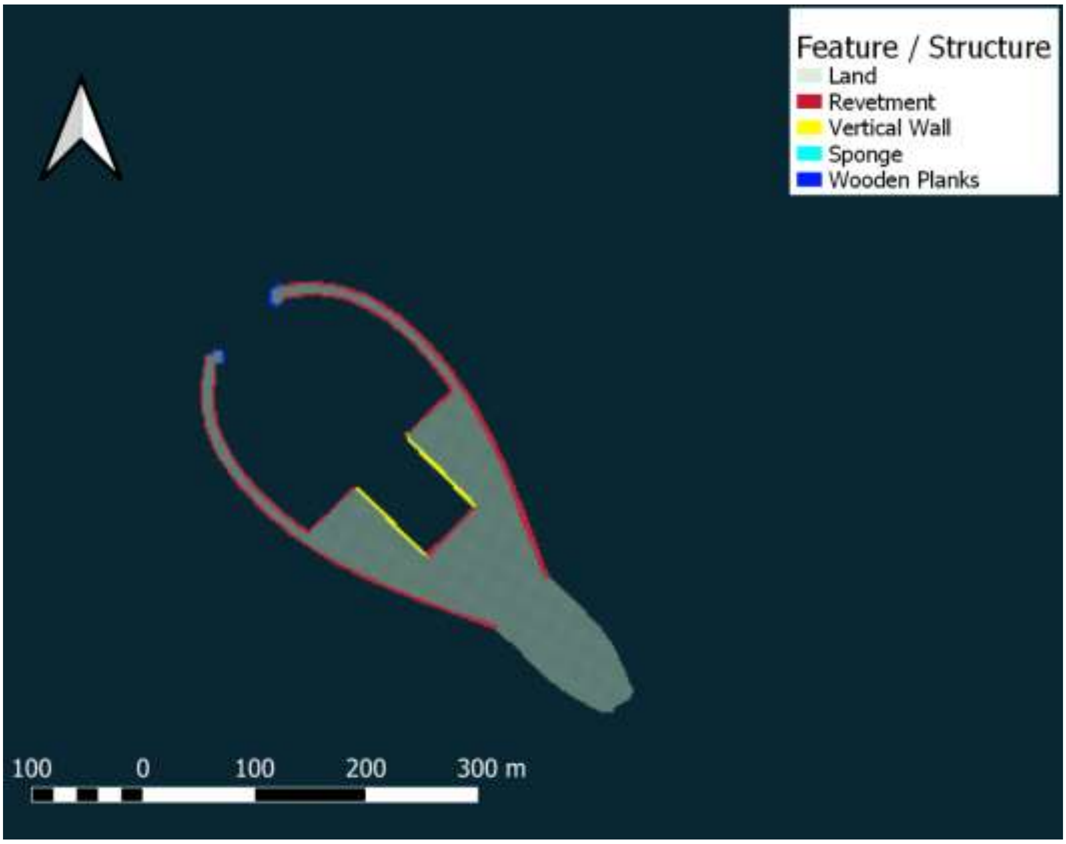


Figure 4-10 *Location of almost fully reflecting vertical walls, wooden planks, and partially reflecting revetments for Layout 2b.*

Figure 4-11 *Location of almost fully reflecting vertical walls, wooden planks, and partially reflecting revetments for Layout 2c.*

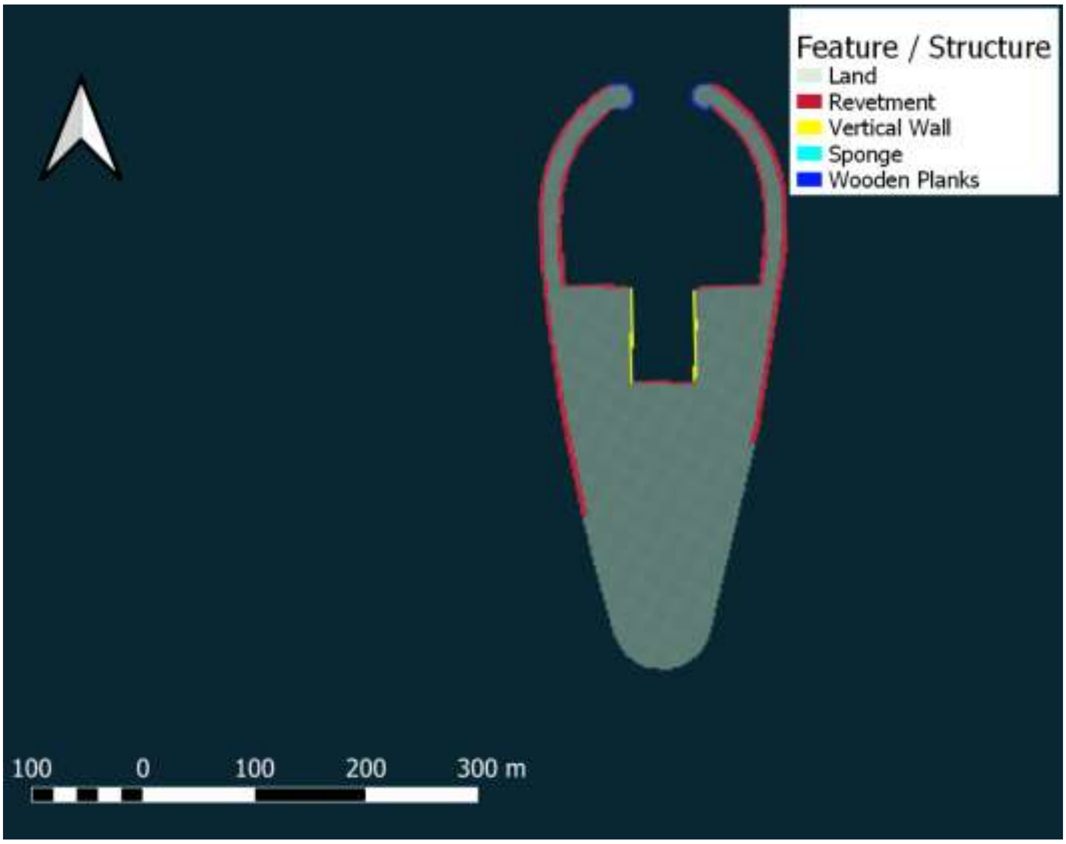


Figure 4-12 *Location of almost fully reflecting vertical walls, wooden planks, and partially reflecting revetments for Layout 3a.*

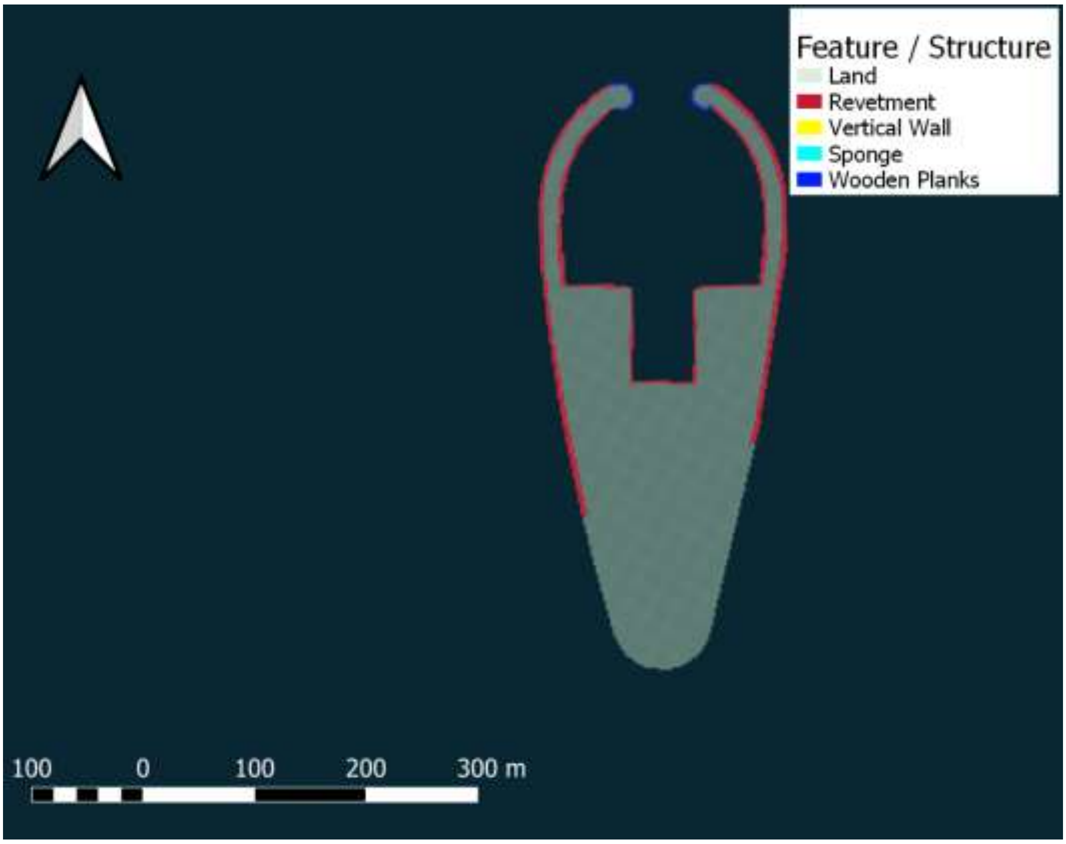


Figure 4-13 *Location of almost fully reflecting vertical walls, wooden planks, and partially reflecting revetments for Layout 3b.*

4.9 Sponge Layer

The waves in the numerical model were generated along lines inside the model boundary, and since no reflection must occur from the boundaries of the numerical model, so-called sponge layers (layers which smoothly absorb all wave energy entering the layers) were introduced. Additionally, wave energy reaching the shoreline and areas within the model domain that do not influence waves at project site are also absorbed using "sponge" layers. This method is generally adopted in wave tranquillity simulations to avoid wave reflection which is not useful in describing wave conditions within the harbour.

Sponge layers are prepared for all the four scenarios. The location of absorbing sponge layers for layouts 1 and 2 is shown in Figure 4-14.

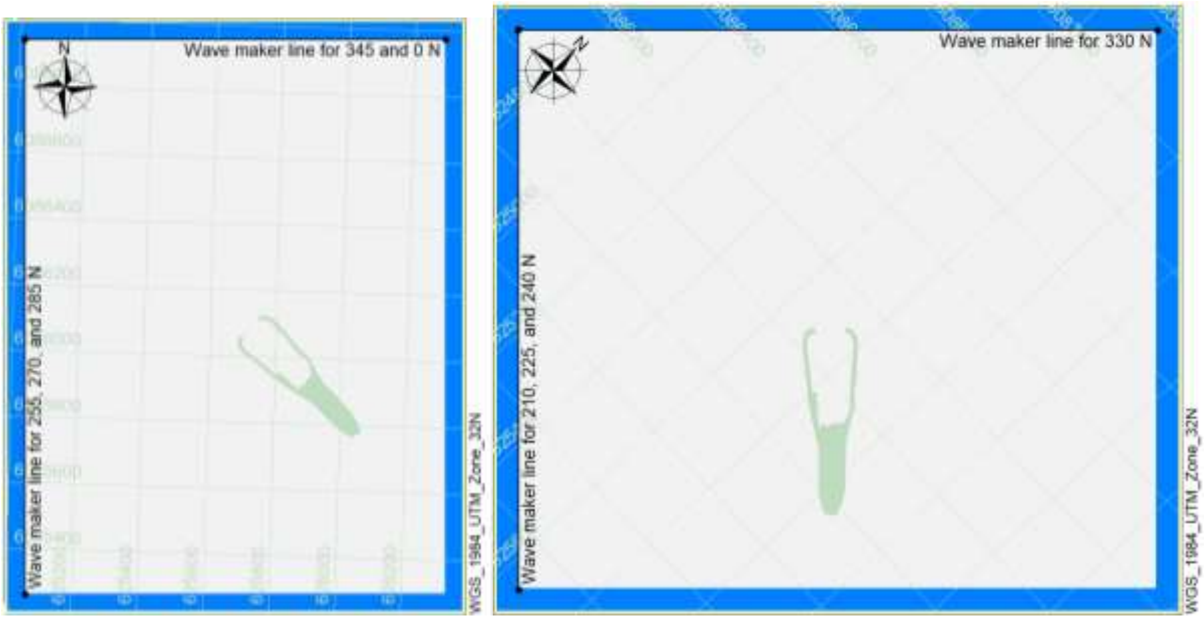


Figure 4-14 Location of sponge layers (blue area) for wave absorption. Left: Model oriented towards 0°N. Right: Model oriented towards 315°N.

4.10 Model Wave Generation

Waves are generated in the model domain by internal wave generation lines along the model boundaries, see Figure 4-14. Irregular random waves were generated based on the JONSWAP spectrum for the input values of wave height (H_{m0}) and wave period (T_p). A maximum deviation of 20° from the mean wave direction is chosen for the simulations.

4.11 Model Results

This section presents the results of the simulations. Detailed disturbance maps and wave patterns for the different layouts are found in Appendix A to Appendix F.

The purpose of the simulations is to document the wave disturbance at berth locations. The simulation matrix with the offshore wave conditions is presented in Table 4-2 and Table 4-3. The total duration of the simulations was 30 minutes, of which the last 20 minutes were used for determination of significant wave heights (H_{m0}) throughout the harbour. An incident significant wave height of $H_{m0,incoming}$ = 1.0 m was applied in the simulations.

4.11.1 Layout 1

Results of the simulations are presented as wave disturbance coefficients in Appendix A. Schematic representation of Layout 1 is given in Figure 4-15. The wave disturbance coefficients ($H_{m0}/H_{m0,incoming}$) have been calculated at the different berth locations, see Figure 4-15. For detailed analysis of the wave conditions along the two berths shown in Figure 4-15, average wave disturbance coefficients, K (corresponding to the total wave energy) were calculated in areas of 50 m x 18 m corresponding to the approximate vessel dimensions and are given in Table 4-5.

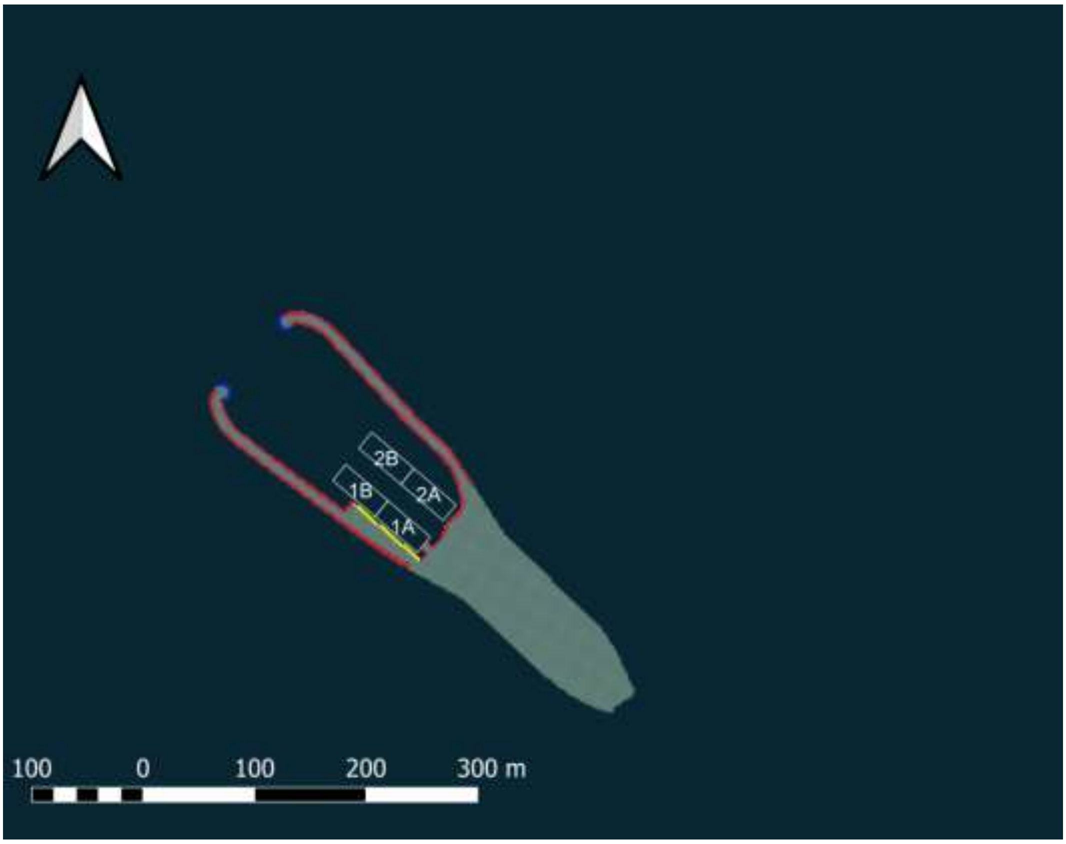


Figure 4-15 Areas within the harbour layout 1 used for mean wave disturbance calculation.

Table 4-5 Mean wave disturbance coefficients for Layout1.

MWD (°N)	Tp (s)	Polygon 1A	Polygon 1B	Polygon 2A	Polygon 2B
210	4.5	0.07	0.07	0.07	0.08
210	6	0.07	0.07	0.07	0.08
225	4.5	0.1	0.1	0.09	0.12
225	6	0.09	0.09	0.08	0.1
240	4.5	0.13	0.16	0.12	0.16
240	6	0.13	0.13	0.11	0.13
255	3.5	0.16	0.16	0.14	0.17
255	5	0.15	0.19	0.13	0.17
270	3.5	0.21	0.25	0.21	0.25
270	5	0.23	0.27	0.22	0.30
285	3.5	0.28	0.29	0.45	0.48
285	5	0.33	0.32	0.38	0.50
300	3.5	0.44	0.46	0.67	0.75
300	5	0.42	0.48	0.56	0.57
315	3.5	0.52	0.63	0.69	0.76
315	5	0.53	0.66	0.65	0.69
330	3.5	0.53	0.69	0.54	0.58
330	5	0.48	0.6	0.44	0.5
345	3.5	0.45	0.52	0.29	0.35
345	5	0.32	0.38	0.31	0.33
0	3.5	0.26	0.28	0.19	0.25
0	5	0.21	0.25	0.21	0.24

Wave disturbance coefficient maps of overall model domain and zoomed view of the harbour are presented in Appendix A.1 and A.2. Instantaneous surface elevation maps are presented in Appendix 0, indicating the wave propagation pattern in the domain.

4.11.2 Layout 2a

The wave disturbance coefficients ($H_{m0}/H_{m0,incoming}$) have been calculated at the different berth locations in Layout 2a, see Figure 4-16. For detailed analysis of the wave conditions along the two berths shown in Figure 4-16, average wave disturbance coefficients, K (corresponding to the total wave energy) were calculated in areas of 50 m x 18 m corresponding to the approximate vessel dimensions and are given in Table 4-5.

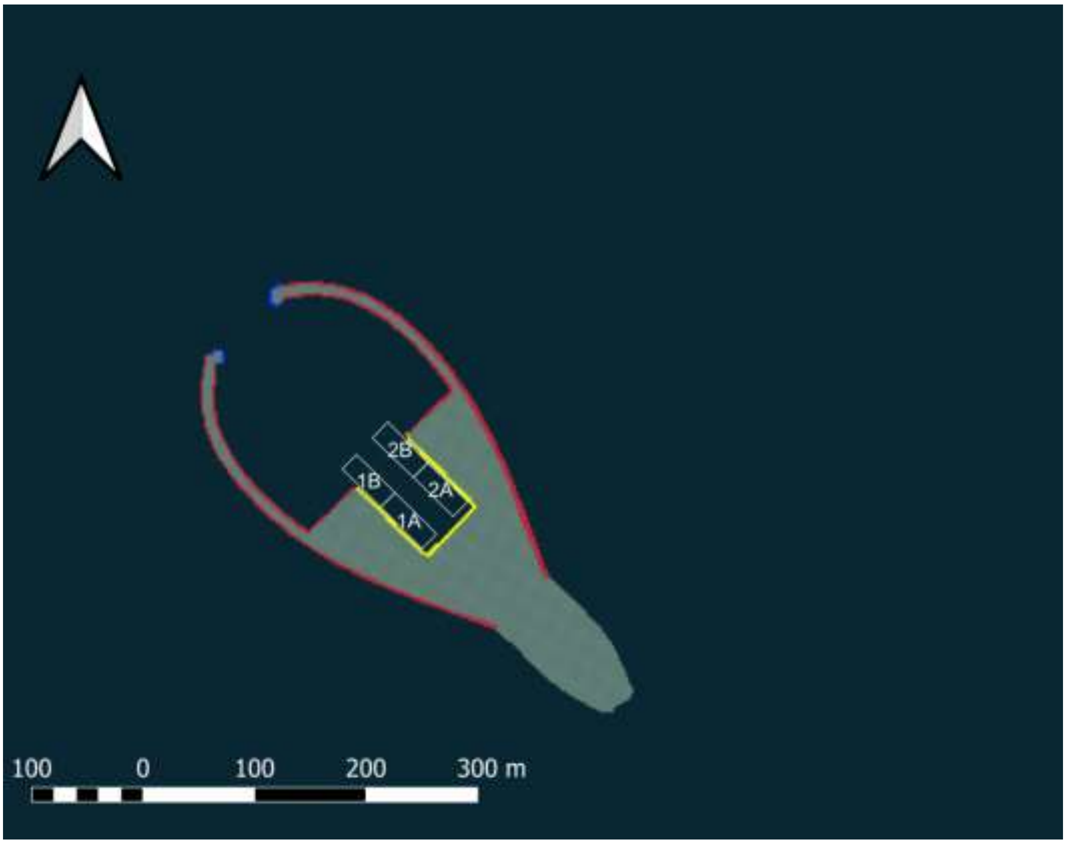


Figure 4-16 Areas within the harbour Layout 2a used for mean wave disturbance calculation.

Table 4-6 Mean wave disturbance coefficients for Layout 2a.

Table	Tp (s)	Polygon 1A	Polygon 1B	Polygon 2A	Polygon 2B
210	4.5	0.09	0.08	0.09	0.08
210	6	0.09	0.09	0.10	0.10
225	4.5	0.13	0.13	0.12	0.11
225	6	0.12	0.12	0.13	0.13
240	4.5	0.19	0.17	0.18	0.17
240	6	0.16	0.16	0.17	0.17
255	3.5	0.26	0.22	0.26	0.25
255	5	0.22	0.19	0.25	0.22
270	3.5	0.29	0.25	0.31	0.29
270	5	0.29	0.24	0.34	0.31
285	3.5	0.40	0.39	0.55	0.54
285	5	0.42	0.36	0.61	0.58
300	3.5	0.66	0.61	0.85	0.83
300	5	0.59	0.53	0.79	0.77
315	3.5	0.90	0.83	0.89	0.87
315	5	0.82	0.77	0.86	0.85
330	3.5	0.91	0.84	0.71	0.68
330	5	0.73	0.69	0.57	0.58
345	3.5	0.67	0.64	0.46	0.41
345	5	0.63	0.57	0.43	0.38
0	3.5	0.34	0.32	0.30	0.28
0	5	0.41	0.36	0.32	0.28

Wave disturbance coefficient maps of overall model domain and zoomed view of the harbour are presented in Appendix B.1 and B.2 Instantaneous surface elevation maps are presented in Appendix 0, indicating the wave propagation pattern in the domain.

4.11.3 Layout 2b

The wave disturbance coefficients ($H_{m0}/H_{m0,incoming}$) have been calculated at the different berth locations in Layout 2b. For detailed analysis of the wave conditions along the two berths, average wave disturbance coefficients, K (corresponding to the total wave energy) were calculated in areas of 50 m x 18 m corresponding to the approximate vessel dimensions and are given in Table 4-7.

Table 4-7 Mean wave disturbance coefficients for Layout 2b.

Table	Tp (s)	Polygon 1A	Polygon 1B	Polygon 2A	Polygon 2B
210	4.5	0.08	0.08	0.08	0.07
210	6	0.09	0.08	0.08	0.08
225	4.5	0.12	0.11	0.11	0.1
225	6	0.11	0.1	0.11	0.11
240	4.5	0.17	0.16	0.16	0.15
240	6	0.15	0.14	0.14	0.13
255	3.5	0.2	0.18	0.21	0.2
255	5	0.18	0.17	0.21	0.18
270	3.5	0.22	0.2	0.25	0.25
270	5	0.24	0.21	0.28	0.25
285	3.5	0.3	0.31	0.45	0.48
285	5	0.36	0.32	0.52	0.47
300	3.5	0.57	0.54	0.73	0.72
300	5	0.52	0.48	0.68	0.64
315	3.5	0.79	0.74	0.76	0.76
315	5	0.73	0.68	0.75	0.7
330	3.5	0.8	0.75	0.6	0.58
330	5	0.63	0.6	0.49	0.46
345	3.5	0.56	0.53	0.36	0.34
345	5	0.54	0.48	0.38	0.34
0	3.5	0.3	0.28	0.24	0.22
0	5	0.34	0.3	0.27	0.24

Wave disturbance coefficient maps of overall model domain and zoomed view of the harbour are presented in Appendix C.1 and C.2. Instantaneous surface elevation maps are presented in Appendix C.3, indicating the wave propagation pattern in the domain.

4.11.4 Layout 2c

The wave disturbance coefficients ($H_{m0}/H_{m0,incoming}$) have been calculated at the different berth locations in Layout 2c. For detailed analysis of the wave conditions along the two berths, average wave disturbance coefficients, K (corresponding to the total wave energy) were calculated in areas of 50 m x 18 m corresponding to the approximate vessel dimensions and are given in Table 4-8.

Table 4-8 Mean wave disturbance coefficients for Layout 2c.

Table	Tp (s)	Polygon 1A	Polygon 1B	Polygon 2A	Polygon 2B
210	4.5	0.06	0.06	0.05	0.06
210	6	0.06	0.07	0.06	0.07
225	4.5	0.08	0.09	0.07	0.08
225	6	0.07	0.09	0.08	0.09
240	4.5	0.11	0.12	0.09	0.11
240	6	0.09	0.12	0.1	0.11
255	3.5	0.12	0.13	0.13	0.15
255	5	0.11	0.13	0.12	0.14
270	3.5	0.13	0.15	0.15	0.18
270	5	0.13	0.16	0.16	0.19
285	3.5	0.15	0.2	0.26	0.34
285	5	0.19	0.24	0.25	0.36
300	3.5	0.35	0.41	0.48	0.59
300	5	0.26	0.39	0.32	0.5
315	3.5	0.48	0.59	0.5	0.62
315	5	0.35	0.56	0.36	0.55
330	3.5	0.5	0.62	0.39	0.46
330	5	0.3	0.5	0.26	0.35
345	3.5	0.31	0.41	0.18	0.22
345	5	0.27	0.37	0.19	0.23
0	3.5	0.17	0.2	0.14	0.16
0	5	0.18	0.23	0.14	0.17

Wave disturbance coefficient maps of overall model domain and zoomed view of the harbour are presented in Appendix D.1 and D.2 Instantaneous surface elevation maps are presented in Appendix D.3, indicating the wave propagation pattern in the domain.

4.11.5 Layout 3a

The wave disturbance coefficients ($H_{m0}/H_{m0,incoming}$) have been calculated at the different berth locations in Layout 3a, see Figure 4-17. For detailed analysis of the wave conditions along the two berths shown in Figure 4-17, average wave disturbance coefficients, K (corresponding to the total wave energy) were calculated in areas of 50 m x 18 m corresponding to the approximate vessel dimensions and are given in Table 4-9.

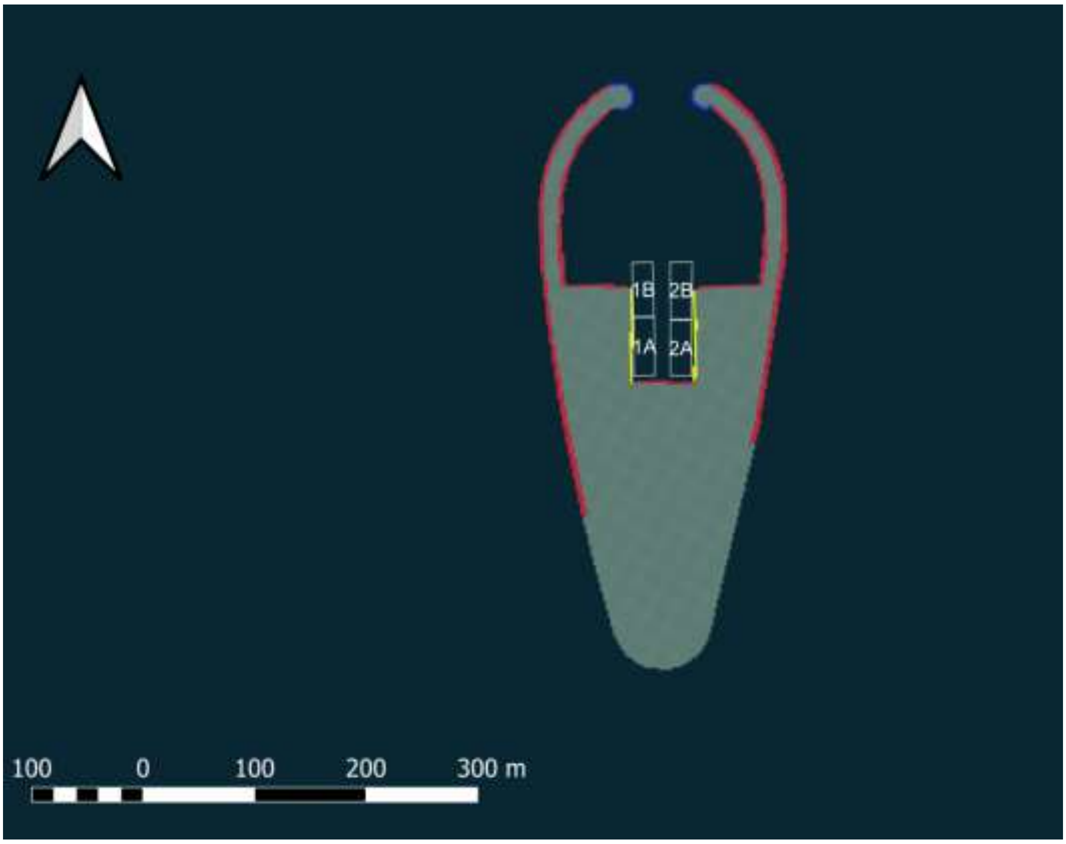


Figure 4-17 Areas within the harbour Layout 3a used for mean wave disturbance calculation.

Table 4-9 Mean wave disturbance coefficients for Layout 3a.

Table	Tp (s)	Polygon 1A	Polygon 1B	Polygon 2A	Polygon 2B
285	3.5	0.16	0.15	0.16	0.15
285	5	0.16	0.16	0.15	0.15
300	3.5	0.26	0.27	0.21	0.21
315	3.5	0.28	0.28	0.25	0.27
330	3.5	0.31	0.32	0.33	0.36
330	5	0.29	0.31	0.41	0.41
345	3.5	0.54	0.5	0.67	0.65
345	5	0.46	0.46	0.57	0.59
0	3.5	0.75	0.72	0.73	0.7
0	5	0.64	0.65	0.67	0.68
15	3.5	0.66	0.67	0.57	0.55
15	5	0.61	0.6	0.49	0.51
30	3.5	0.52	0.53	0.34	0.36
30	3.5	0.47	0.49	0.31	0.32
45	3.5	0.32	0.32	0.25	0.27
45	5	0.33	0.36	0.27	0.28
60	3.5	0.26	0.26	0.21	0.22
60	5	0.23	0.26	0.23	0.23
75	3.5	0.16	0.16	0.17	0.17
75	5	0.15	0.16	0.16	0.16

Wave disturbance coefficient maps of overall model domain and zoomed view of the harbour are presented in Appendix E.1 and E.2 Instantaneous surface elevation maps are presented in Appendix E.3, indicating the wave propagation pattern in the domain.

4.11.6 Layout3b

The wave disturbance coefficients ($H_{m0}/H_{m0,incoming}$) have been calculated at the different berth locations in Layout 3b, see Figure 4-17. For detailed analysis of the wave conditions along the two berths shown in Figure 4-17, average wave disturbance coefficients, K (corresponding to the total wave energy) were calculated in areas of 50 m x 18 m corresponding to the approximate vessel dimensions and are given in Table 4-10.

Table 4-10 Mean wave disturbance coefficients for Layout 3b.

Table	Tp (s)	Polygon 1A	Polygon 1B	Polygon 2A	Polygon 2B
285	3.5	0.12	0.11	0.11	0.13
285	5	0.13	0.09	0.1	0.12
300	3.5	0.19	0.16	0.13	0.16
315	3.5	0.2	0.16	0.17	0.21
330	3.5	0.22	0.17	0.22	0.29
330	5	0.19	0.15	0.22	0.33
345	3.5	0.37	0.31	0.42	0.54
345	5	0.37	0.25	0.3	0.49
0	3.5	0.57	0.45	0.47	0.58
0	5	0.53	0.33	0.36	0.57
15	3.5	0.53	0.42	0.36	0.45
15	5	0.49	0.28	0.28	0.4
30	3.5	0.38	0.28	0.2	0.25
30	3.5	0.36	0.24	0.18	0.23
45	3.5	0.22	0.18	0.17	0.21
45	5	0.25	0.18	0.14	0.2
60	3.5	0.18	0.15	0.15	0.18
60	5	0.17	0.15	0.13	0.17
75	3.5	0.13	0.11	0.13	0.14
75	5	0.13	0.1	0.1	0.14

Wave disturbance coefficient maps of overall model domain and zoomed view of the harbour are presented in Appendix F.1 and F.2 Instantaneous surface elevation maps are presented in Appendix F.3, indicating the wave propagation pattern in the domain.

5 Downtime Assessment

5.1 Wave Time Series in the Harbour

To establish the basis for calculating the wave statistics in selected areas of the harbour, the results of the wave disturbance modelling were combined with the long-term wave conditions outside the harbour at point P1 in Figure 3-7. This was done by establishing transfer functions, describing the transformation of wave heights from point BW outside the harbour to a given area inside the harbour (based on the wave disturbance simulations), and then combine the transfer functions with the long-term time series of wave conditions at point BW. This provides a long-term time series of the wave heights at selected locations, for subsequent statistical analysis.

5.1.1 Transfer functions

Transfer functions were generated based on a Neural Network (NN), which is an advanced computer model which can be used to study the behaviour of complex systems where several parameters determine the behaviour/response of the system.

The purpose of the neural network was to generate an expression $K(\theta_m, T_p)$ that could calculate the wave disturbance coefficient at a given area inside the harbour for any combination of offshore mean wave direction, θ_m, and peak wave period T_p. Multiplying the wave disturbance coefficient derived by the NN with the incoming significant wave height ($H_{m0,in}$) at point P1 (see Figure 3-7), gives the resulting significant wave height (H_{m0}) inside the harbour.

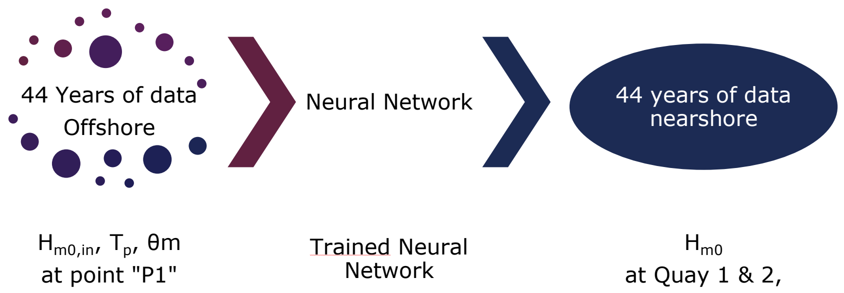


Figure 5-1 Illustration of procedure for calculating nearshore wave heights using a neural network.

The procedure for calculating wave heights (H_{m0}) inside the harbour is illustrated in Figure 5-1 and consists in calculating - for each time-step in the 11 year hindcast – the wave disturbance coefficient, $K_x(\theta_m, T_p)$, for that specific sea state at location, x, inside the harbour.

The wave height at location, x, inside the harbour at that time step can then be calculated as:

$$H_{m0,x}(t) = H_{m0,in}(t) * K_x(\theta_{m,in}(t), T_{p,in}(t))$$

The analysis was performed using the Multi-layer Perceptron algorithm in the machine learning library Scikit-learn v.1.2.1 for the Python programming language. Scikit-learn's

Multi-layer Perceptron algorithm can learn linear models as well as non-linear models like the present. For more information reference is made to (https://scikit-learn.org /).

Training dataset

A neural network was trained to predict wave conditions in two locations and for each of the six layout solutions. Hence, in total 2x6=12 neural networks were trained.

The accuracy of the Neural Network was increased by artificially increasing the number of results from the MIKE 21 BW simulations through *Data Augmentation*. Data Augmentation is a technique that can be used to artificially expand the size of a training dataset by creating modified data from the existing data. Data augmentation is used to prevent overfitting, and it is also good for enhancing the performance of a neural network.

Three sets of augmented data were generated for each layout. The procedure for Layout 3a and 3b is described in the following:

No waves dataset

The harbour (Layout 3a and 3b) is well protected against waves from E, S and W and will not experience downtime during waves from these directions. It was thus assumed that the wave height would be H_{m0}=0m for offshore wave directions in the interval 105≤θ_m≤270. Hence.

… = k(θ_m = 105°,T_p=5s) = k(θ_m = 120°,T_p=5s) = k(θ_m = 270°,T_p=5s) = 0

This leads to:

› 4 (wave periods) x 12 (wave directions) = 48 additional results

ENE and E waves dataset

Waves from ENE and (75°) are rare and were thus not simulated. It was assumed that simulations with waves from NE (60°) can be expanded to cover this direction.

Hence, k(θ_m = 75°,T_p=5s) = k(θ_m = 60°,T_p=5s)
k(θ_m = 75°,T_p=3.5s) = k(θ_m = 60°,T_p=3.5s)

Moreover, waves from E (90°) are calculated by interpolating between no waves at a direction of k(θ_m = 105°, ..) = 0 and k(θ_m = 75°,..) > 0 :

k(θ_m = 90°,T_p=5s) = k(θ_m = 75°,T_p=5s) * 1/2
k(θ_m = 90°,T_p=3.5s) = k(θ_m = 75°,T_p=3.5s) * 1/2

2 (wave directions) x 2 (wave periods) = 4 additional results.

For both Layout 3a and 3b a total of 17 simulations were performed in MIKE 21 BW. This dataset was augmented to form (4+48+17) 69 combinations of wave direction (θ_m) and wave periods (T_p) where we know the wave disturbance coefficient from the MIKE 21 BW results. These 69 combinations are called the “Training Dataset” and were used to train the NN.

Example

An example showing the transformation of waves from Point P1 to Quay 1 is described in the following.

Step 1: Incoming wave conditions

The incoming wave conditions are shown in Figure 5-2. The figure shows that waves higher than 1m from the most exposed directions (240-100°) have wave periods ranging from $1.5<T_p<6$ s.

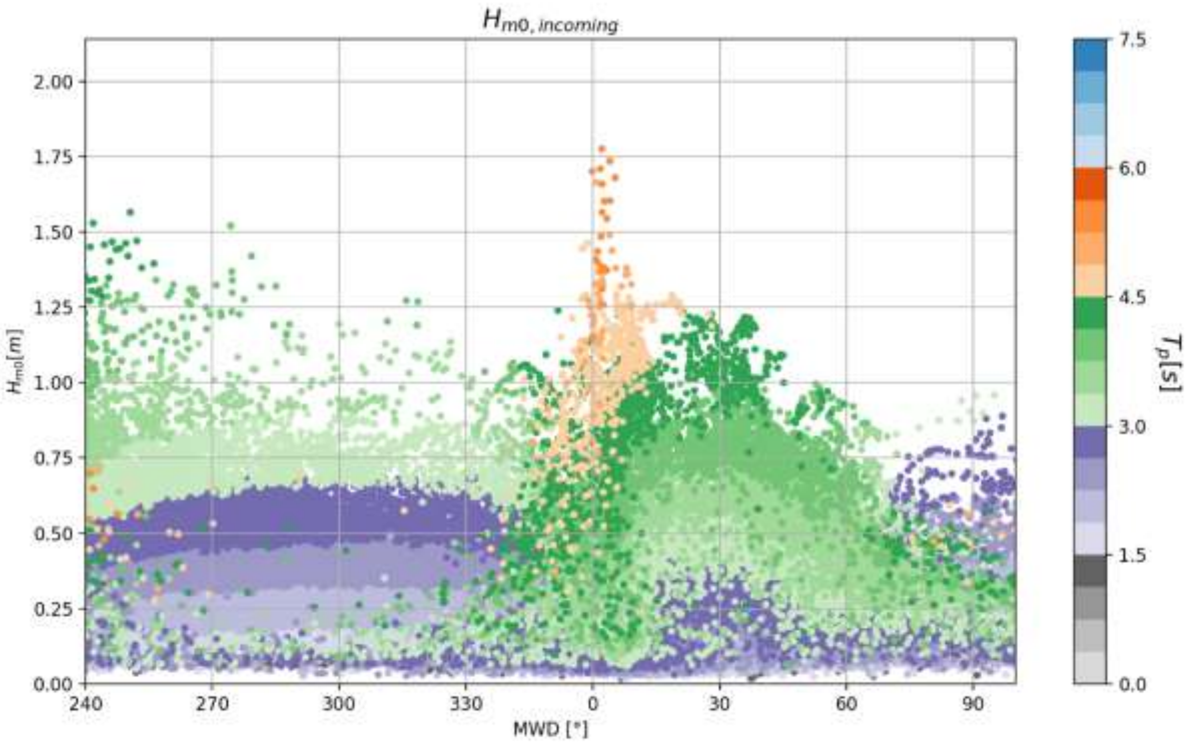


Figure 5-2 Incoming wave conditions $H_{m0,in}$, T_p and MWD (θ_m) at point P1 based on 11 years of simulations.

Step 2: Training the NN

The training dataset consisting of 74 combinations of T_p, MWD (θ_m) and $K(T_p,\theta_m)$ at the most exposed part of Quay 1 and Layout 1 was established.

The predictions of the trained NN for Quay 1 and Layout 1 during all hourly timesteps with waves from 180-45° are shown in Figure 5-3.

As shown, the NN model matches with the training dataset at the 14 “locations” where K is known from wave disturbance simulations (illustrated by black circles and data labels in the plot). In the rest of the (T_p,θ_m)-domain, the model predicts a gradual transition much in agreement with expectations.

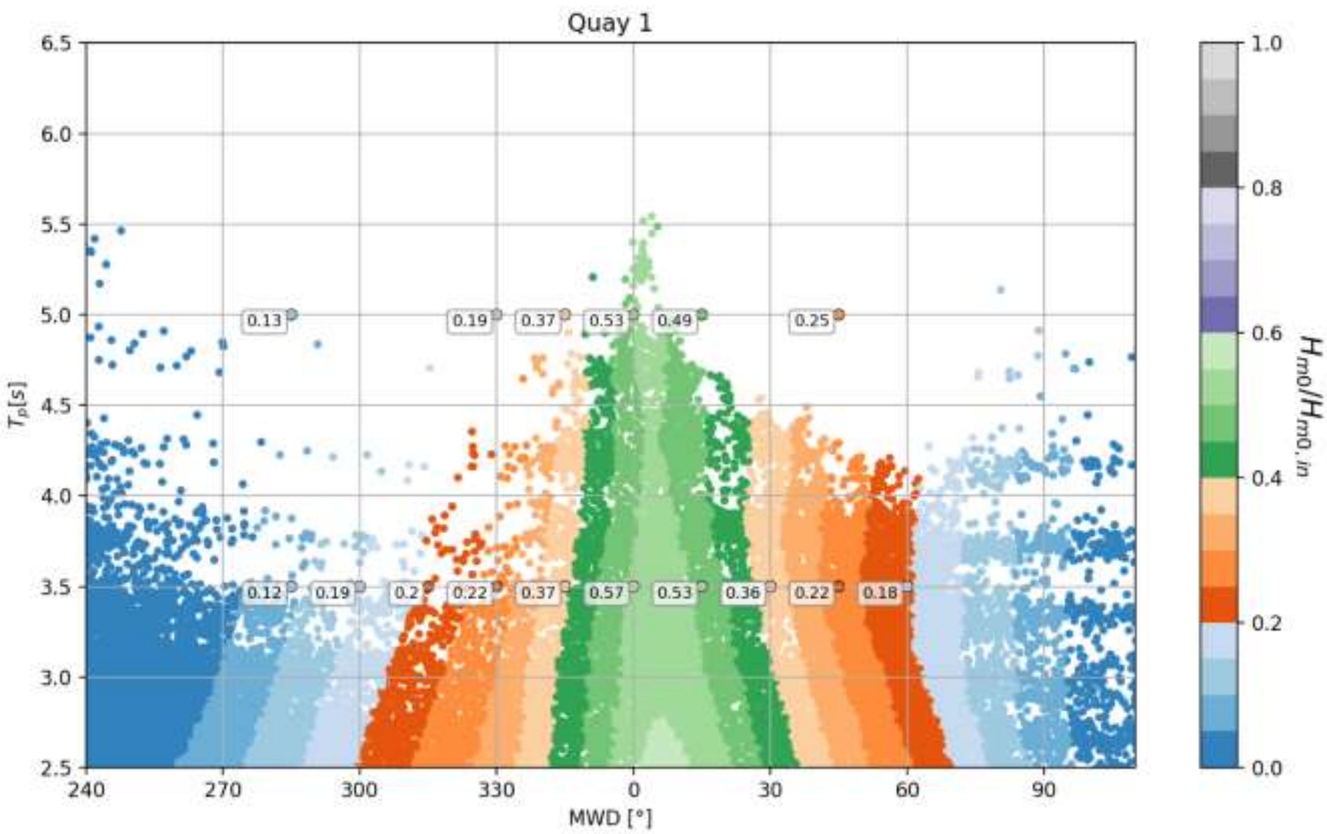


Figure 5-3 *NN predictions of wave disturbance coefficients $K=H_{m0}/H_{m0,in}$ for Quay 1 in layout 3b. Results of the MIKE 21 BW model from Table 4-10 are labelled in the figure.*

<u>Step 3: Calculation of wave conditions at Quay 1</u>

The wave conditions at Quay 1 are calculated by multiplying the incoming wave height ($H_{m0,in}$) shown in Figure 5-2 with the transfer function of the NN shown in Figure 5-3 (the wave disturbance coefficient at Quay 1 predicted by NN). The process and the result are illustrated in Figure 5-4.

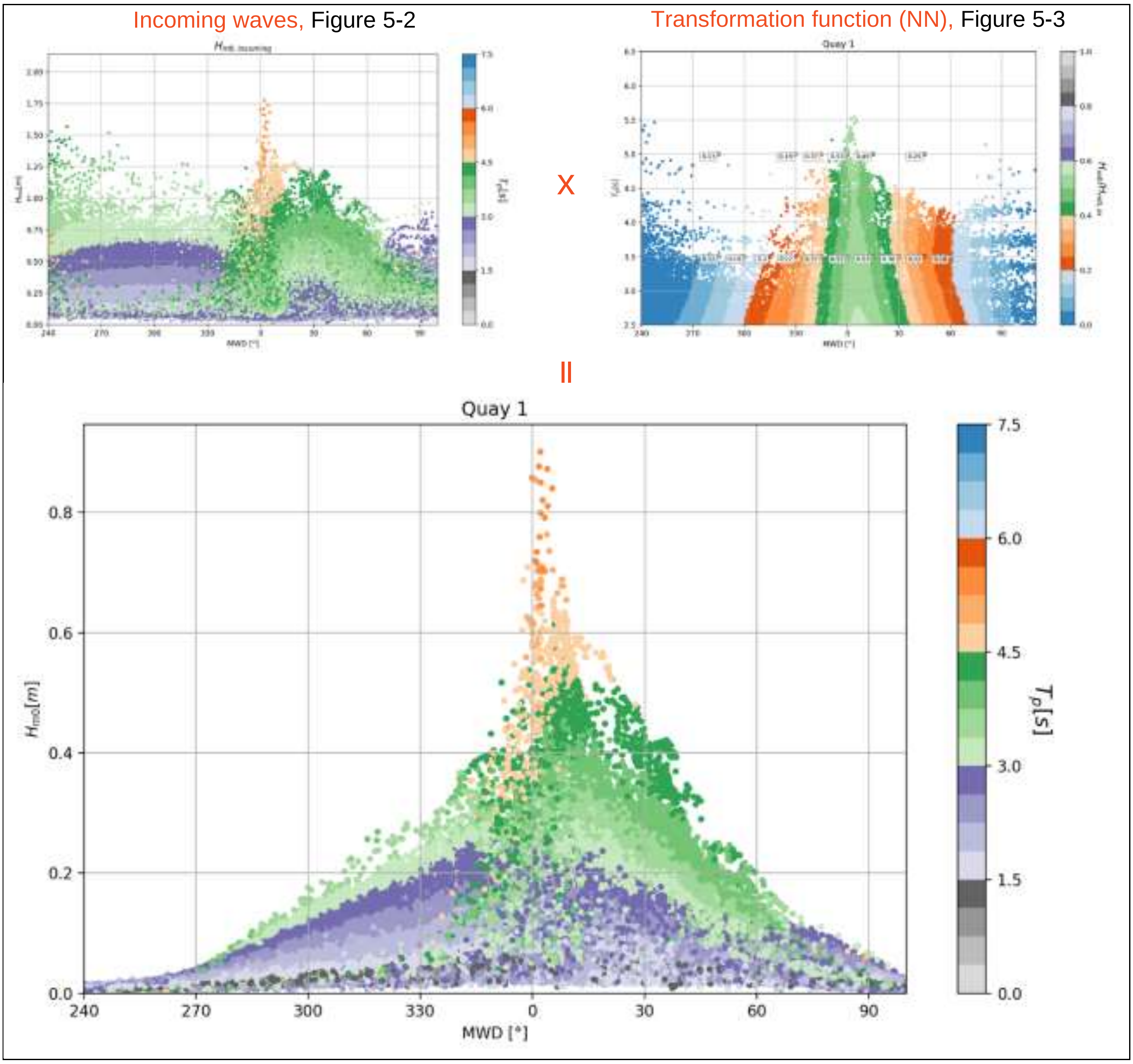


Figure 5-4 *Calculation of significant wave height (Hm0) at Quay 1, Layout 3b based on incoming wave height at point P1 and wave disturbance coefficients predicted by NN.*

5.2 Wave Height Exceedance Analyses

Based on the transformed time series at the selected locations, wave height exceedance analysis was carried out.

Figure 5-5 to Figure 5-10 shows a wave height exceedance frequency plot at Quay 1 for Layout 1, Layout 2a, Layout 2b, Layout 2c, Layout 3a and Layout 3b. All data (all years) were included. From such an exceedance plot, the percentage of time or number of hours, where a certain wave height is exceeded, can be read. As an example, H_{m0} = 0.3m is expected to be exceeded in 1.4% of the time at Quay 1 with Layout 1 and 3.1% of the time with Layout 2a. With Layout 1 the figures show that waves will reach the order of H_{m0}

= 0.65m annually at Quay 1. During extreme storm events (1 hr/10 years) wave heights are expected to reach H_{m0} = 0.75 at Quay 1.

A similar analysis is performed for Layout 1, Layout 2a, Layout 2b, Layout 2c, Layout 3a and Layout 3b and results are summarised in Figure 5-11 to Figure 5-16.

Layout 1

Figure 5-11 shows that a threshold wave height of H_{m0}=0.5m is exceeded 0.1% of the time at Quay 1 and 0.22% of the time at Quay 2 for Layout 1. Corresponding to 8 and 19 hours per year. Hence, while Quay 2 is more exposed than Quay 1, they both meet a downtime criterion of H_{m0} > 0.5m less than 1% of the time.

Layout 2a

For Layout 2a, Figure 5-12 shows that a threshold wave height of H_{m0}=0.5m is exceeded 0.6% of the time at Quay 1 and 0.7% of the time at Quay 2. Corresponding to 49 and 59 hours per year. Hence, both quays meet a downtime criterion of H_{m0} > 0.5m less than 1% of the time, but with a smaller margin than Layout 1.

Layout 2b

For Layout 2b, Figure 5-13 shows that a threshold wave height of H_{m0}=0.5m is exceeded 0.3% of the time at Quay 1 and 0.25% of the time at Quay 2. Corresponding to 27 and 21 hours per year. Hence, both quays meet a downtime criterion of H_{m0} > 0.5m less than 1% of the time. The downtime is approximately half of Layout 2a.

Layout 2c

For Layout 2c, Figure 5-14 shows that a threshold wave height of H_{m0}=0.5m is exceeded 0.05% of the time at both Quay 1 and Quay 2. Corresponding to 5-6 hours per year. Hence, the downtime is improved considerably compared to the other options.

Layout 3a

For Layout 3a, Figure 5-15 shows that a threshold wave height of H_{m0}=0.5m is exceeded 1.25% of the time at Quay 1 and 0.95% of the time at Quay 2. Corresponding to 110 and 85 hours per year. Hence, Quay 1 *exceeds* a downtime criterion of H_{m0} > 0.5m less than 1% of the time and Quay 2 meets the requirement with a very small margin.

Layout 3b

For Layout 3b, Figure 5-16 shows that a threshold wave height of H_{m0}=0.5m is exceeded 0.4% of the time at Quay 1 and 0.35% of the time at Quay 2. Corresponding to 35 and 30 hours per year. Hence, both Quay 1 and 2 meets a downtime criterion of H_{m0} > 0.5m less than 1% of the time.

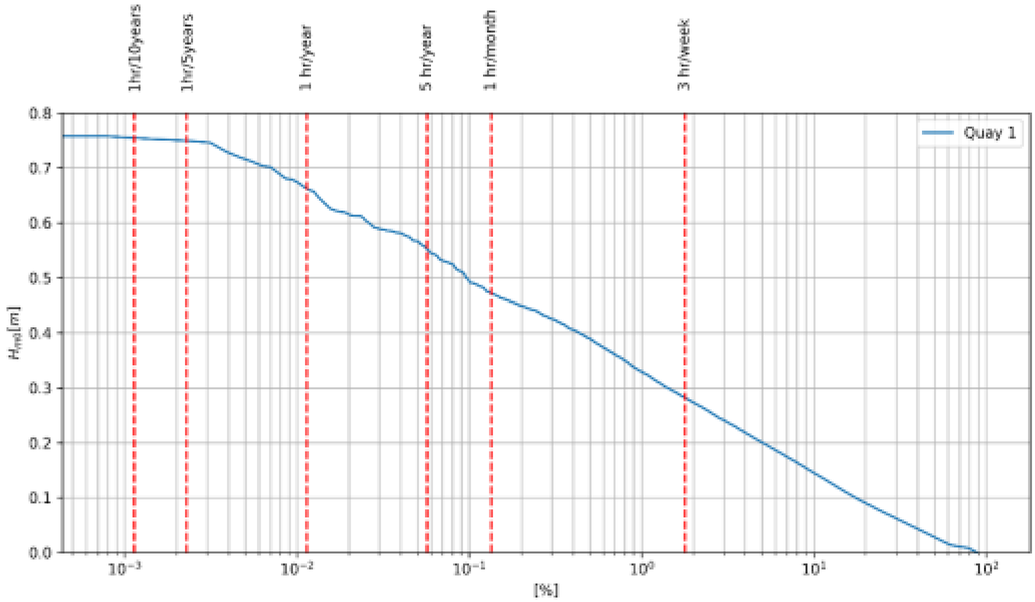


Figure 5-5 *Wave height exceedance plot for H_{m0} at the most exposed part of Quay 1. 11 years of data. Layout 1.*

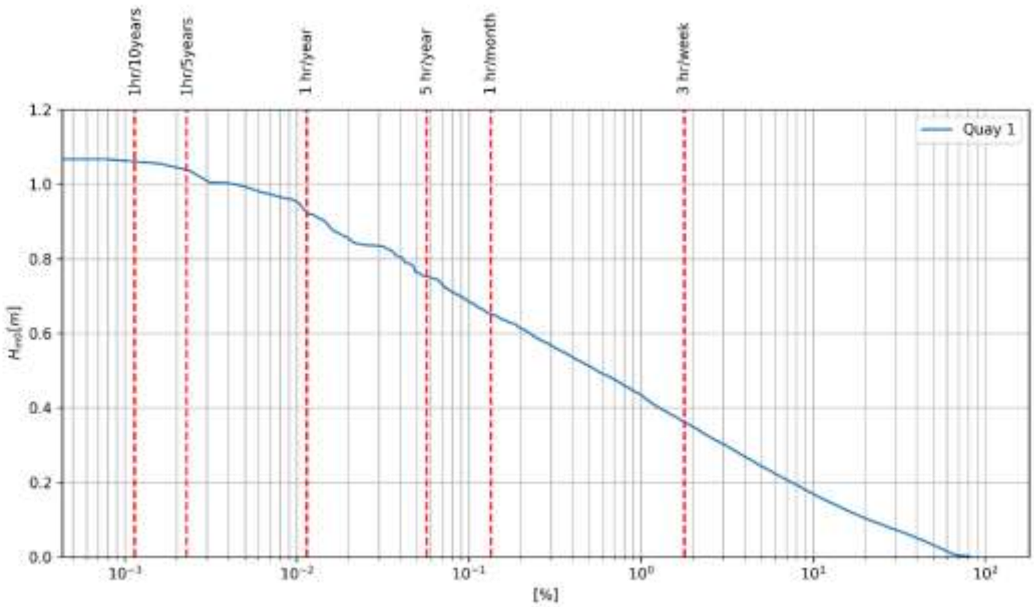


Figure 5-6 *Wave height exceedance plot for H_{m0} at the most exposed part of Quay 1. 11 years of data. Layout 2a.*

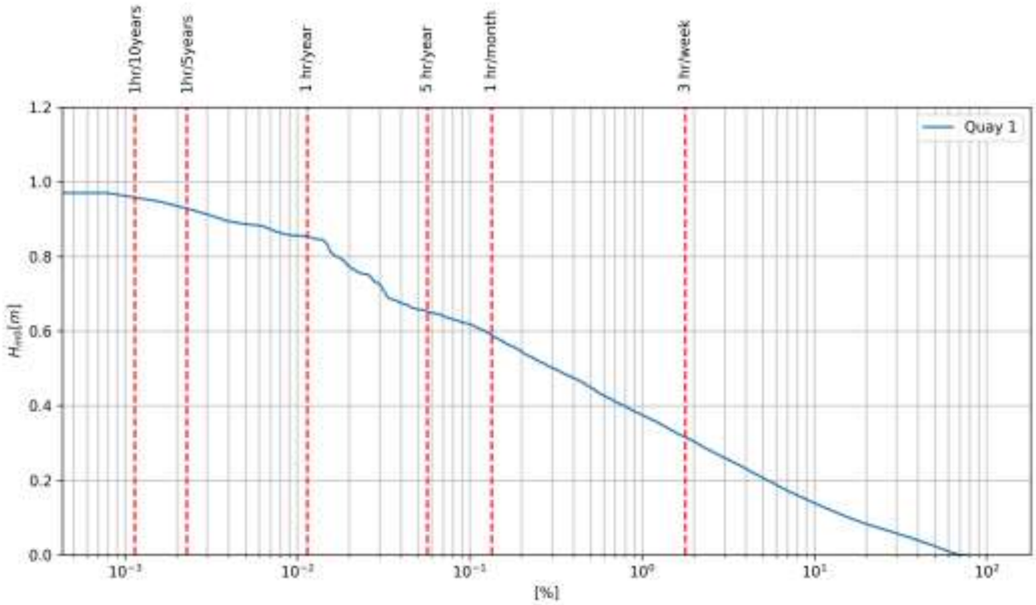


Figure 5-7 *Wave height exceedance plot for H_{m0} at the most exposed part of Quay 1. 11 years of data. Layout 2b.*

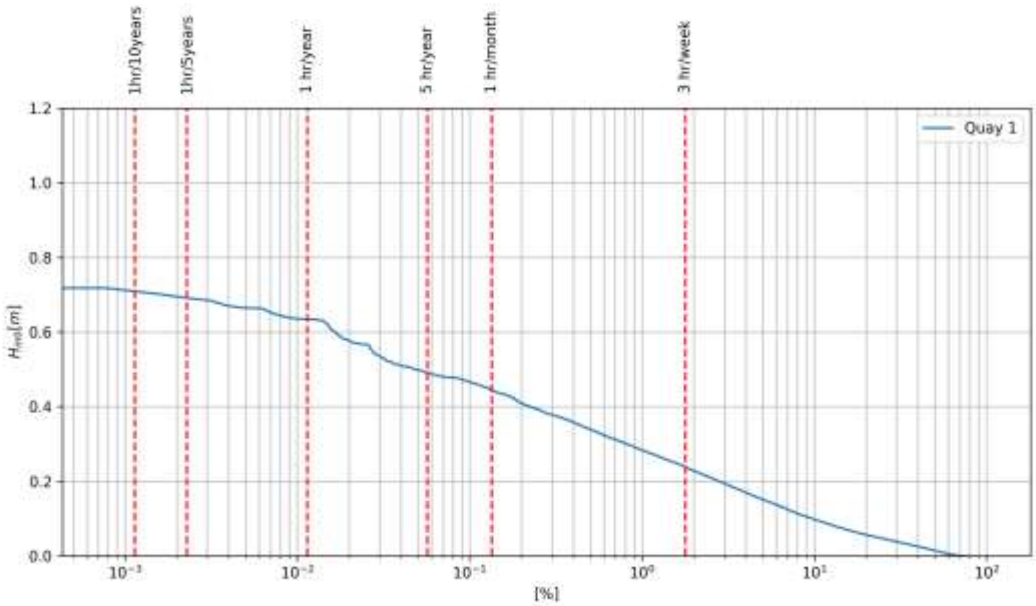


Figure 5-8 *Wave height exceedance plot for H_{m0} at the most exposed part of Quay 1. 11 years of data. Layout 2c.*

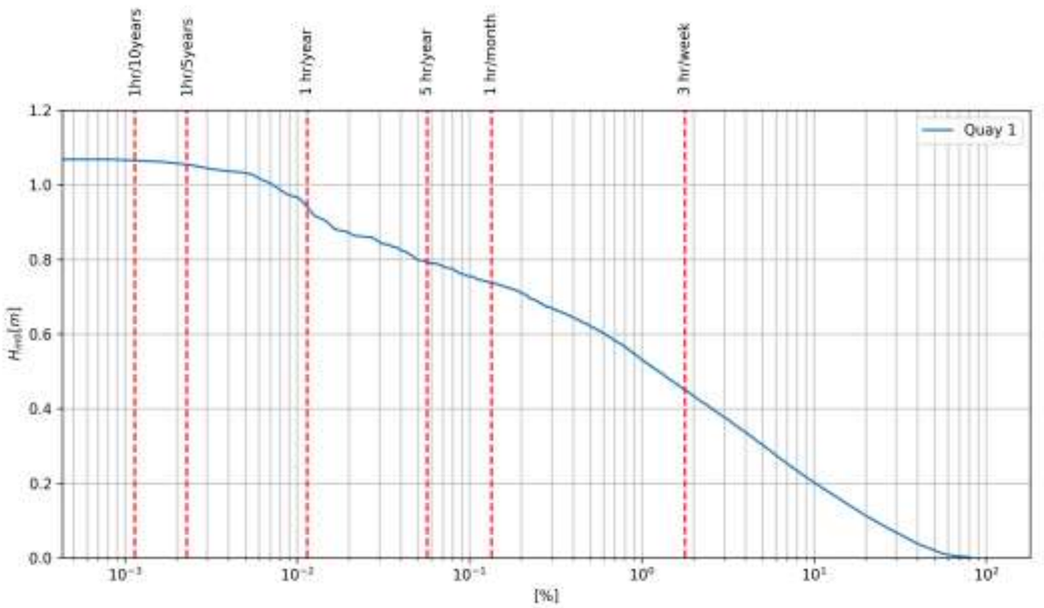


Figure 5-9 *Wave height exceedance plot for H_{m0} at the most exposed part of Quay 1. 11 years of data. Layout 3a.*

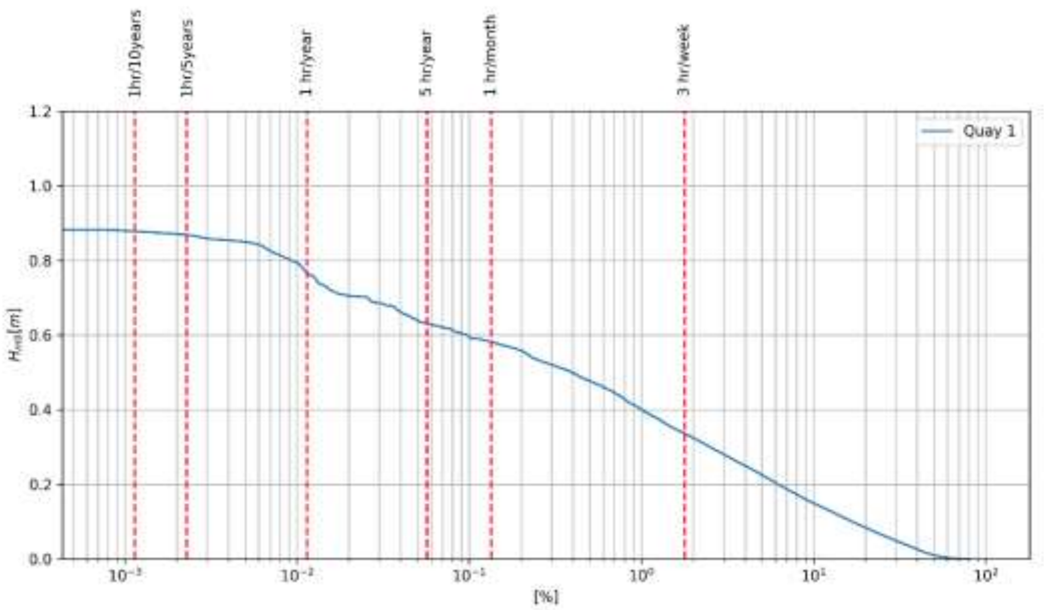


Figure 5-10 *Wave height exceedance plot for H_{m0} at the most exposed part of Quay 1. 11 years of data. Layout 3b.*

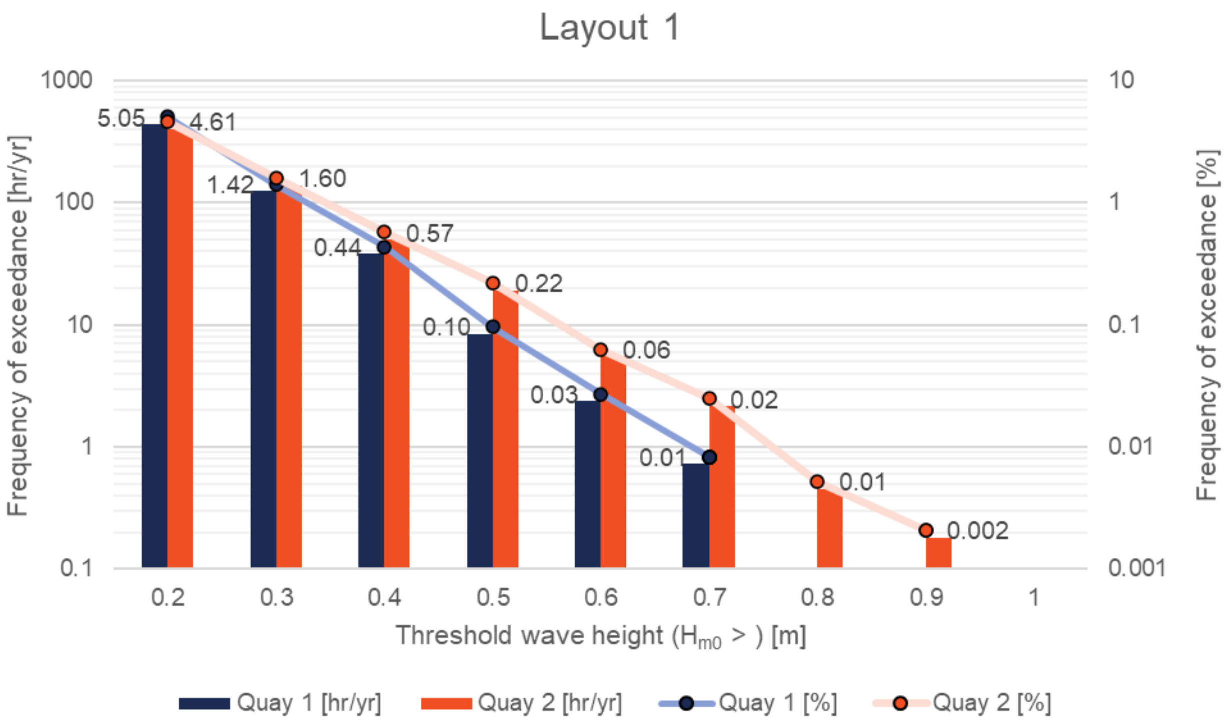


Figure 5-11 Exceedance statistics for wave heights (H_{m0}) at Quay 1 and Quay 2. Layout 1.

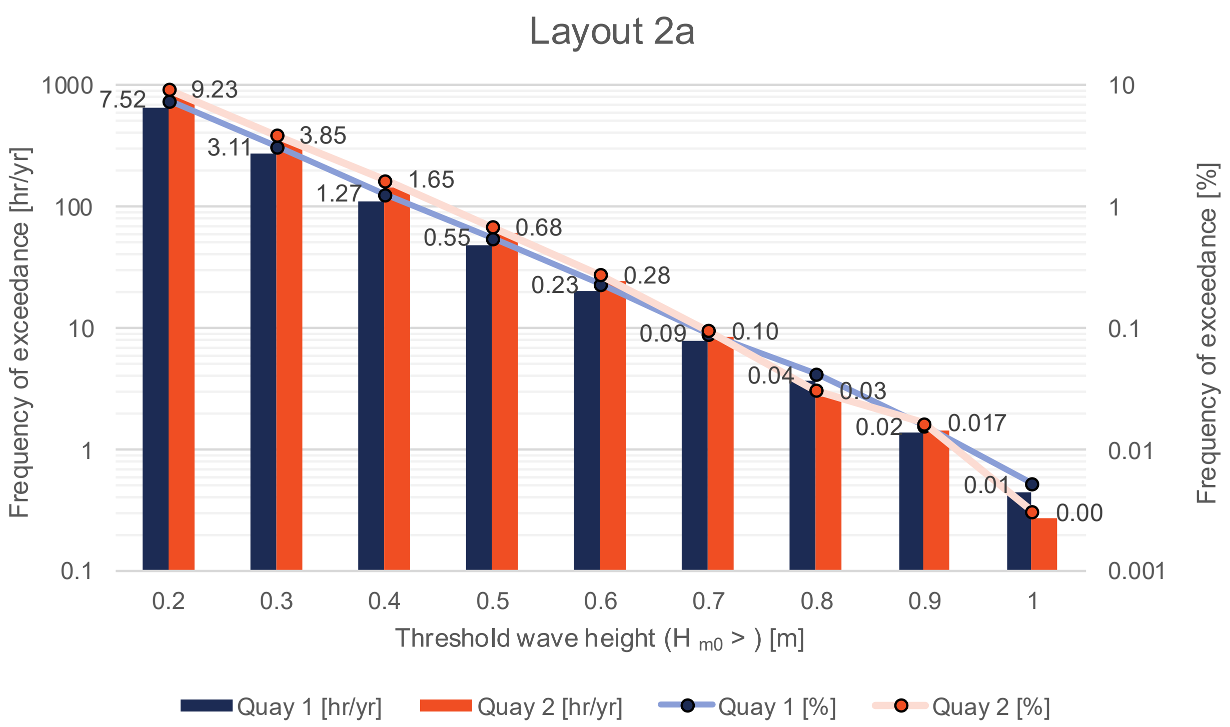


Figure 5-12 Exceedance statistics for wave heights (H_{m0}) at Quay 1 and Quay 2. Layout 2a.

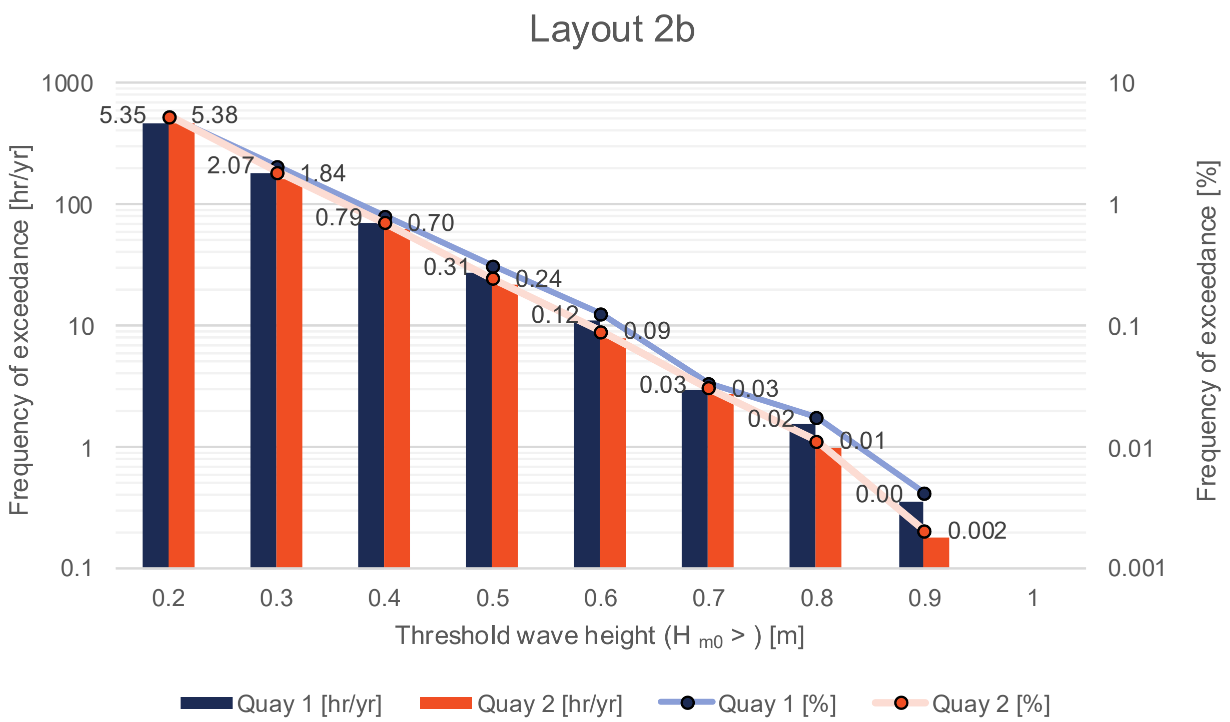


Figure 5-13 *Exceedance statistics for wave heights (H_{m0}) at Quay 1 and Quay 2. Layout 2b.*

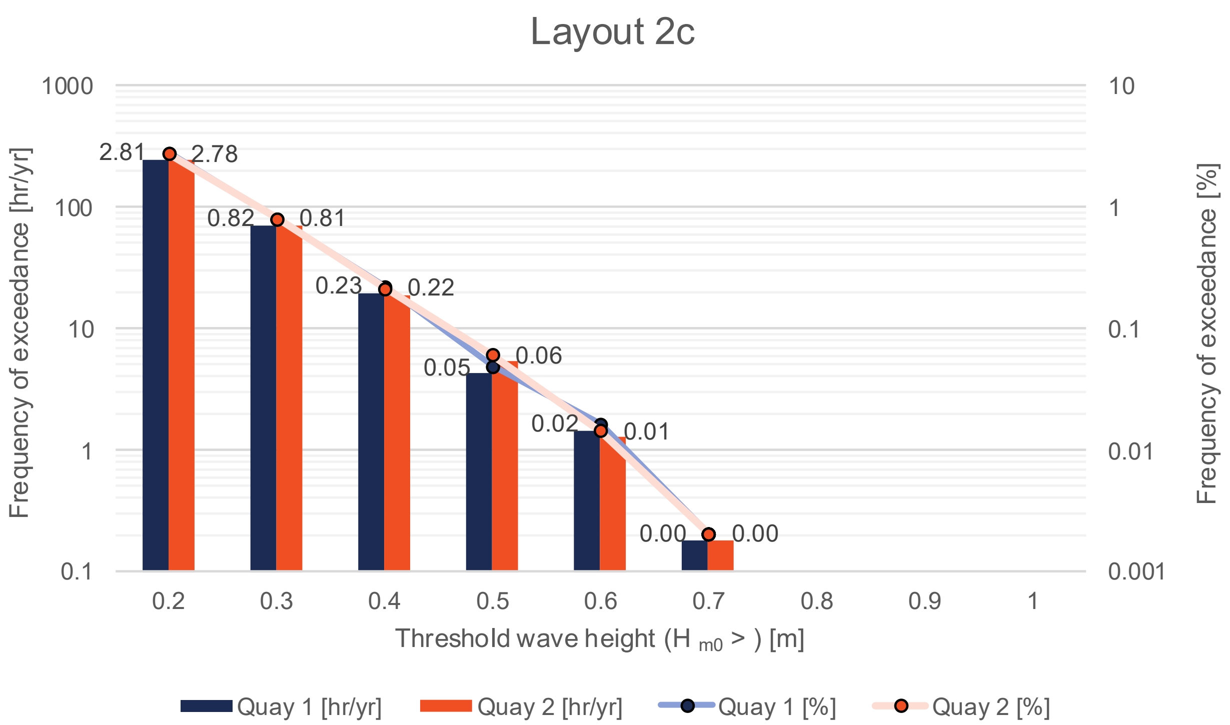


Figure 5-14 *Exceedance statistics for wave heights (H_{m0}) at Quay 1 and Quay 2. Layout 2c.*

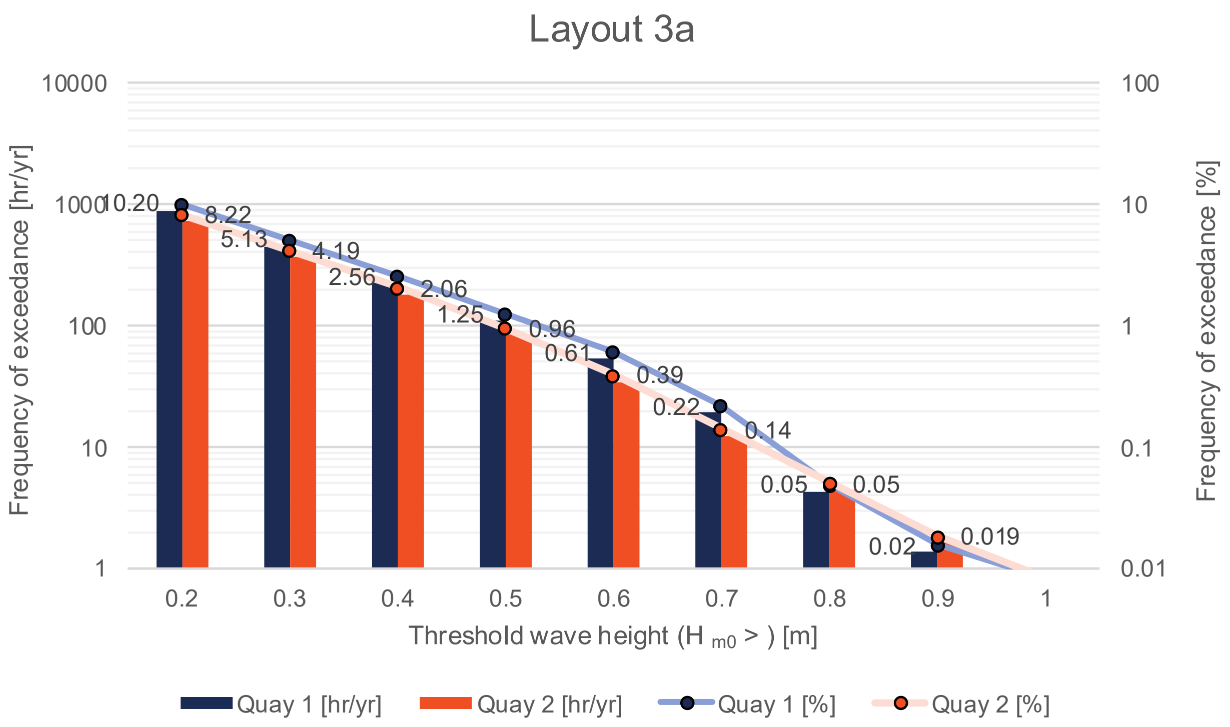


Figure 5-15 Exceedance statistics for wave heights (H_{m0}) at Quay 1 and Quay 2. Layout 3a.

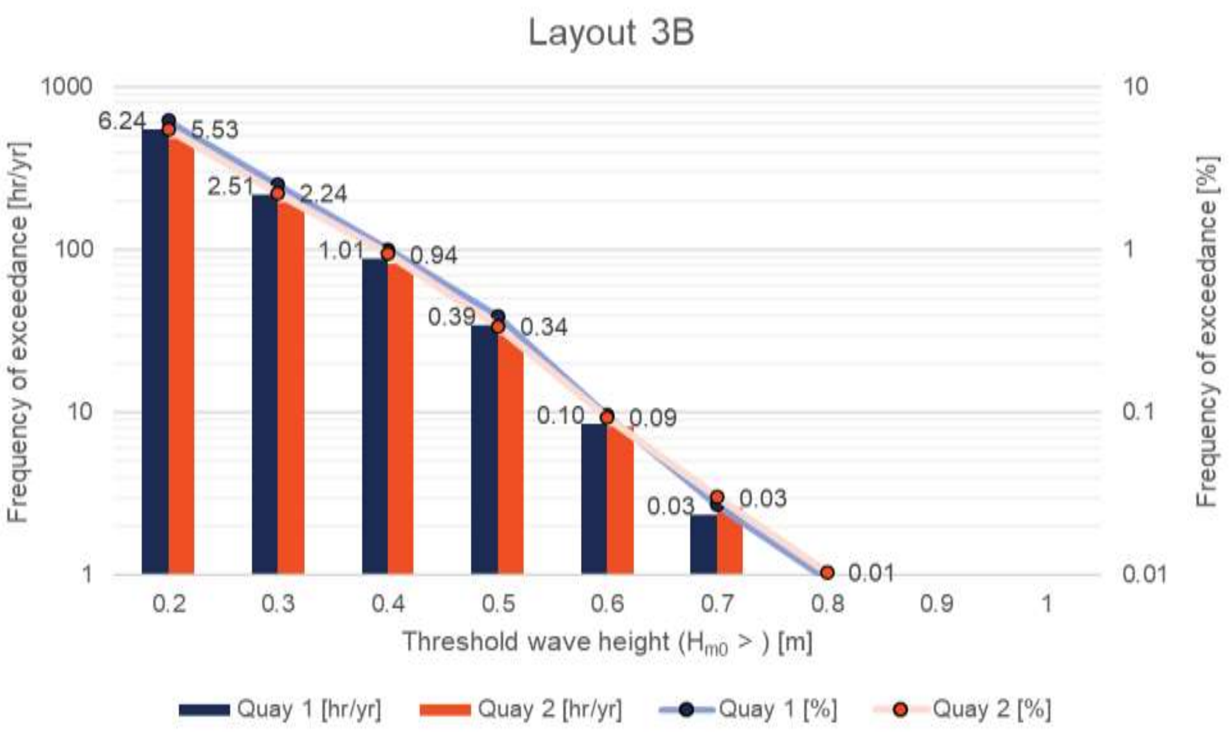


Figure 5-16 Exceedance statistics for wave heights (H_{m0}) at Quay 1 and Quay 2. Layout 3b.

Appendix A Disturbance maps for Layout 1

A.1 Overall Wave Disturbance Maps for Layout 1

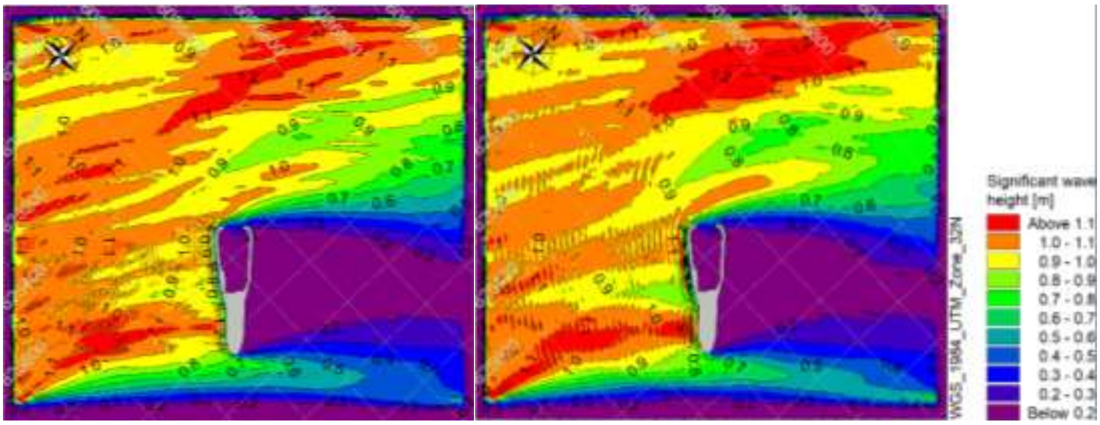


Figure A-1 Wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec and Right: Tp = 6 sec.

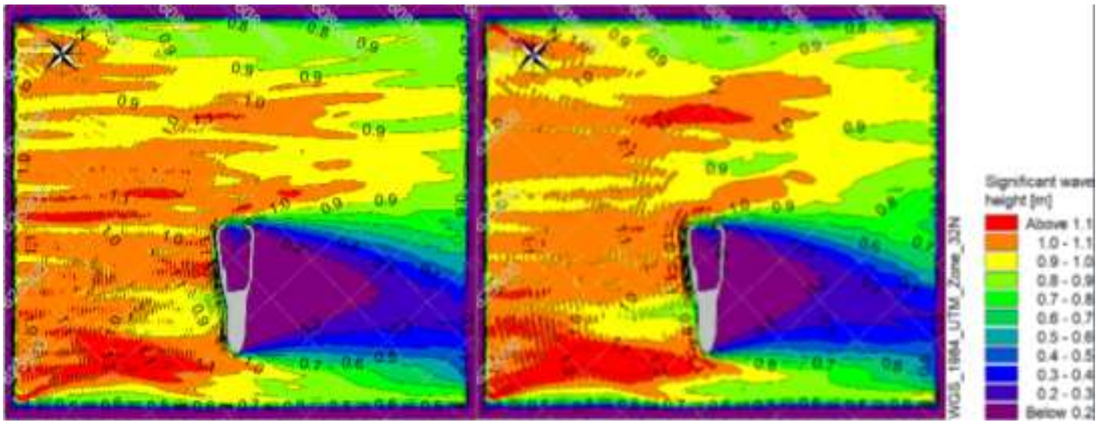


Figure A-2 Wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec and Right: Tp = 6 sec.

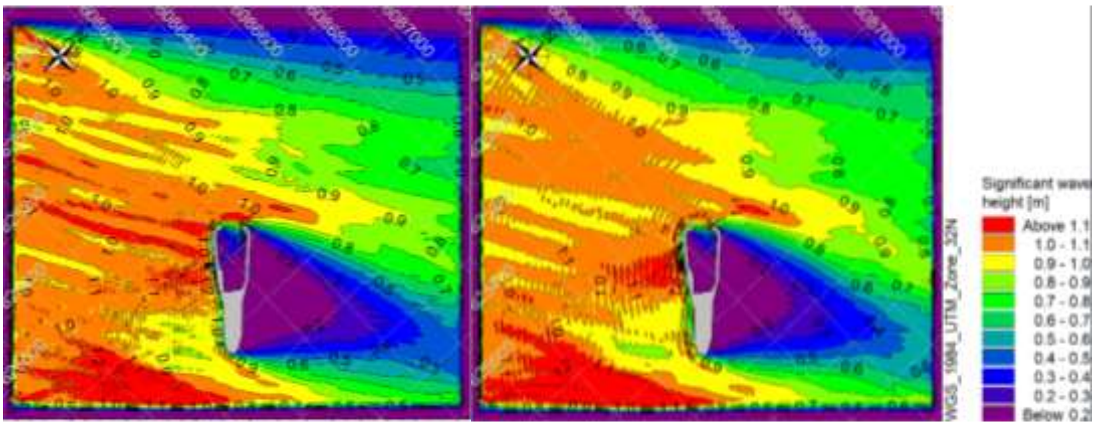


Figure A-3 Wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec and Right: Tp = 6 sec.

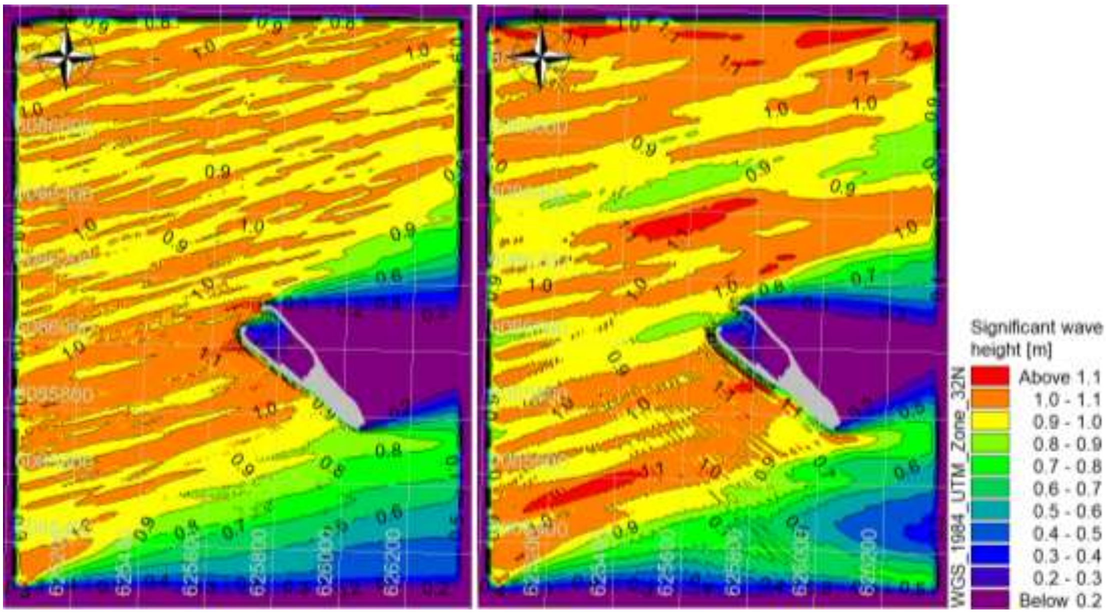


Figure A-4 *Wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

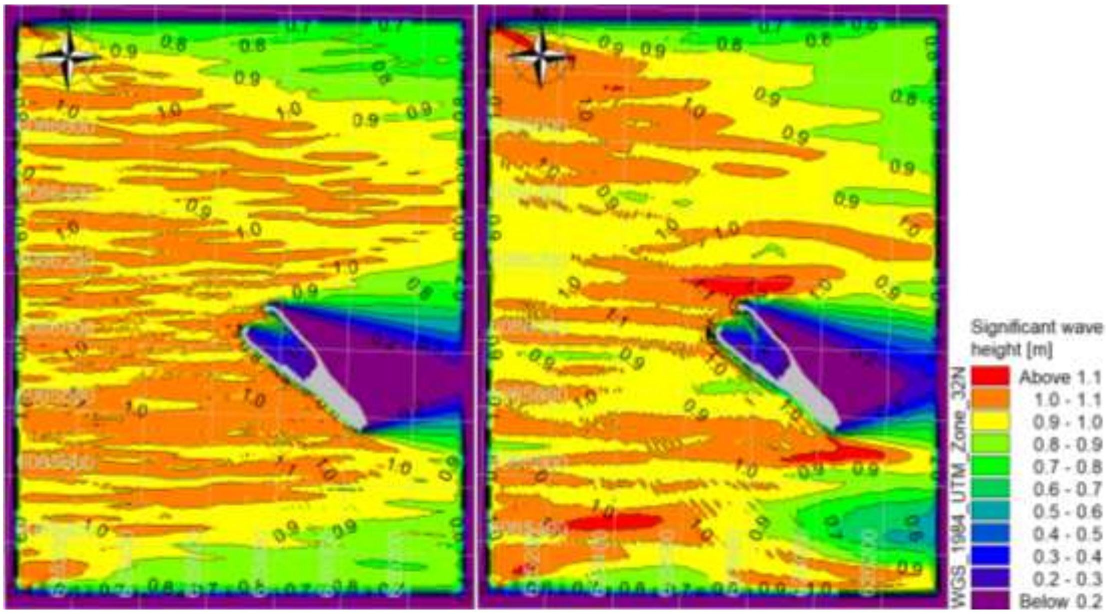


Figure A-5 *Wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

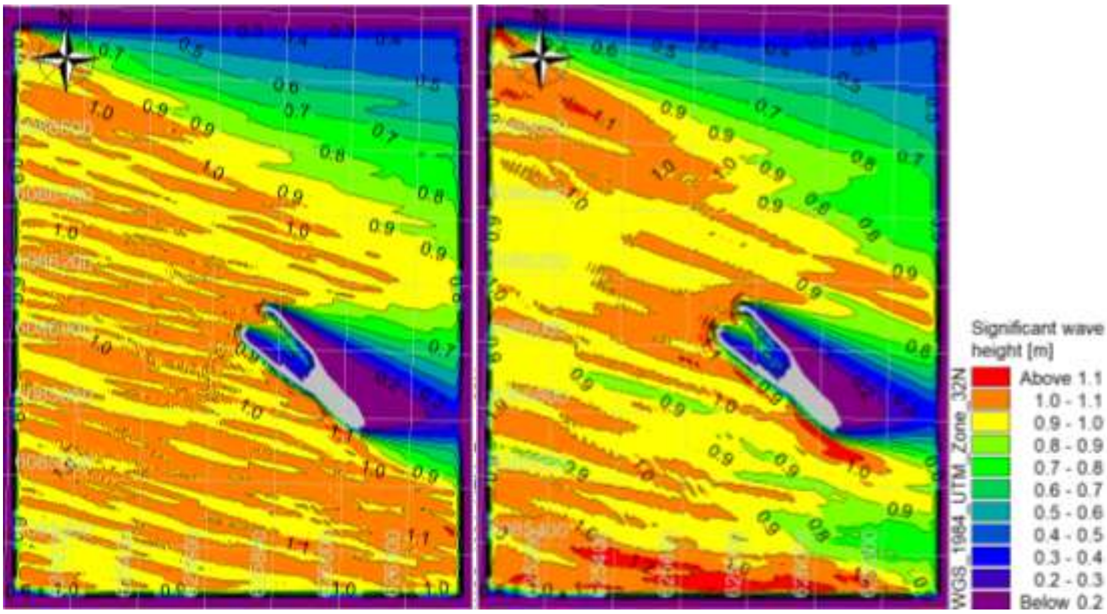


Figure A-6 Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.

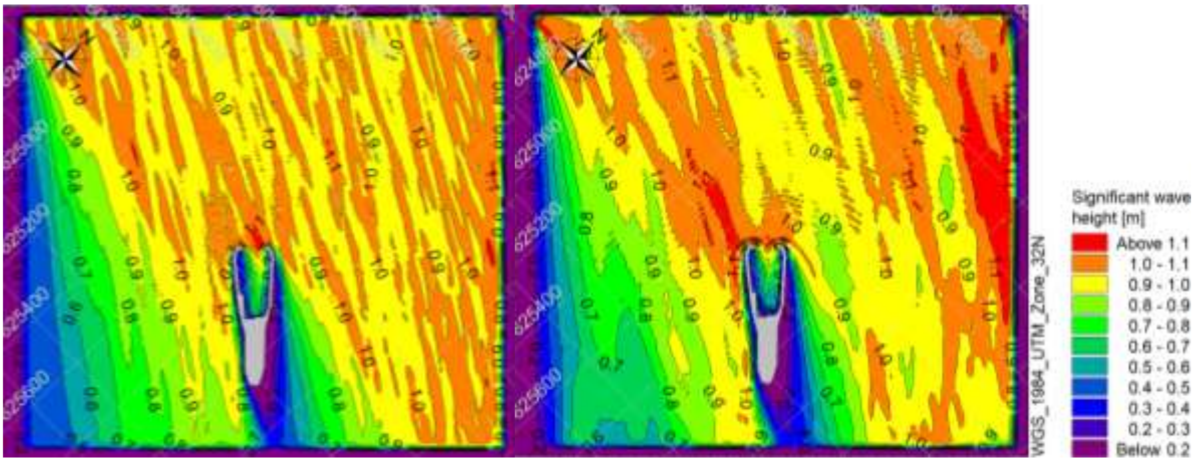


Figure A-7 Wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.

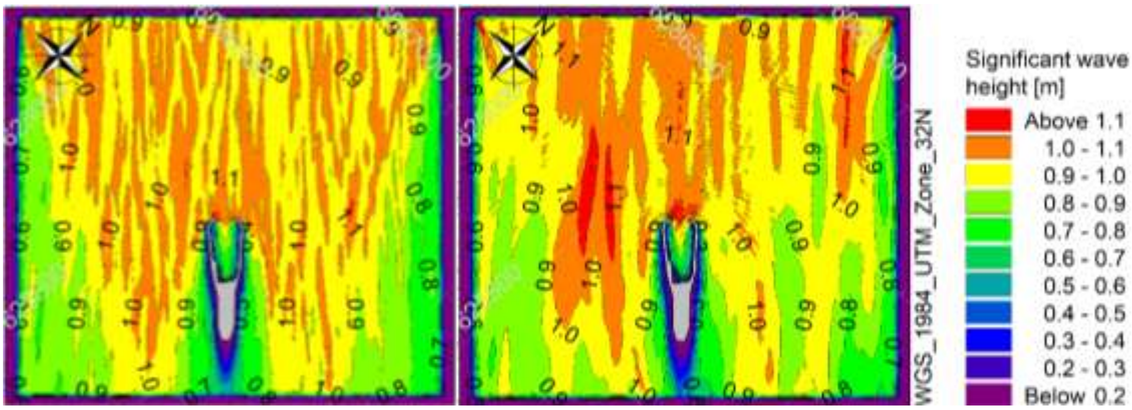


Figure A-8 Wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.

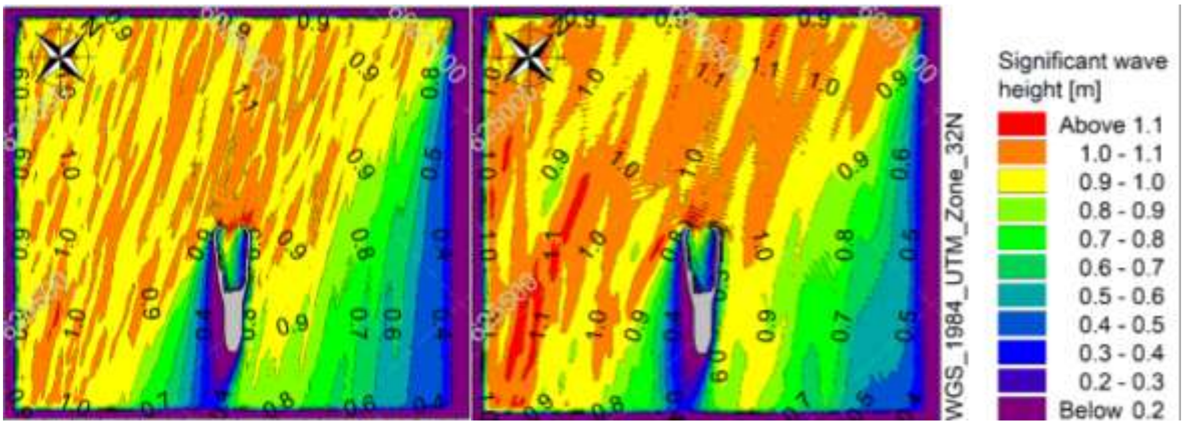


Figure A-9 Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.

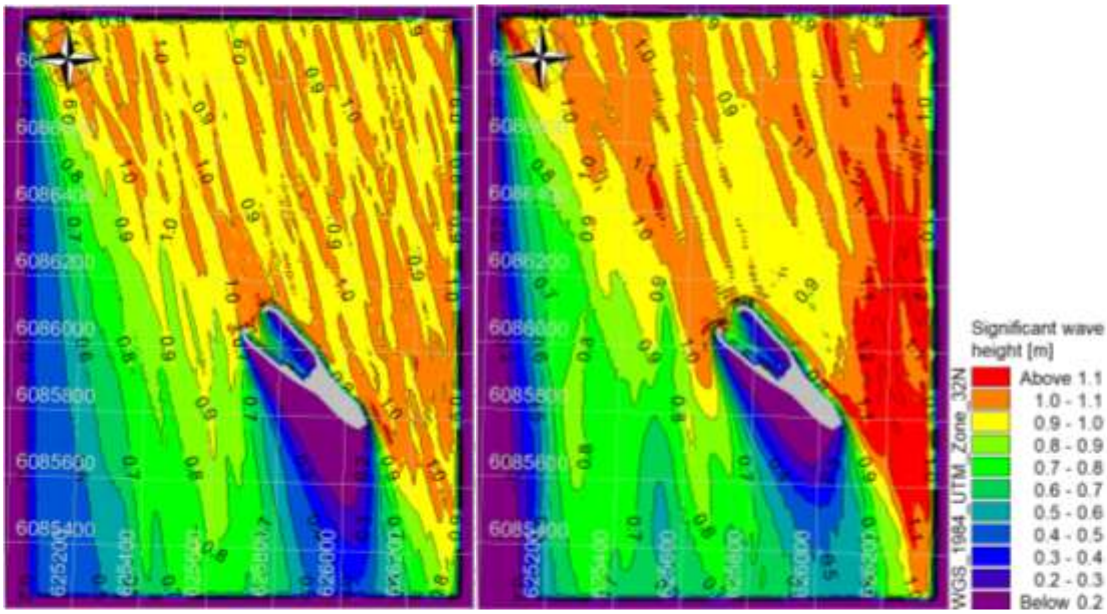


Figure A-10 Wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.

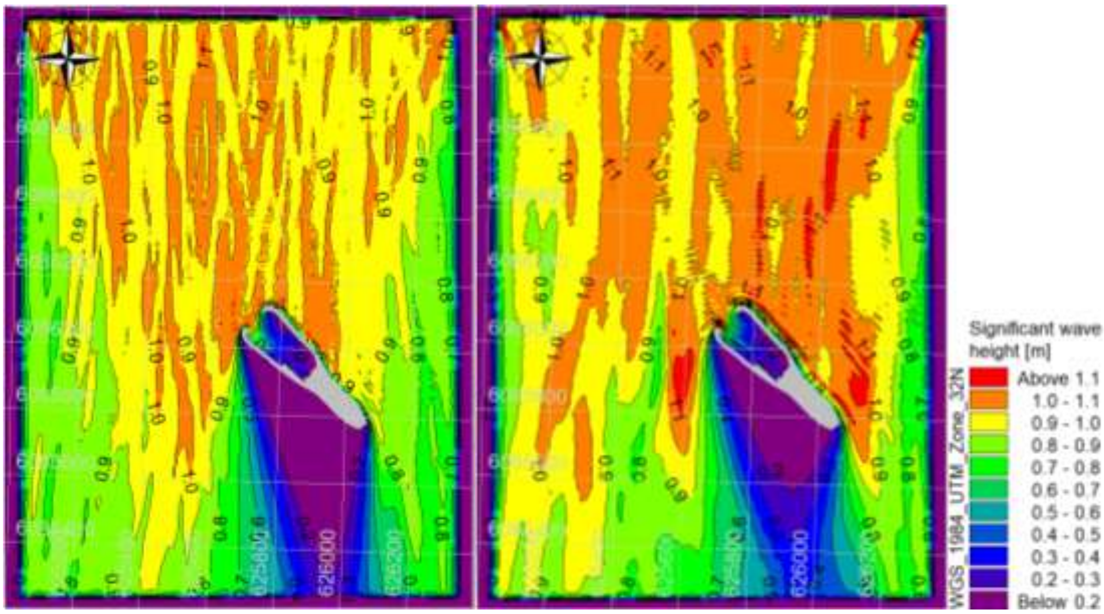


Figure A-11 *Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.*

A.2 Closeup of Wave Disturbance Plot for Layout 1

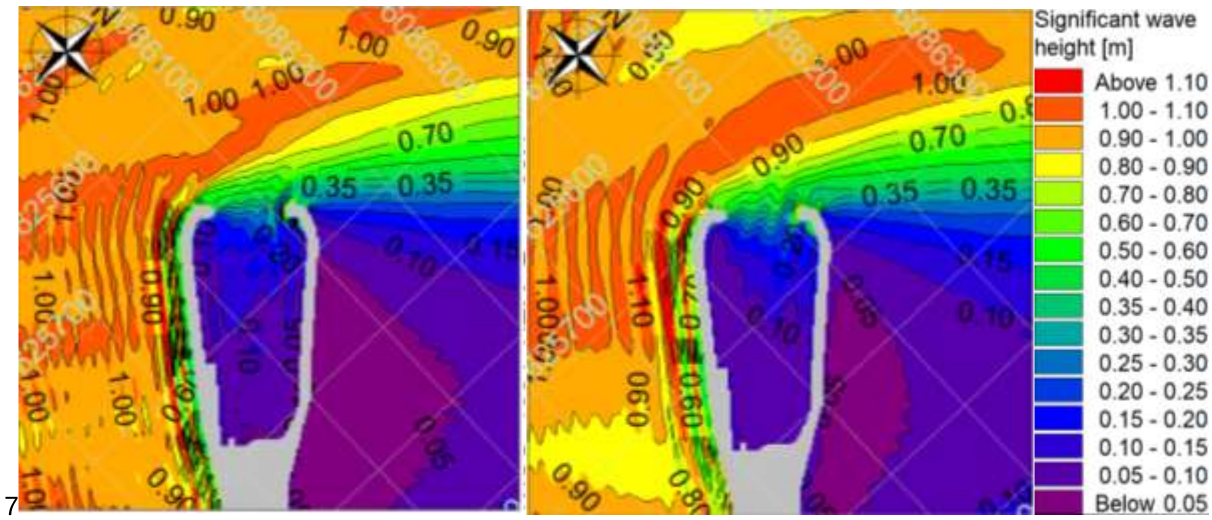


Figure A-12 *Closeup of wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec and Right: Tp = 6 sec.*

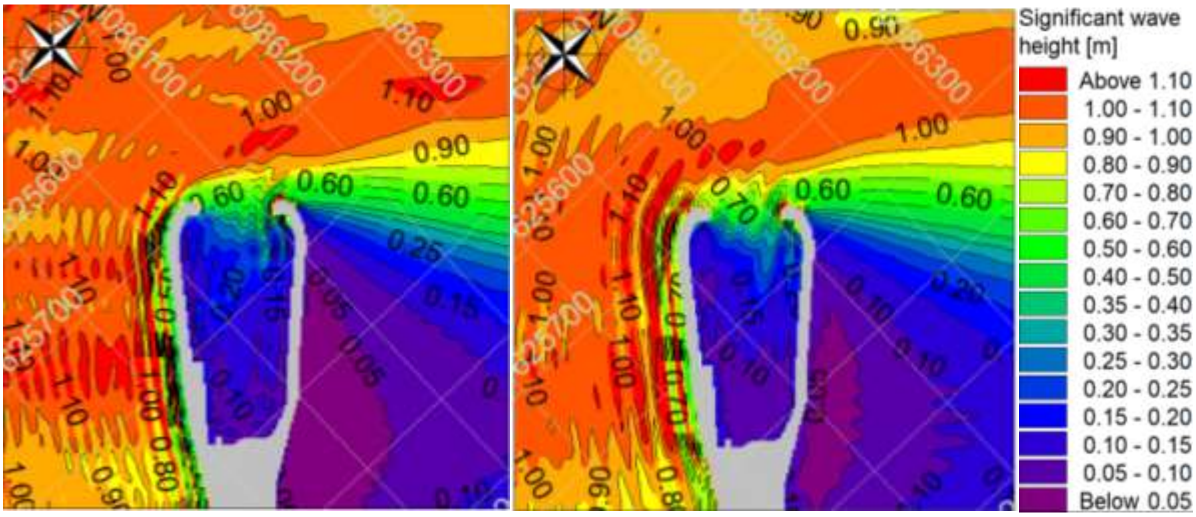


Figure A-13 *Closeup of wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec and Right: Tp = 6 sec.*

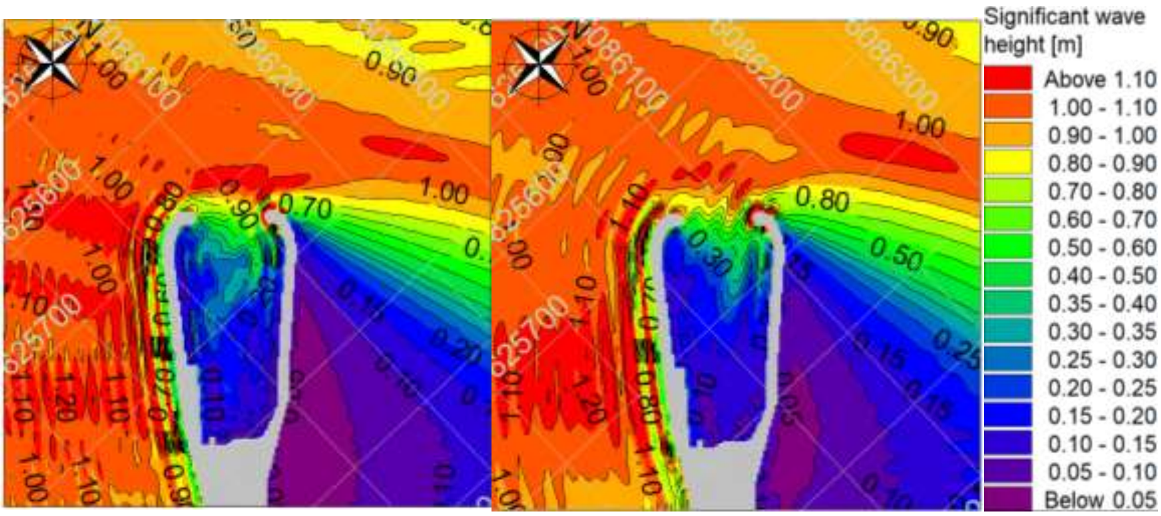


Figure A-14 *Closeup of wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec and Right: Tp = 6 sec.*

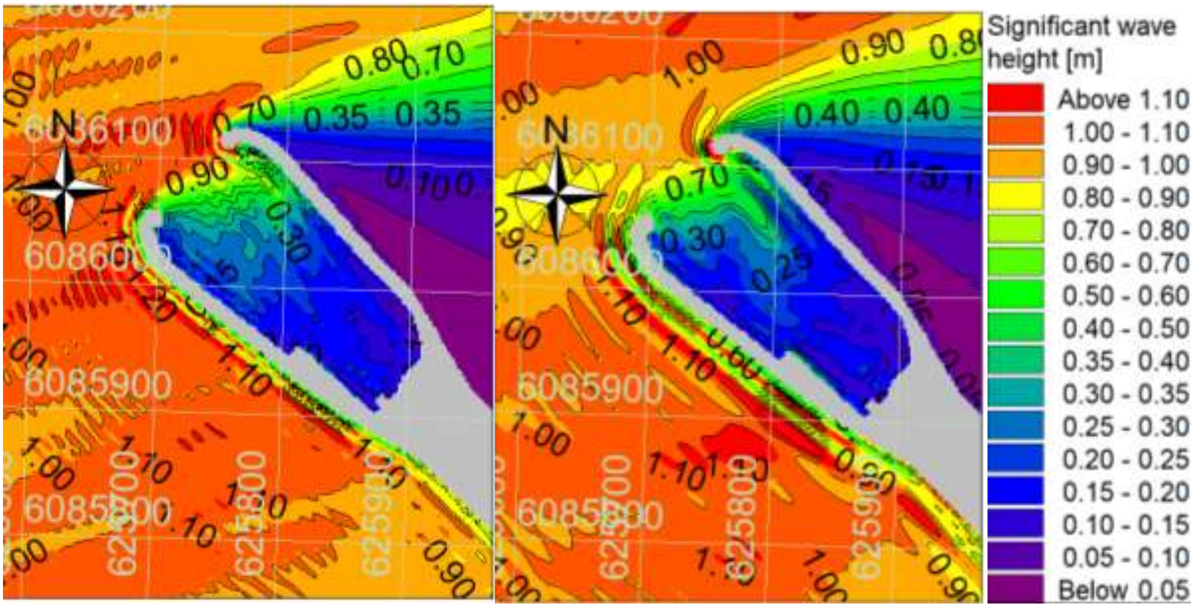


Figure A-15 *Closeup of wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

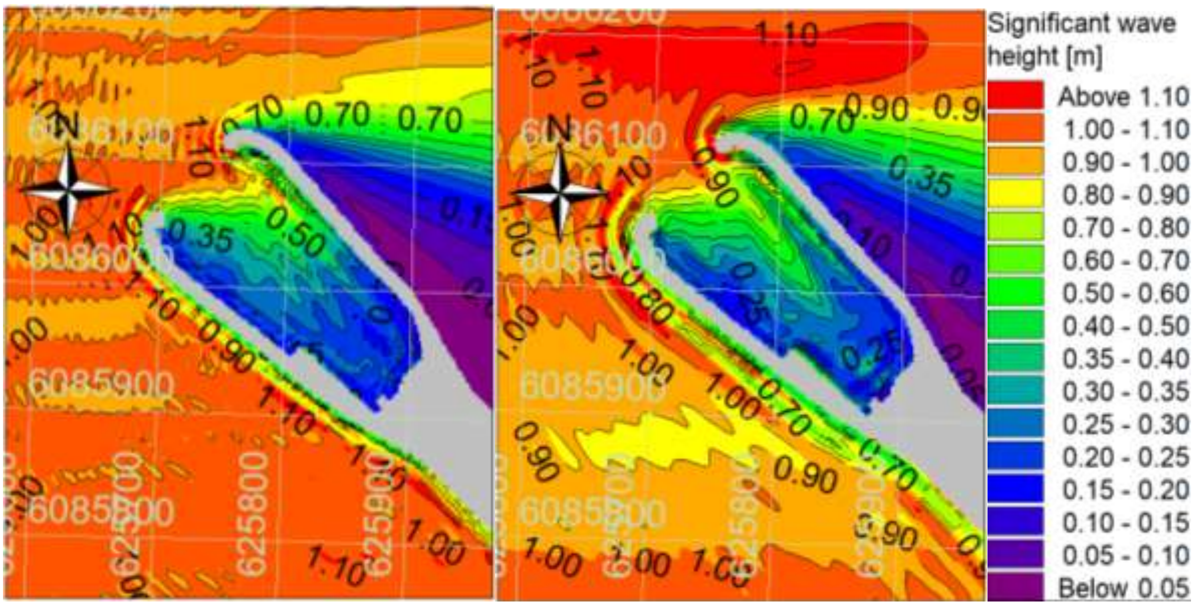


Figure A-16 *Closeup of wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

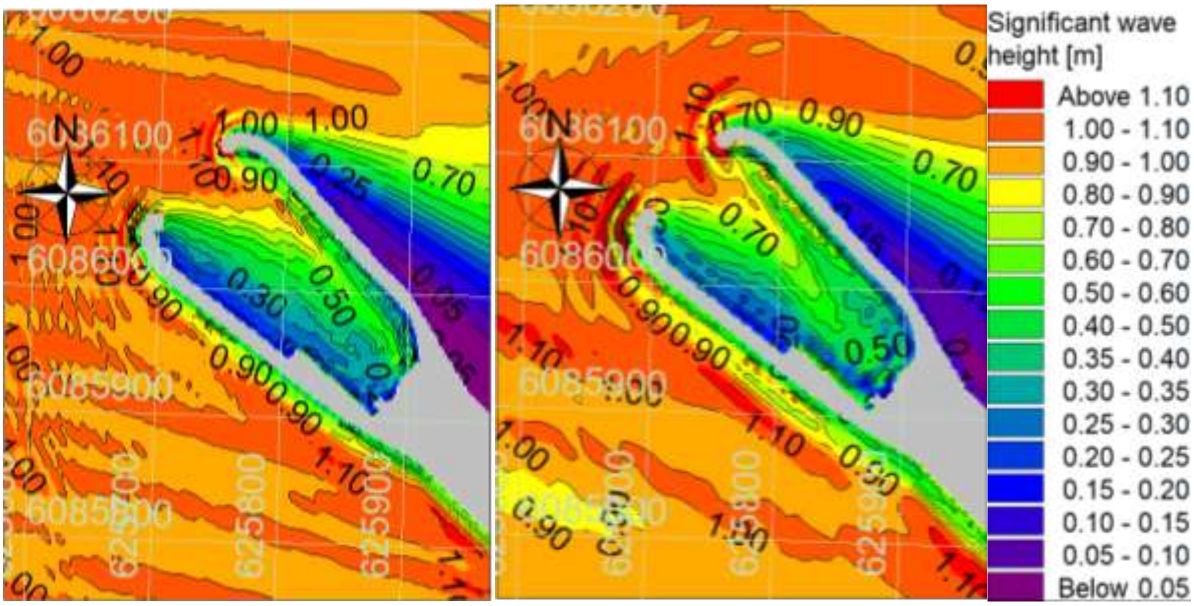


Figure A-17 *Closeup of wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

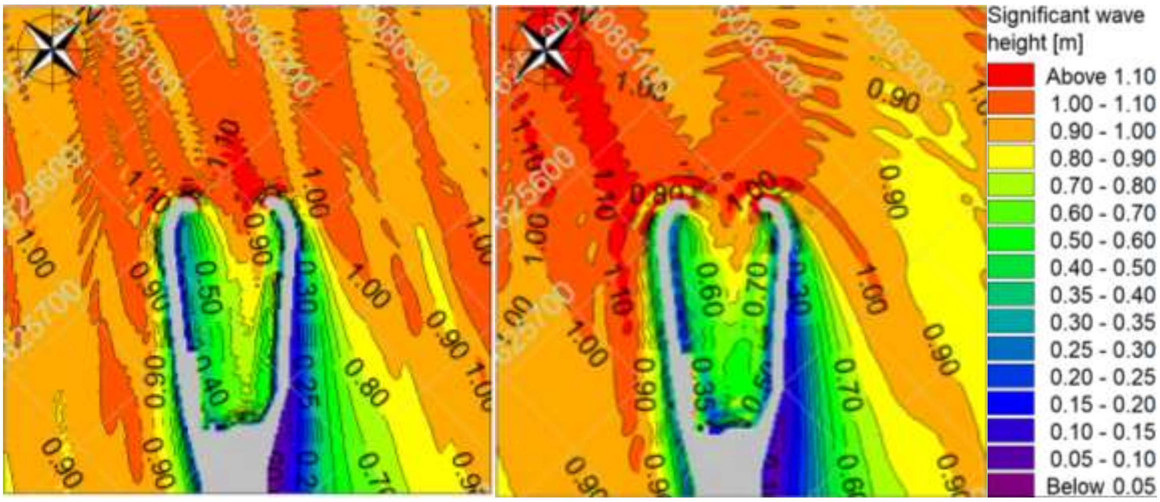


Figure A-18 *Closeup of wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

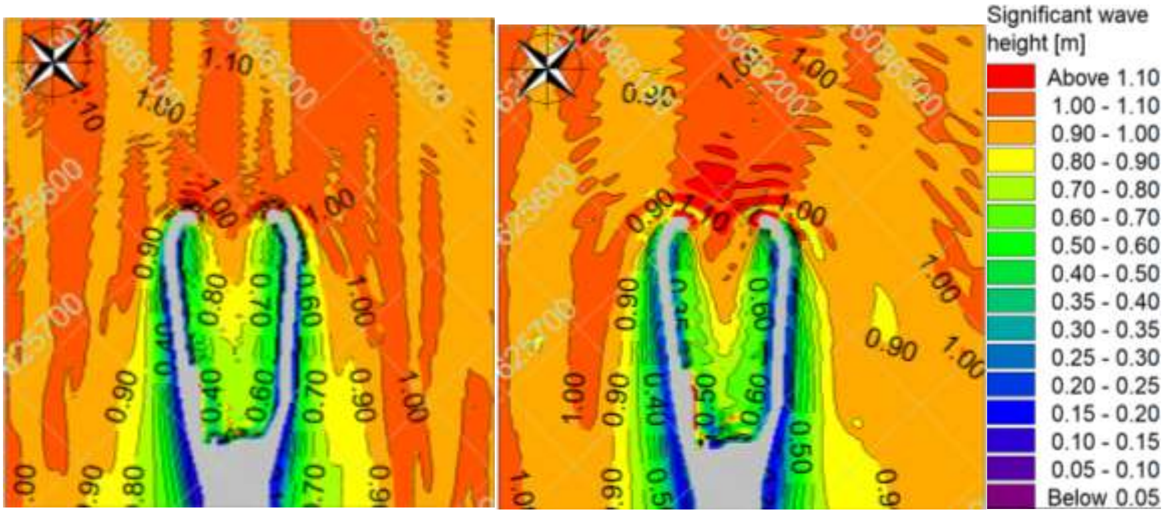


Figure A-19 *Closeup of wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

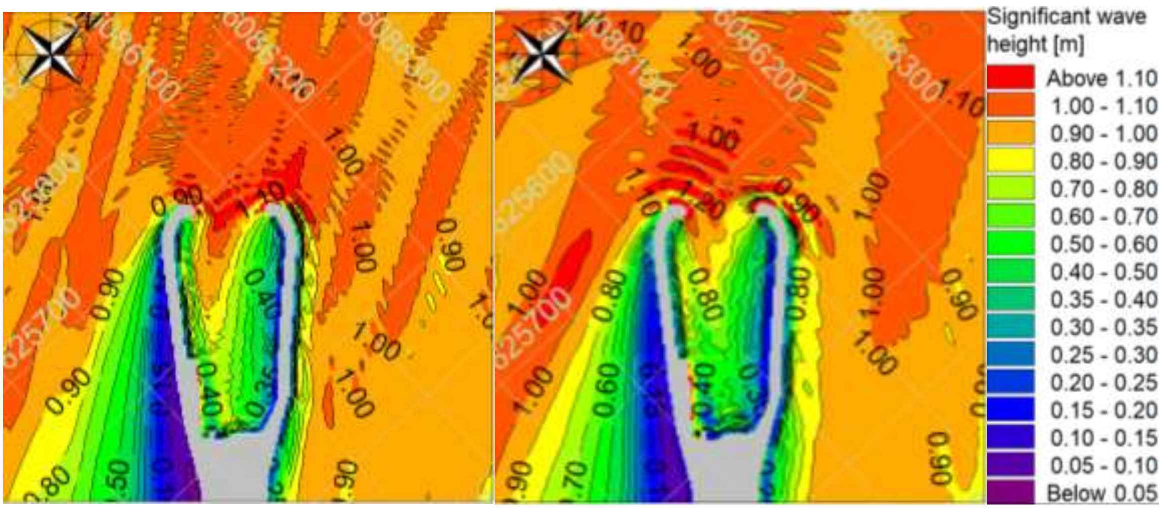


Figure A-20 *Closeup of wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

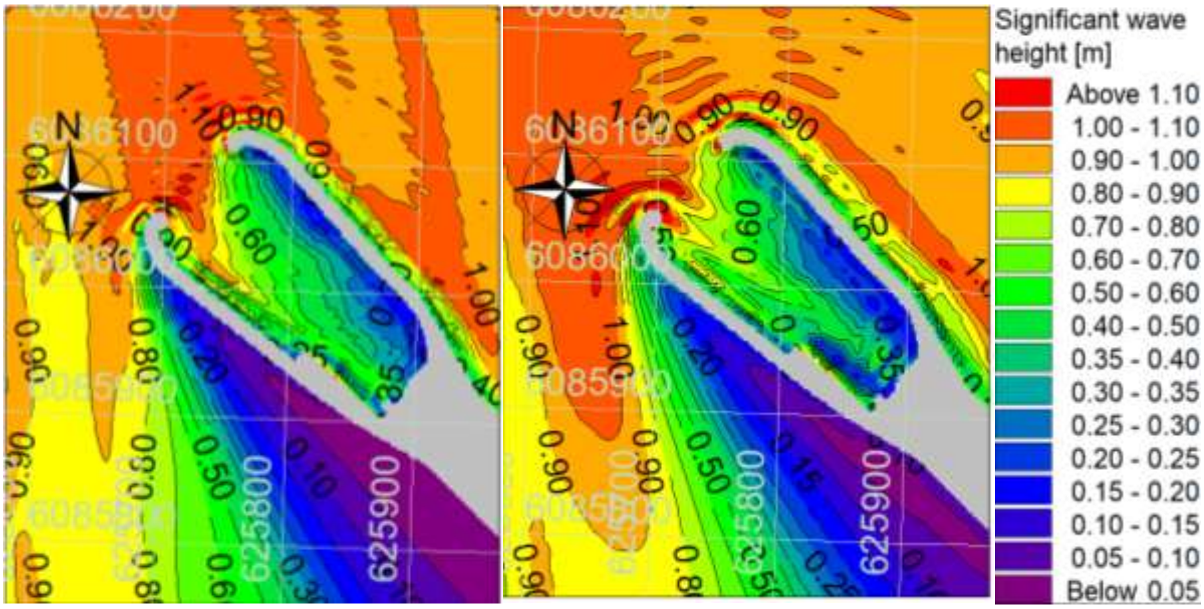


Figure A-21 *Closeup of wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec and Right: Tp = 5 sec.*

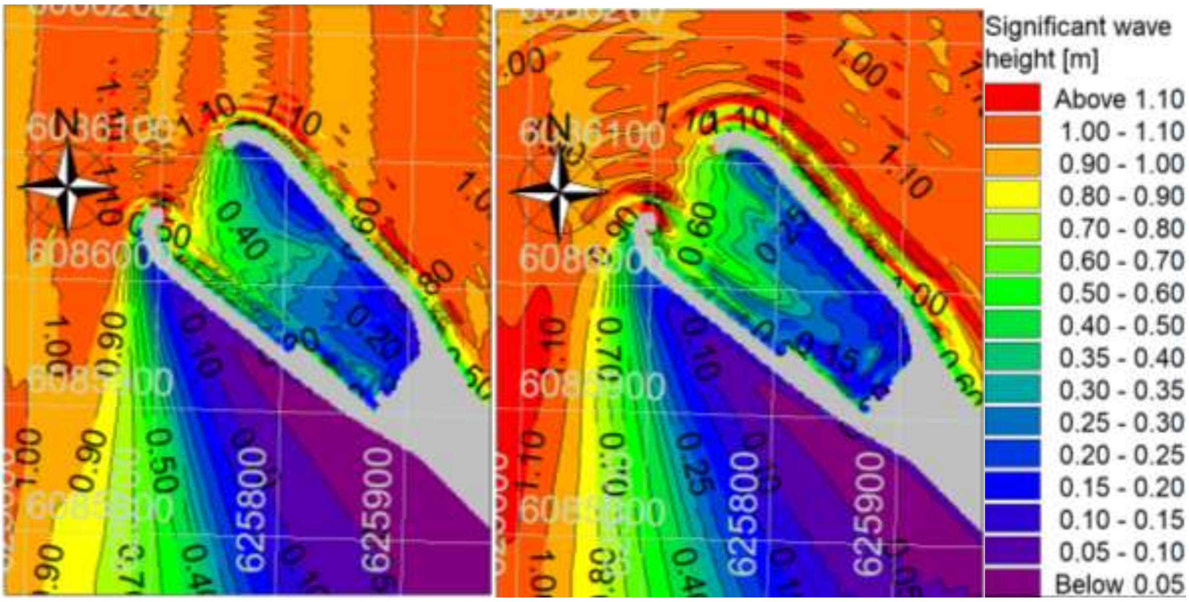


Figure A-22 *Closeup of wave disturbance plot for wave direction = 0°N. Left: Tp = 5 sec and Right: Tp = 3.5 sec.*

A.3 Instantaneous Surface Elevation Maps for Layout 1

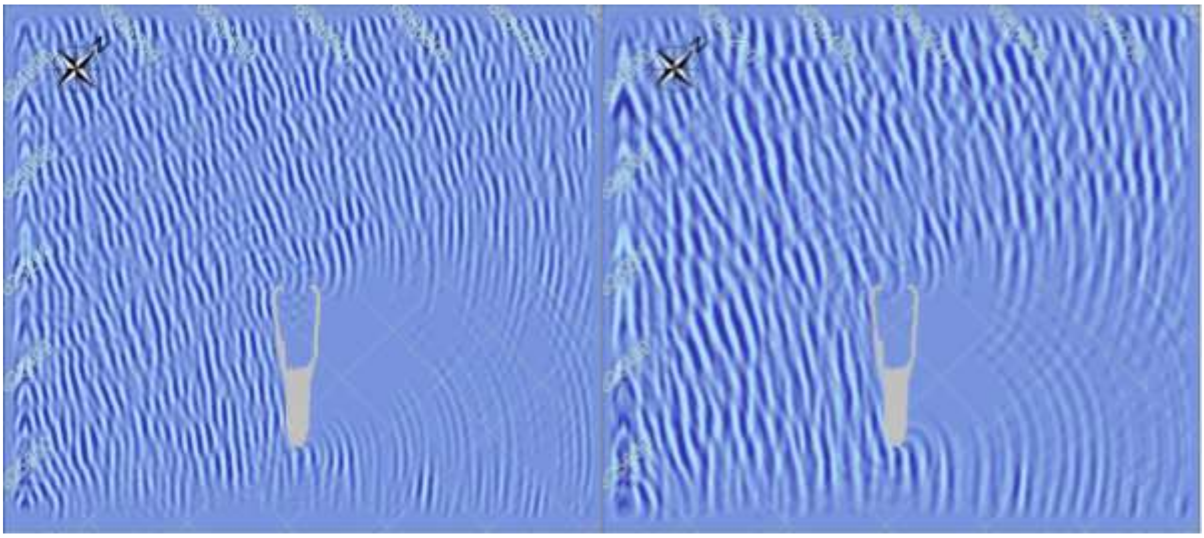


Figure A-23 Surface elevation plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec.

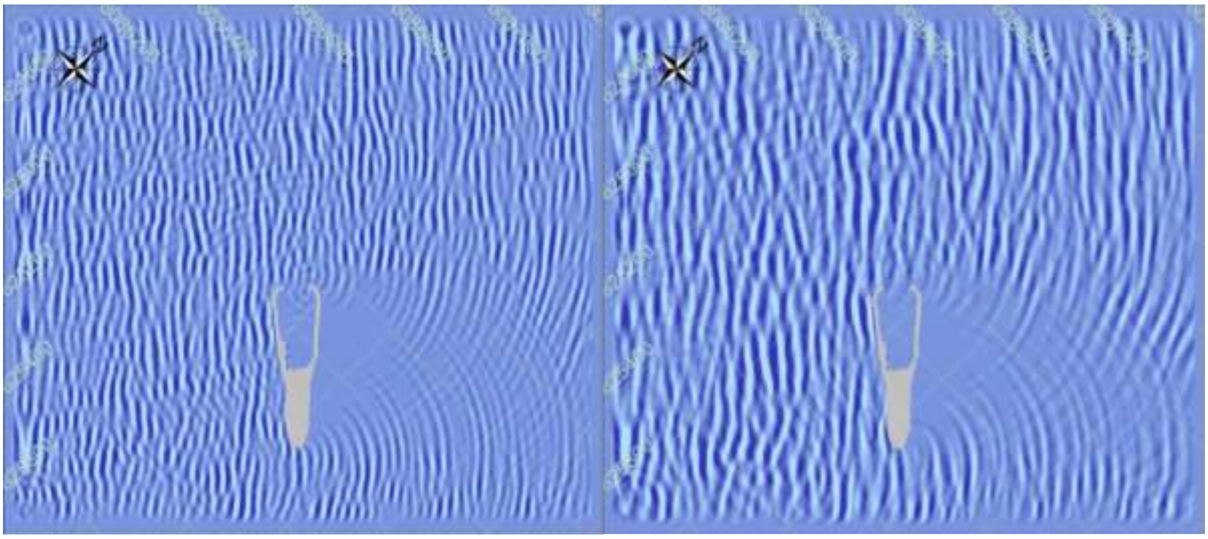


Figure A-24 Surface elevation plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec.

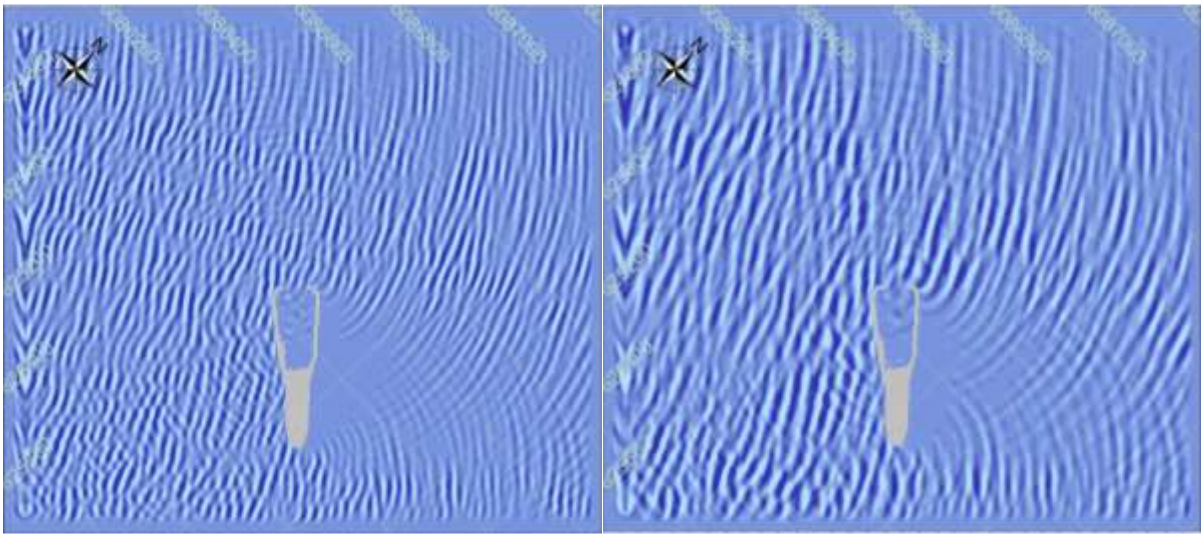


Figure A-25 Surface elevation plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec.

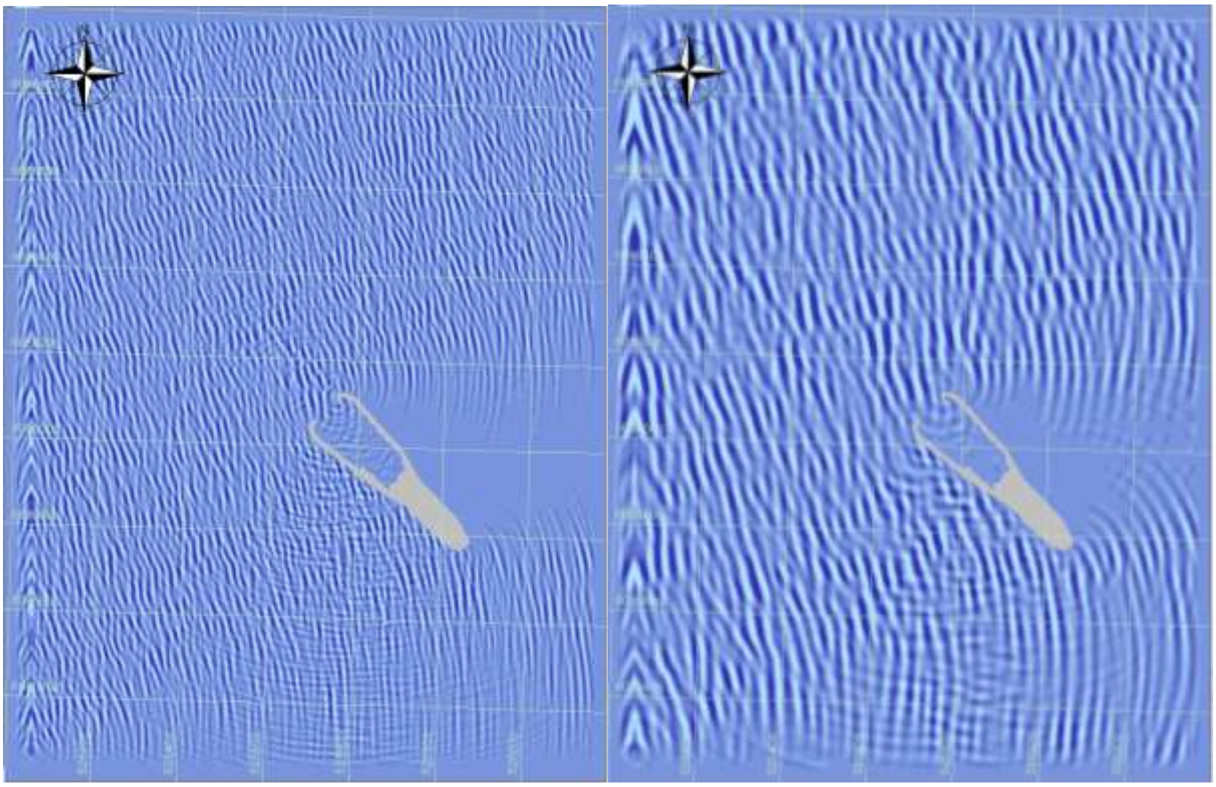


Figure A-26 Surface elevation plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

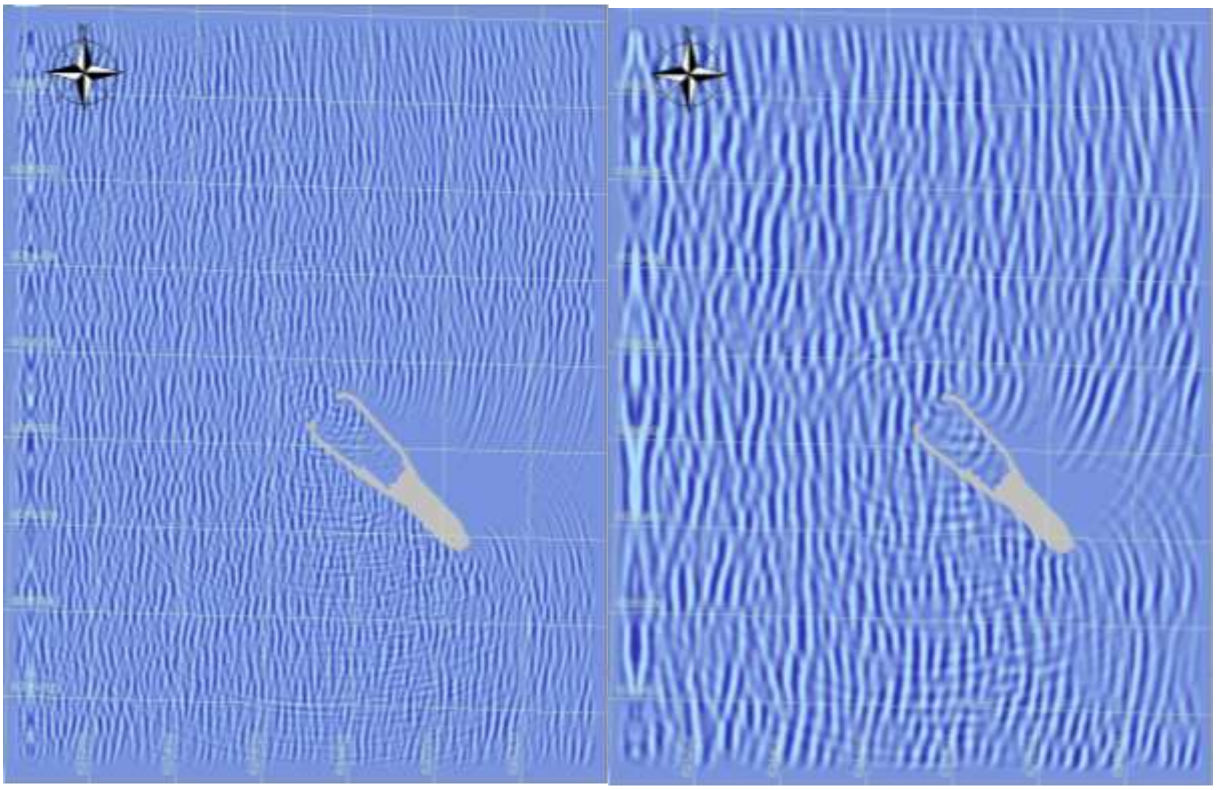


Figure A-27 Surface elevation plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

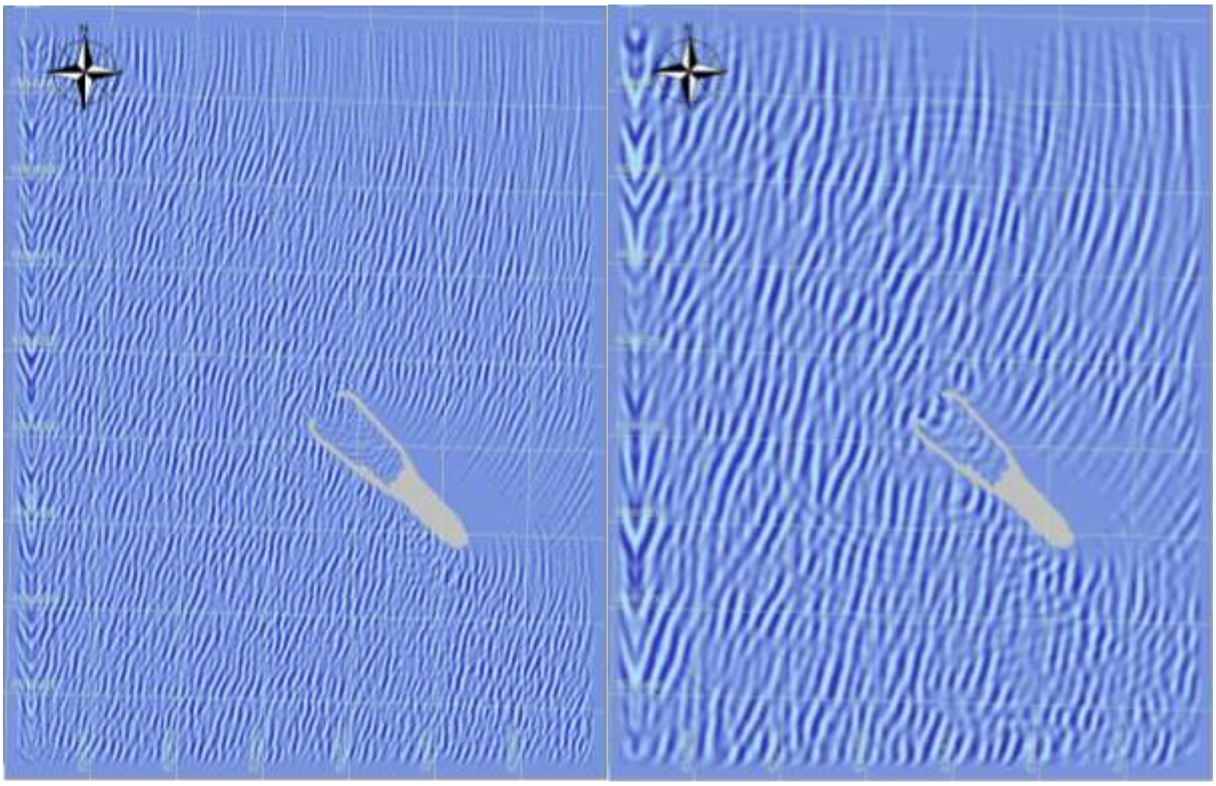


Figure A-28 Surface elevation plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

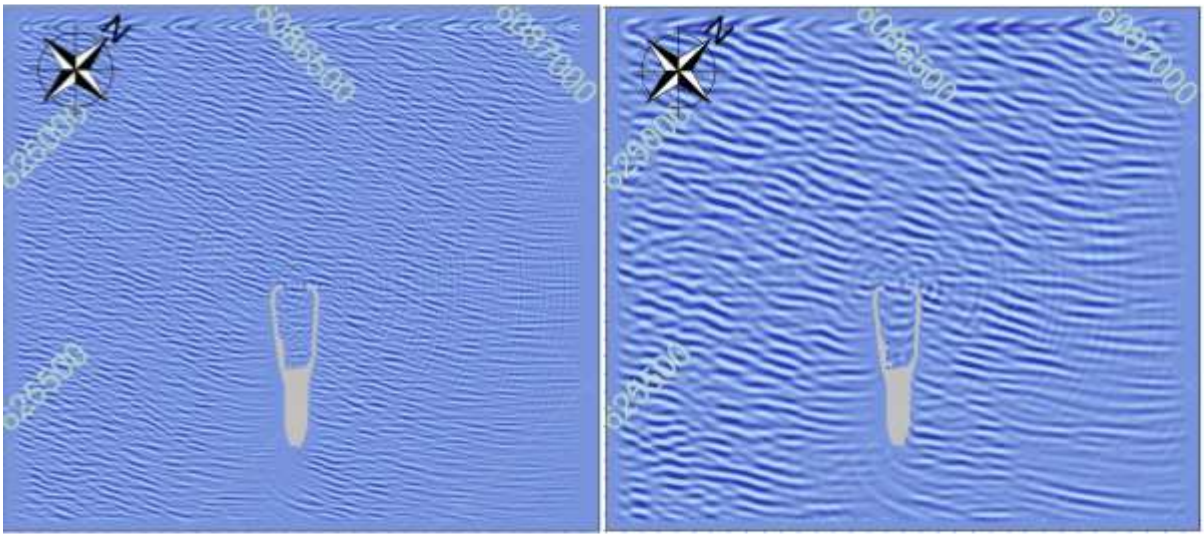


Figure A-29 Surface elevation plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

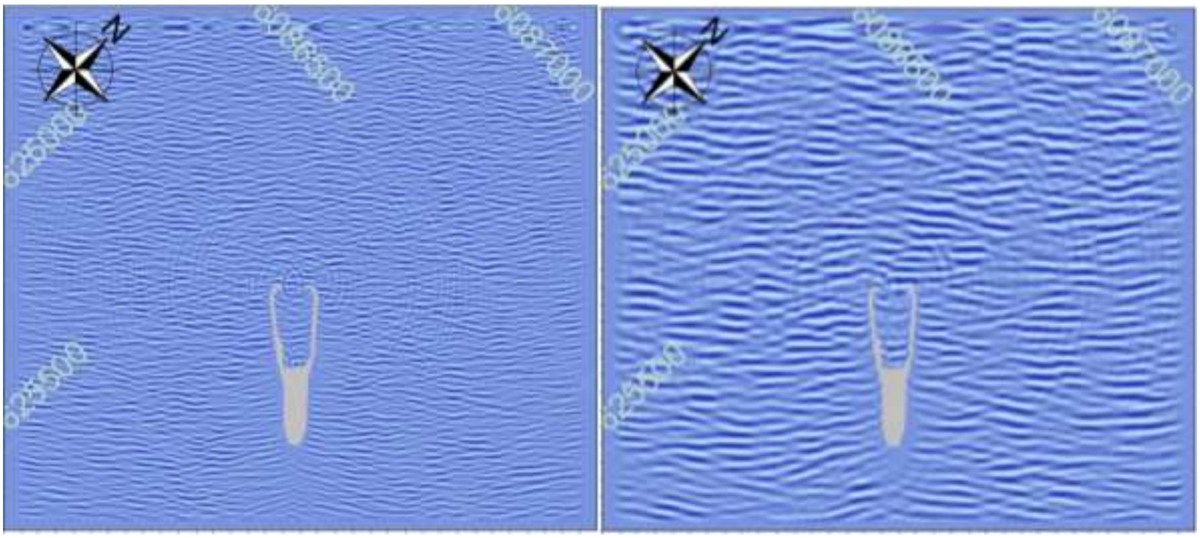


Figure A-30 Surface elevation plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

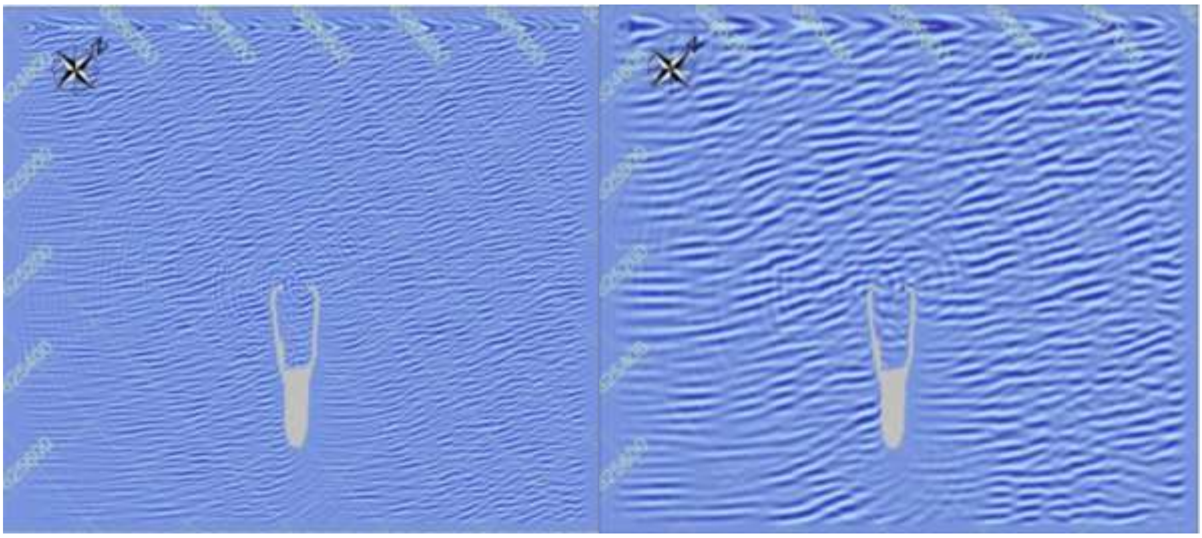


Figure A-31 Surface elevation plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

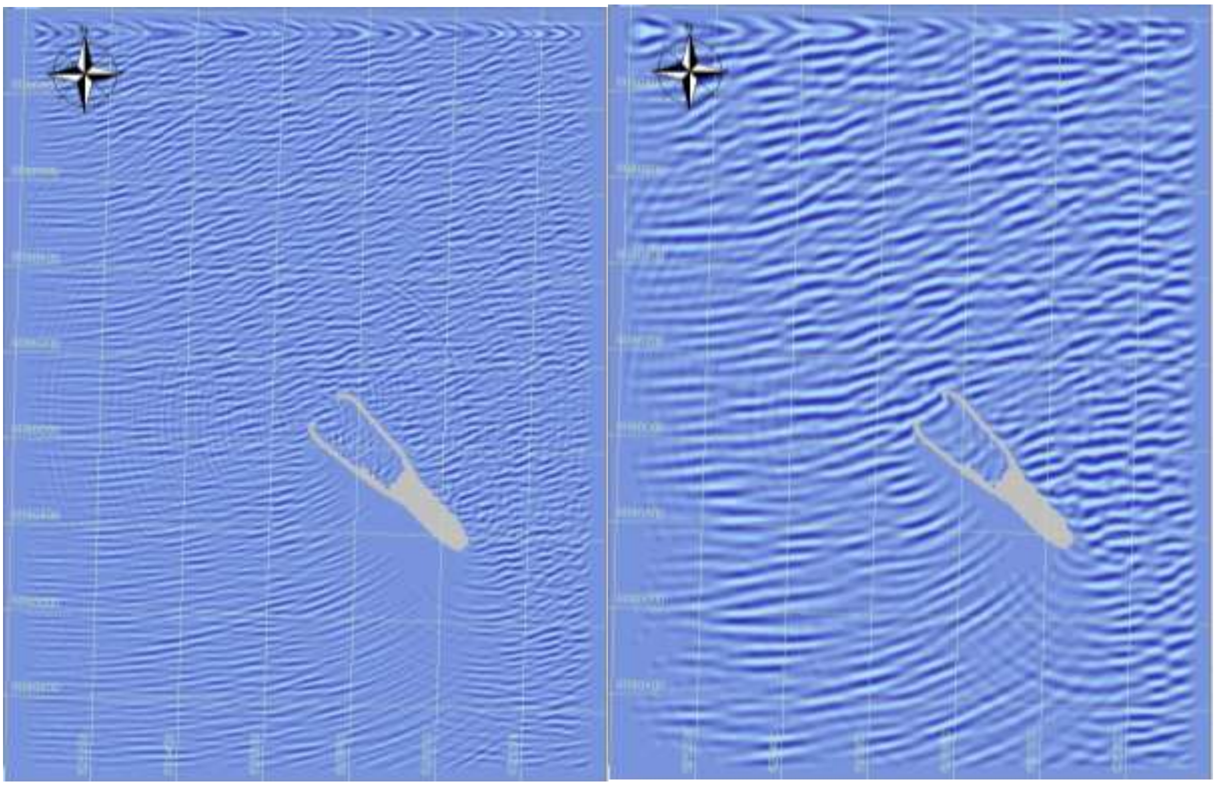


Figure A-32 Surface elevation plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

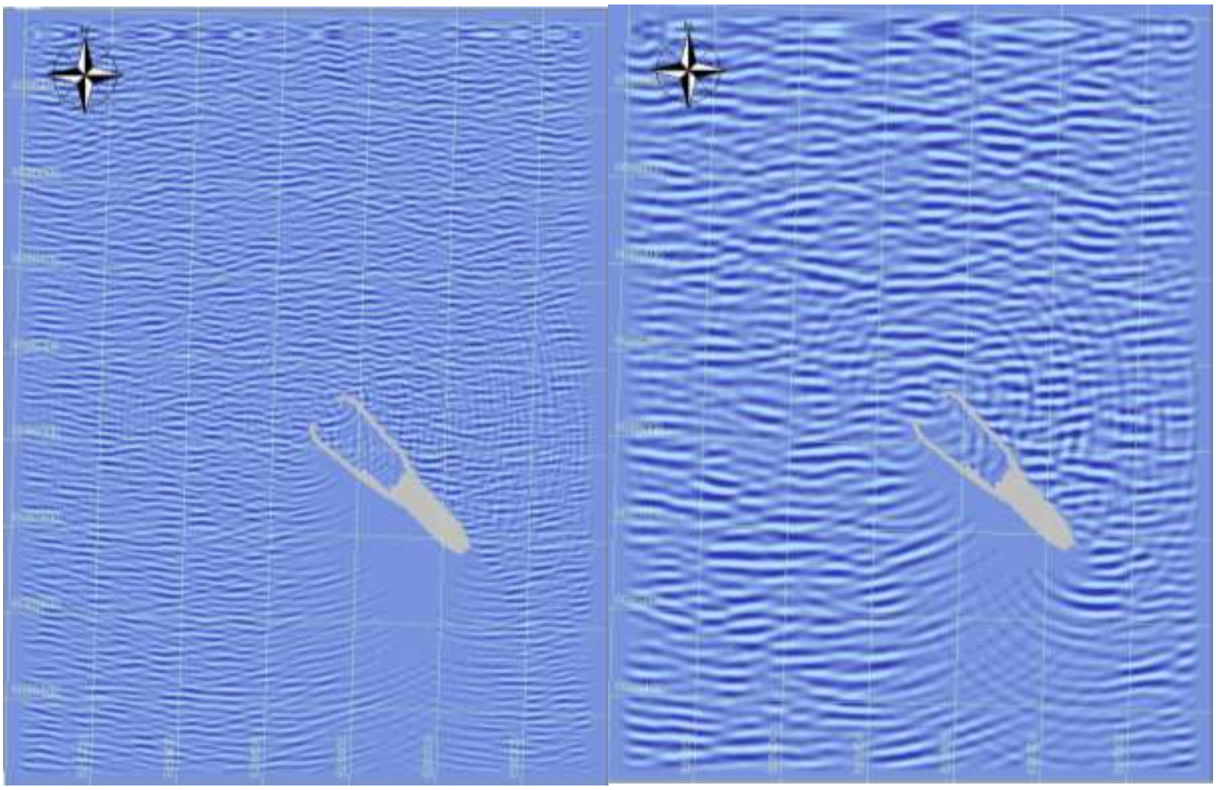


Figure A-33 Surface elevation plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

Appendix B Disturbance maps for Layout 2a

B.1 Overall Wave Disturbance Maps for Layout 2a

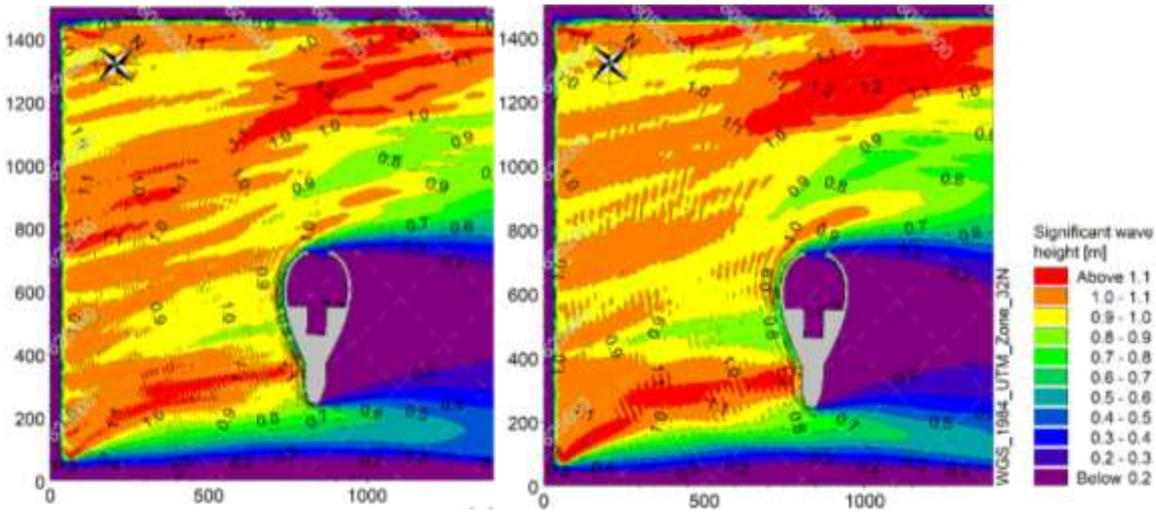


Figure B-1 Wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp =6 sec.

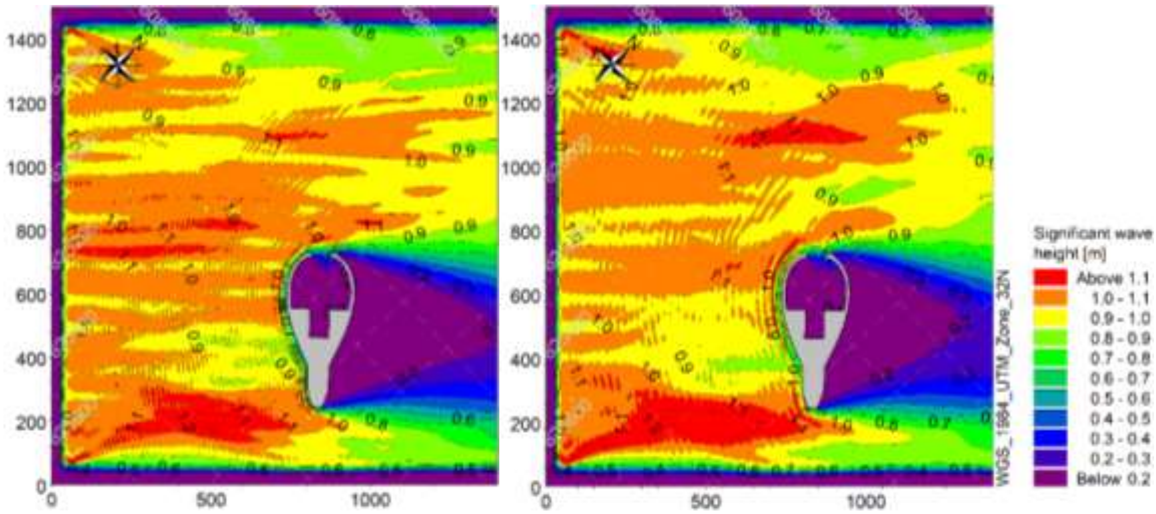


Figure B-2 Wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp =6 sec.

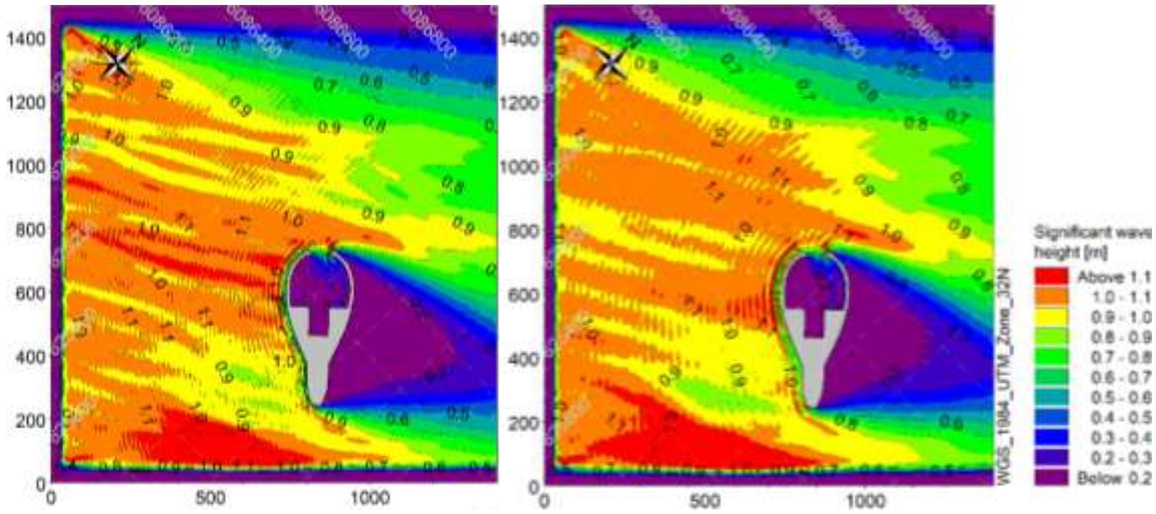


Figure B-3 *Wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp =6 sec.*

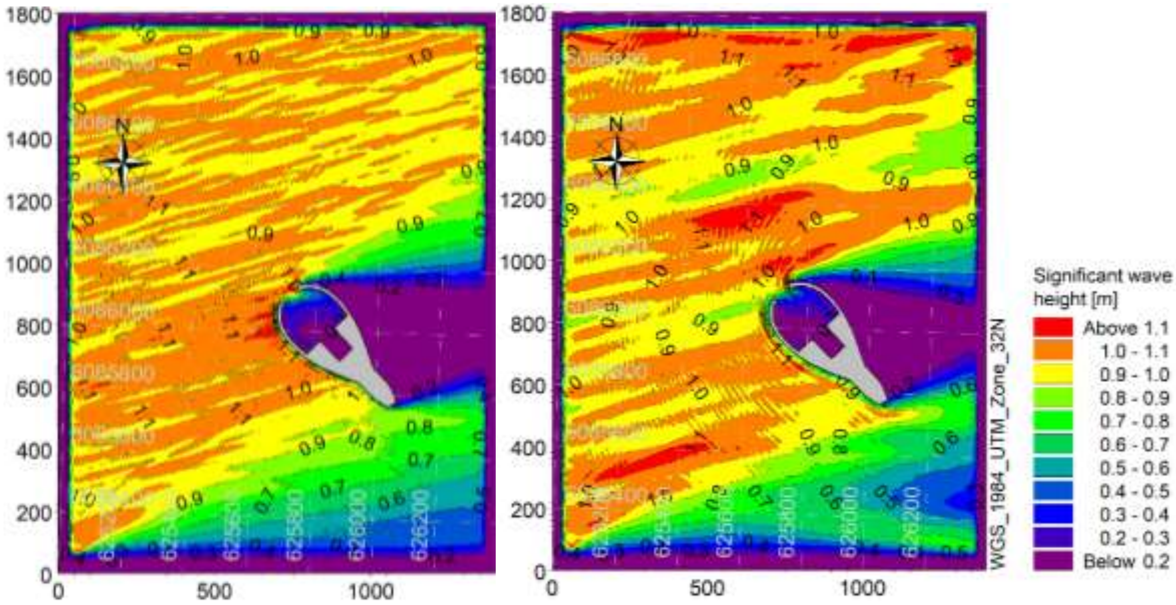


Figure B-4 *Wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp =5 sec.*

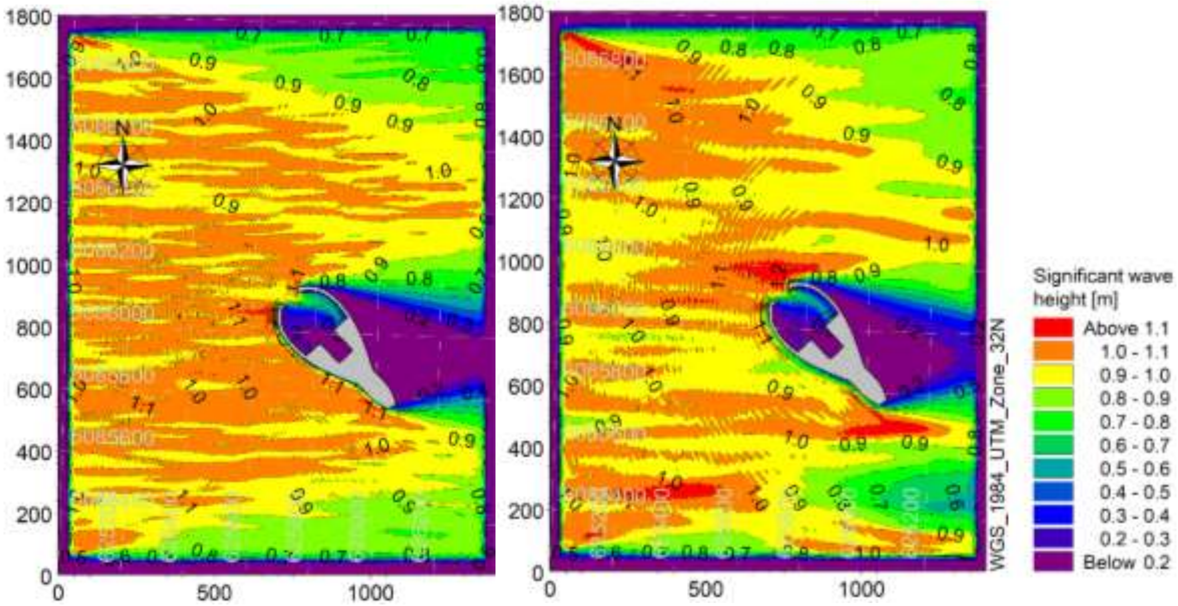


Figure B-5 Wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

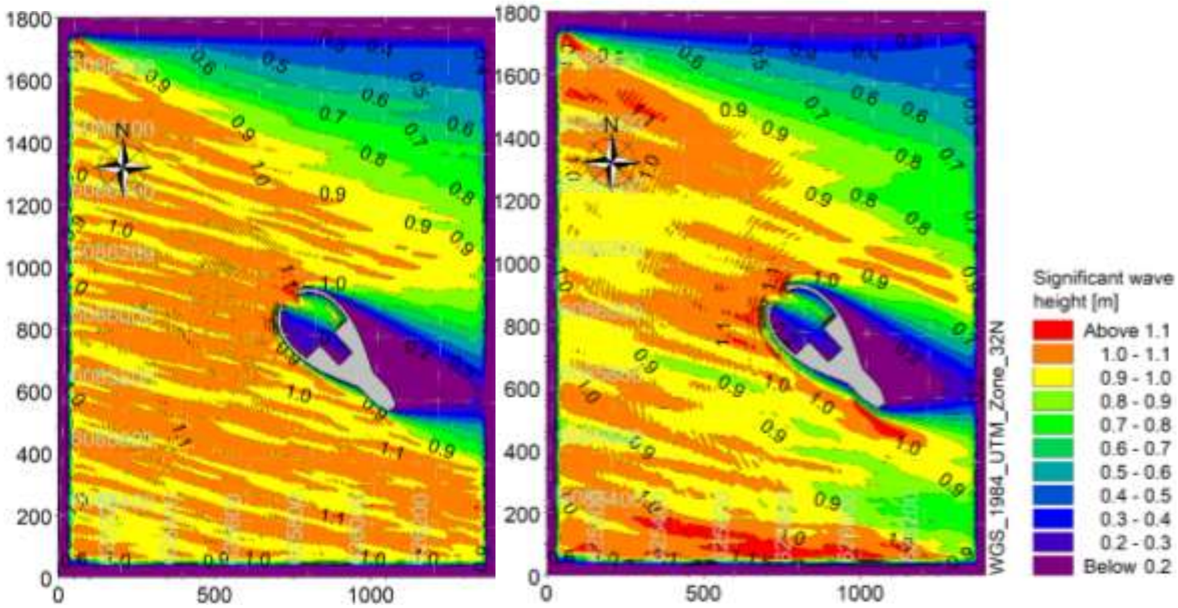


Figure B-6 Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

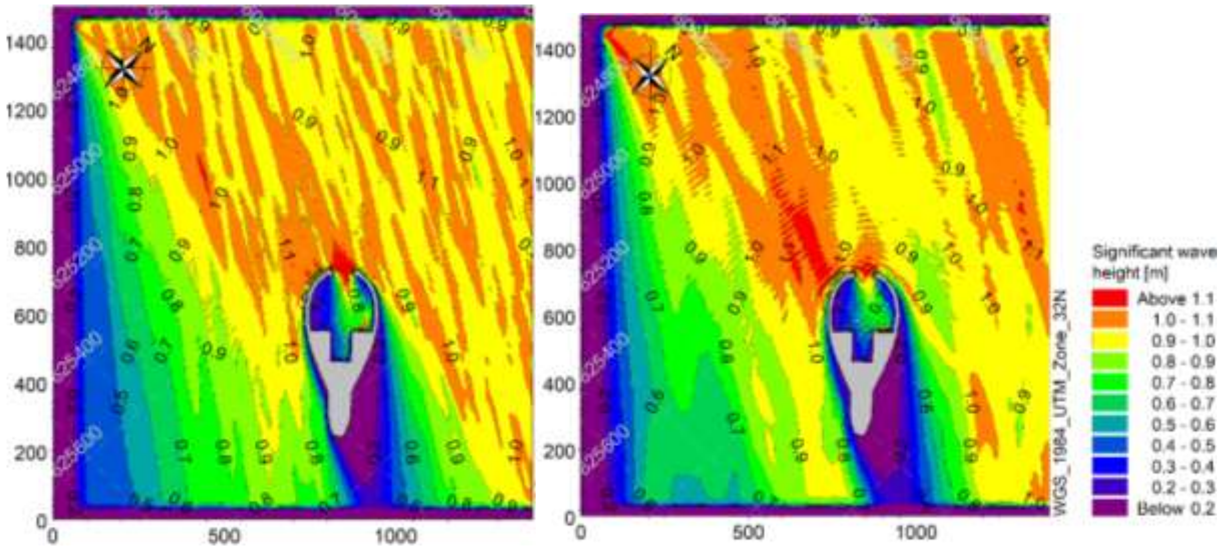


Figure B-7 Wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

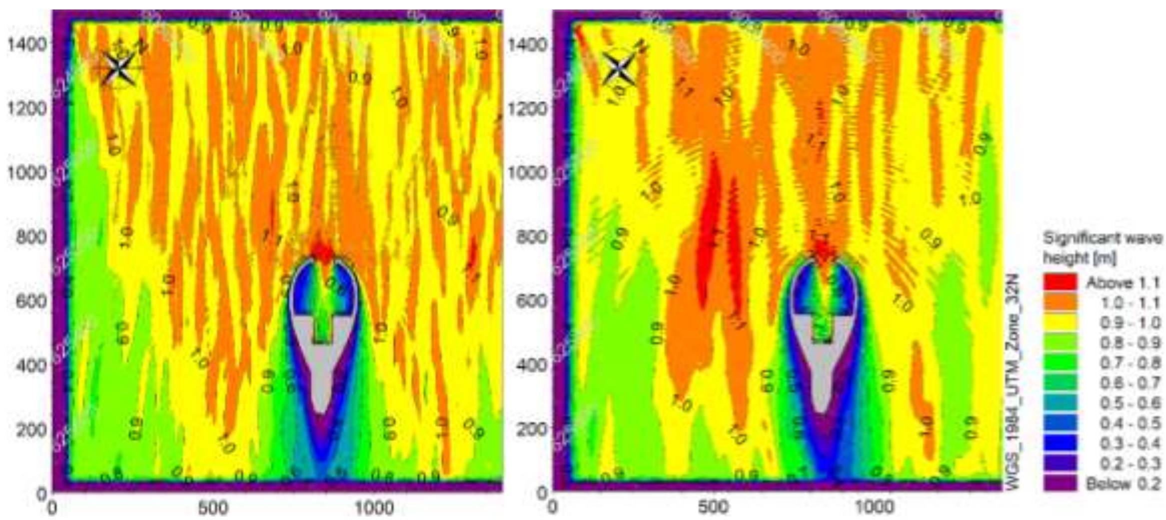


Figure B-8 Wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

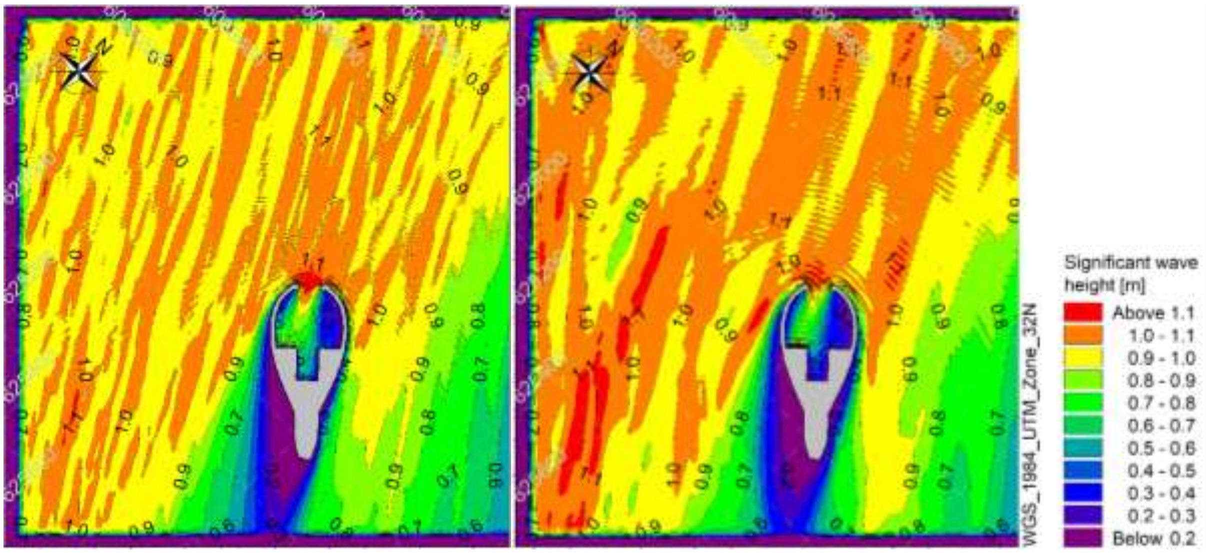


Figure B-9 *Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

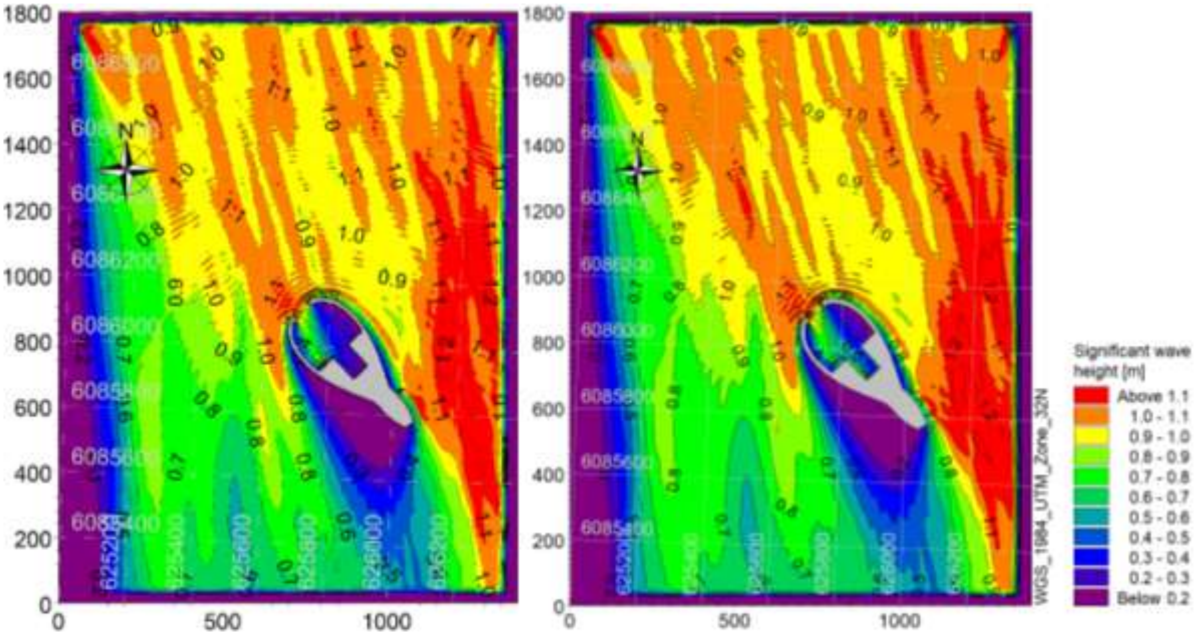


Figure B-10 *Wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

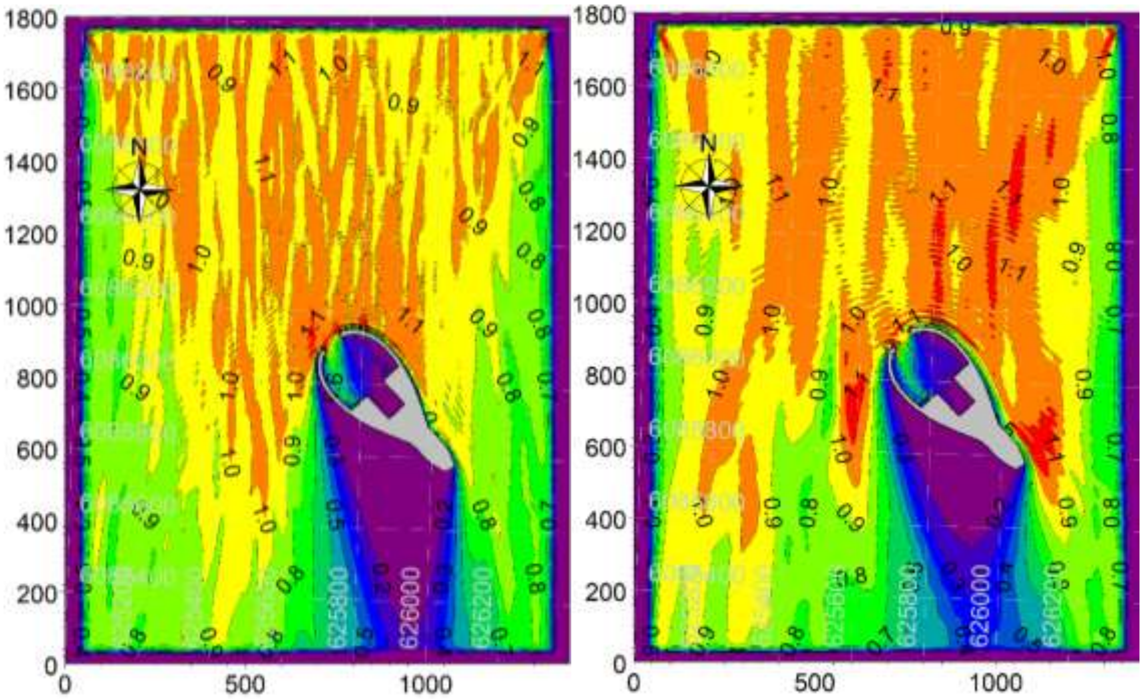


Figure B-11 *Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

B.2 Closeup of Wave Disturbance Maps for Layout 2a

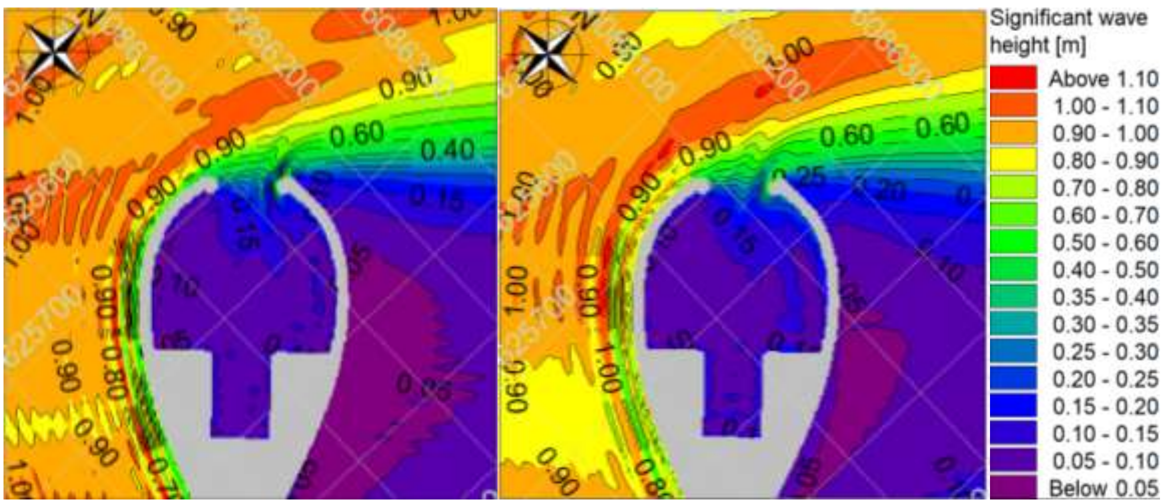


Figure B-12 *Closeup of wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp =6 sec*

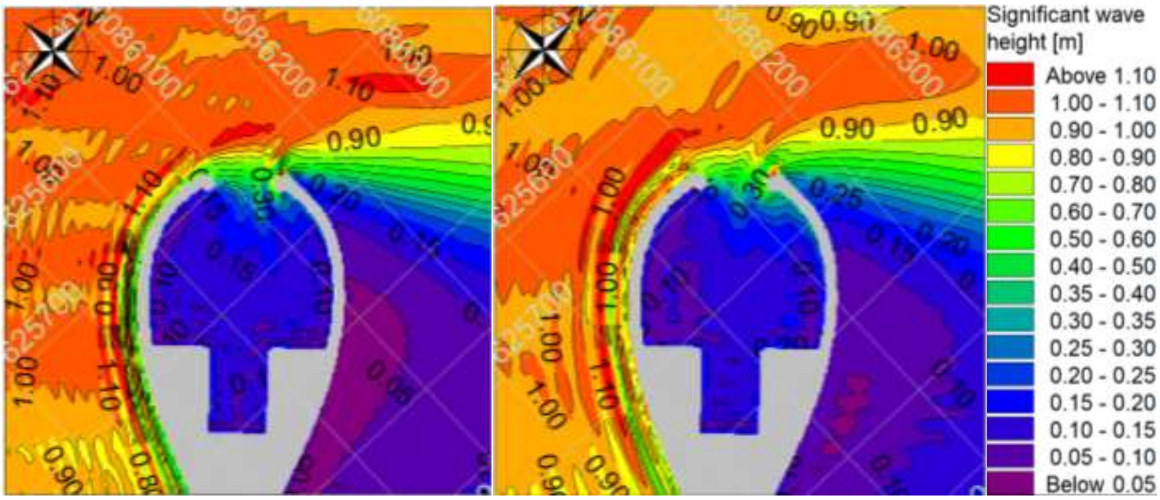


Figure B-13 Closeup of wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

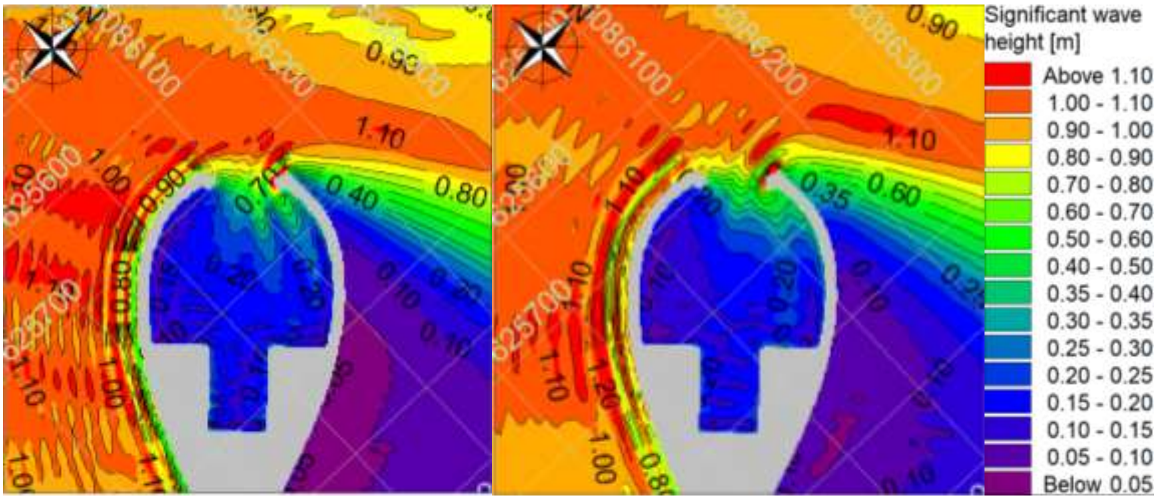


Figure B-14 Closeup of wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

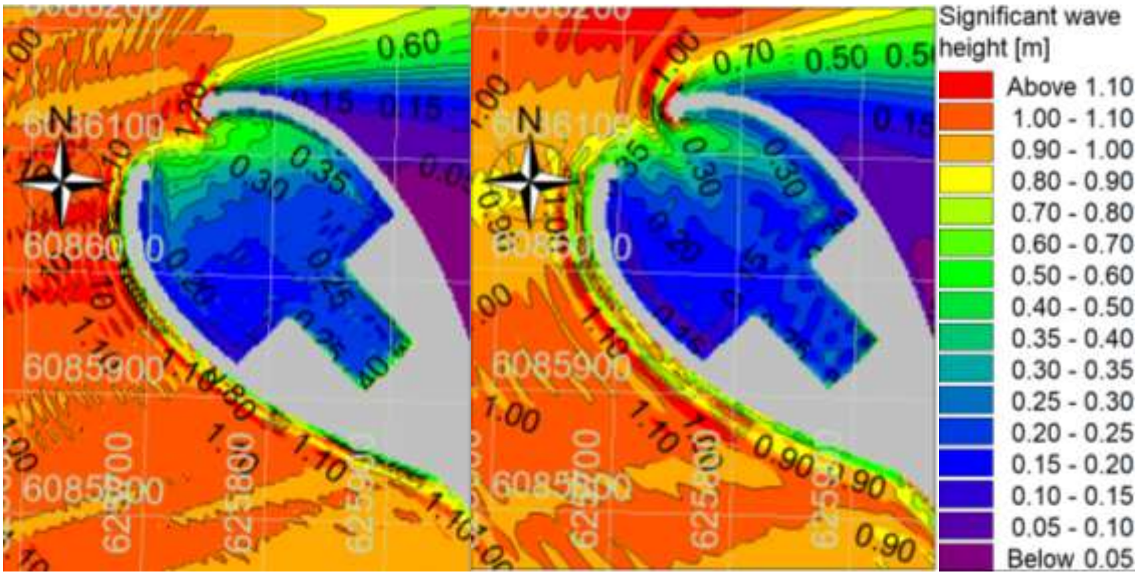


Figure B-15 Closeup of wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

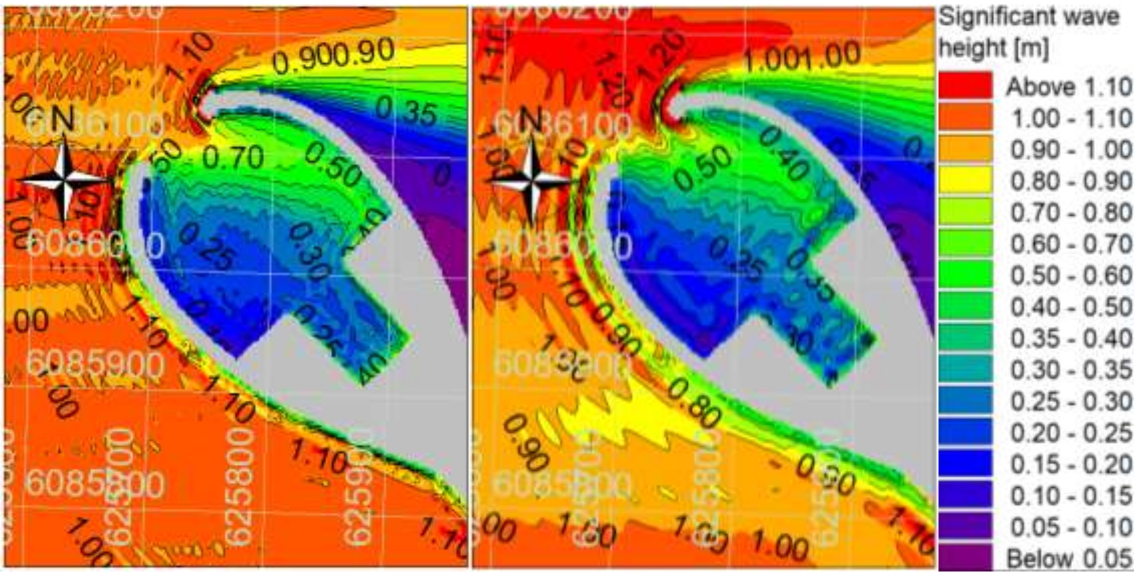


Figure B-16 *Closeup of wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

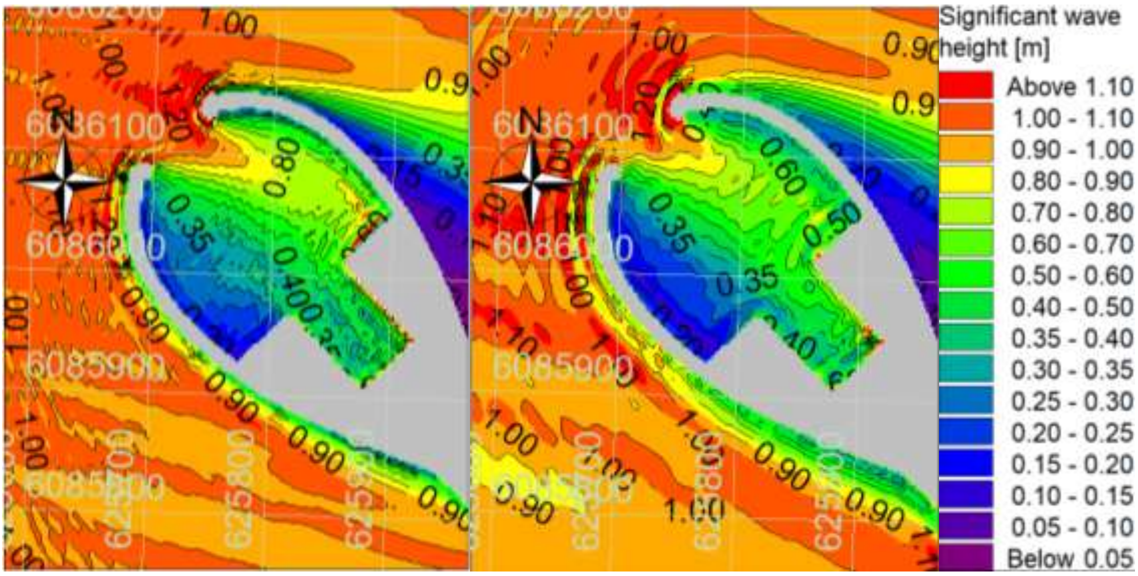


Figure B-17 *Closeup of wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

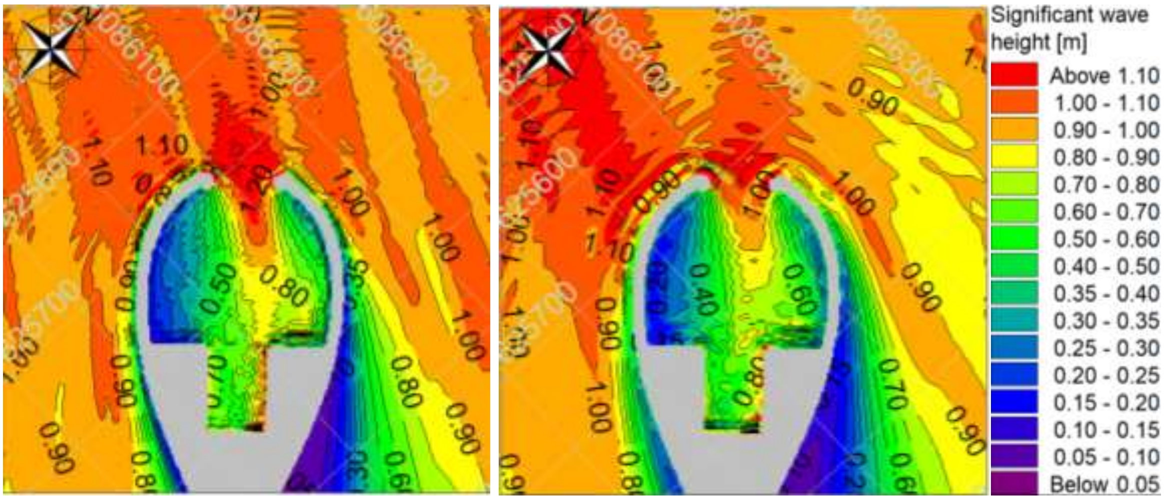


Figure B-18 *Closeup of wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

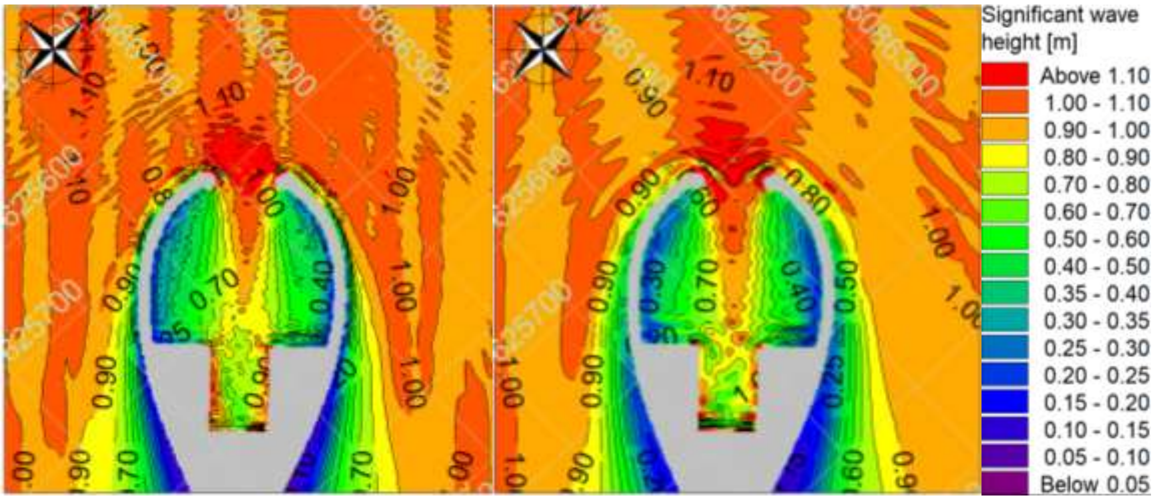


Figure B-19 *Closeup of wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

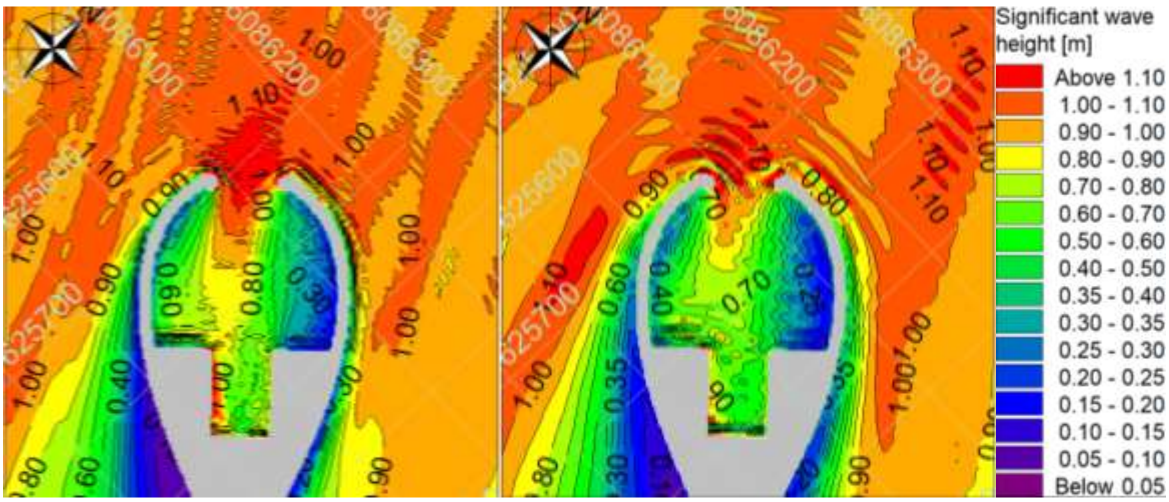


Figure B-20 *Closeup of wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

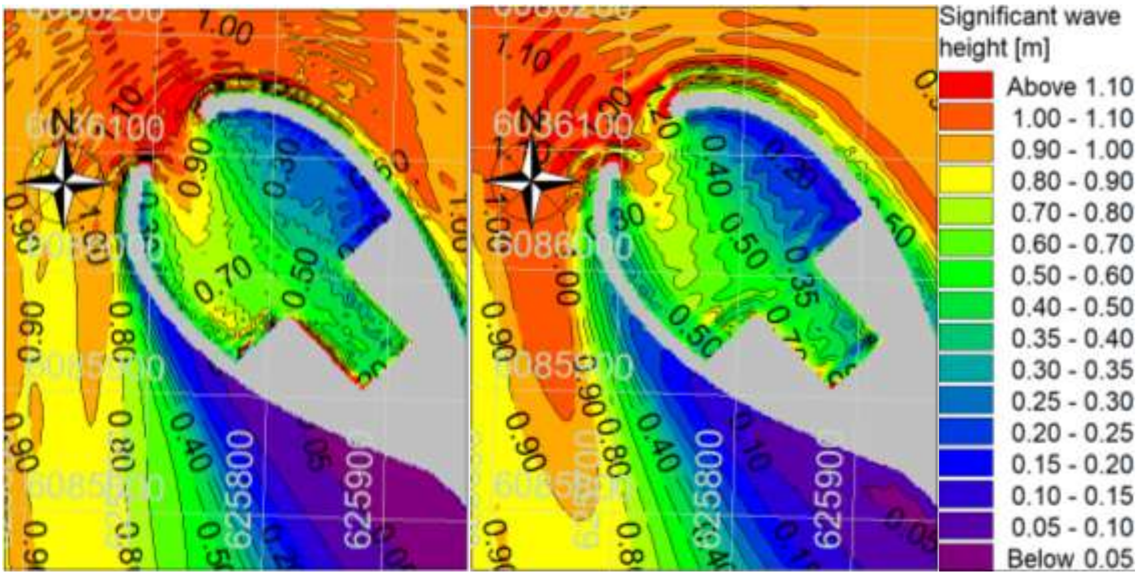


Figure B-21 *Closeup of wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

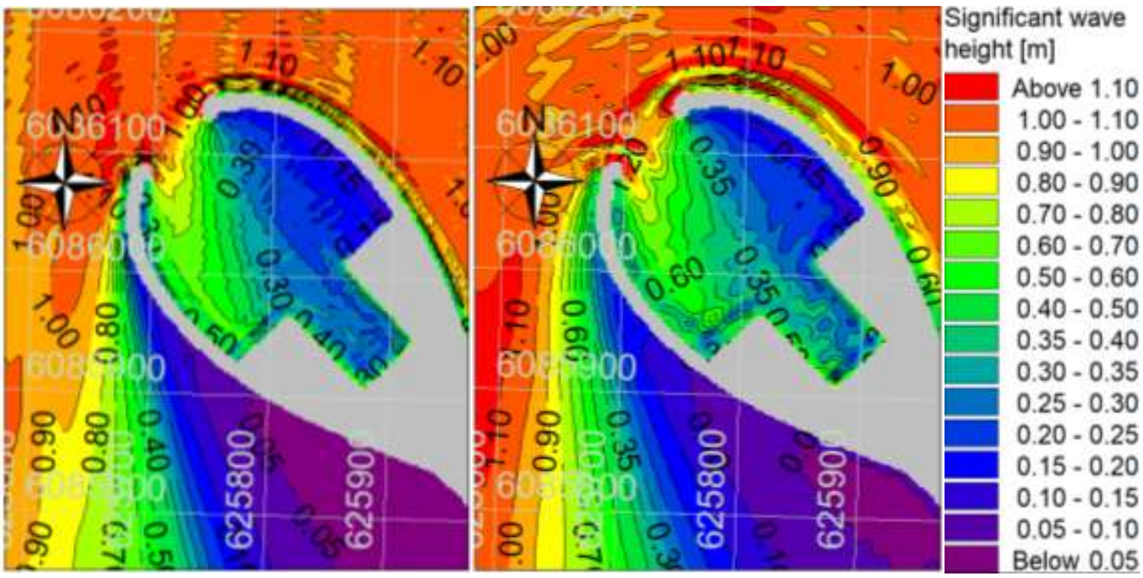


Figure B-22 *Closeup of wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

B.3 Instantaneous Surface Elevation Maps for Layout 2a

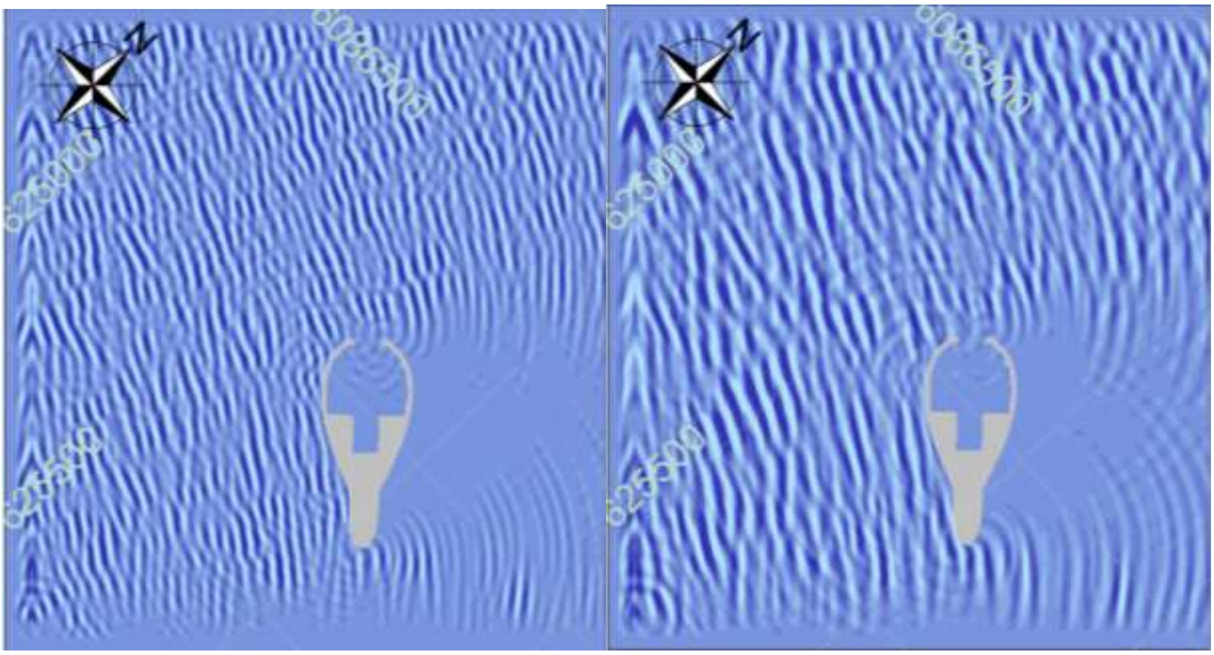


Figure B-23 Surface elevation plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec.

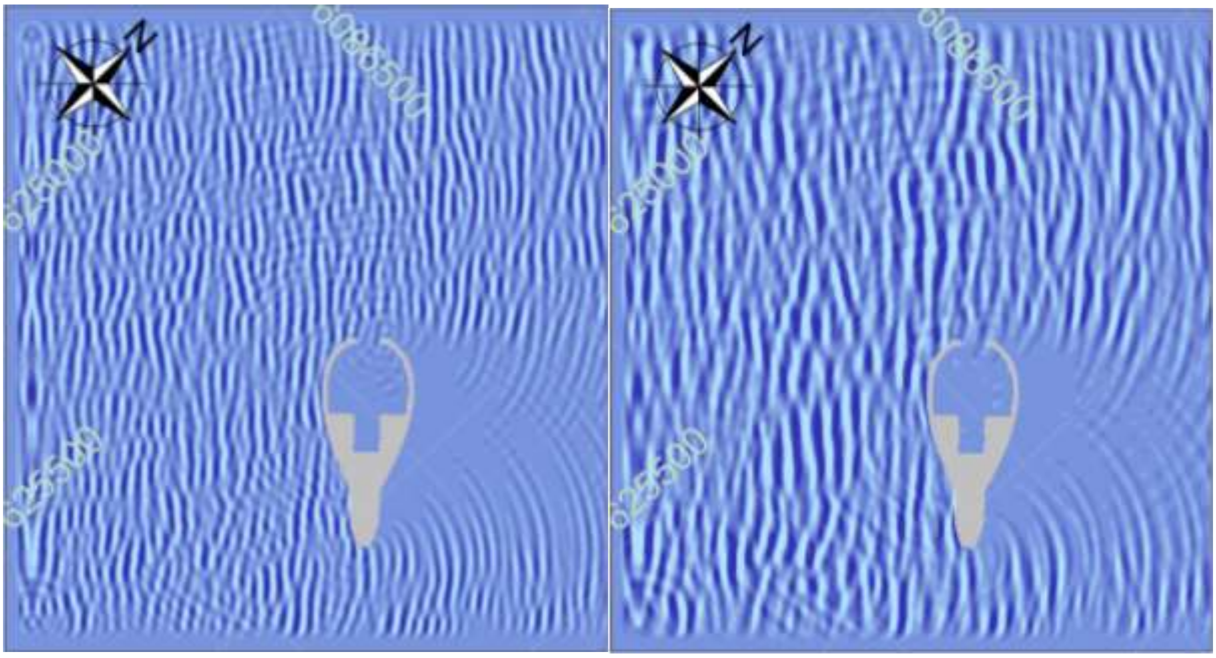


Figure B-24 Surface elevation plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec.

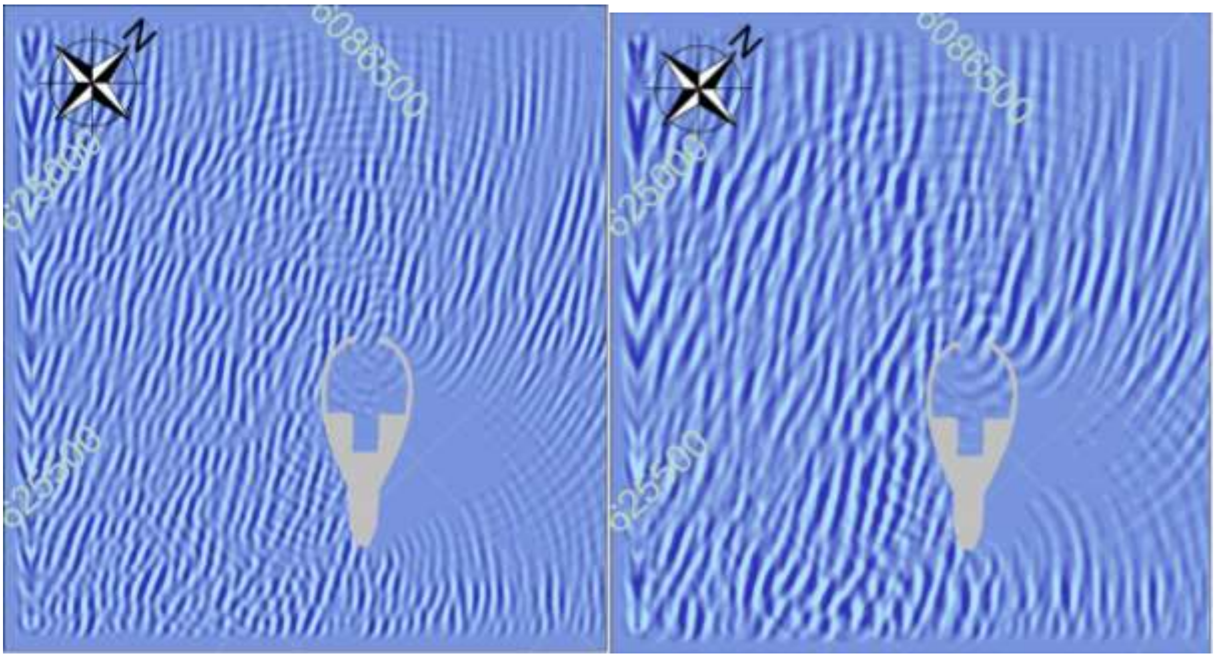


Figure B-25 Surface elevation plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec.

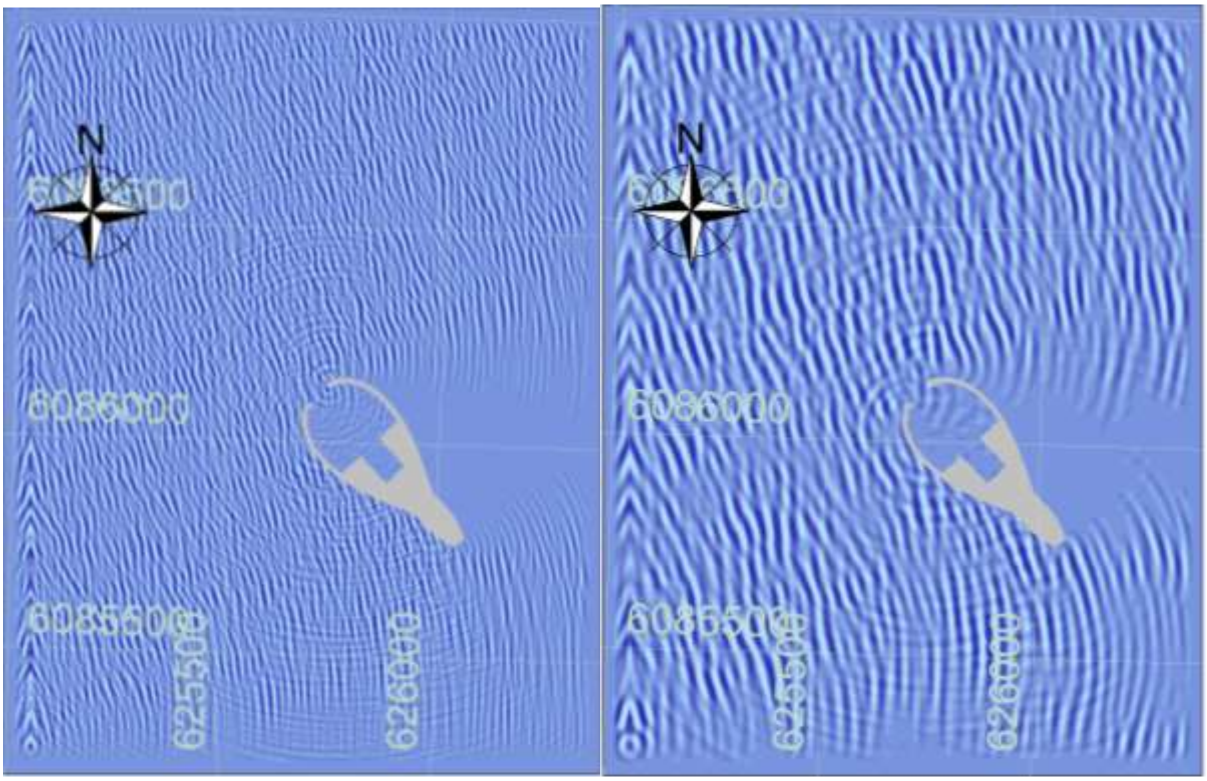


Figure B-26 Surface elevation plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.

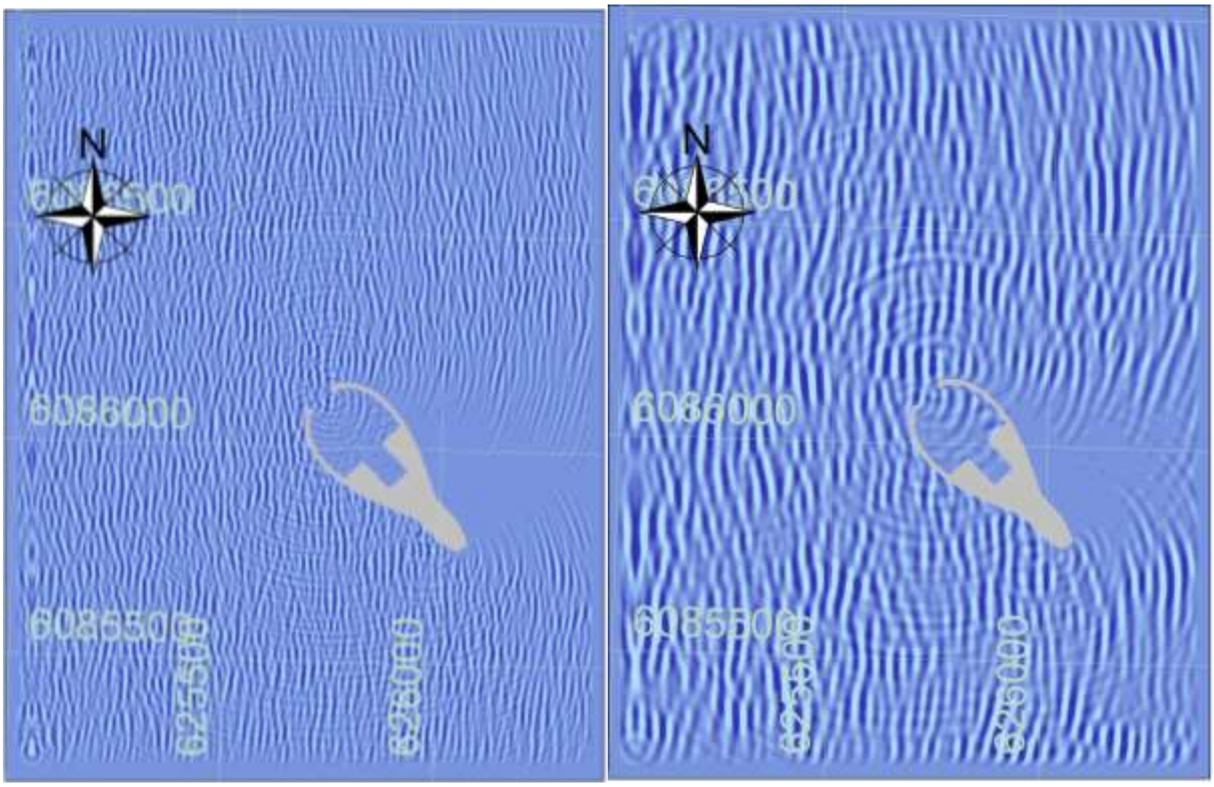


Figure B-27 *Surface elevation plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.*

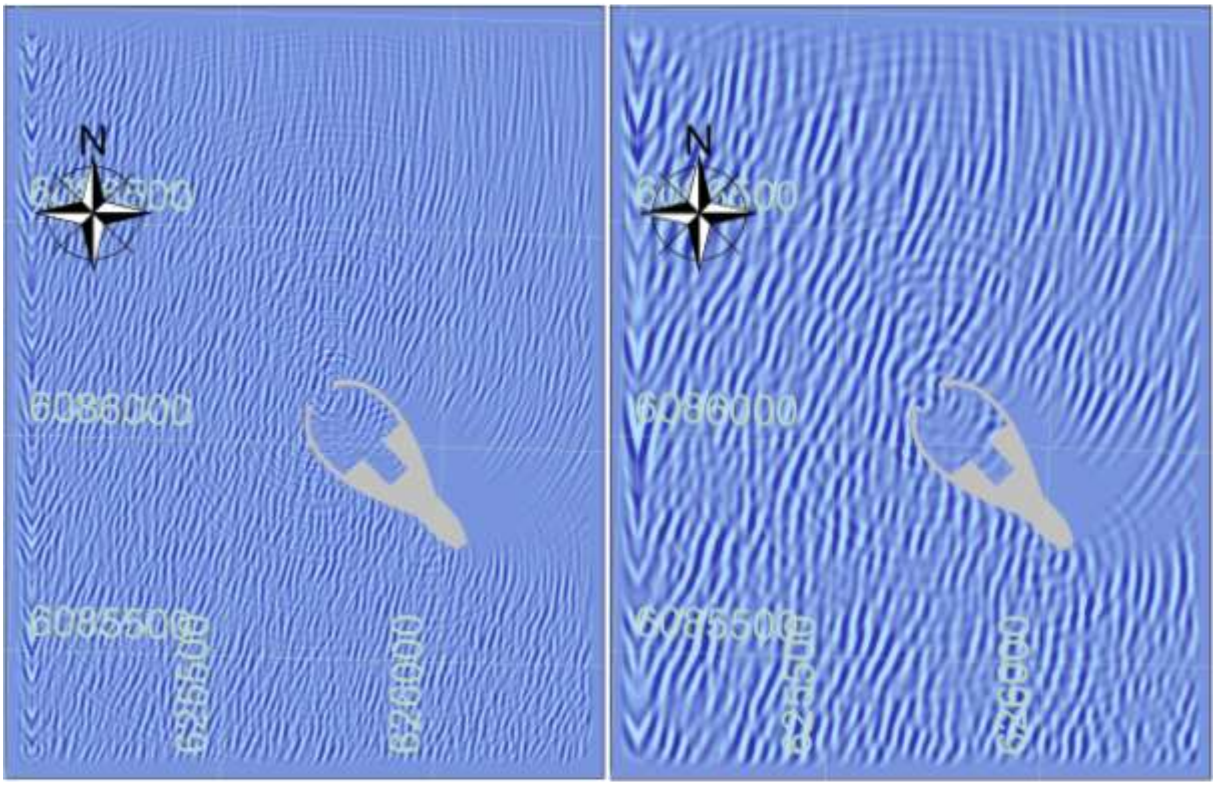


Figure B-28 *Surface elevation plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec.*

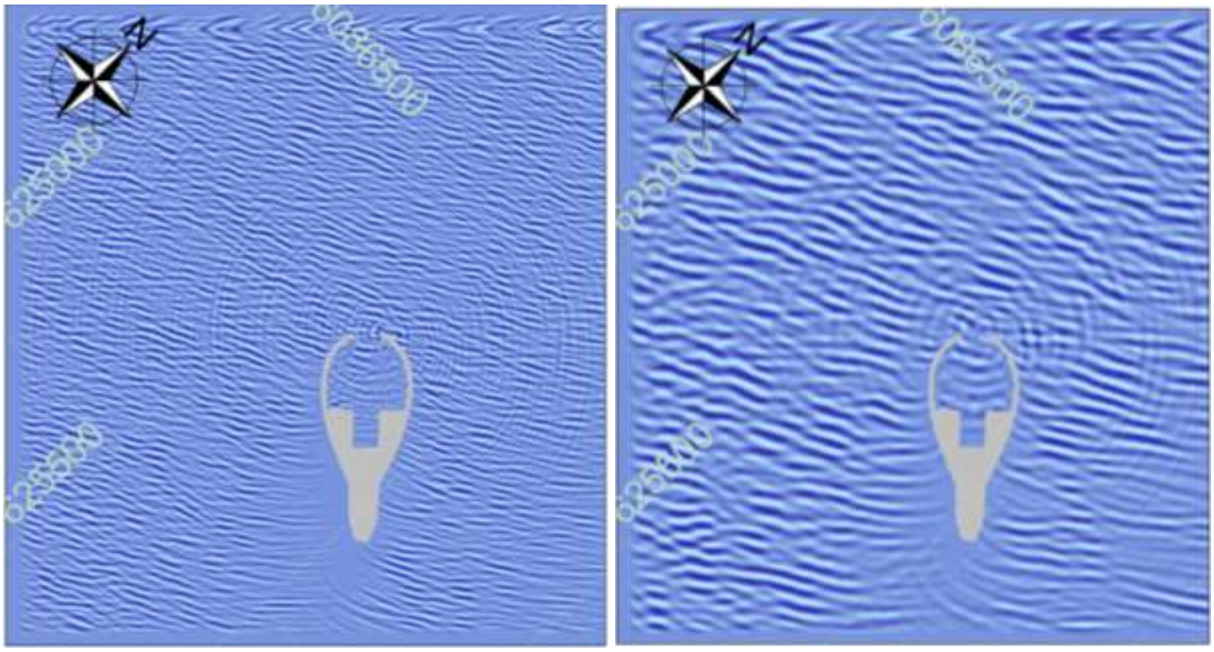


Figure B-29 Surface elevation plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

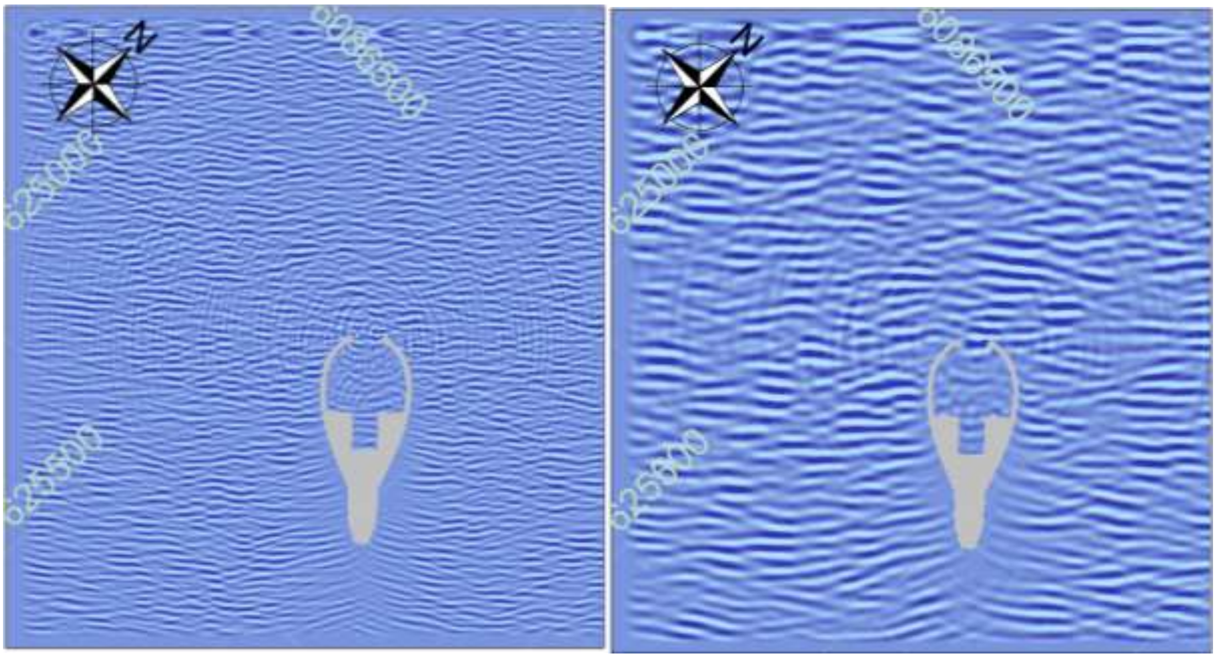


Figure B-30 Surface elevation plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

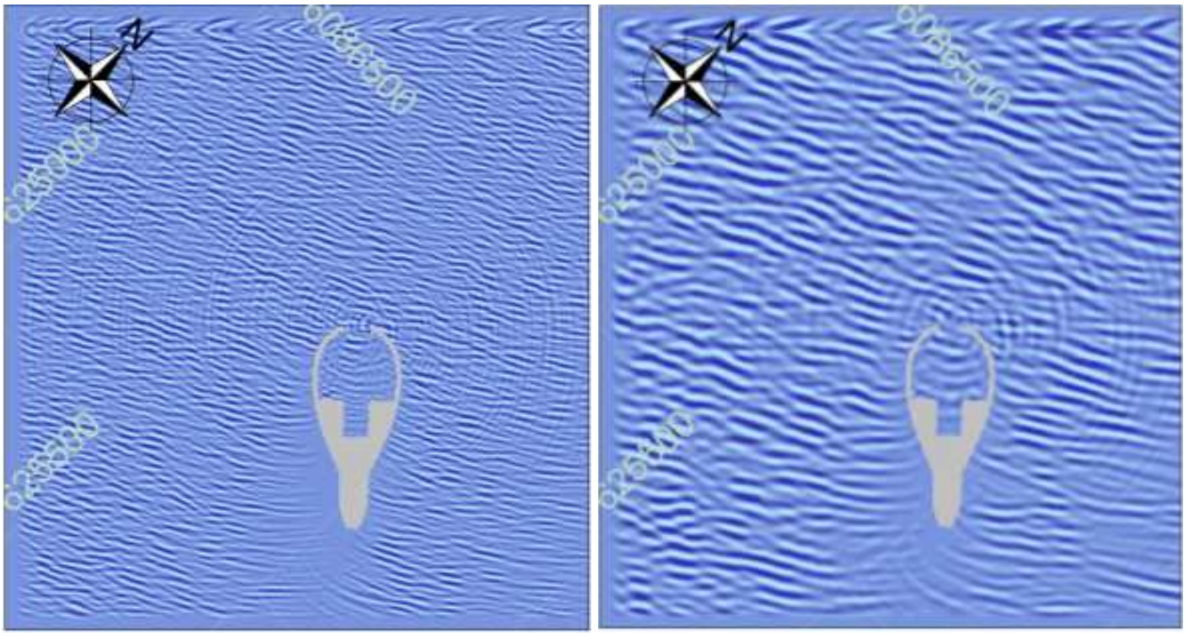


Figure B-31 Surface elevation plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

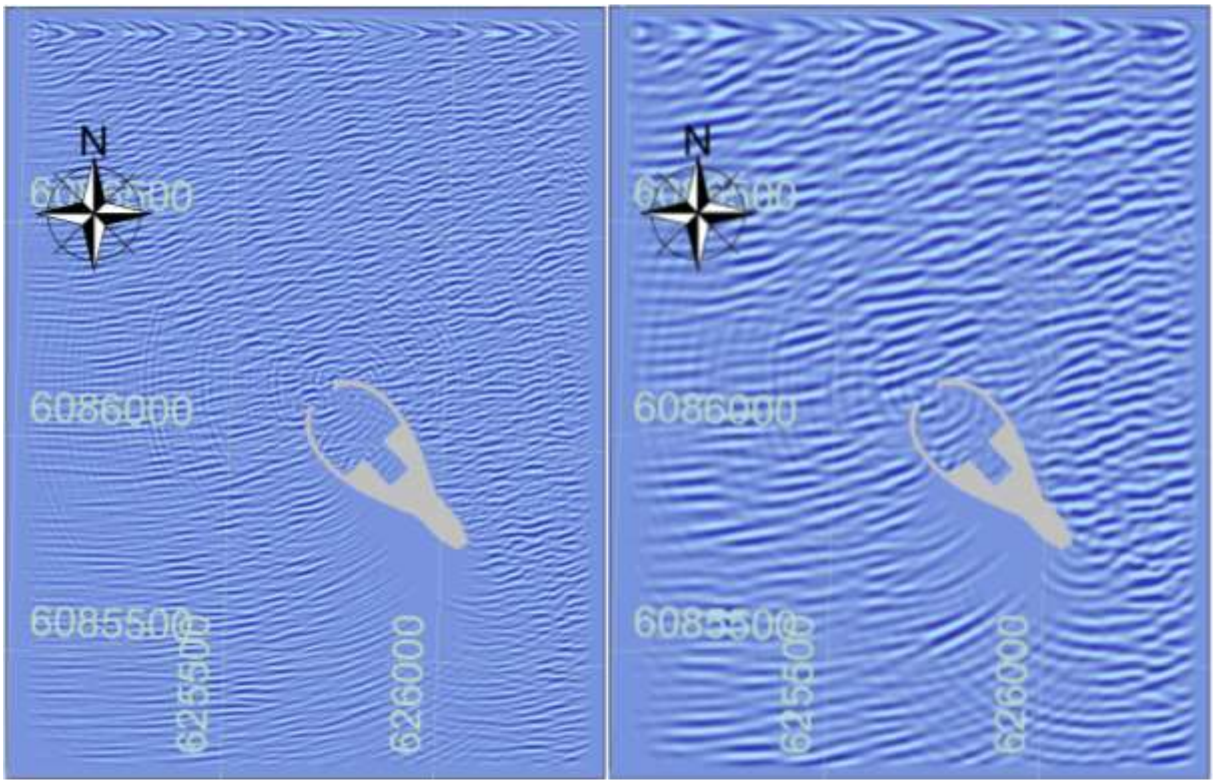


Figure B-32 Surface elevation plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

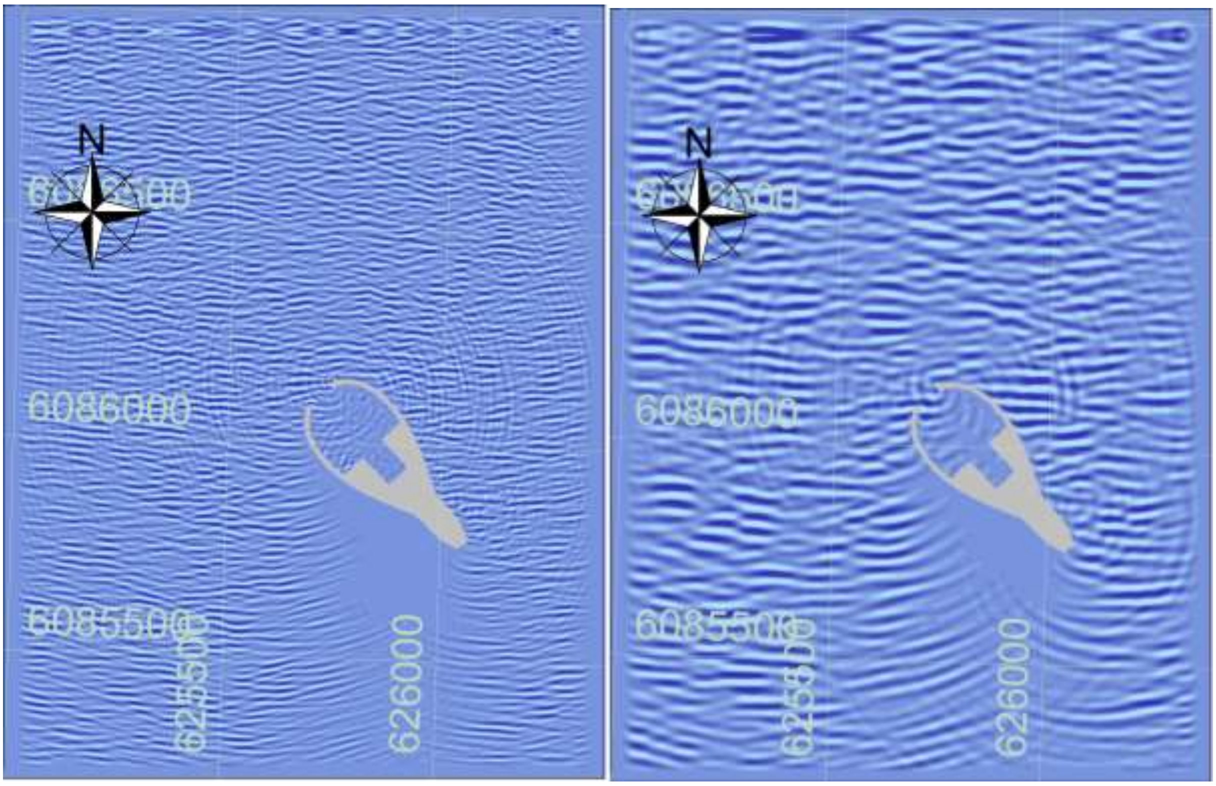


Figure B-33 Surface elevation plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

Appendix C Disturbance maps for Layout 2b

C.1 Overall Wave Disturbance Maps for Layout 2b

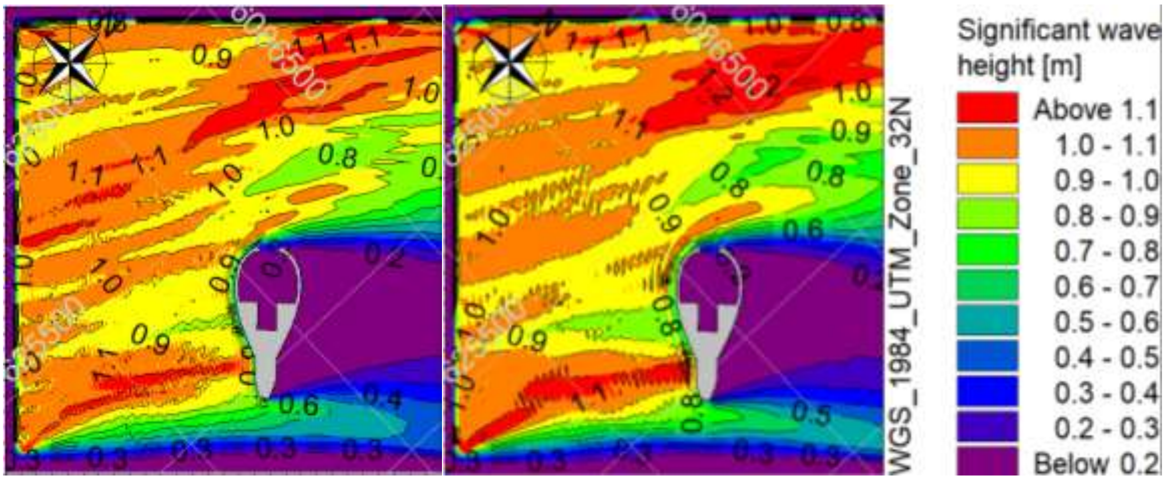


Figure C-1 Wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

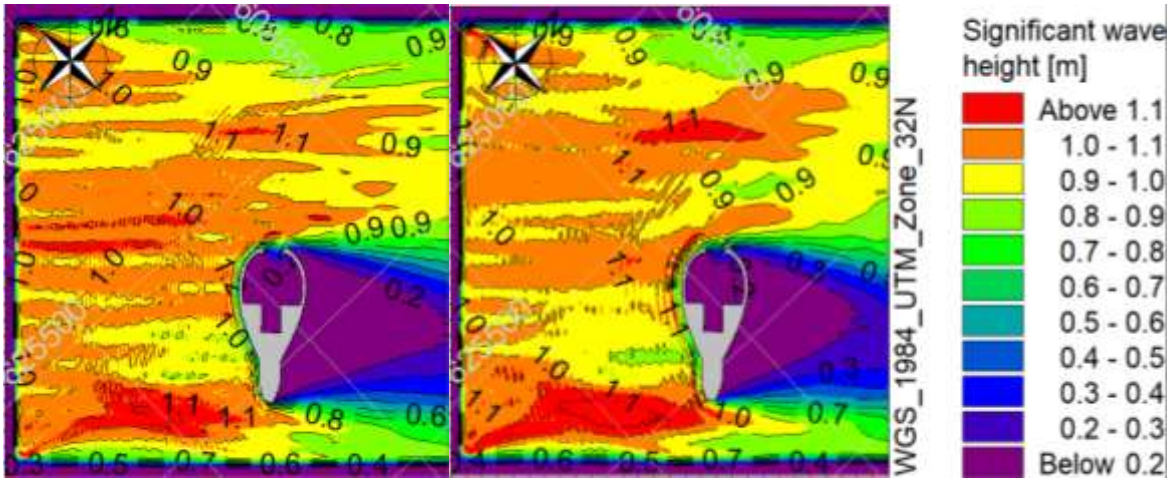


Figure C-2 Wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

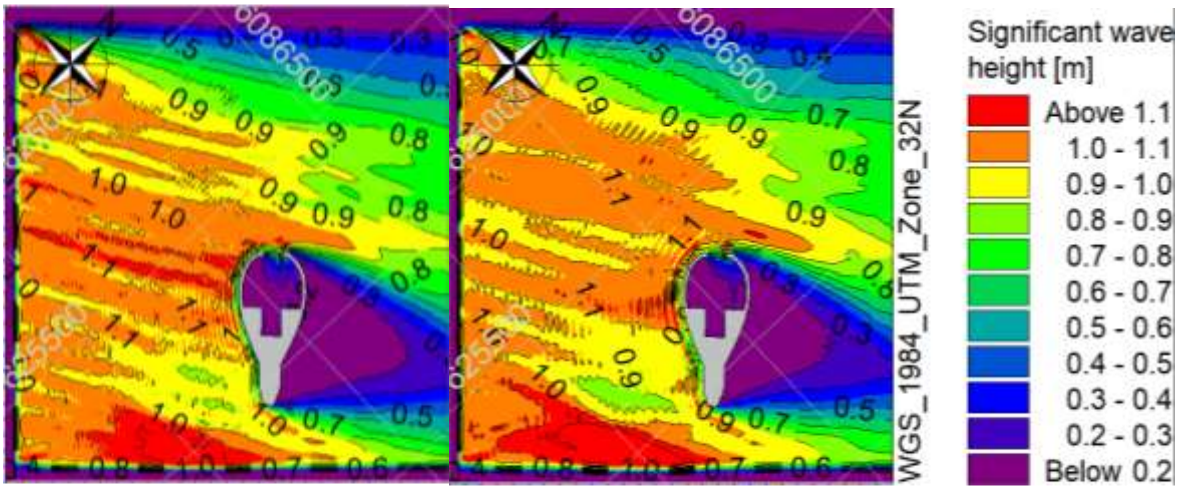


Figure C-3 *Wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp =6 sec*

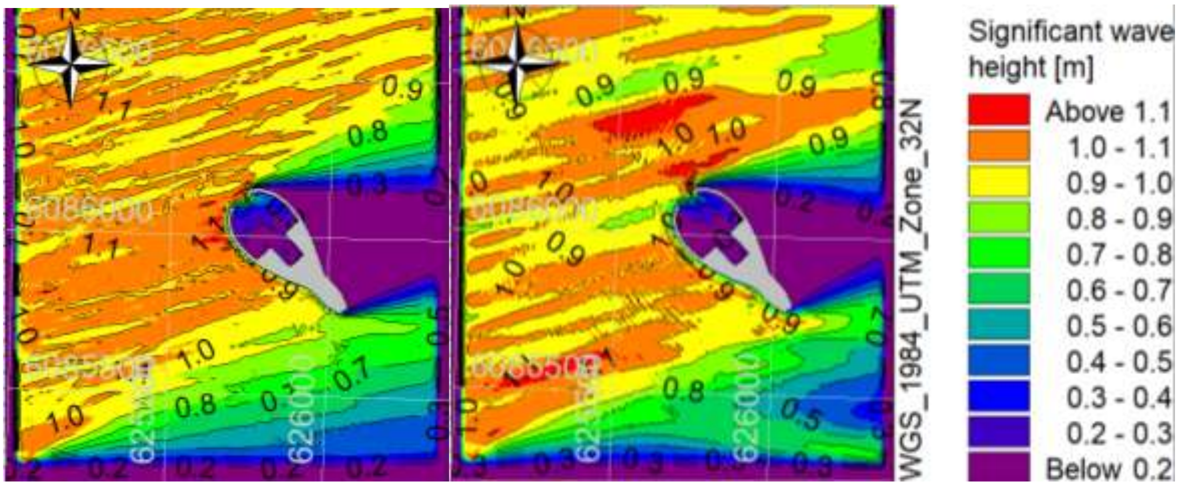


Figure C-4 *Wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

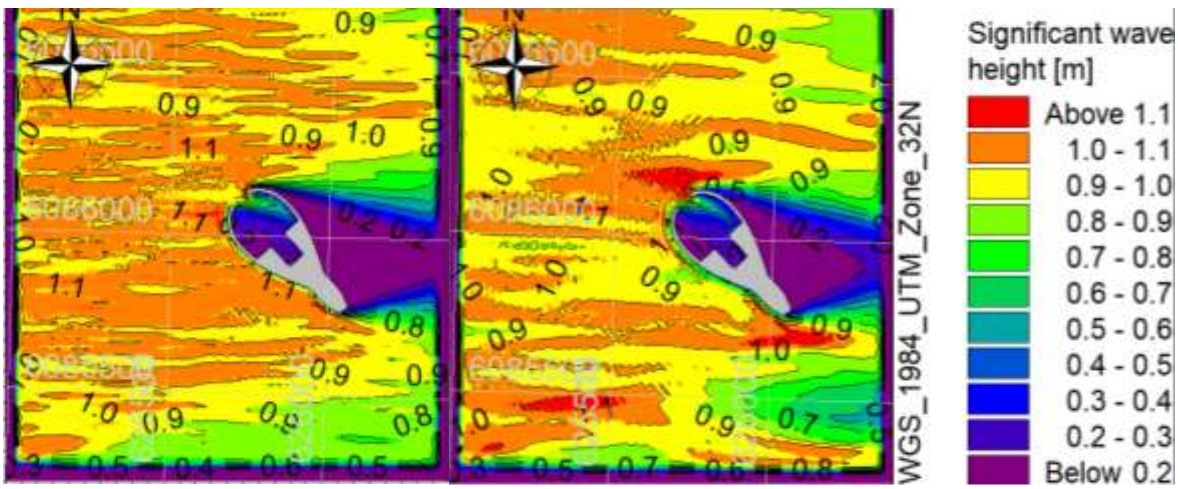


Figure C-5 *Wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

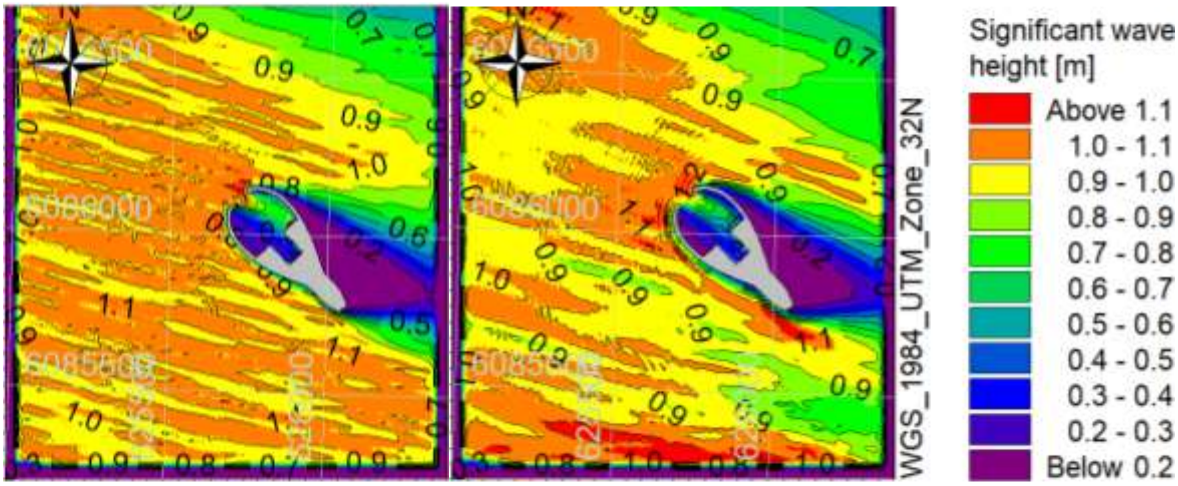


Figure C-6 *Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

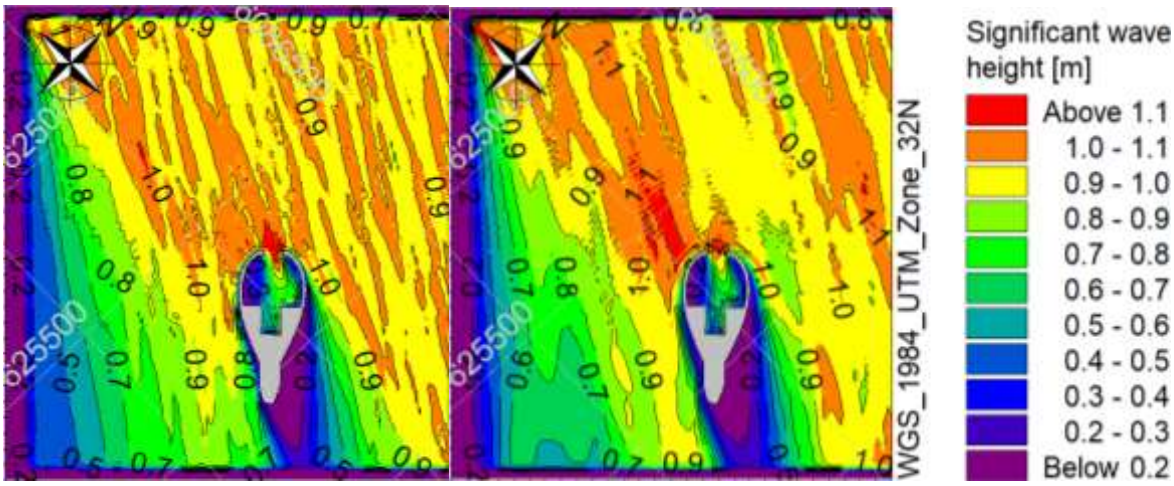


Figure C-7 *Wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

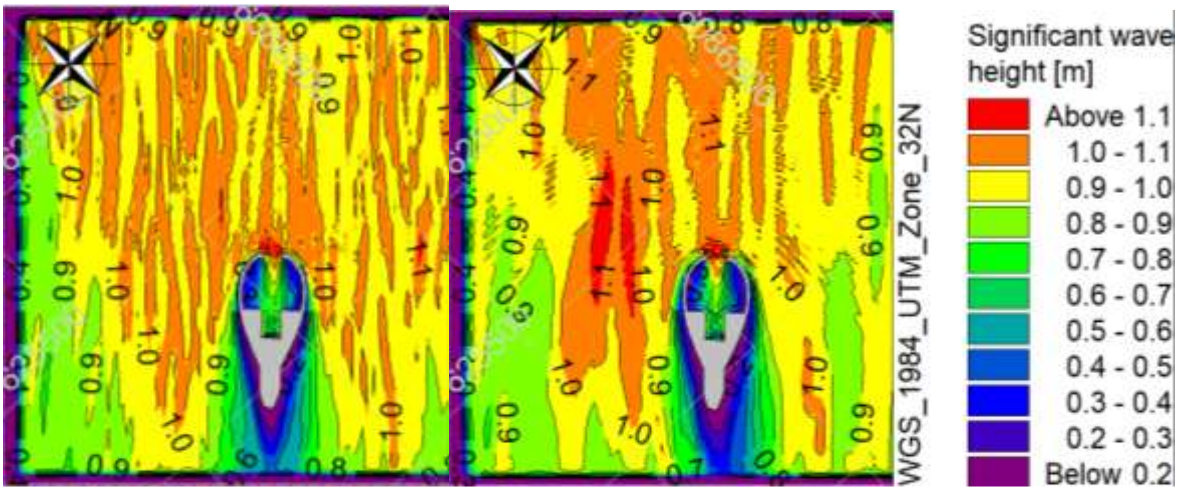


Figure C-8 *Wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

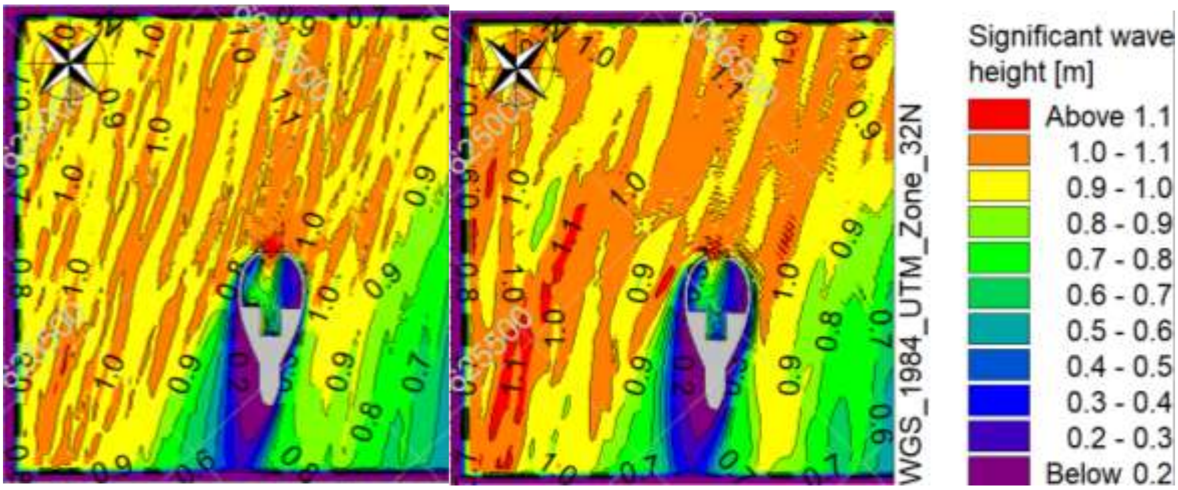


Figure C-9 Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

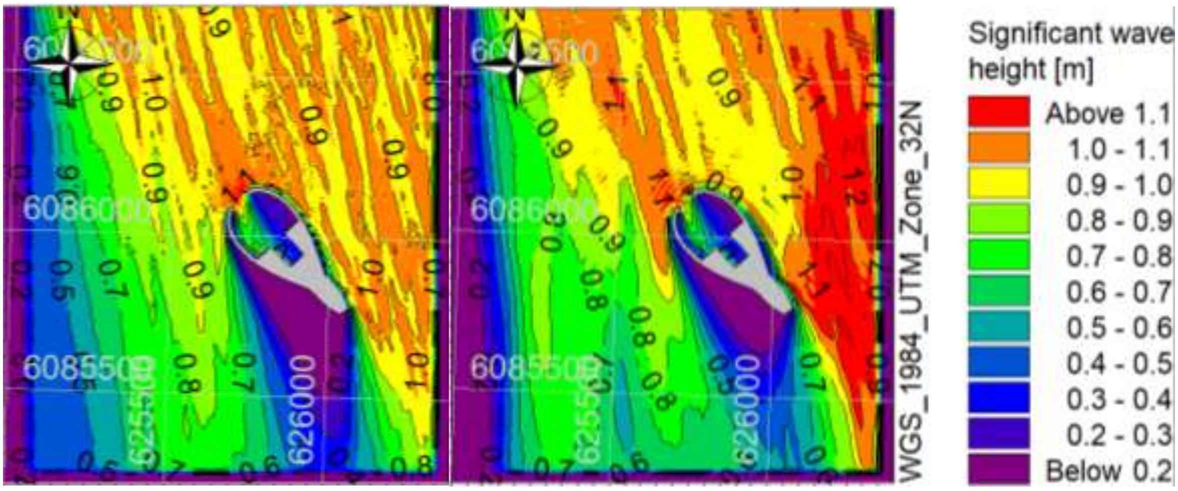


Figure C-10 Wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

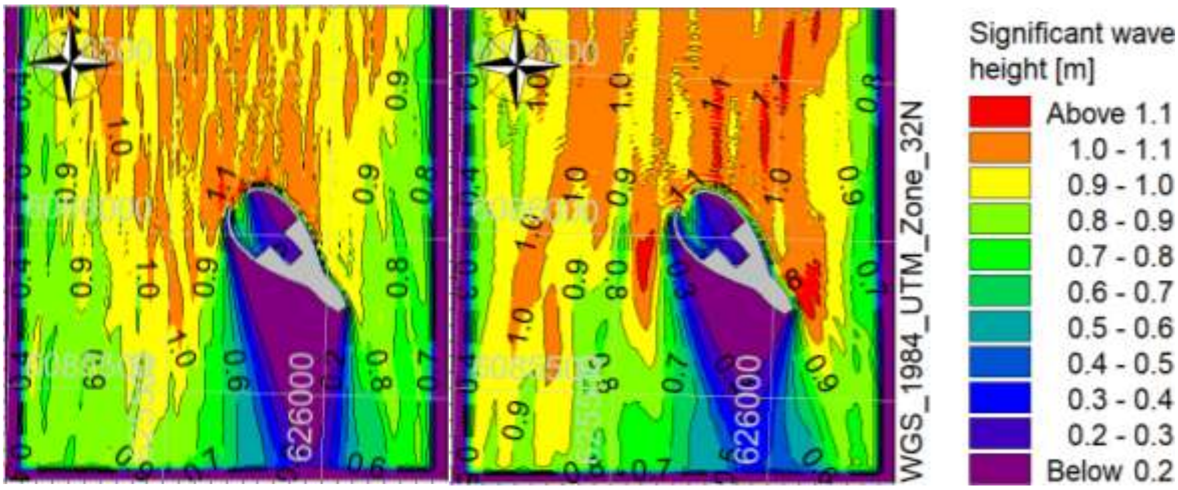


Figure C-11 Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

C.2 Closeup of Wave Disturbance Maps for Layout 2b

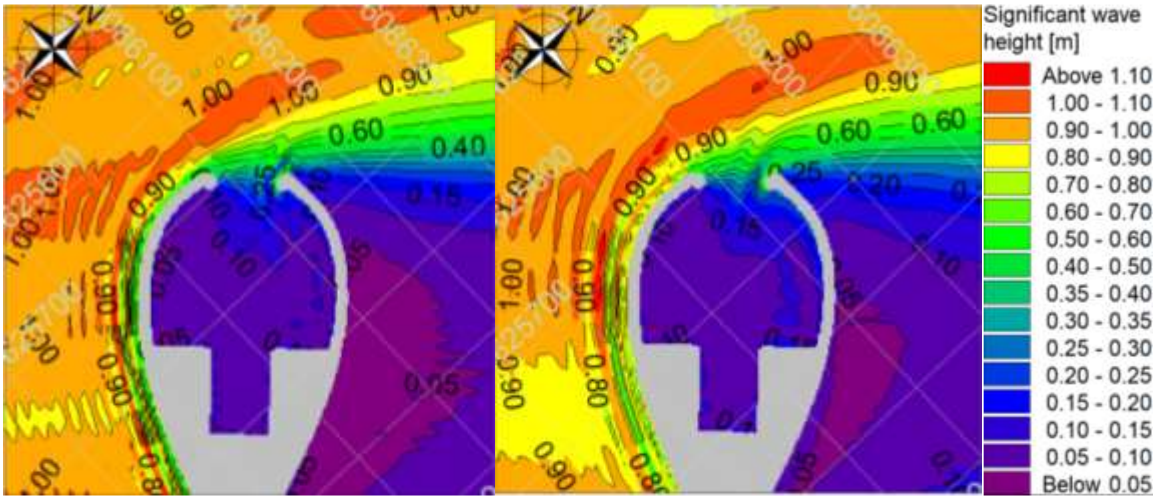


Figure C-12 Wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

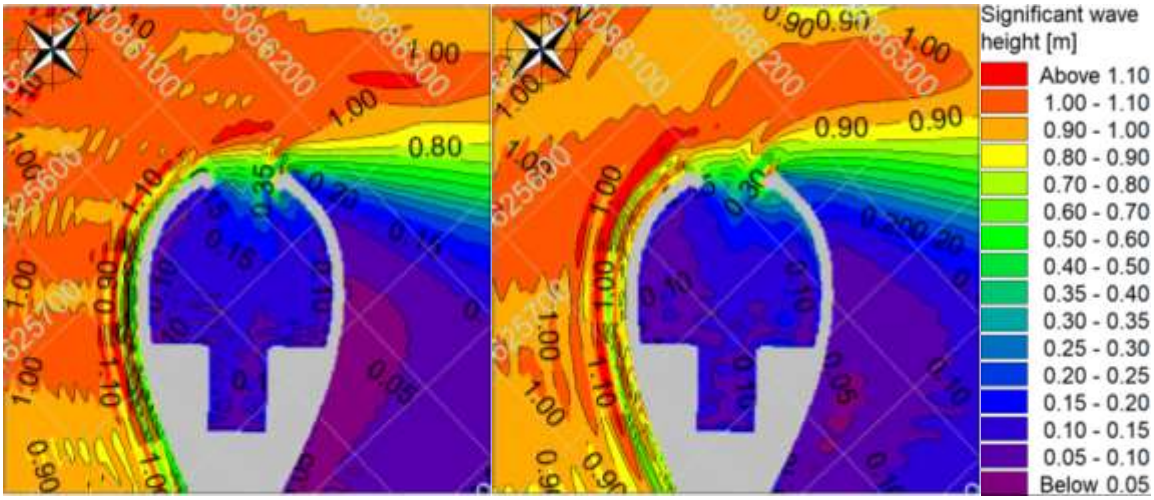


Figure C-13 Wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

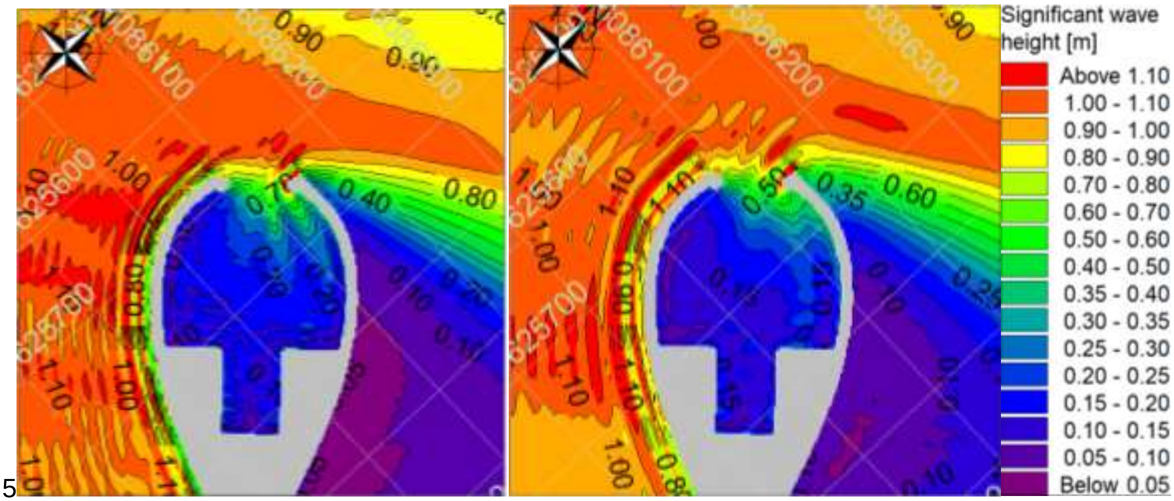
5


Figure C-14 Wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

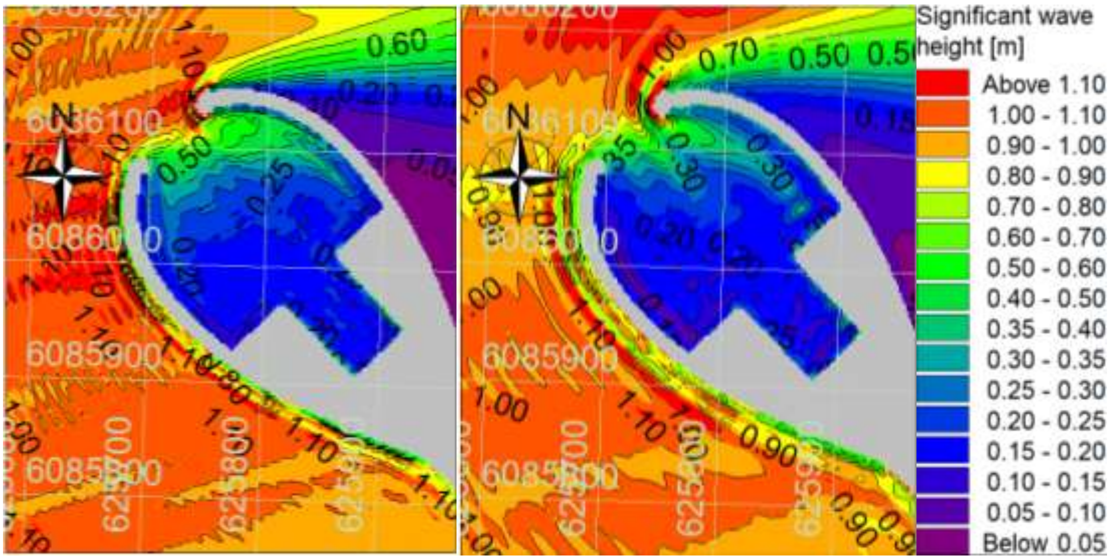


Figure C-15 Wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

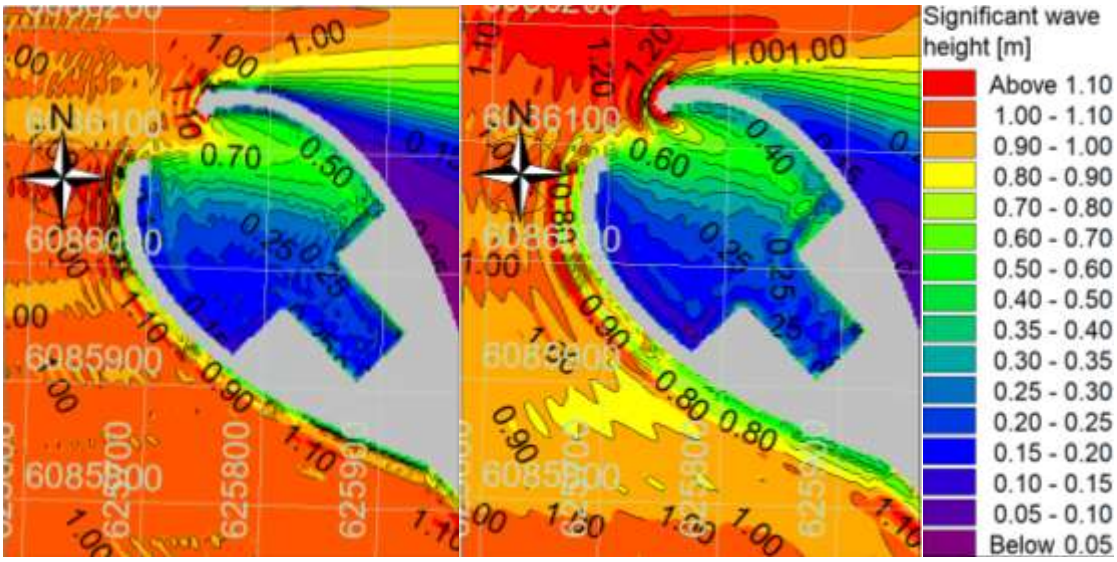


Figure C-16 Wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

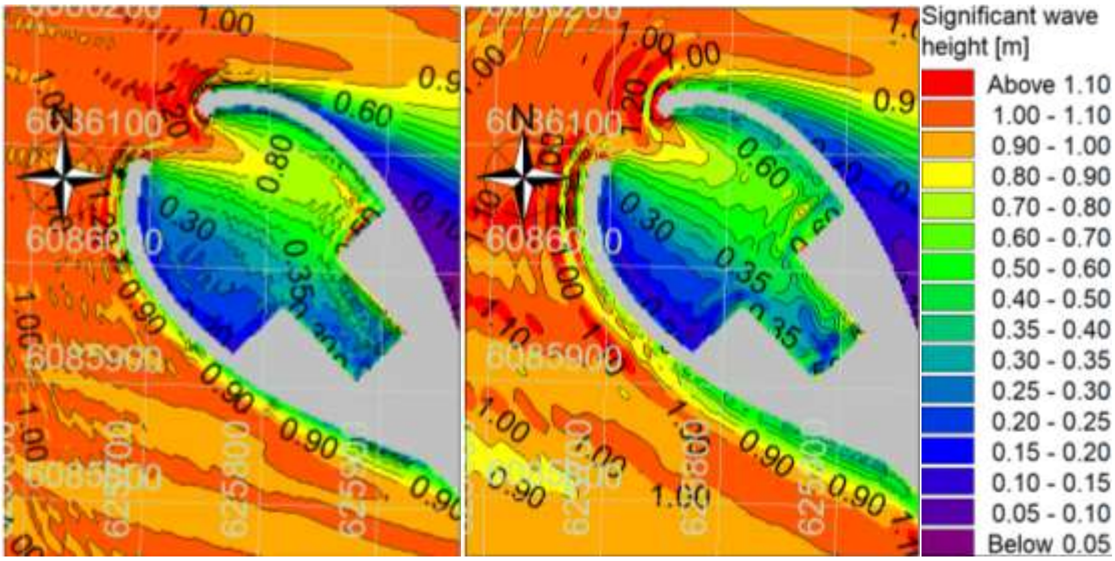


Figure C-17 *Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

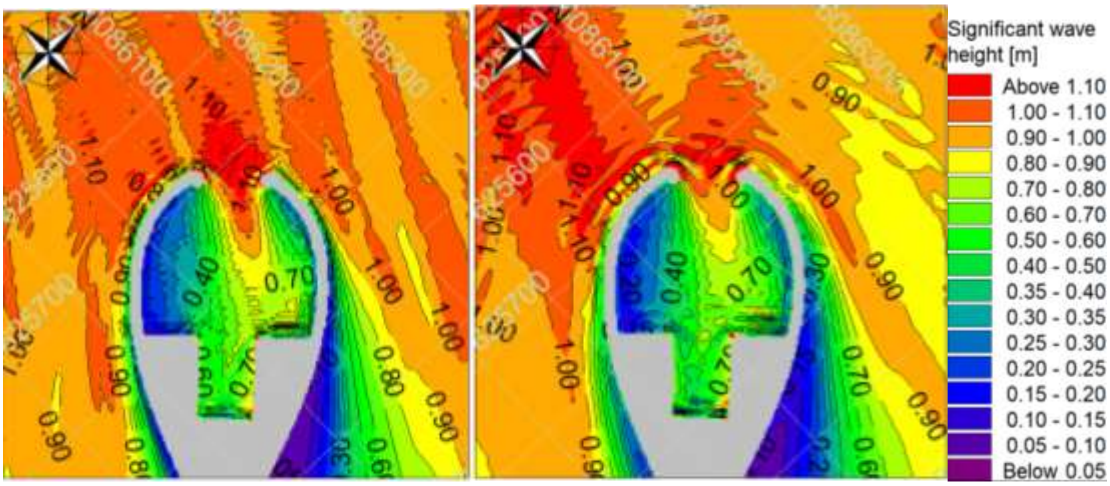


Figure C-18 *Wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

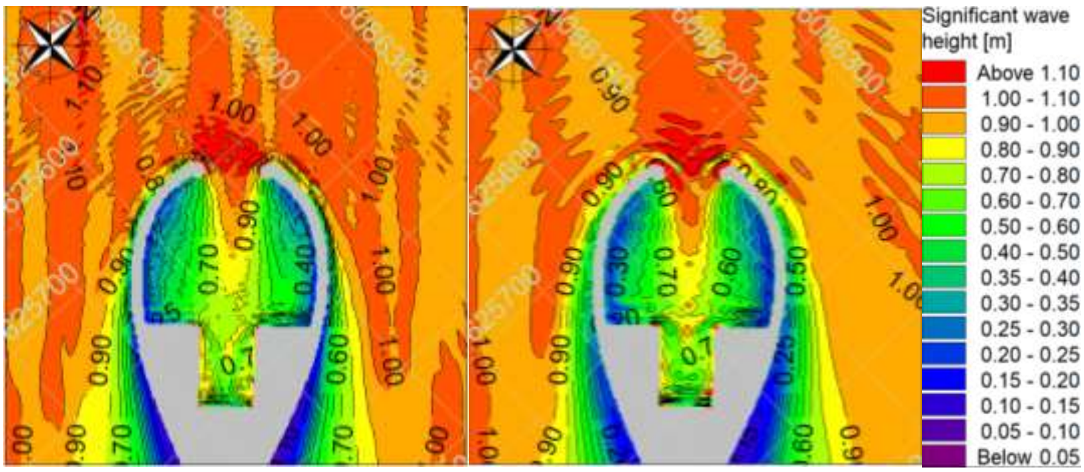


Figure C-19 *Wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

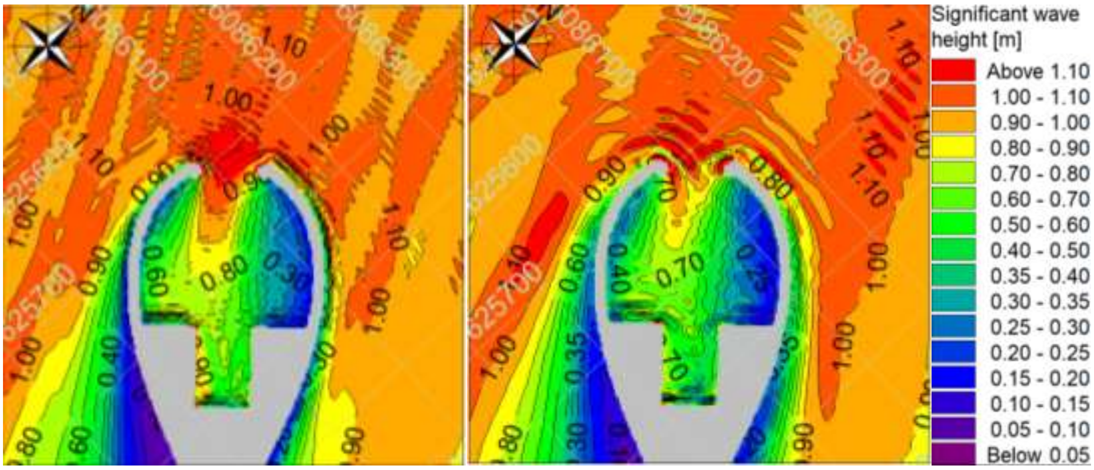


Figure C-20 Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

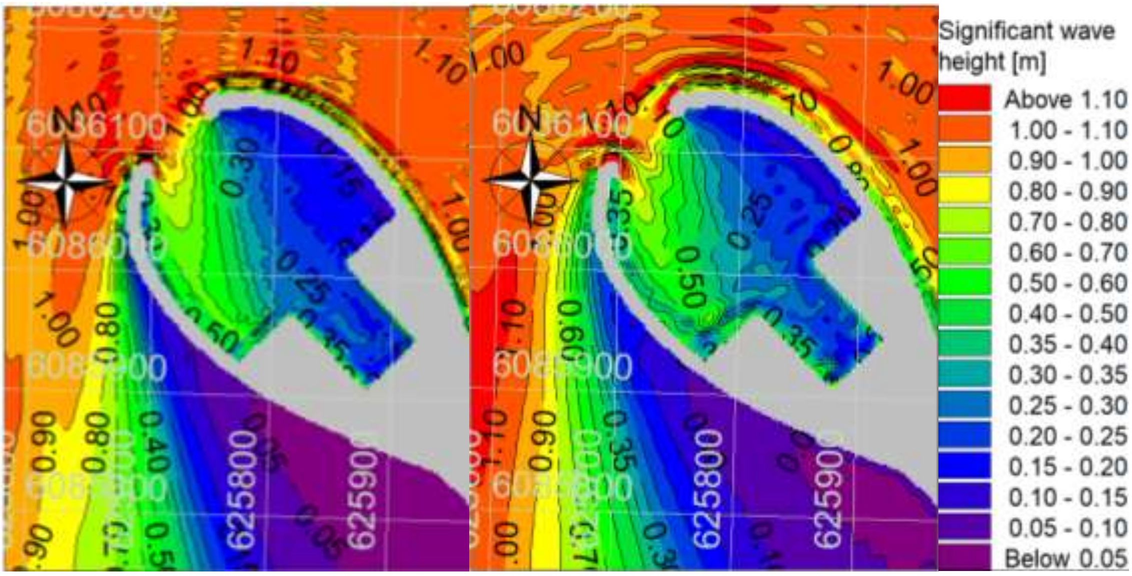


Figure C-21 Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

C.3 Instantaneous Surface Elevation Maps for Layout 2b

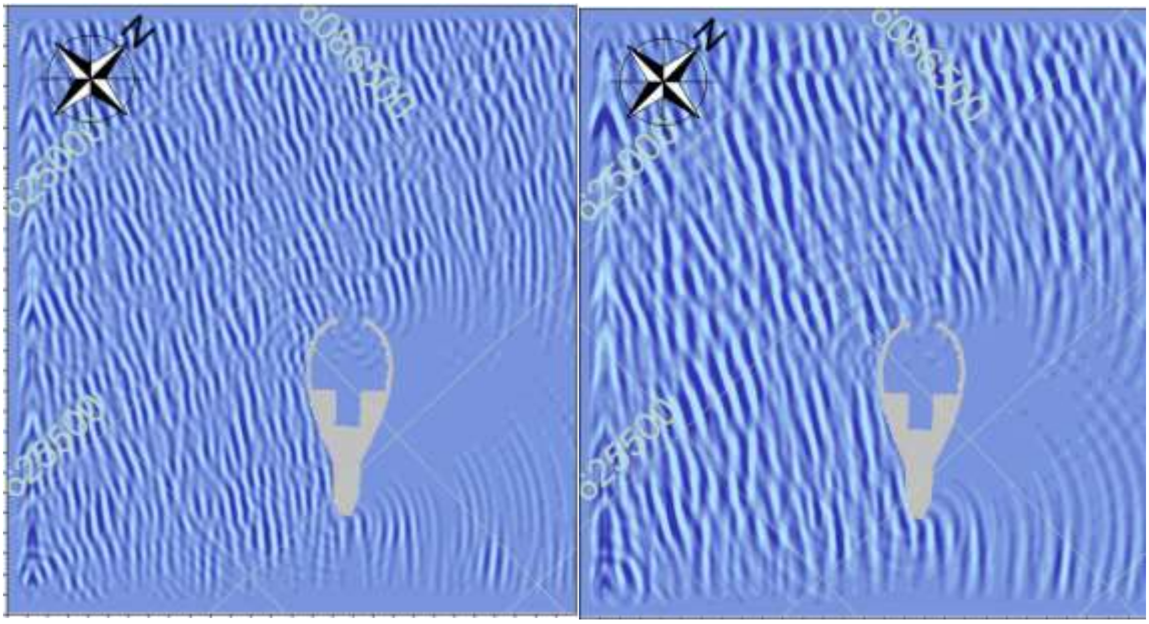


Figure C-22 Surface elevation plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec

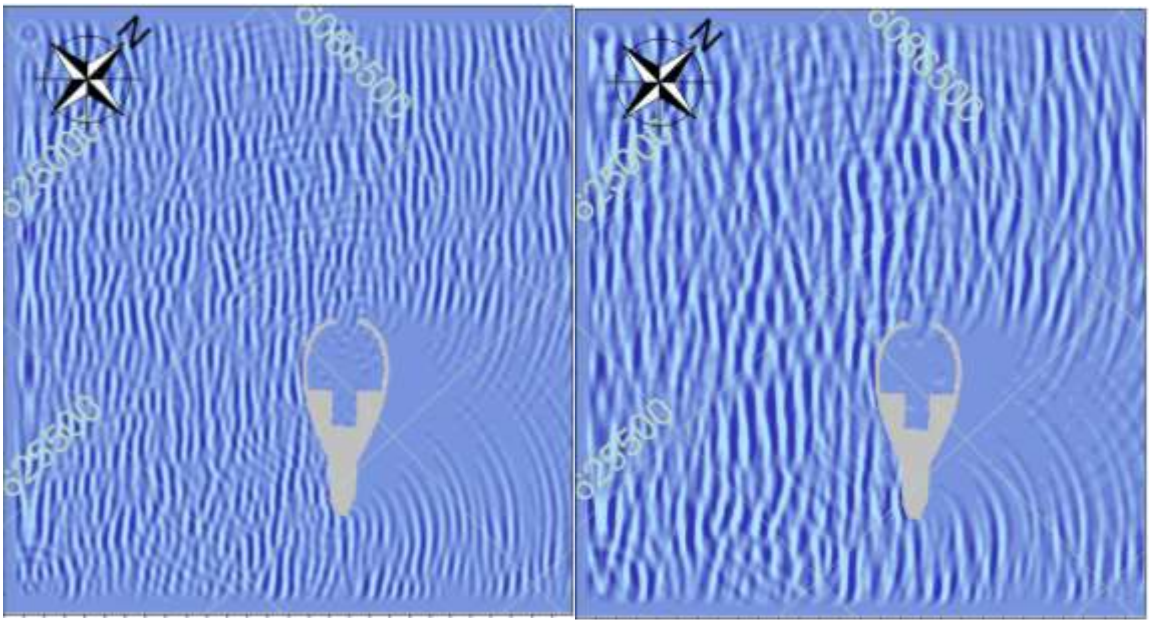


Figure C-23 Surface elevation plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec

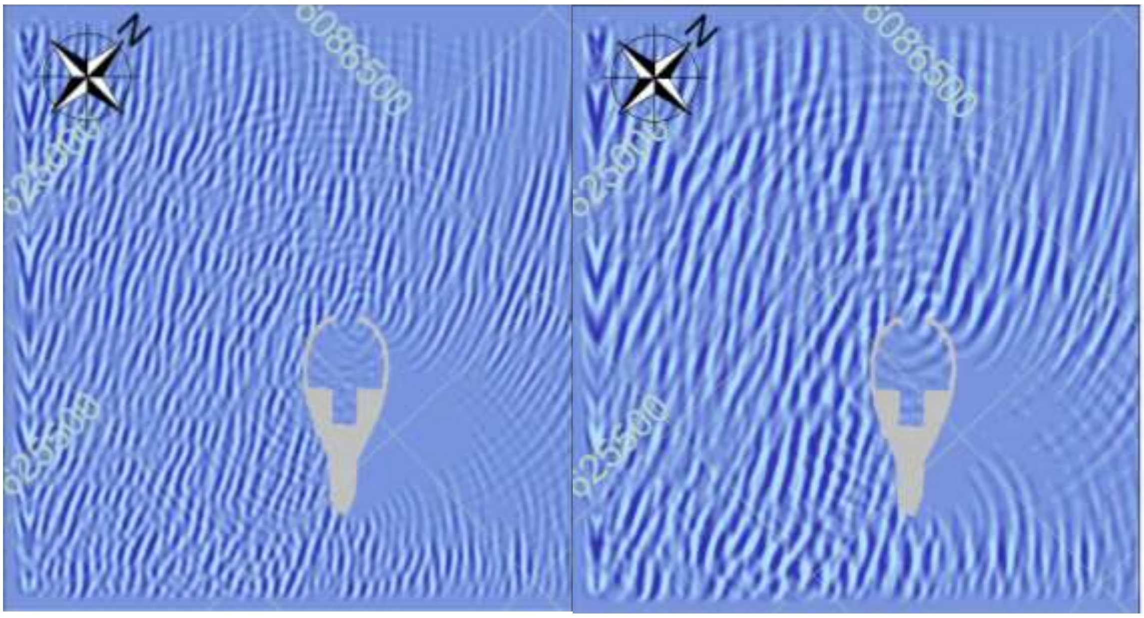


Figure C-24 Surface elevation plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp = 6 sec

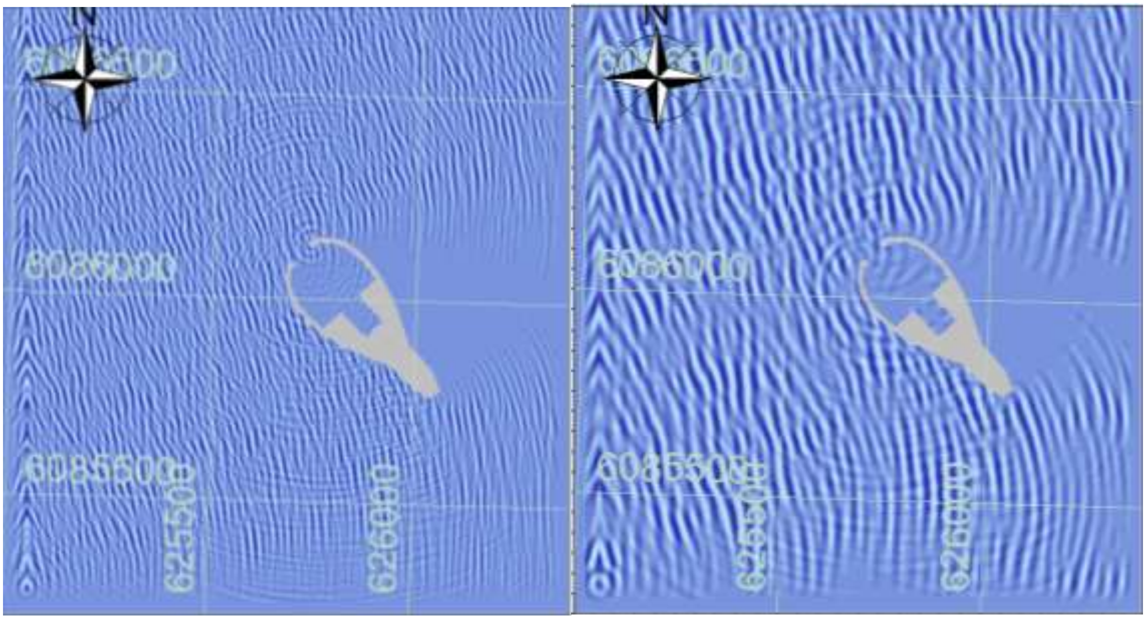


Figure C-25 Surface elevation plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

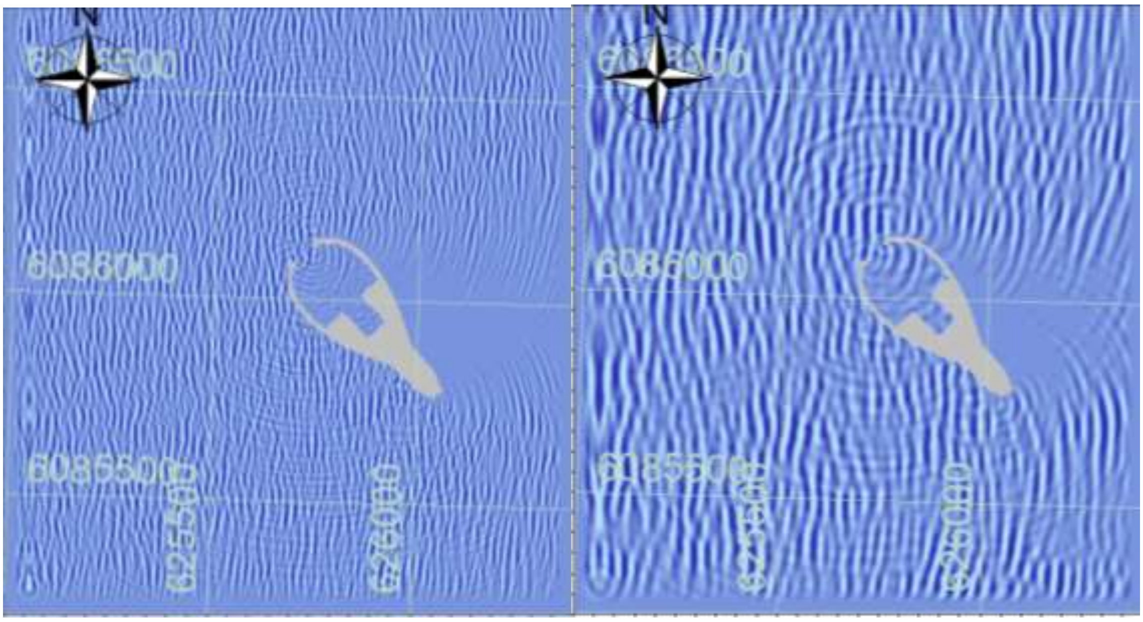


Figure C-26 *Surface elevation plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec'*

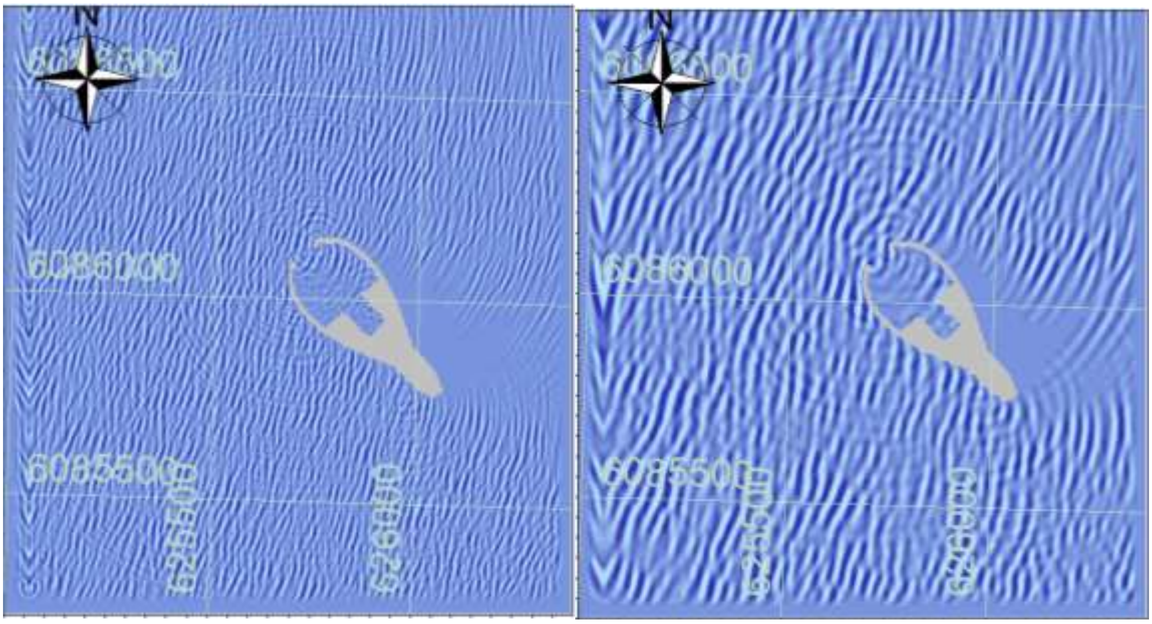


Figure C-27 *Surface elevation plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec*

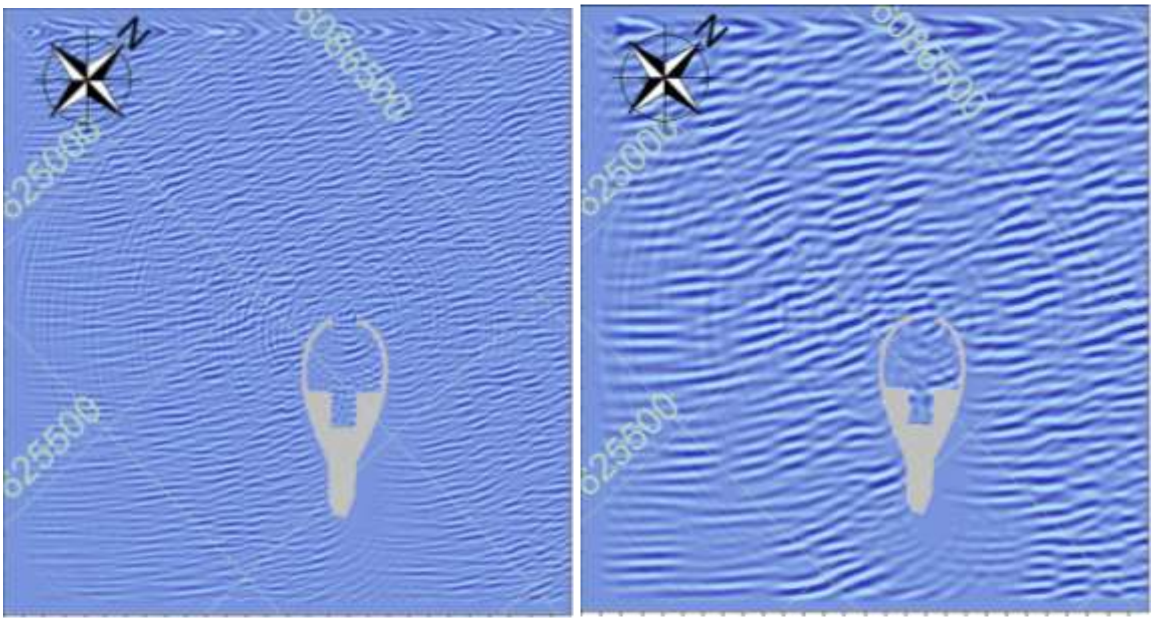


Figure C-28 Surface elevation plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

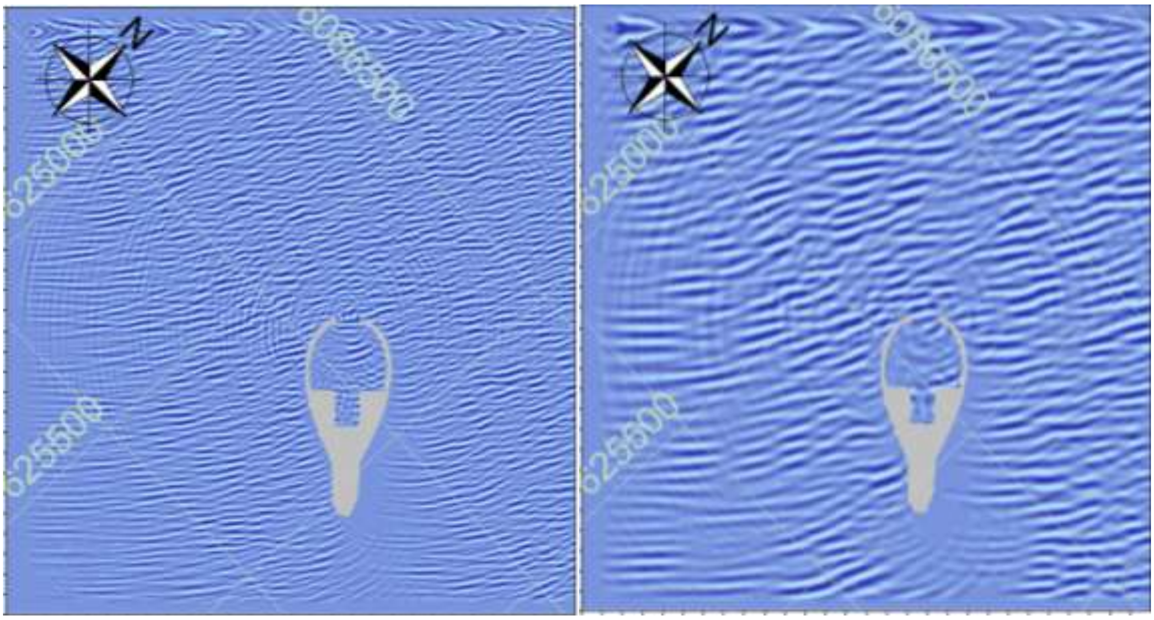


Figure C-29 Surface elevation plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

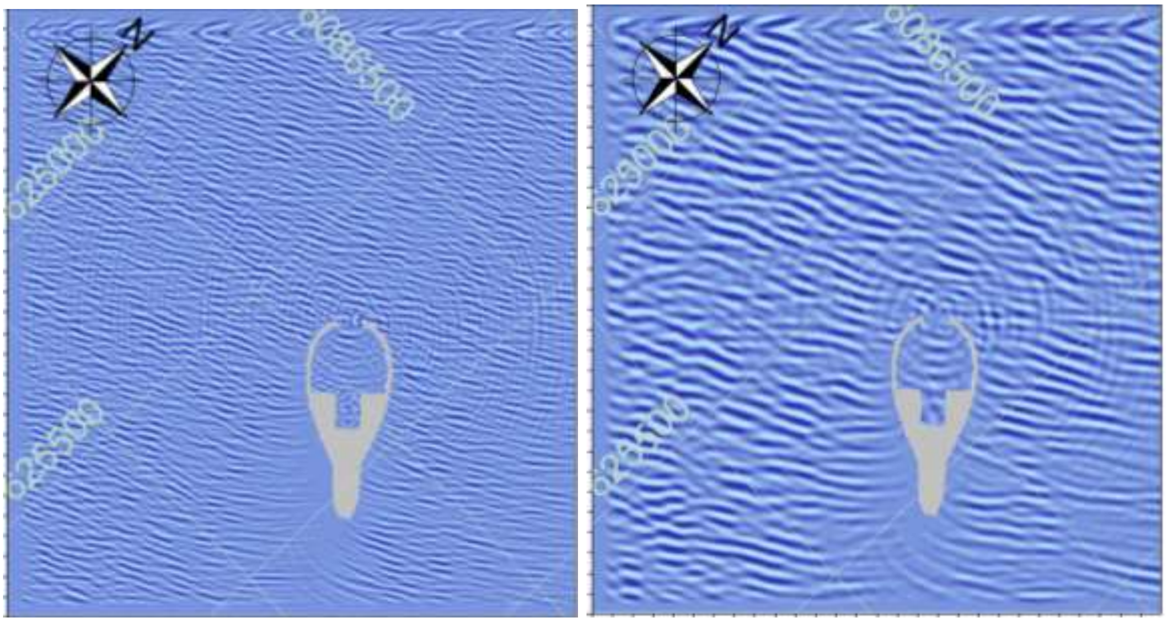


Figure C-30 Surface elevation plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

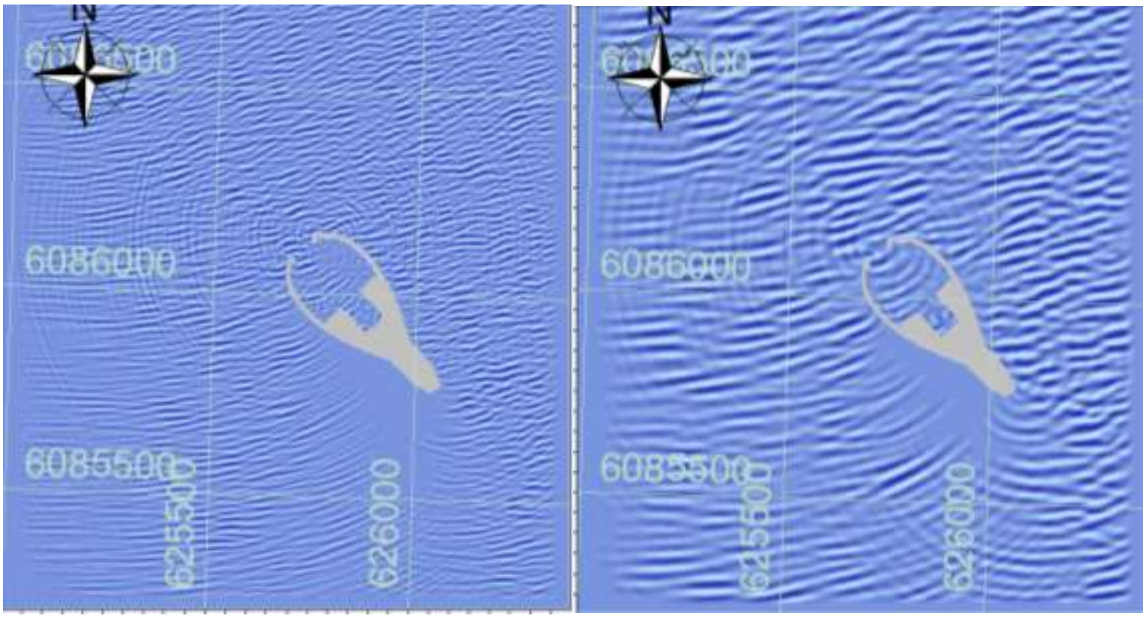


Figure C-31 Surface elevation plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

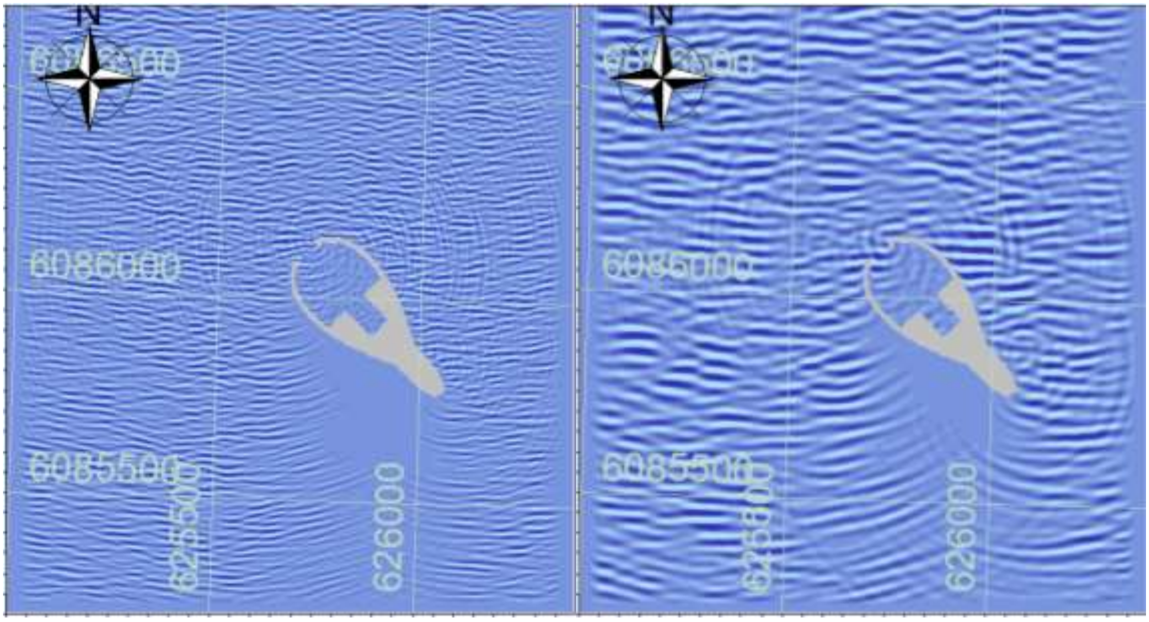


Figure C-32 Surface elevation plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp = 5 sec

Appendix D Disturbance maps for Layout 2c

D.1 Wave Disturbance Maps for Layout 2c

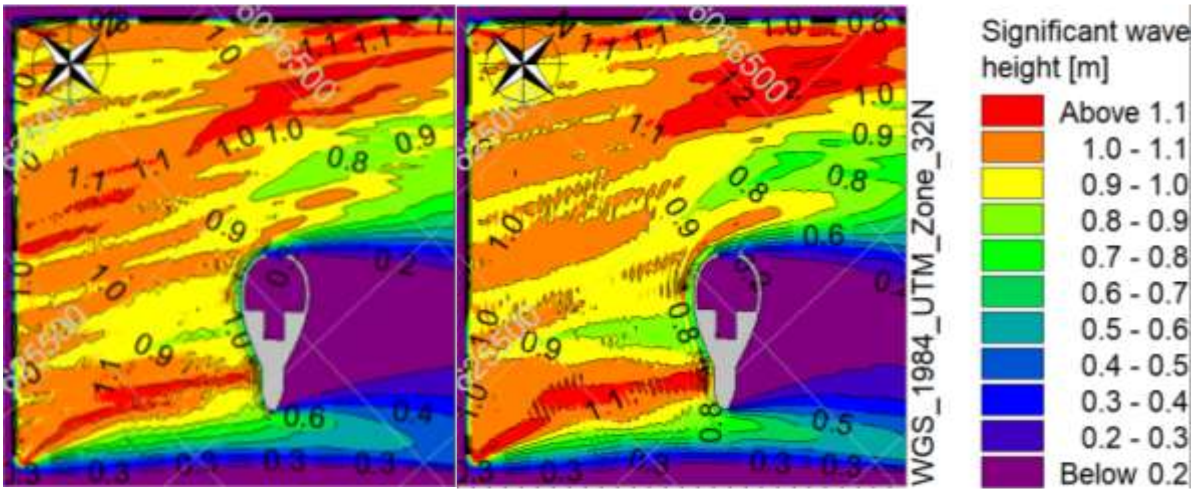


Figure D-1 Wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

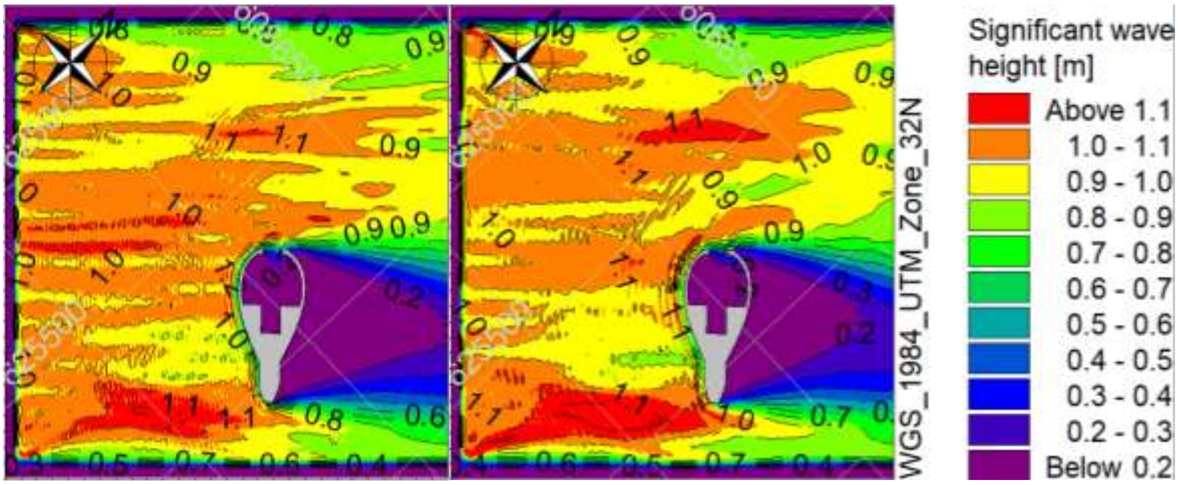


Figure D-2 Wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

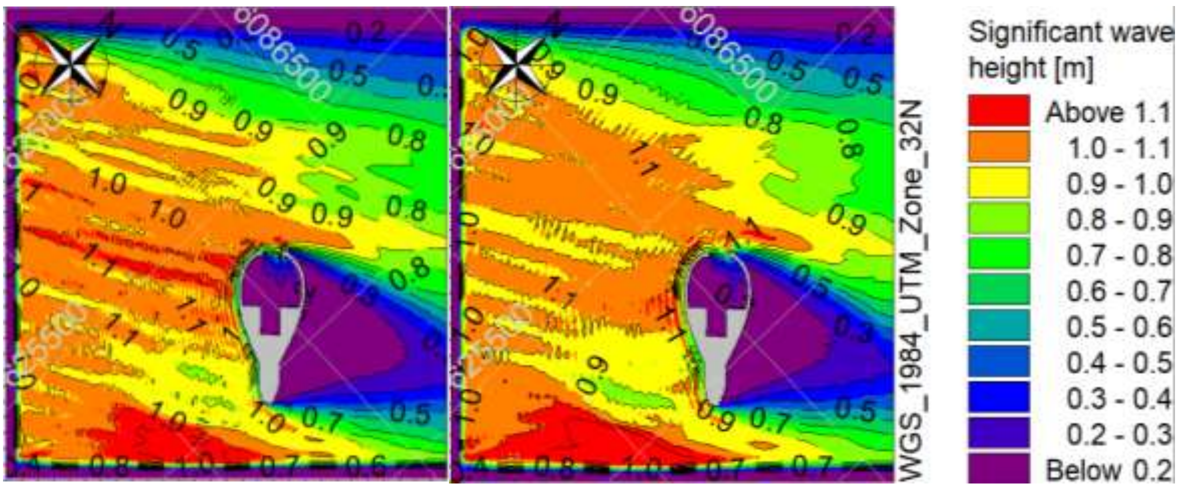


Figure D-3 Wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

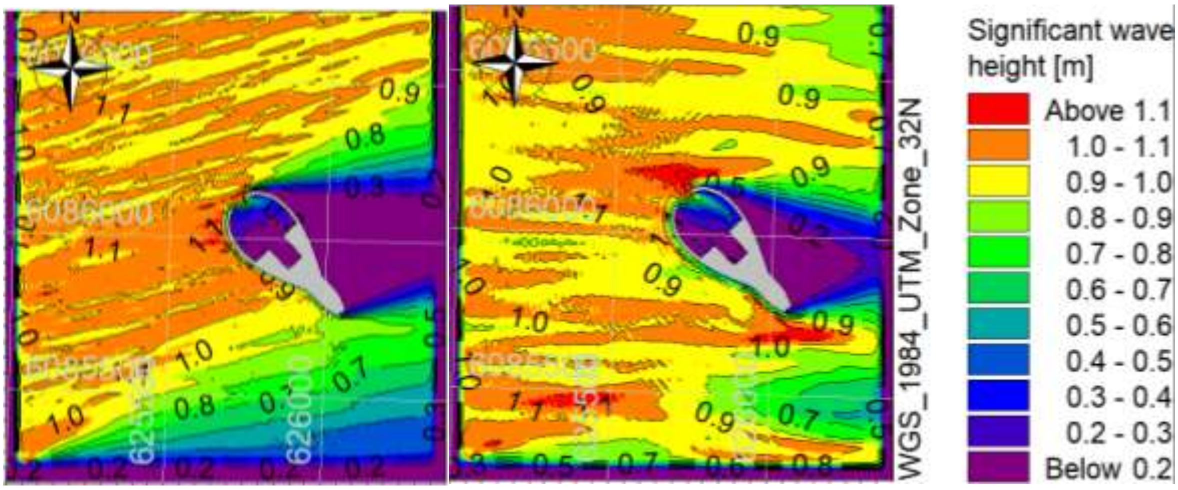


Figure D-4 Wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

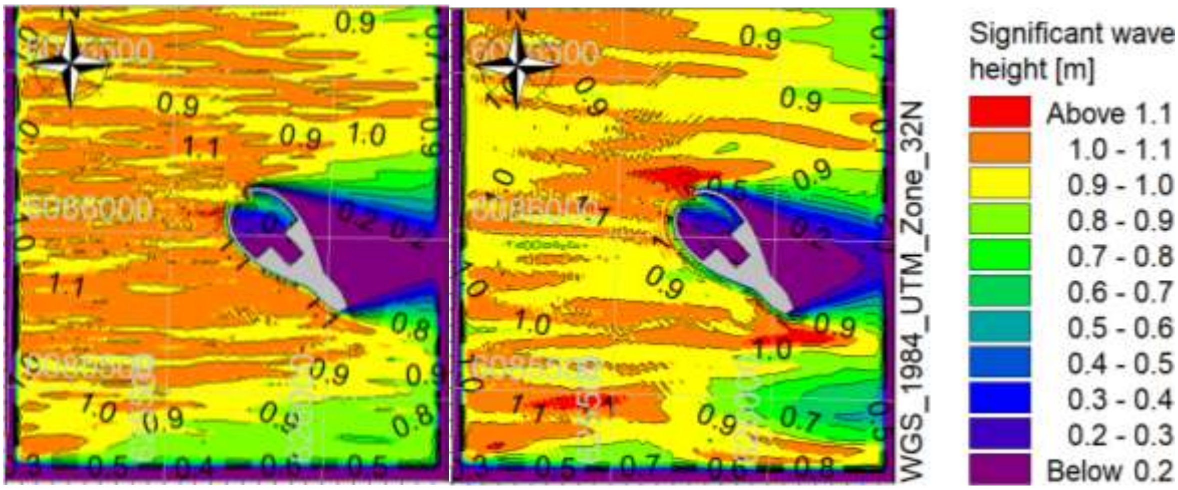


Figure D-5 Wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

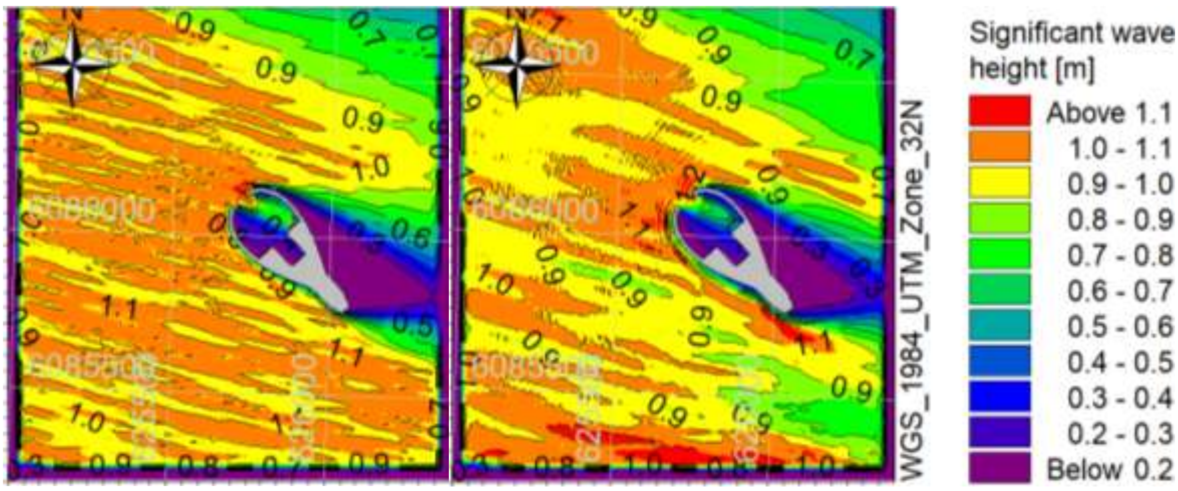


Figure D-6 Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

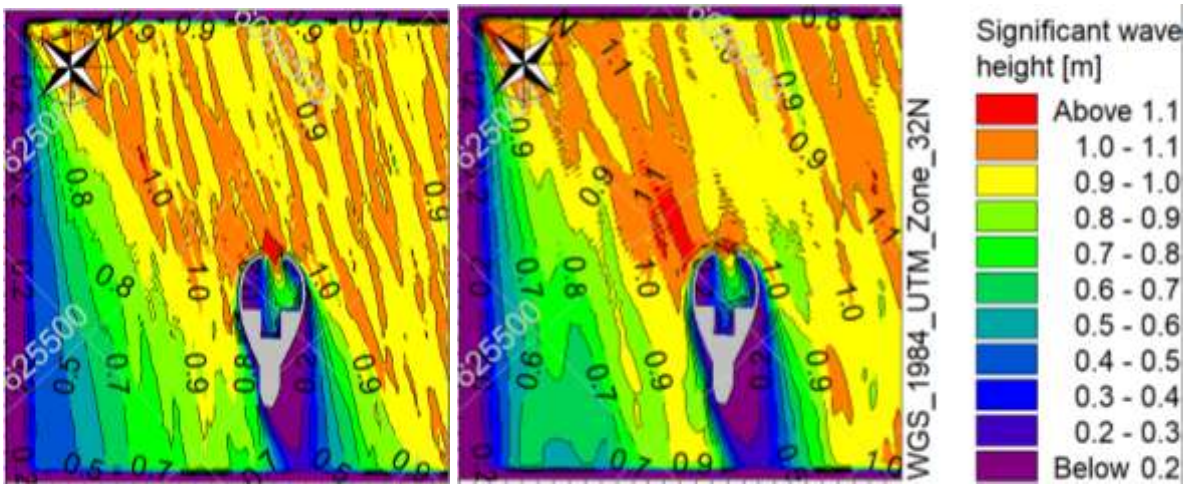


Figure D-7 *Wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

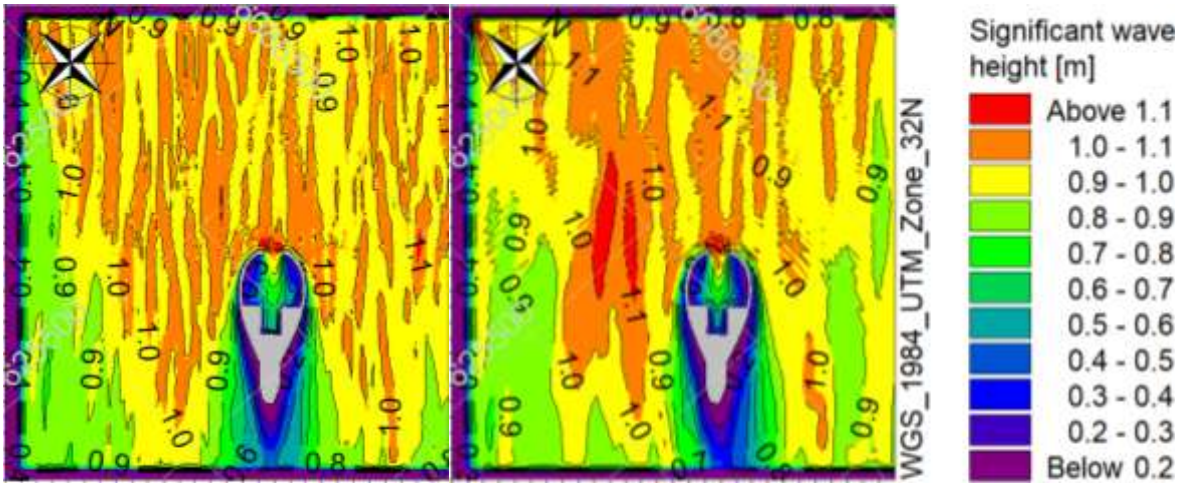


Figure D-8 *Wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

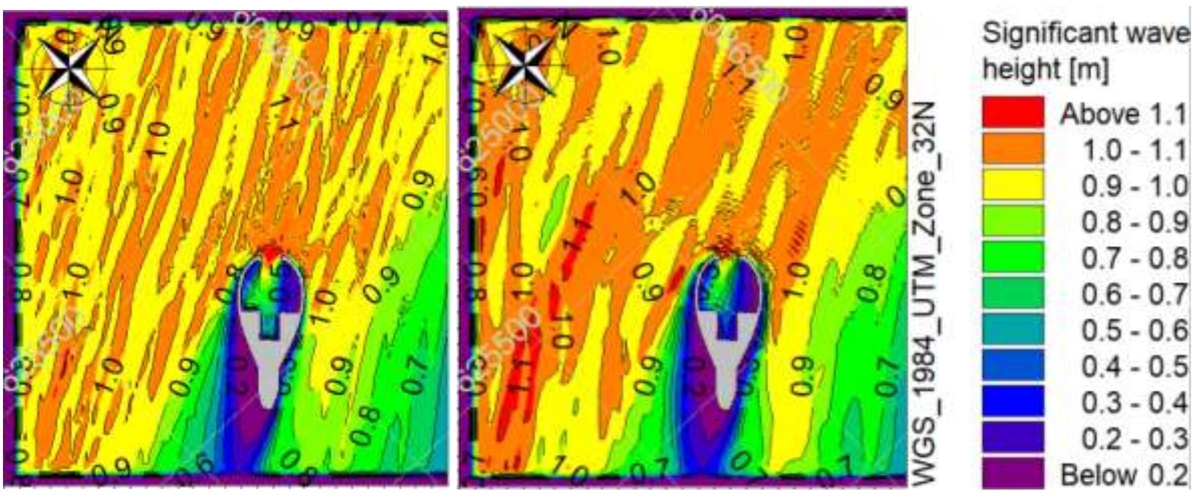


Figure D-9 *Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec*

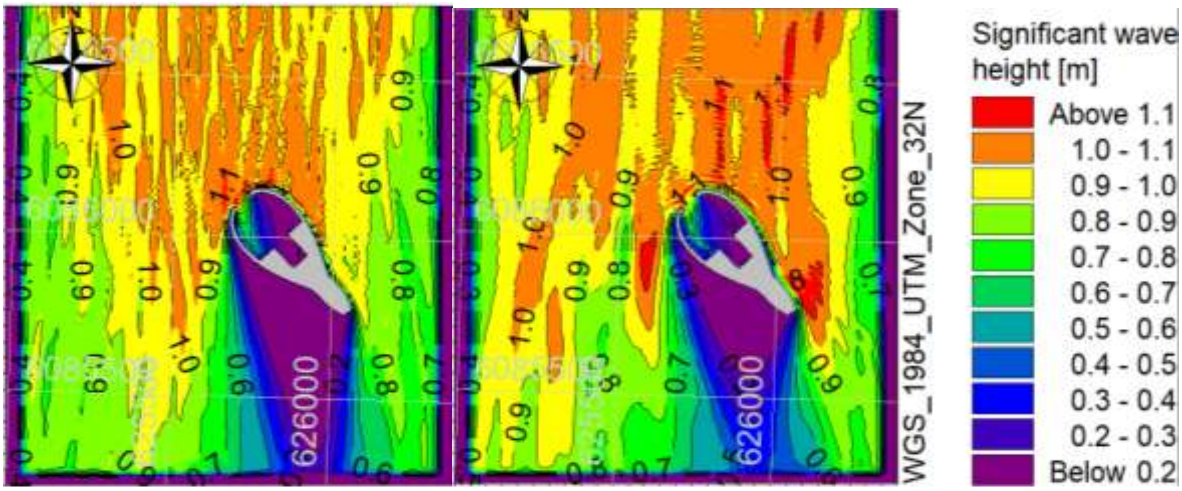


Figure D-10 Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

D.2 Closeup of Wave Disturbance Maps for Layout 2c

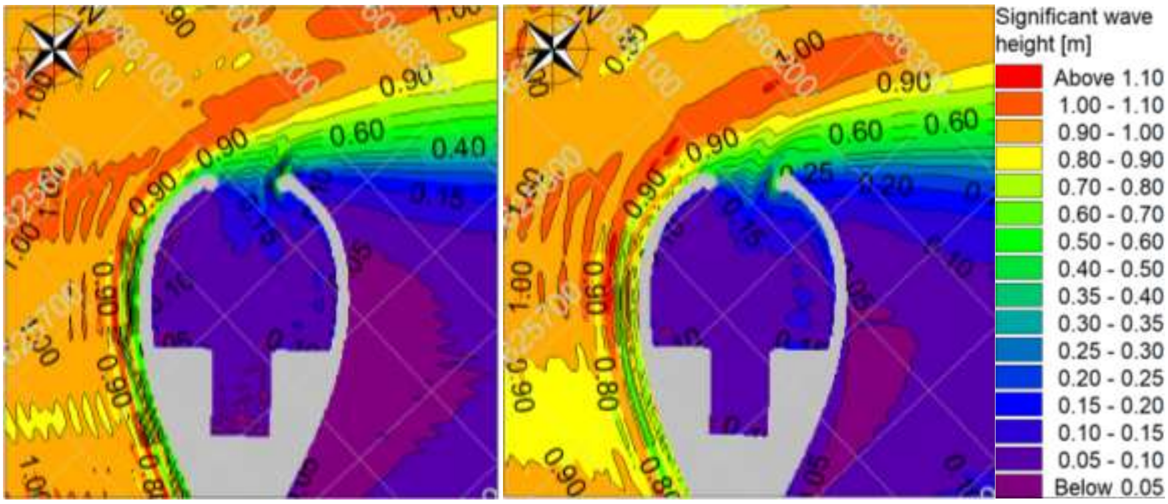


Figure D-11 Wave disturbance plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

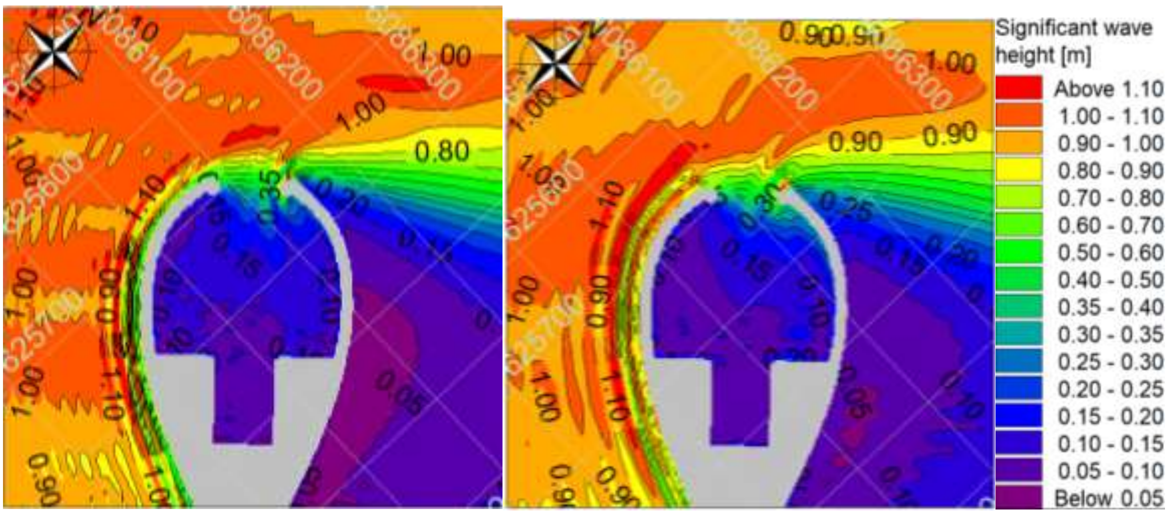


Figure D-12 Wave disturbance plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

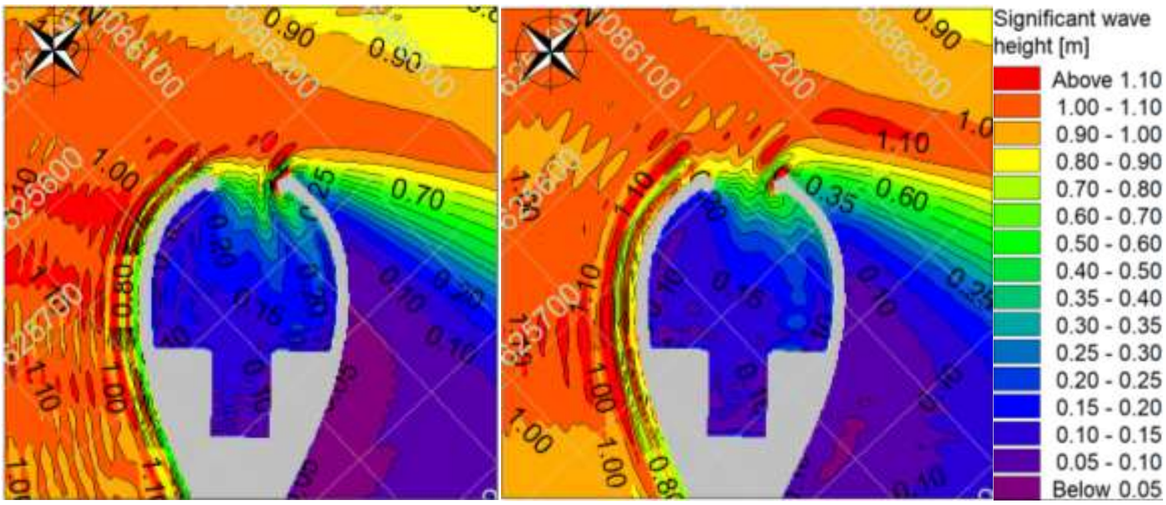


Figure D-13 Wave disturbance plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

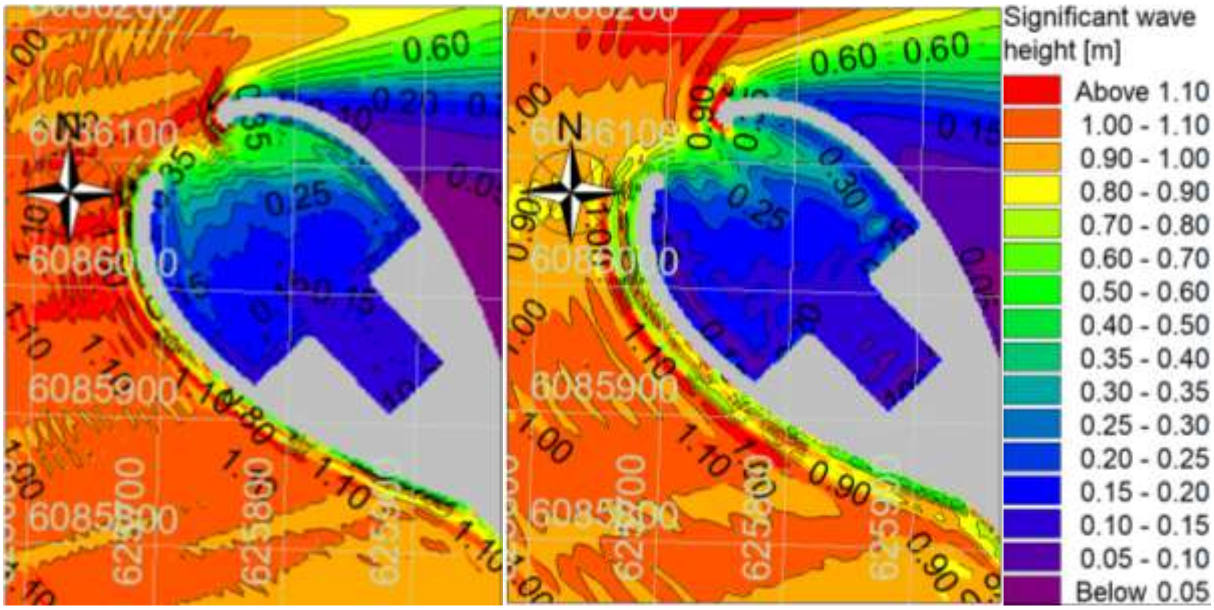


Figure D-14 Wave disturbance plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

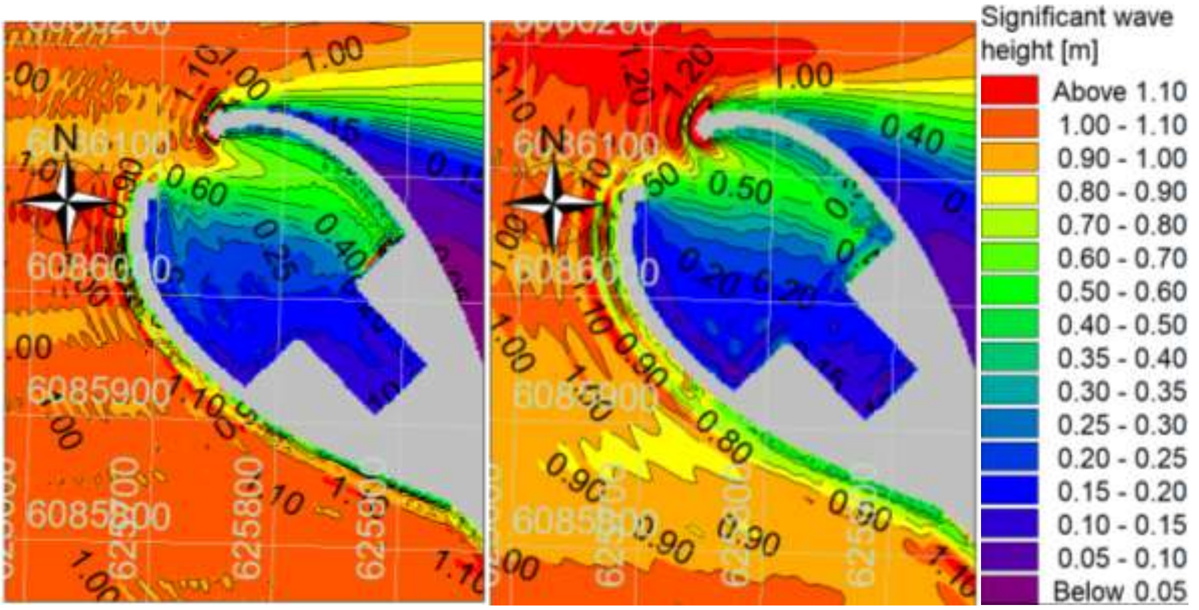


Figure D-15 Wave disturbance plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

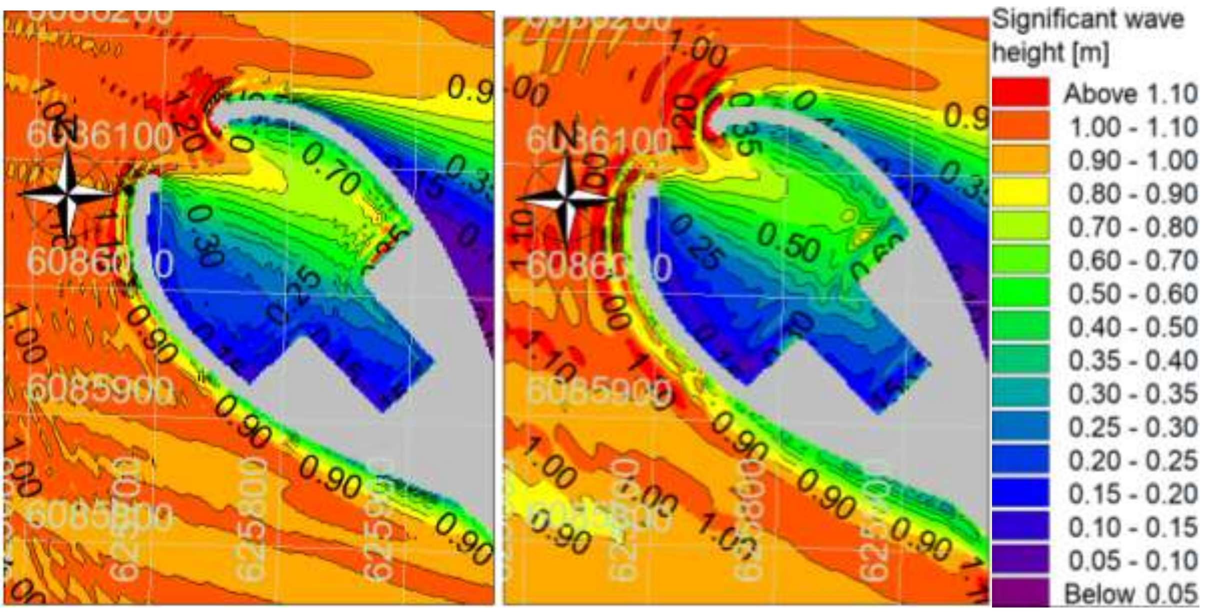


Figure D-16 Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

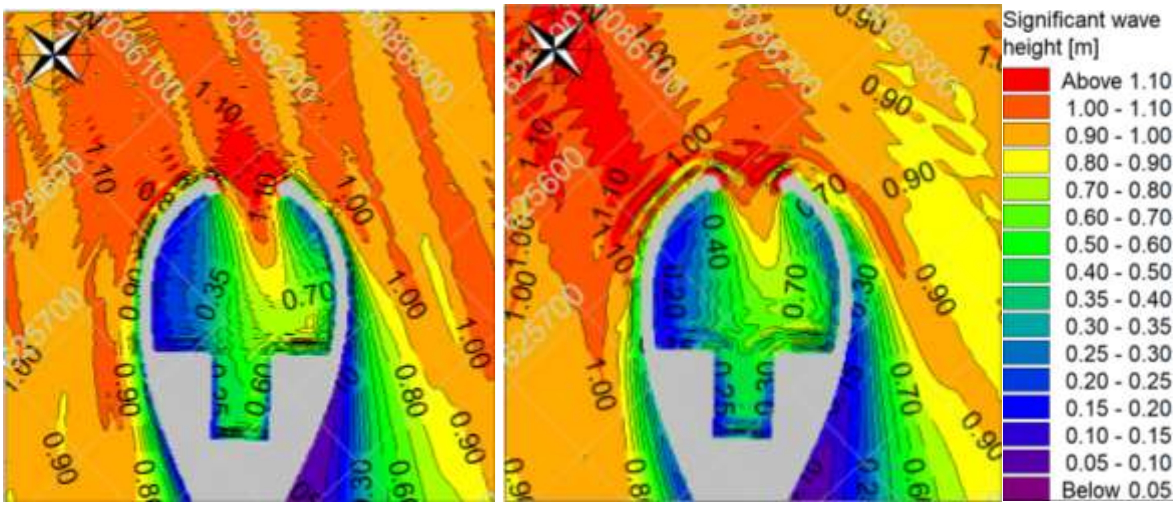


Figure D-17 Wave disturbance plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

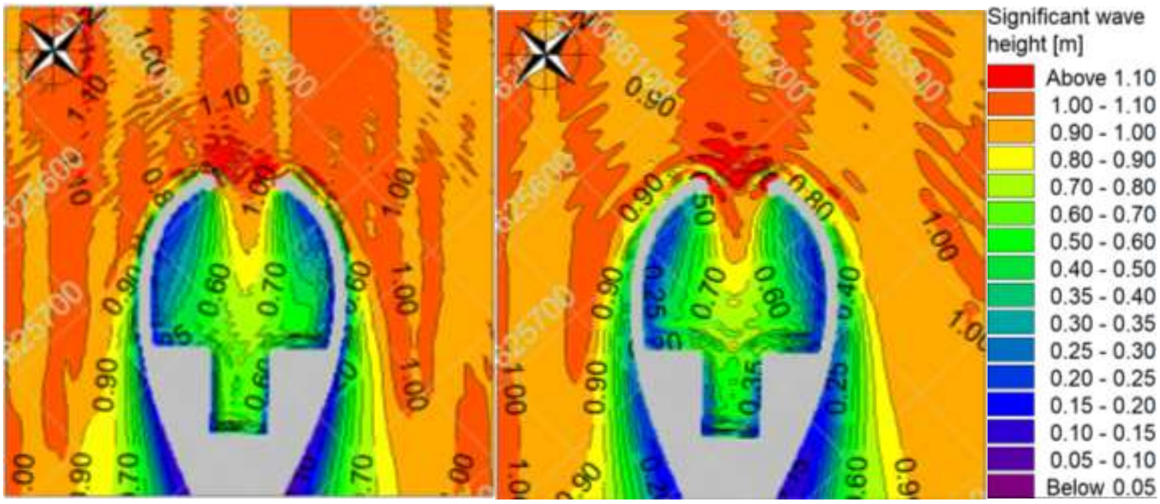


Figure D-18 Wave disturbance plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

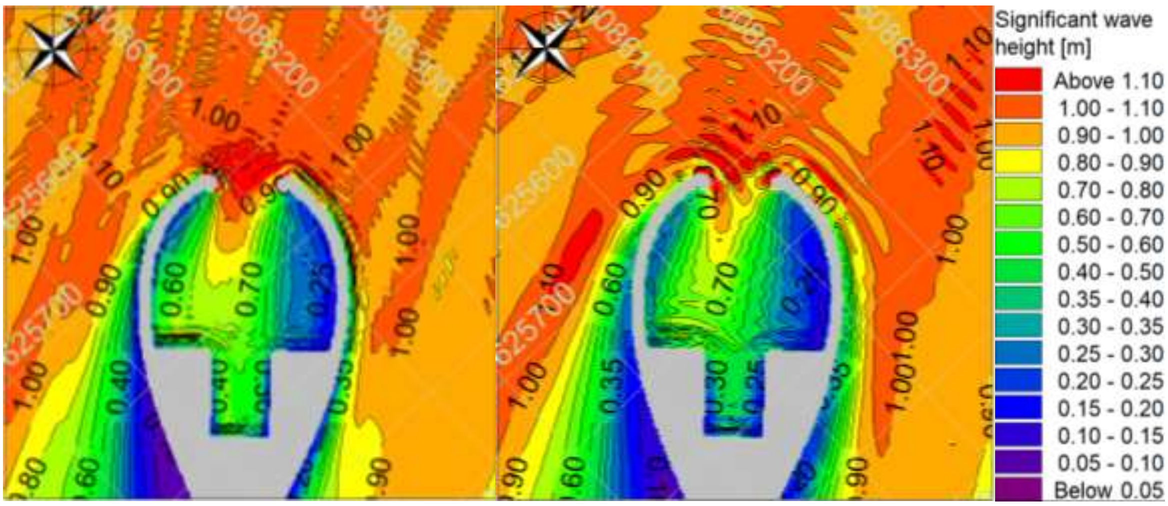


Figure D-19 Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

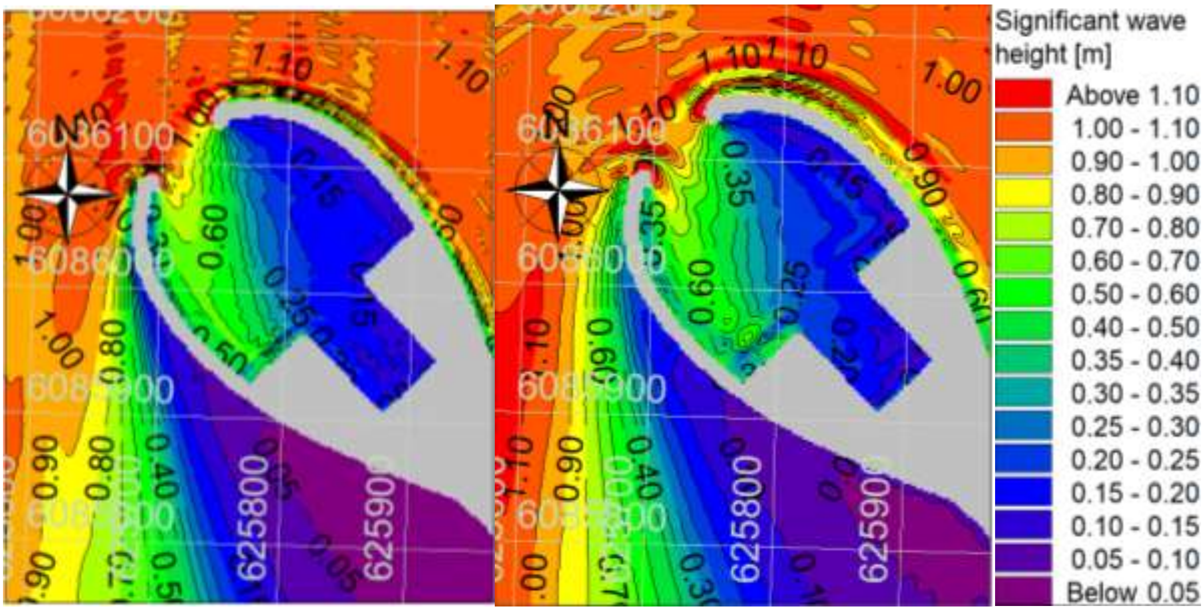


Figure D-20 Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

D.3 Instantaneous Surface Elevation Maps for Layout 2c

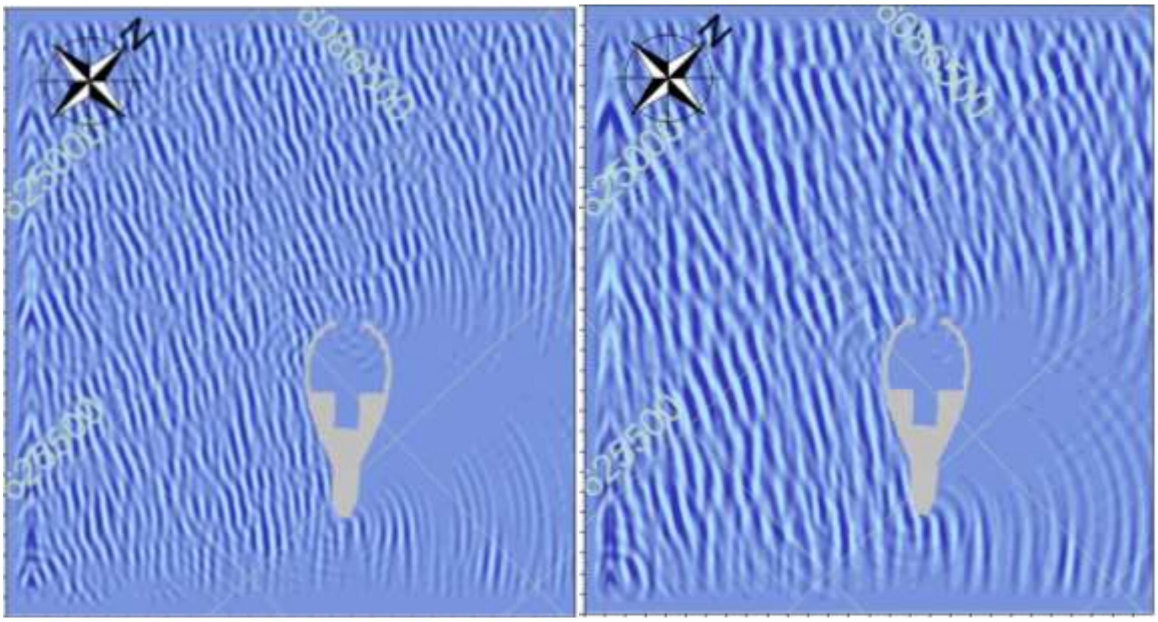


Figure D-21 Surface elevation plot for wave direction = 210°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

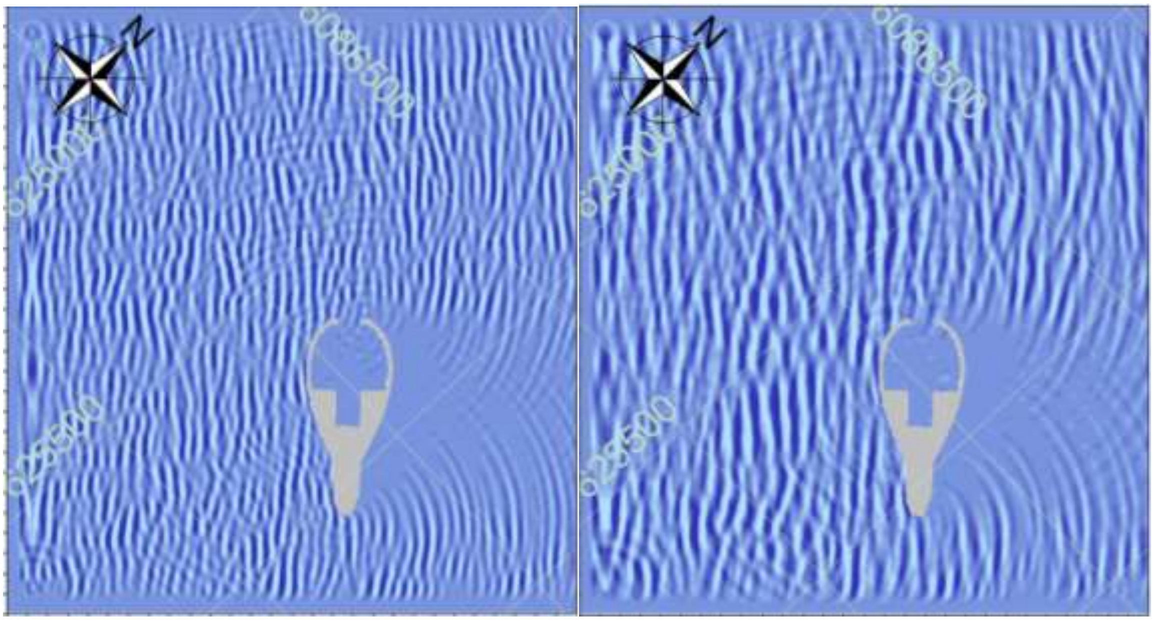


Figure D-22 Surface elevation plot for wave direction = 225°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

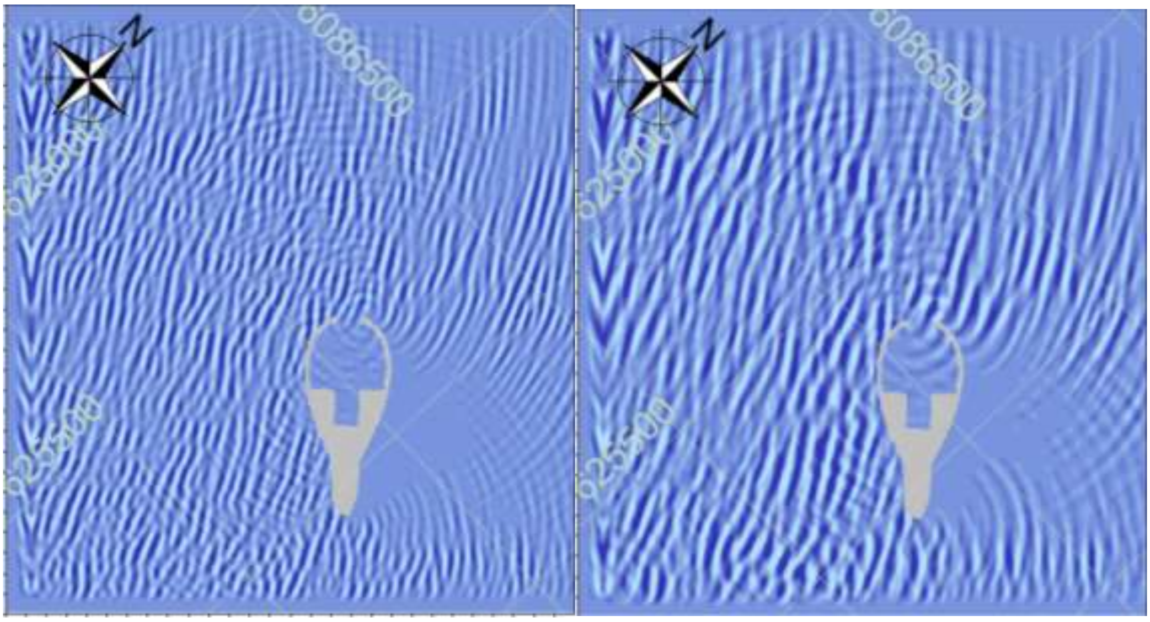


Figure D-23 Surface elevation plot for wave direction = 240°N. Left: Tp = 4.5 sec, Right: Tp =6 sec

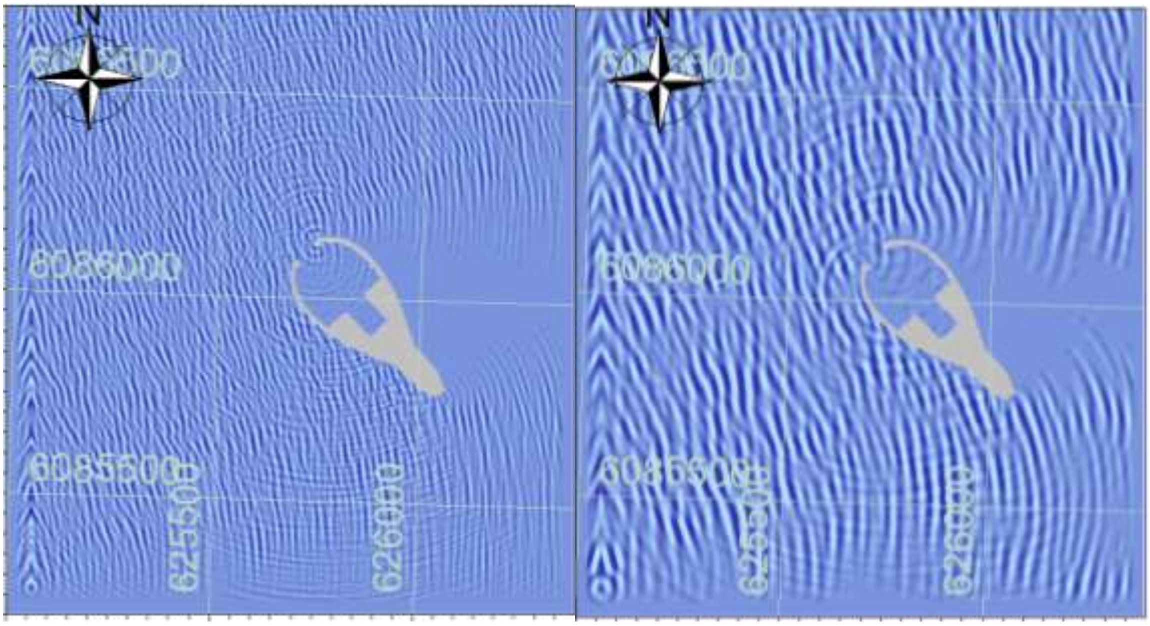


Figure D-24 Surface elevation plot for wave direction = 255°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

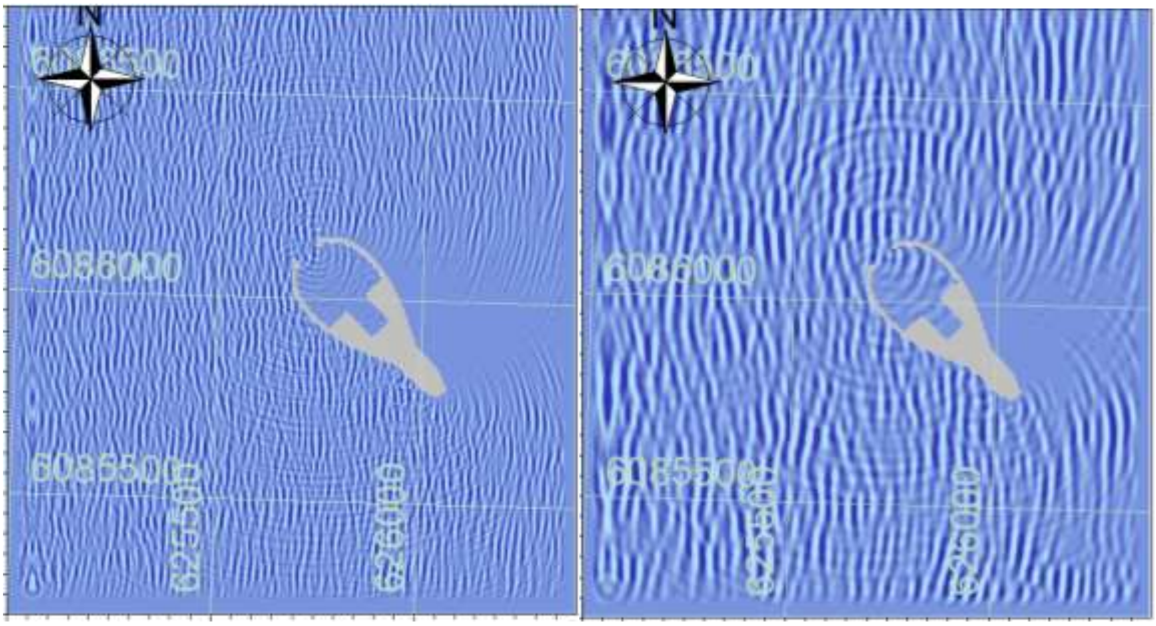


Figure D-25 Surface elevation plot for wave direction = 270°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

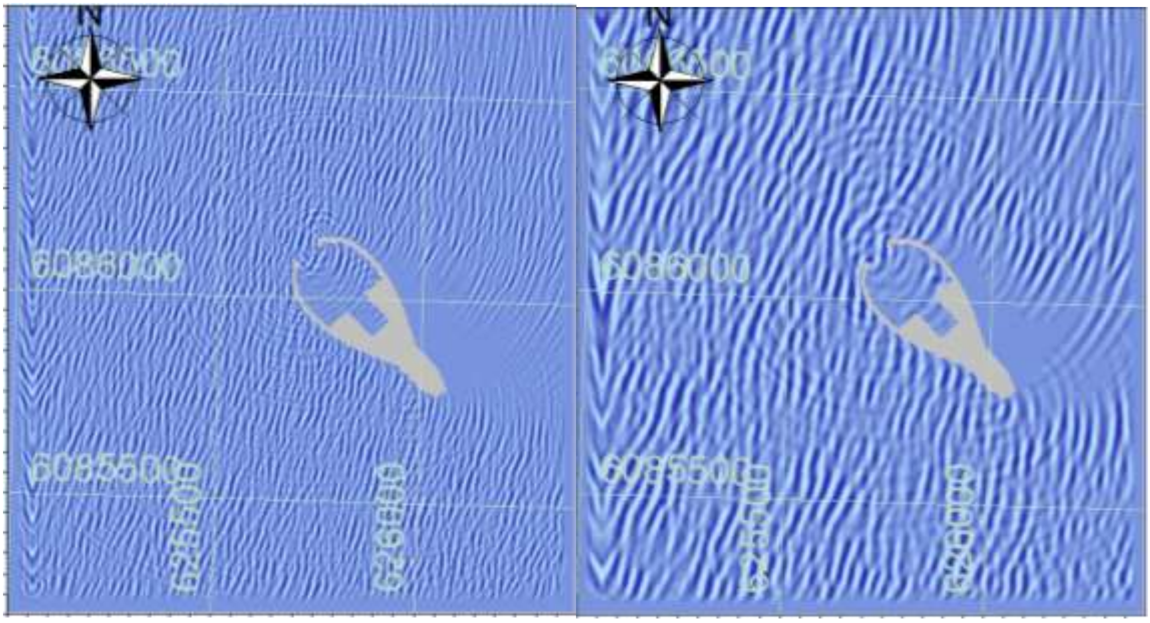


Figure D-26 Surface elevation plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

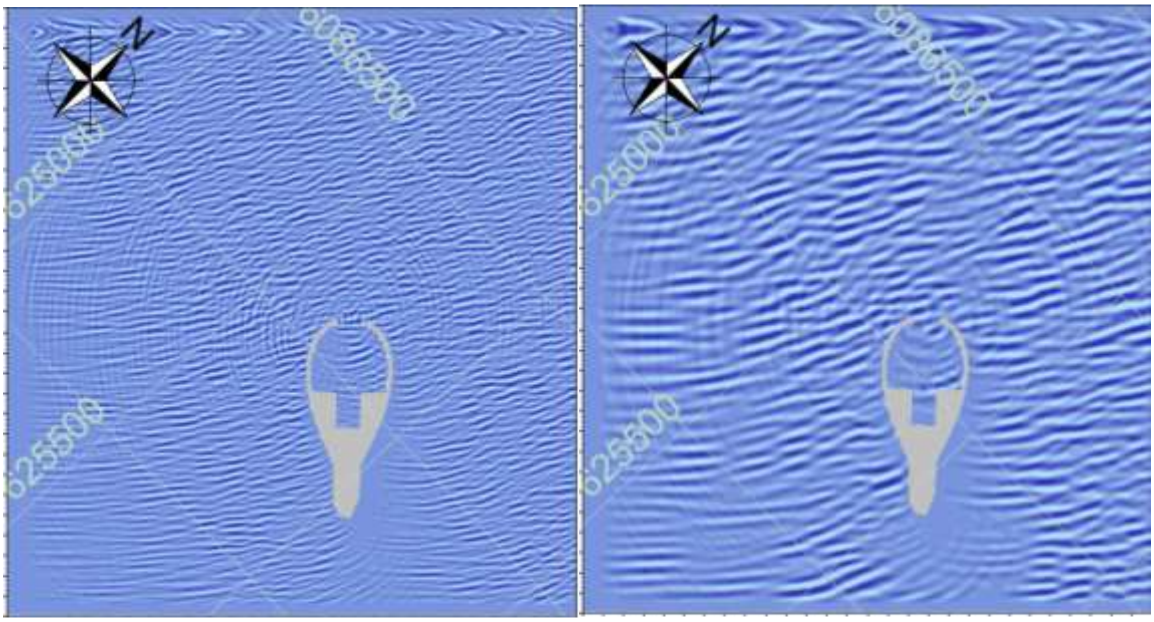


Figure D-27 Surface elevation plot for wave direction = 300°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

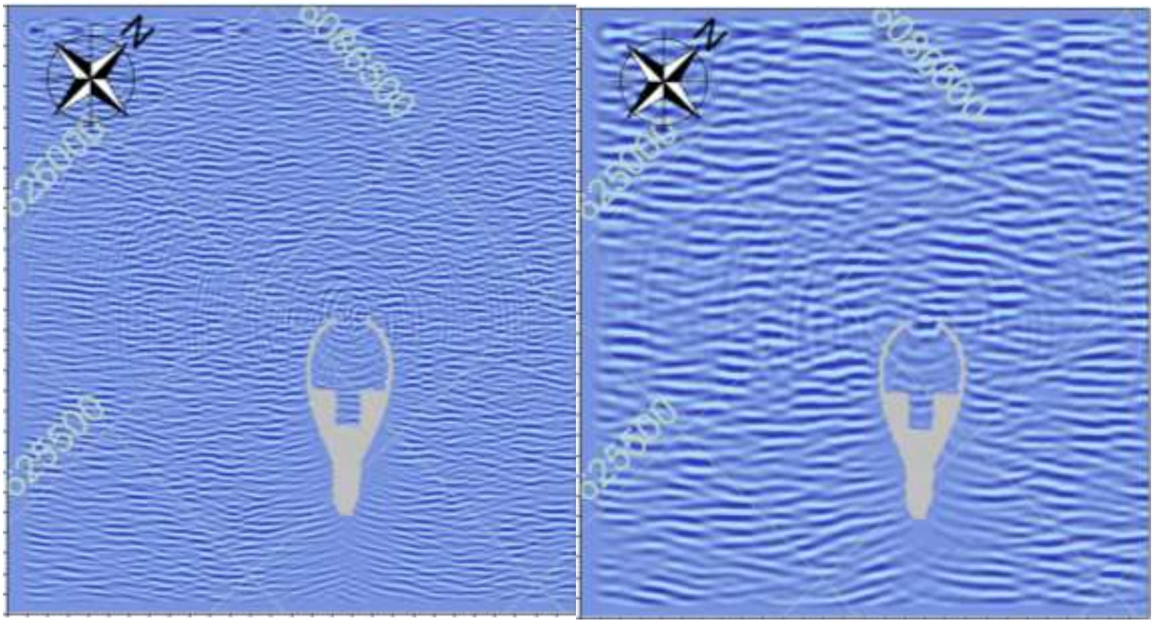


Figure D-28 Surface elevation plot for wave direction = 315°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

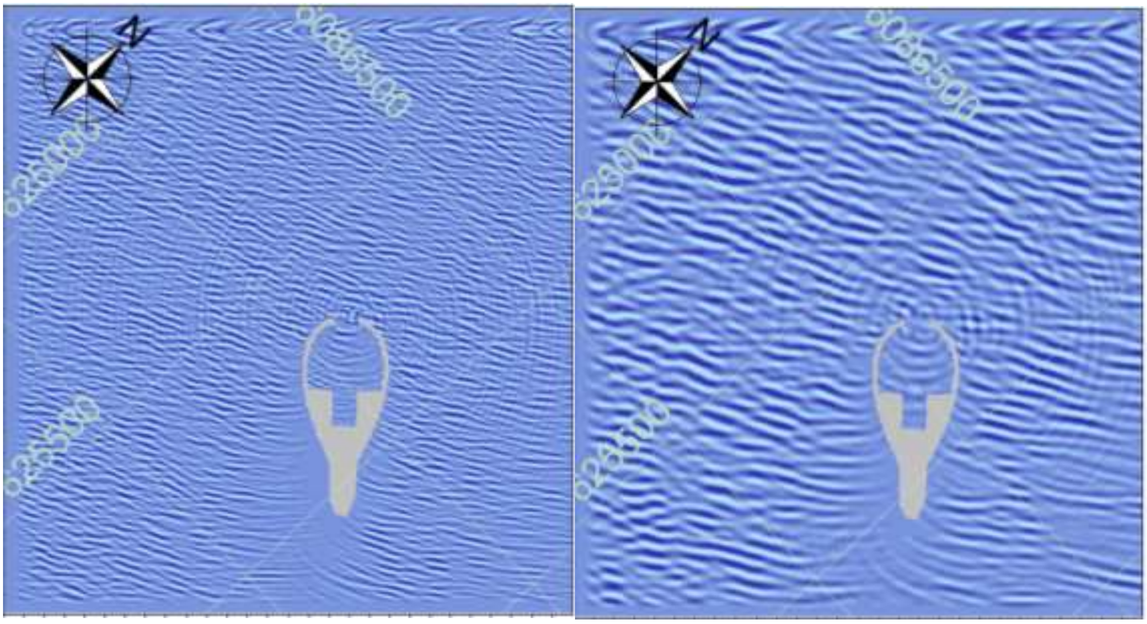


Figure D-29 Surface elevation plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

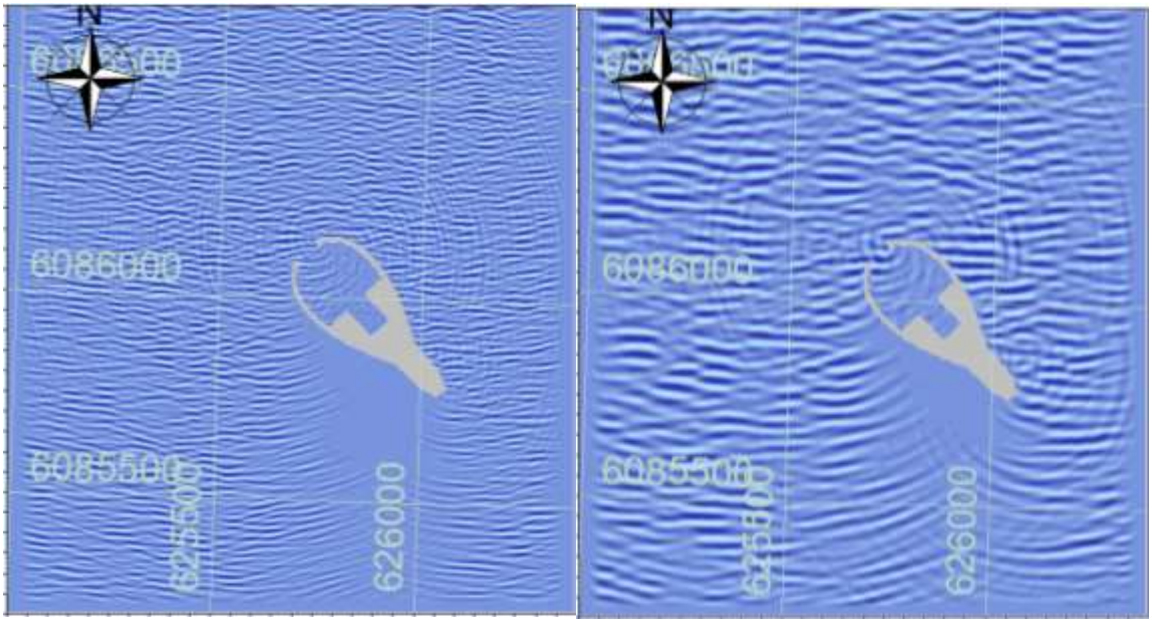


Figure D-30 Surface elevation plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

Appendix E Disturbance maps for Layout 3a

E.1 Overall Wave Disturbance Maps for Layout 3a

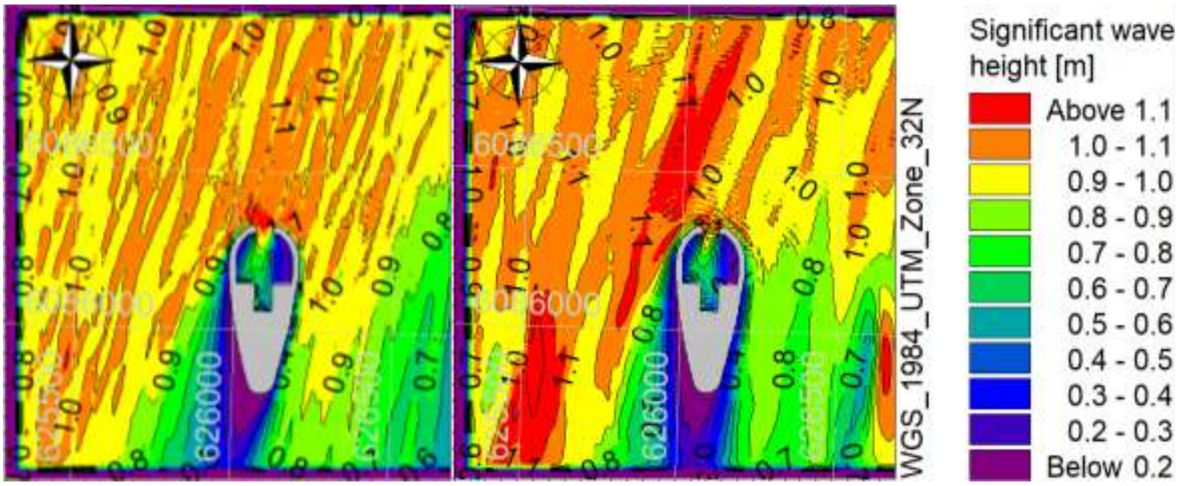


Figure E-1 Wave disturbance plot for wave direction = 15°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

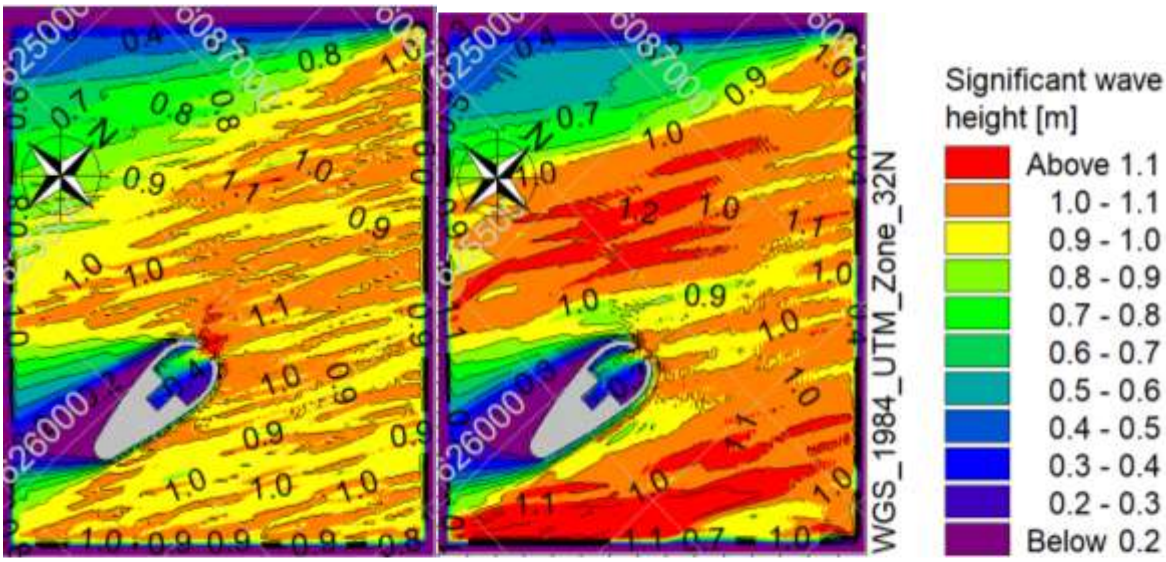


Figure E-2 Wave disturbance plot for wave direction = 30°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

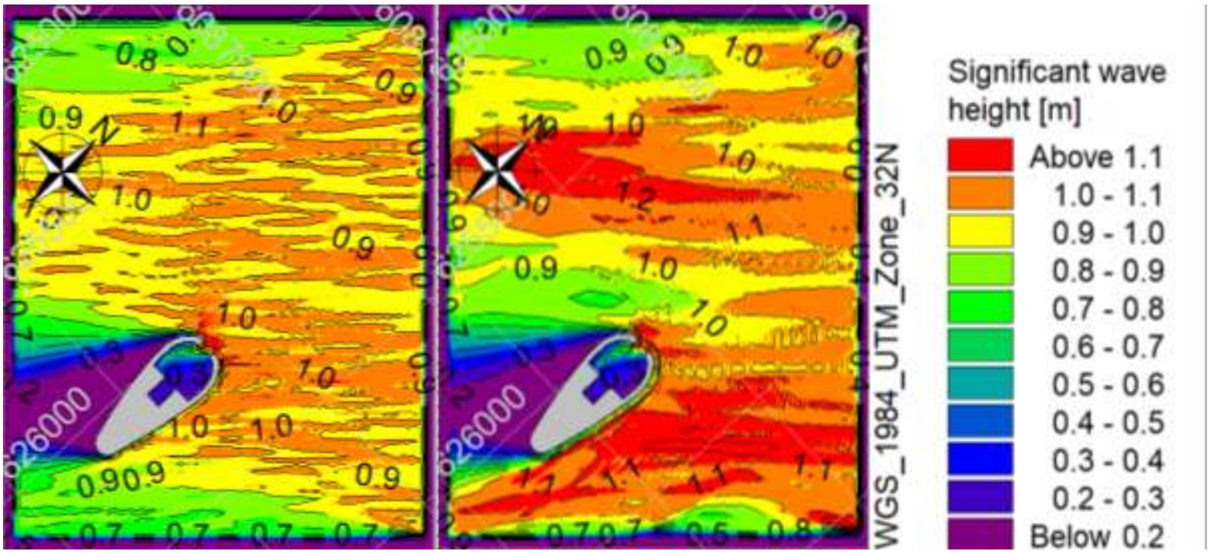


Figure E-3 Wave disturbance plot for wave direction = 45°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

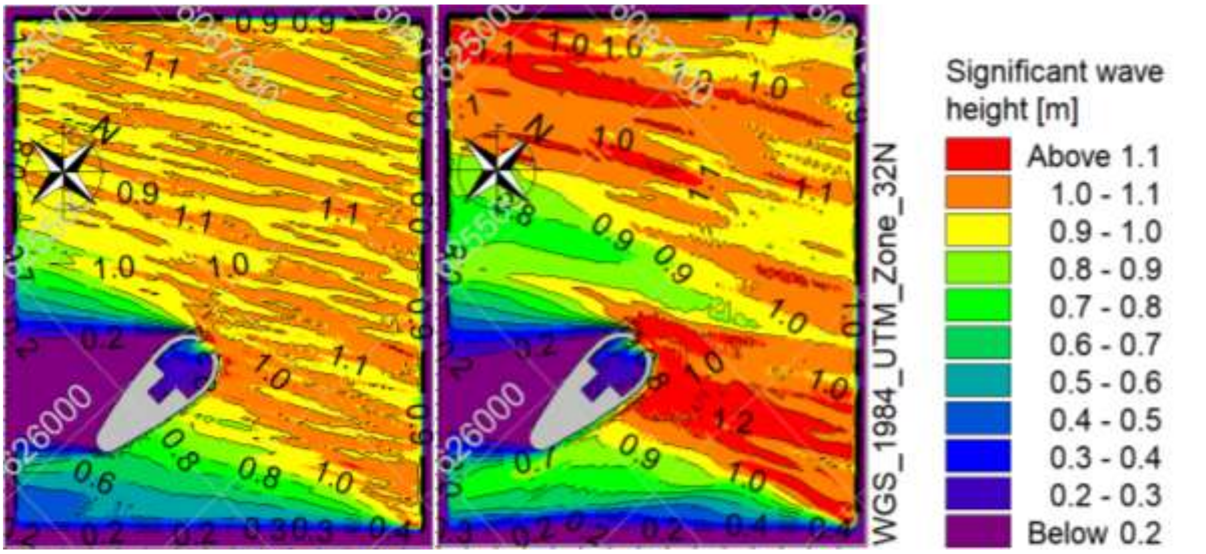


Figure E-4 Wave disturbance plot for wave direction = 60°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

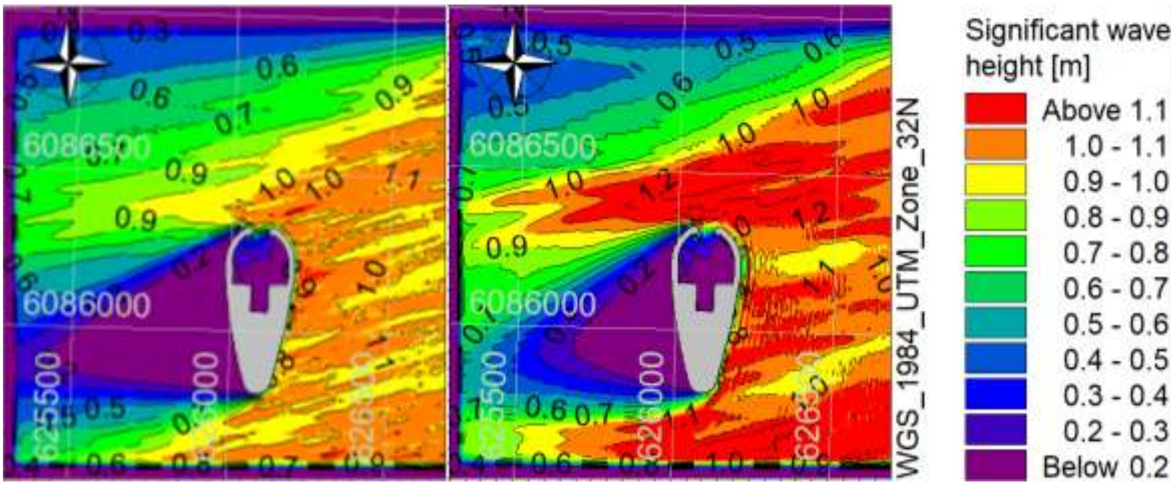


Figure E-5 Wave disturbance plot for wave direction = 75°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

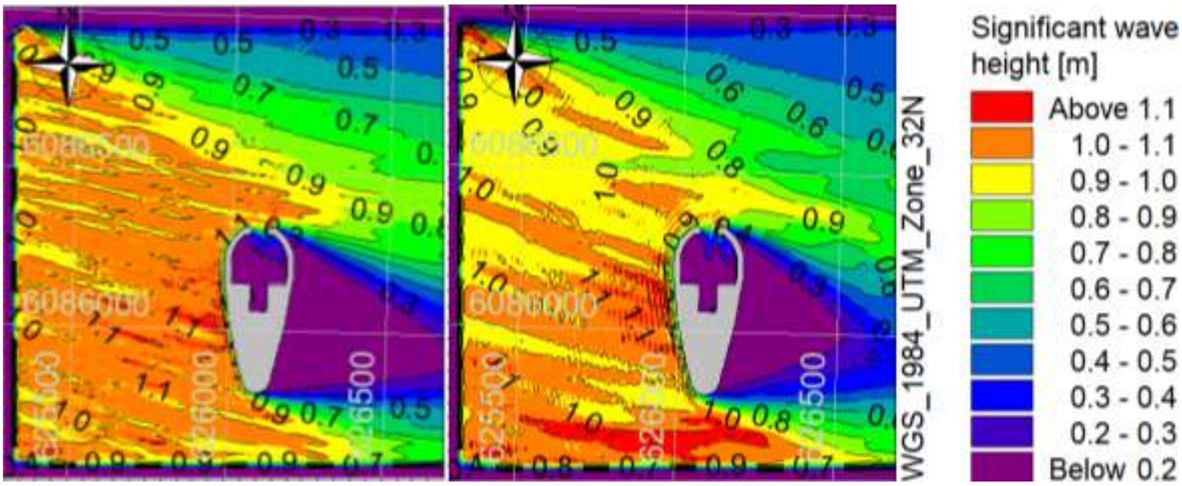


Figure E-6 Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

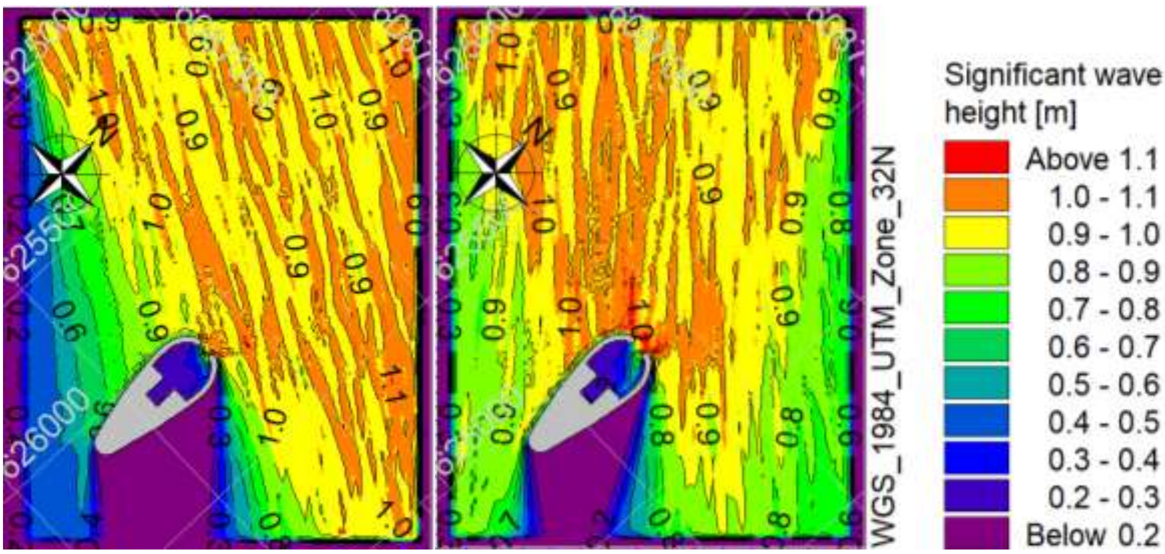


Figure E-7 Wave disturbance plot for Tp =3.5 sec. Left: MWD =300°N, Right: MWD =315°N

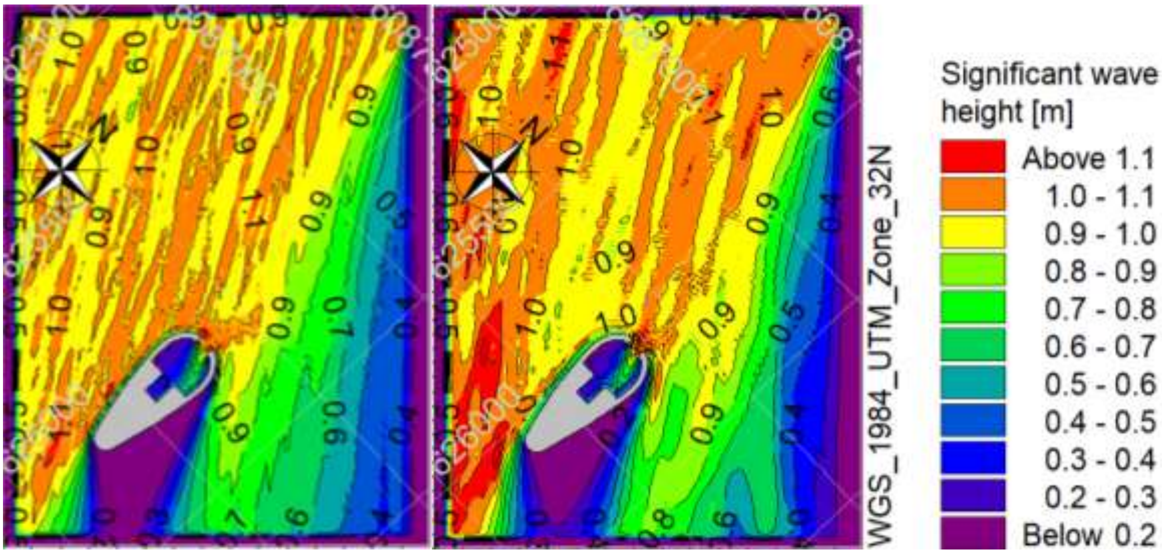


Figure E-8 Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

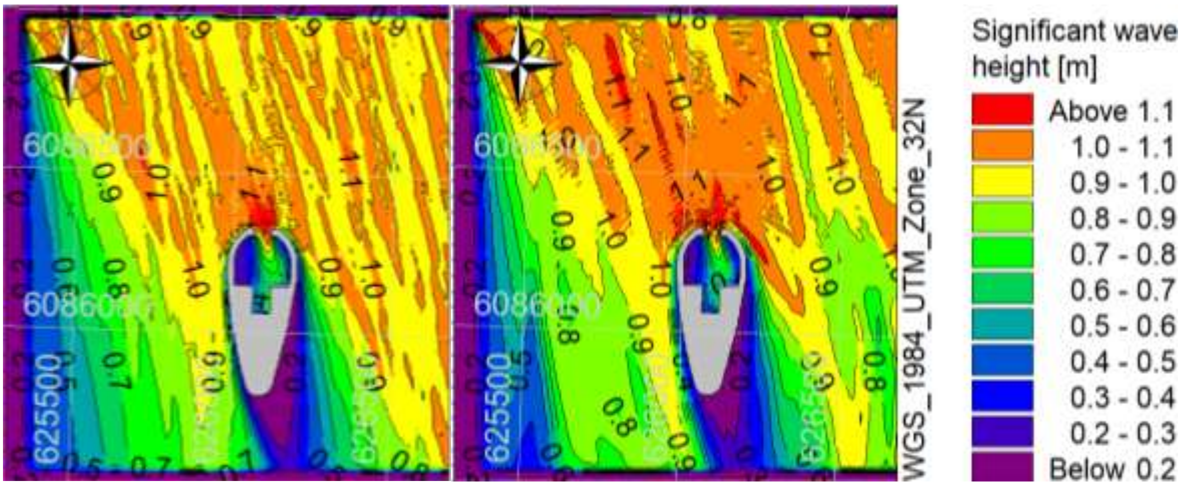


Figure E-9 Wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

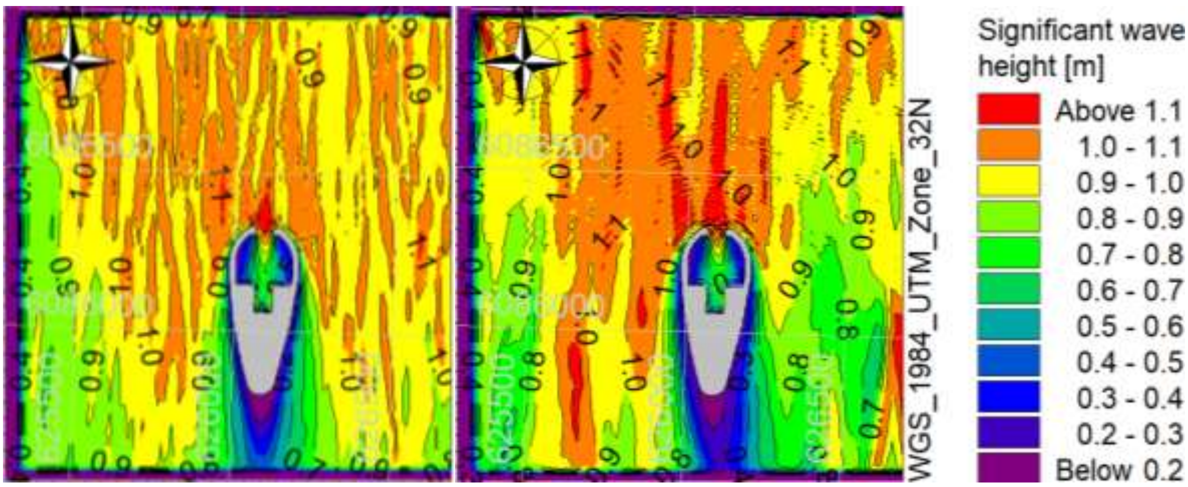


Figure E-10 Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

E.2 Closeup of Wave Disturbance Maps for Layout 3a

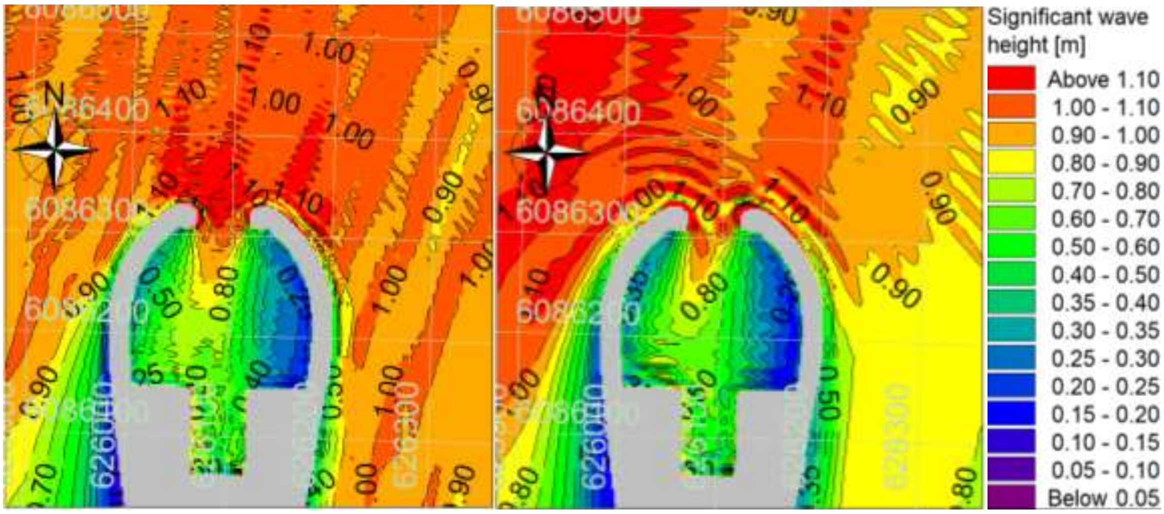


Figure E-11 Wave disturbance plot for wave direction = 15°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

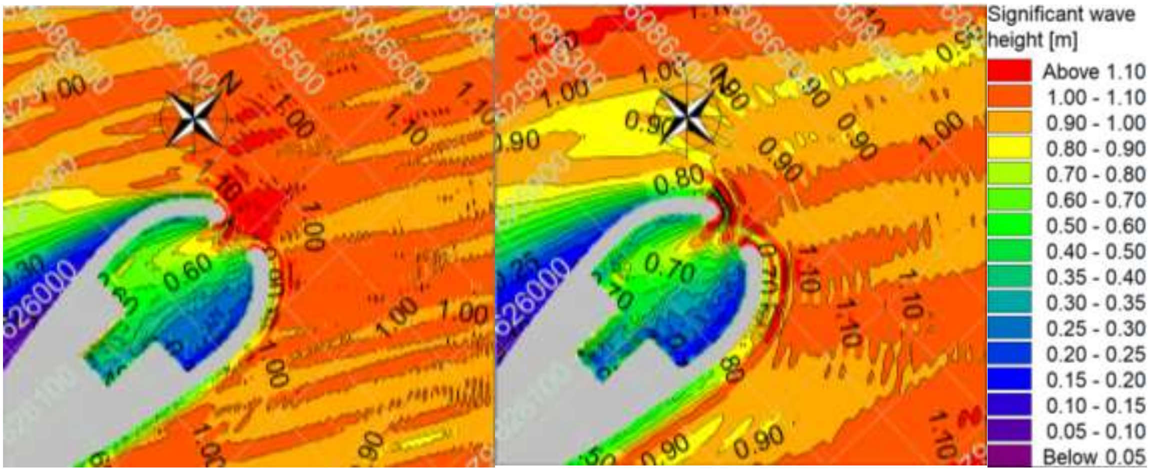


Figure E-12 Wave disturbance plot for wave direction = 30°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

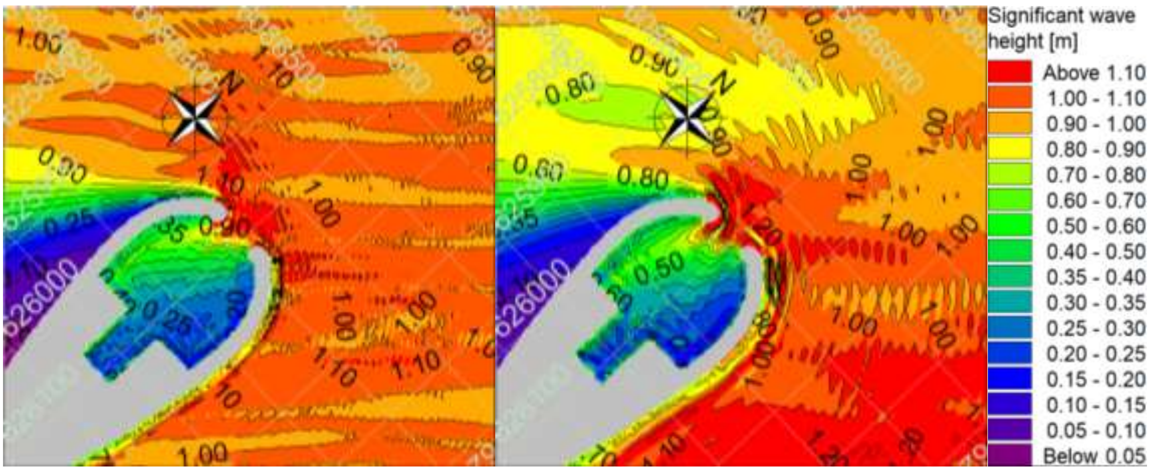


Figure E-13 Wave disturbance plot for wave direction = 45°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

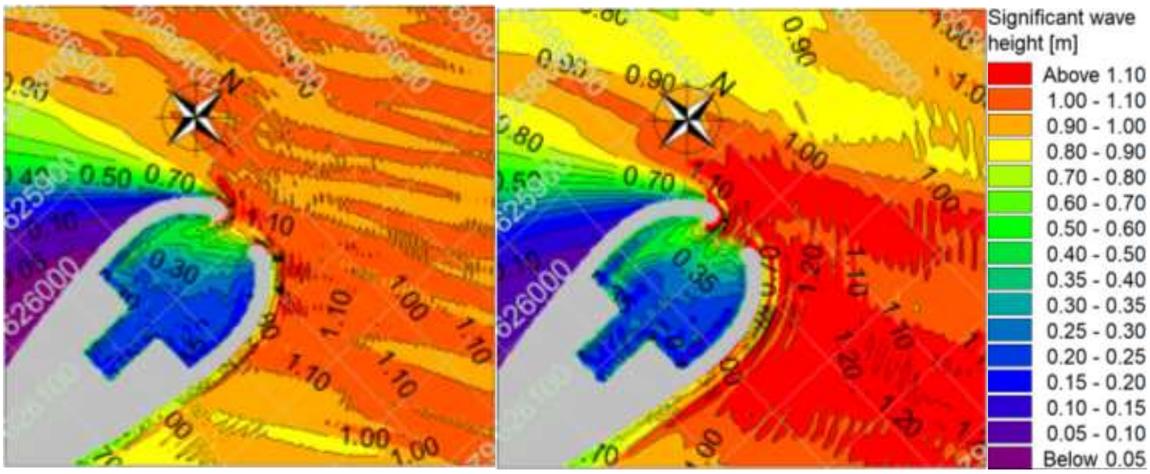


Figure E-14 Wave disturbance plot for wave direction = 60°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

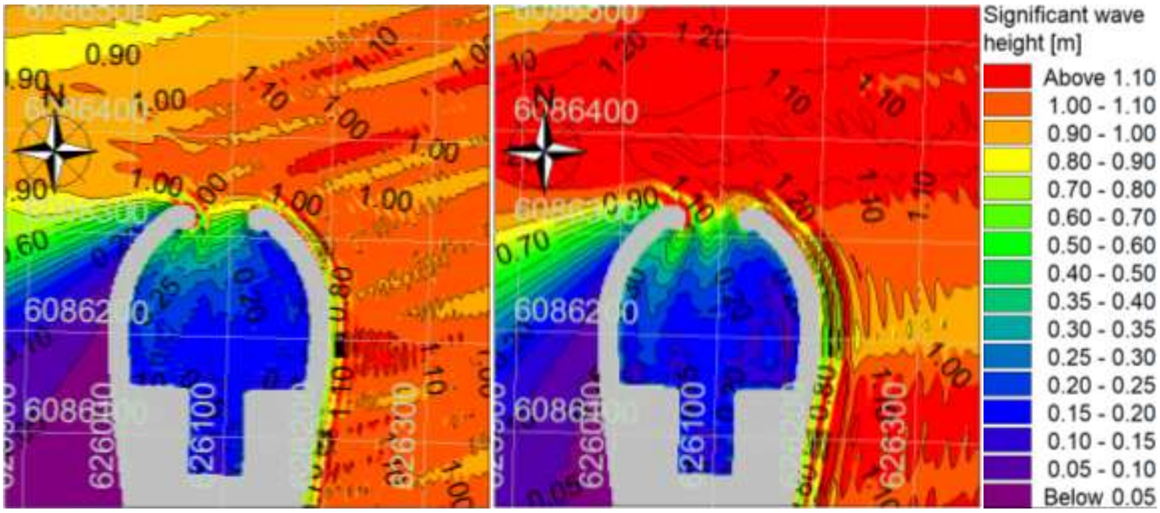


Figure E-15 Wave disturbance plot for wave direction = 75°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

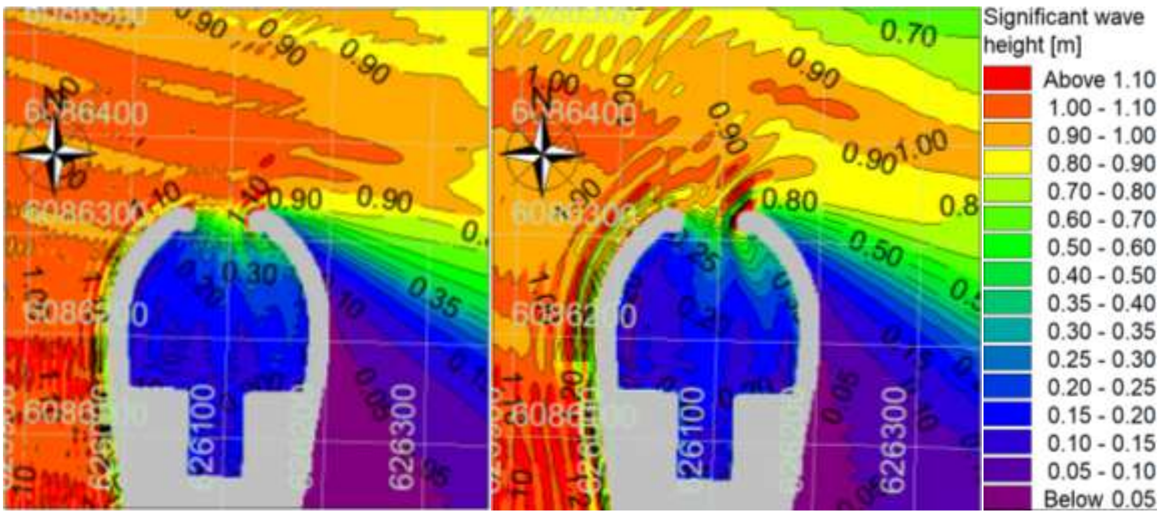


Figure E-16 Wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

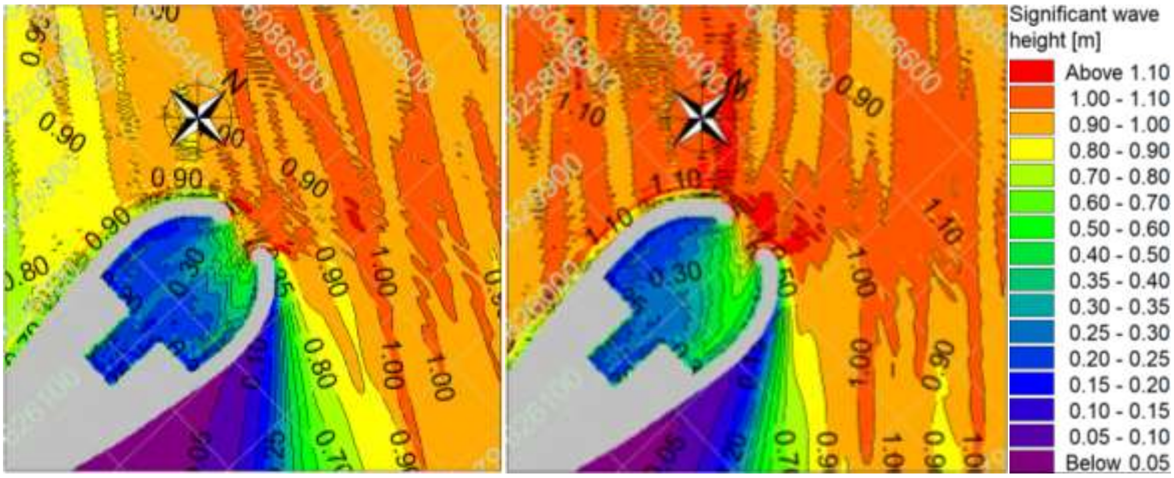


Figure E-17 Wave disturbance plot for Tp =3.5 sec. Left: MWD =300°N, Right: MWD =315°N

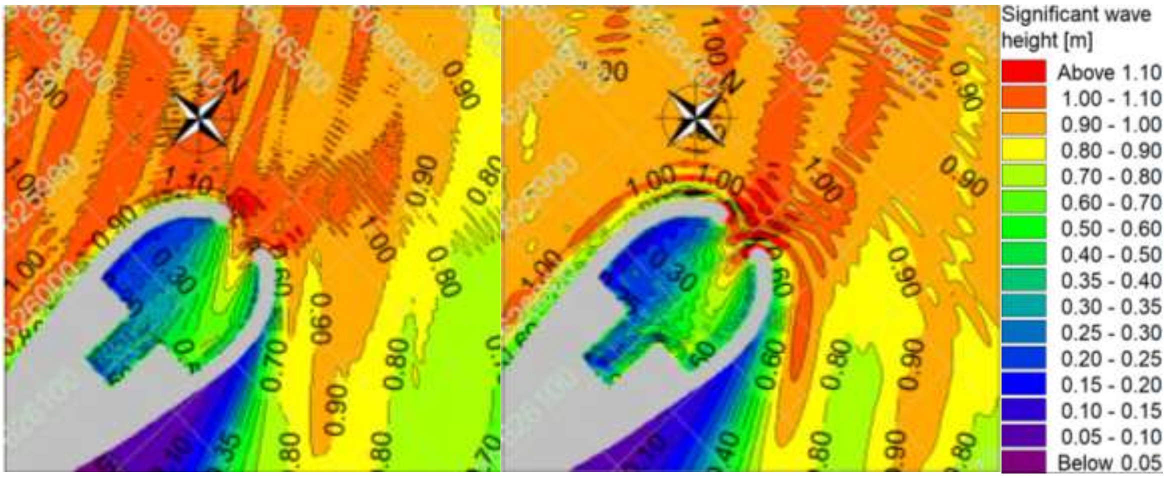


Figure E-18 Wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

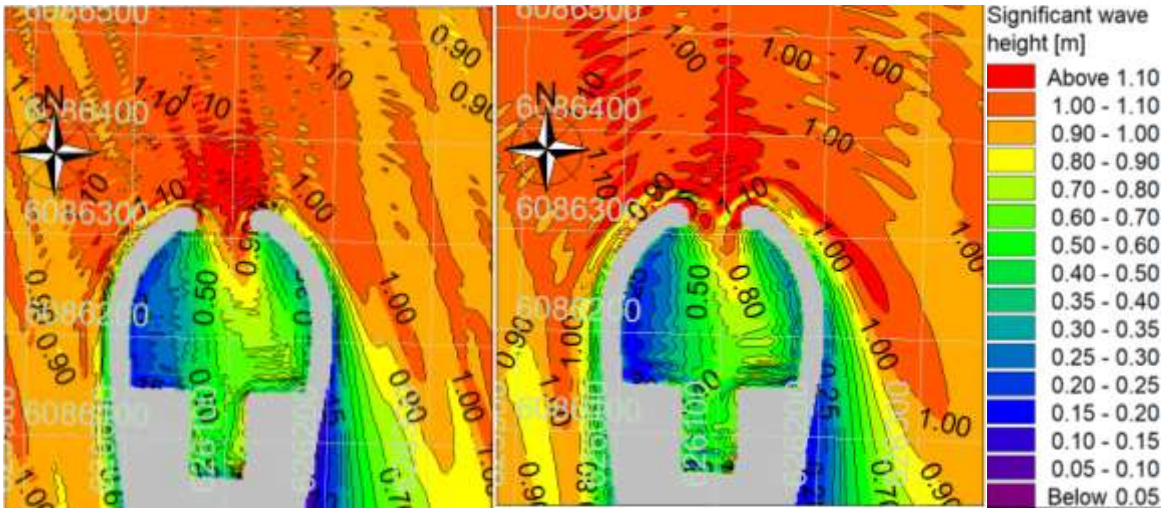


Figure E-19 Wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

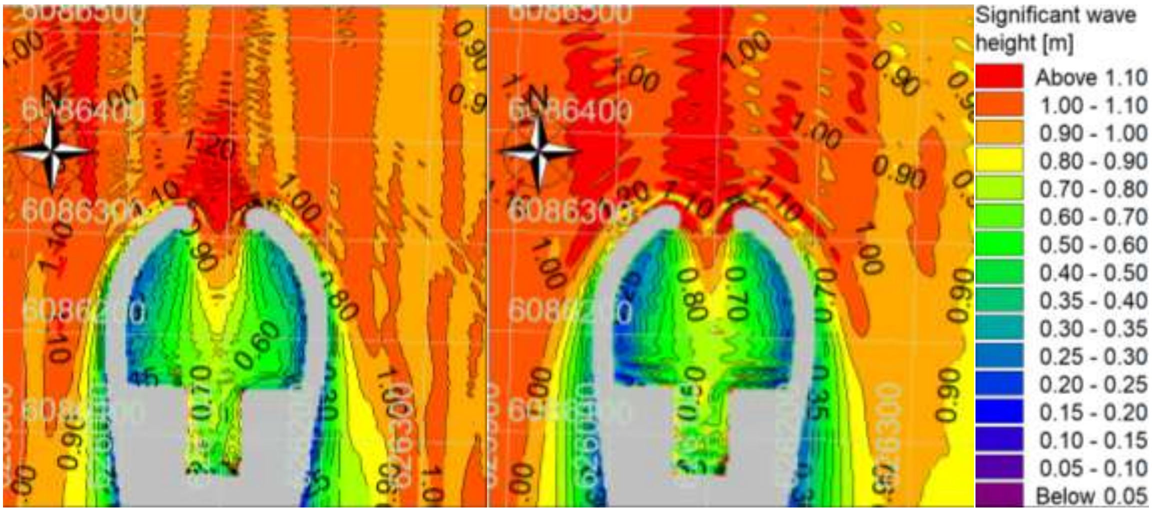


Figure E-20 Wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

E.3 Instantaneous Surface Elevation Maps for Layout 3a

Figure E-21 Surface elevation plot for wave direction = 15°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

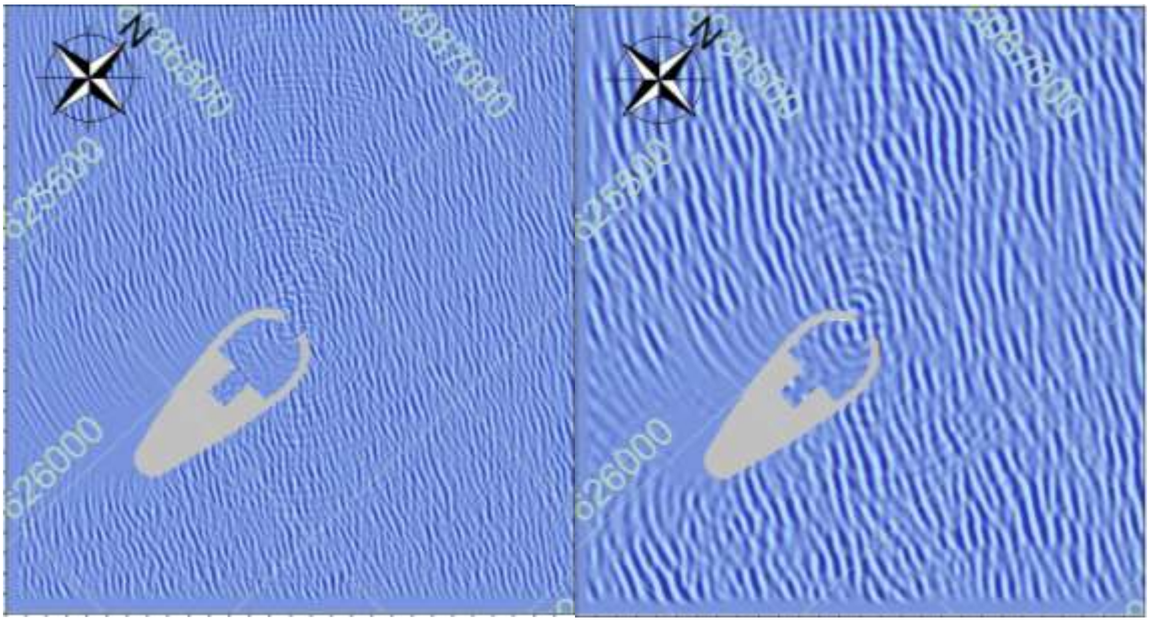


Figure E-22 Surface elevation plot for wave direction = 30°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

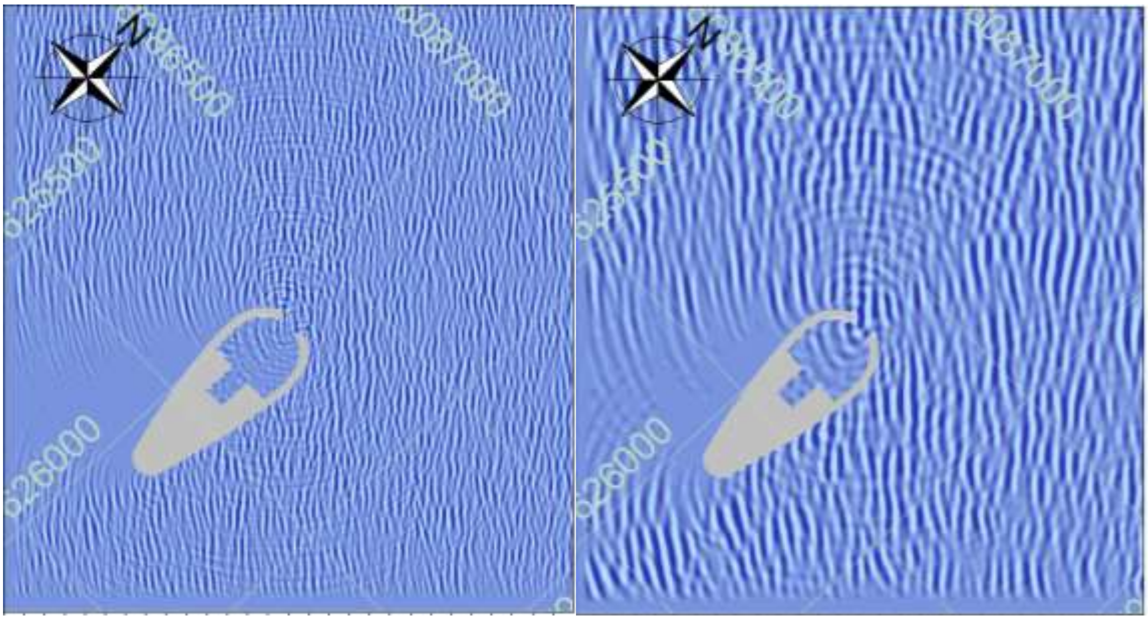


Figure E-23 Surface elevation plot for wave direction = 45°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

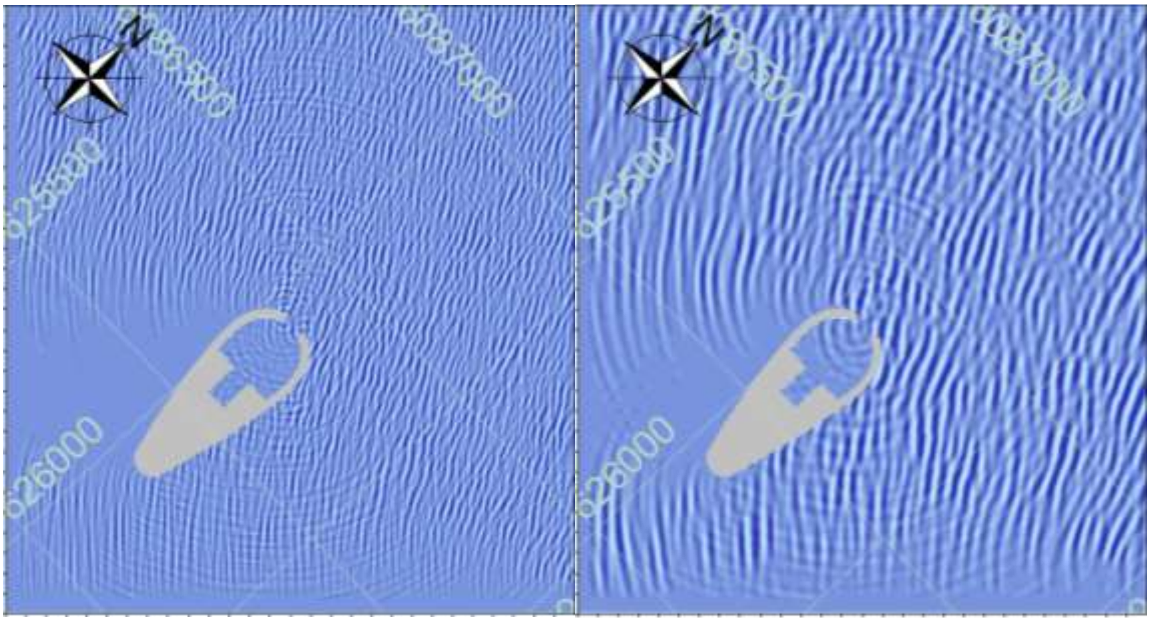


Figure E-24 Surface elevation plot for wave direction = 60°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

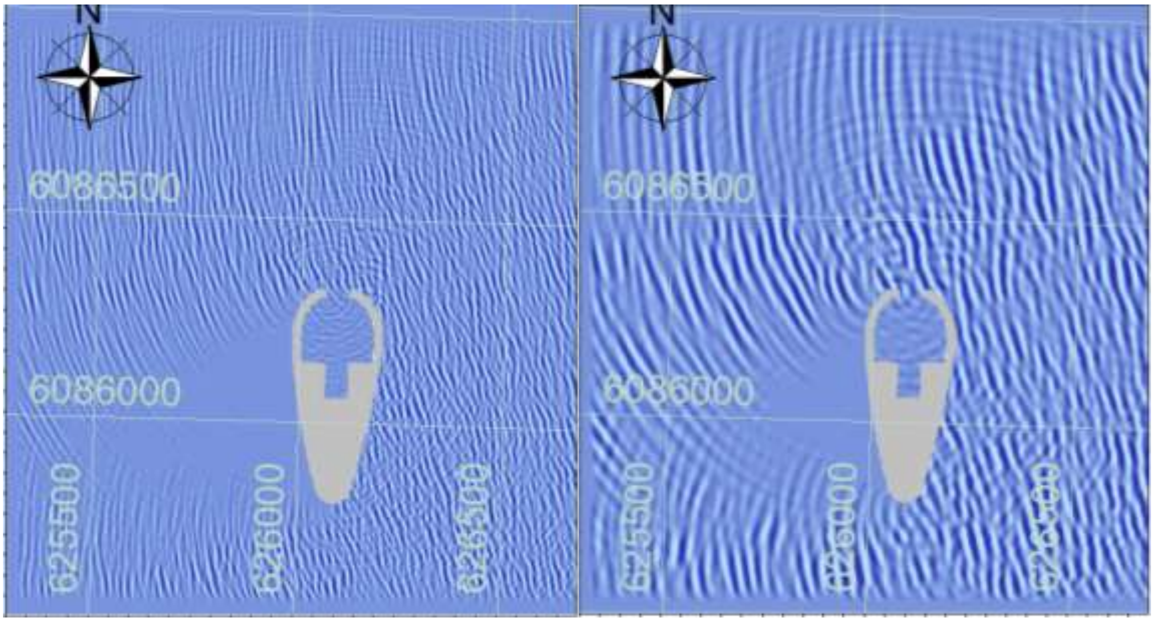


Figure E-25 Surface elevation plot for wave direction = 75°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

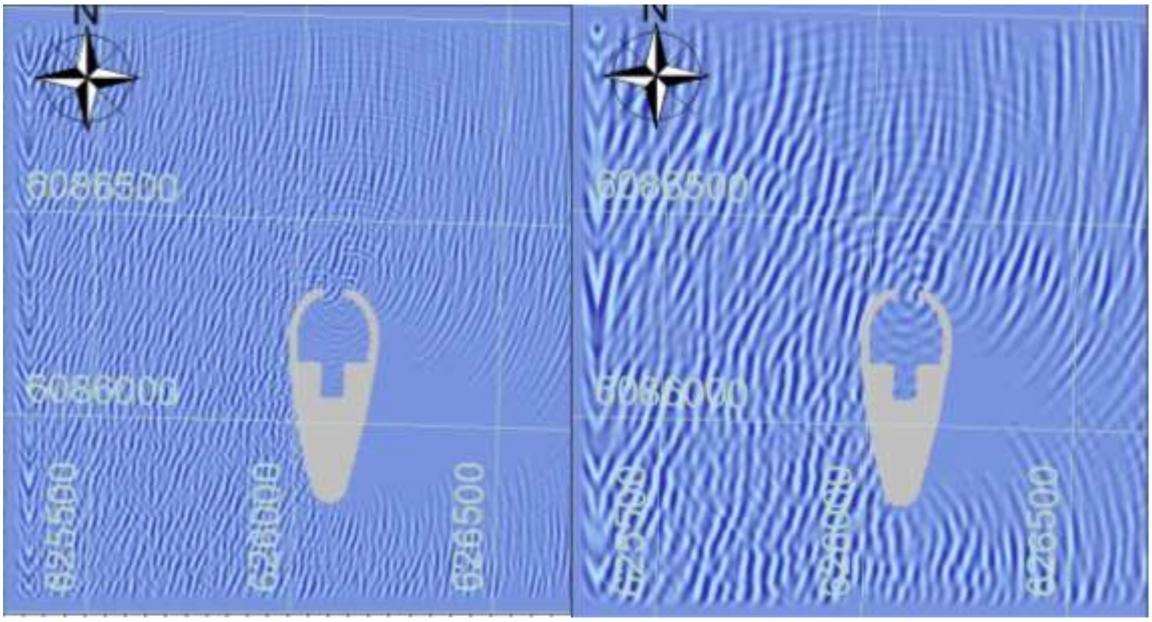


Figure E-26 Surface elevation plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

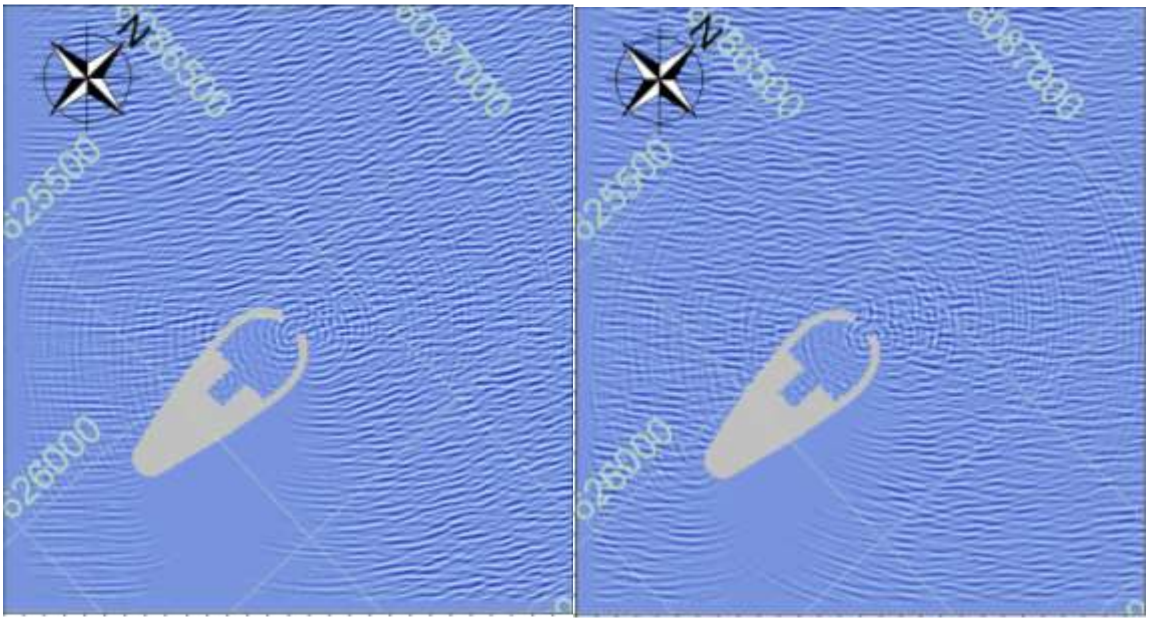


Figure E-27 Surface elevation plot for Tp =3.5 sec. Left: MWD =300°N, Right: MWD =315°N

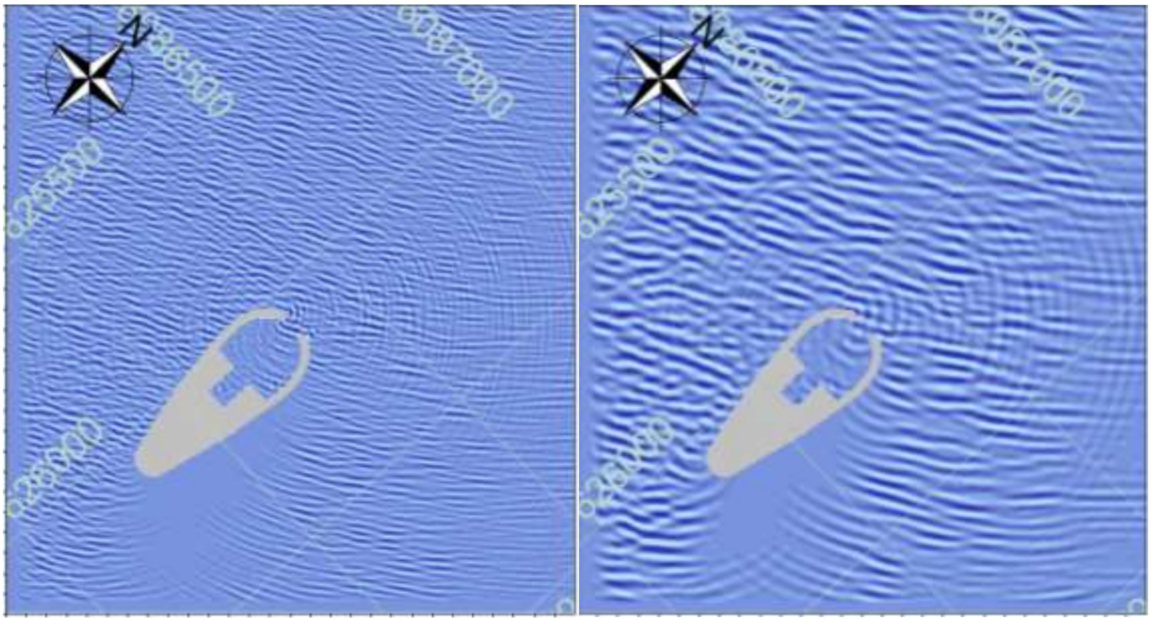


Figure E-28 Surface elevation plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

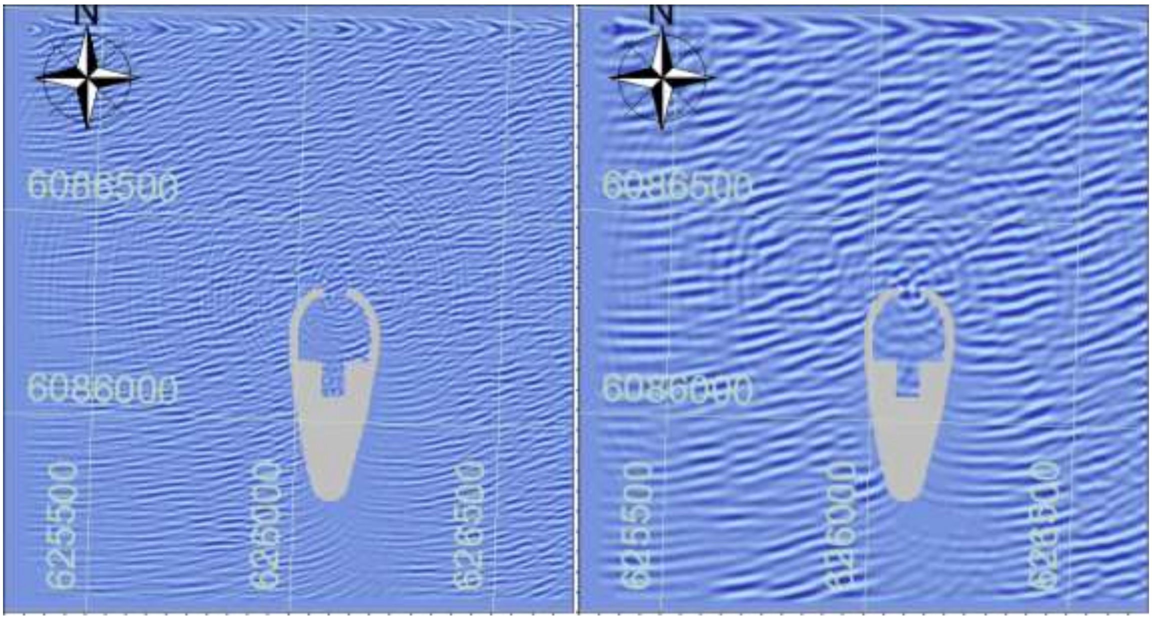


Figure E-29 Surface elevation plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

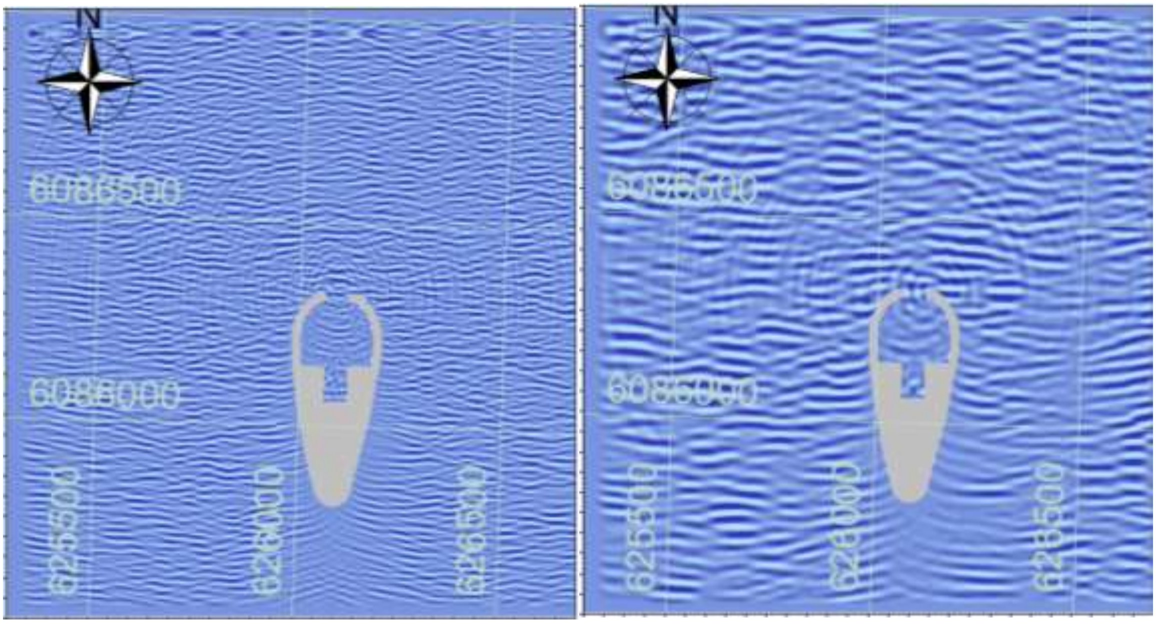


Figure E-30 Surface elevation plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

Appendix F Disturbance maps for Layout 3b

F.1 Overall Wave Disturbance Maps for Layout 3b

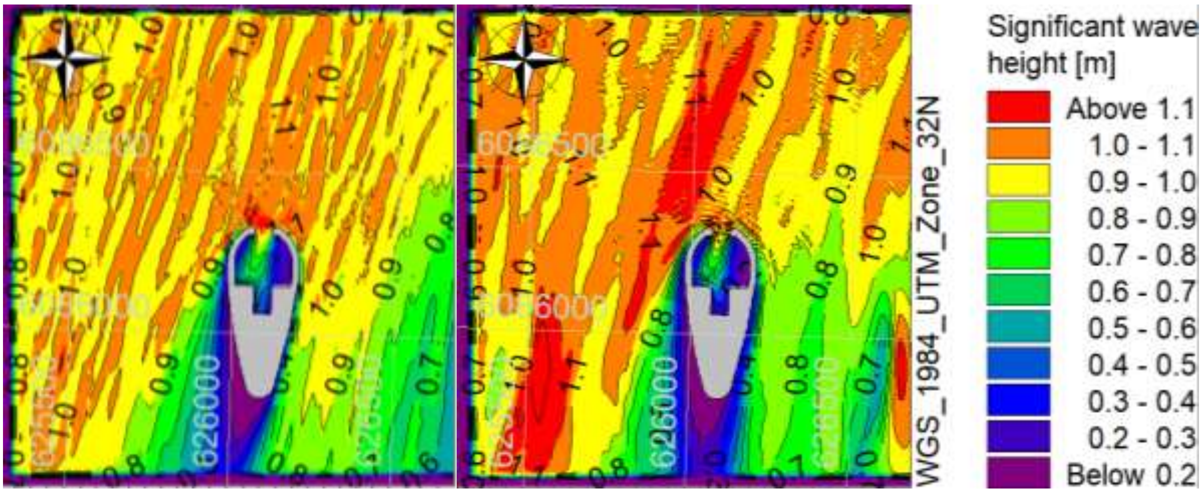


Figure F-1 Wave disturbance plot for wave direction = 15°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

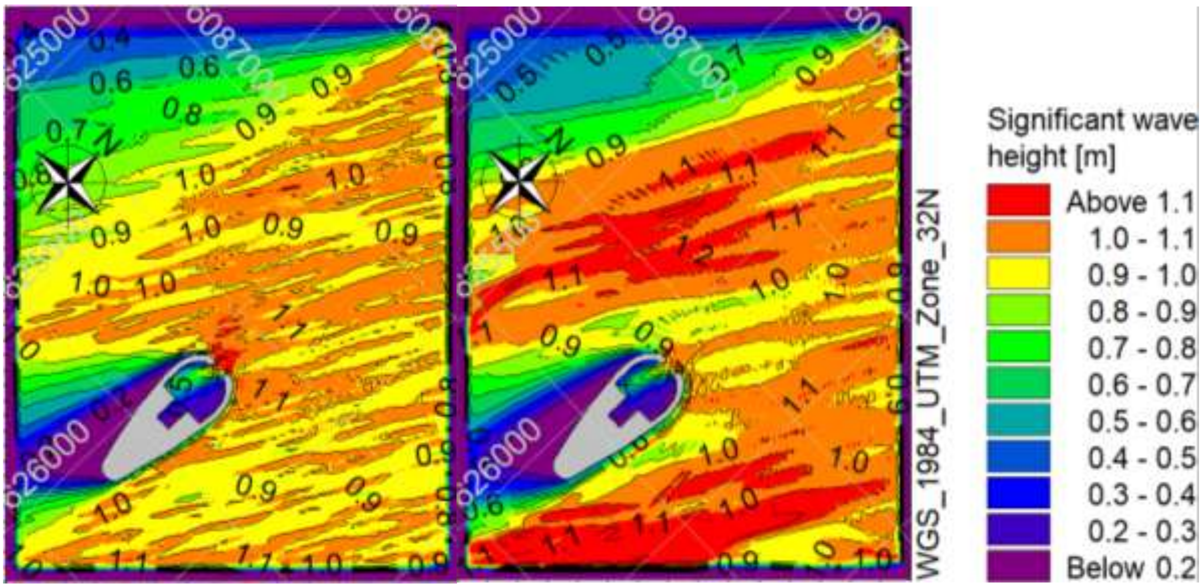


Figure F-2 Wave disturbance plot for wave direction = 30°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

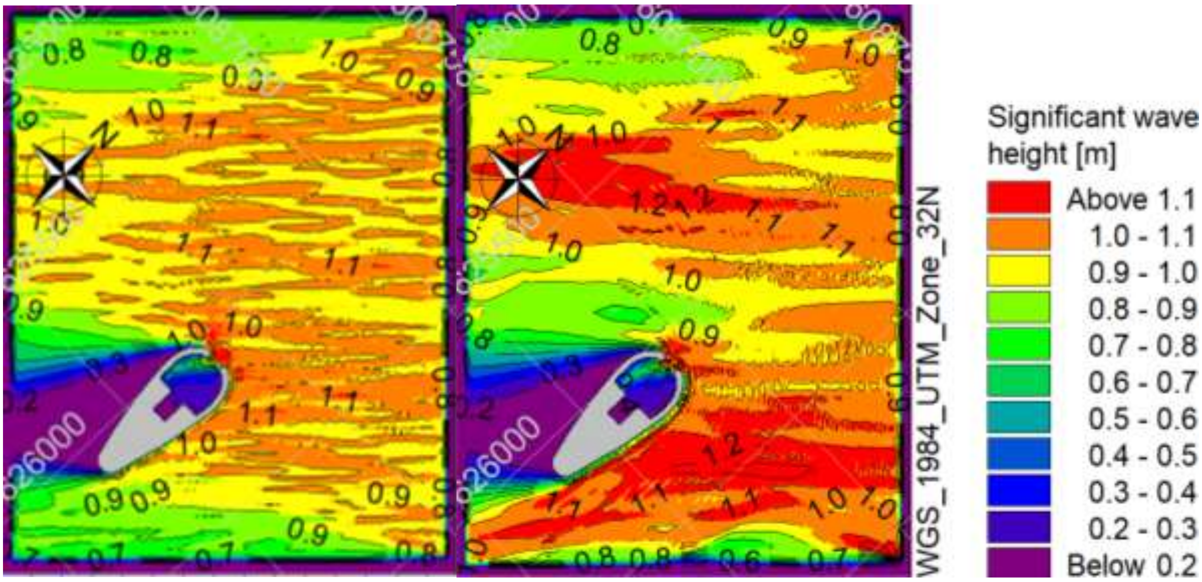


Figure F-3 Wave disturbance plot for wave direction =45°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

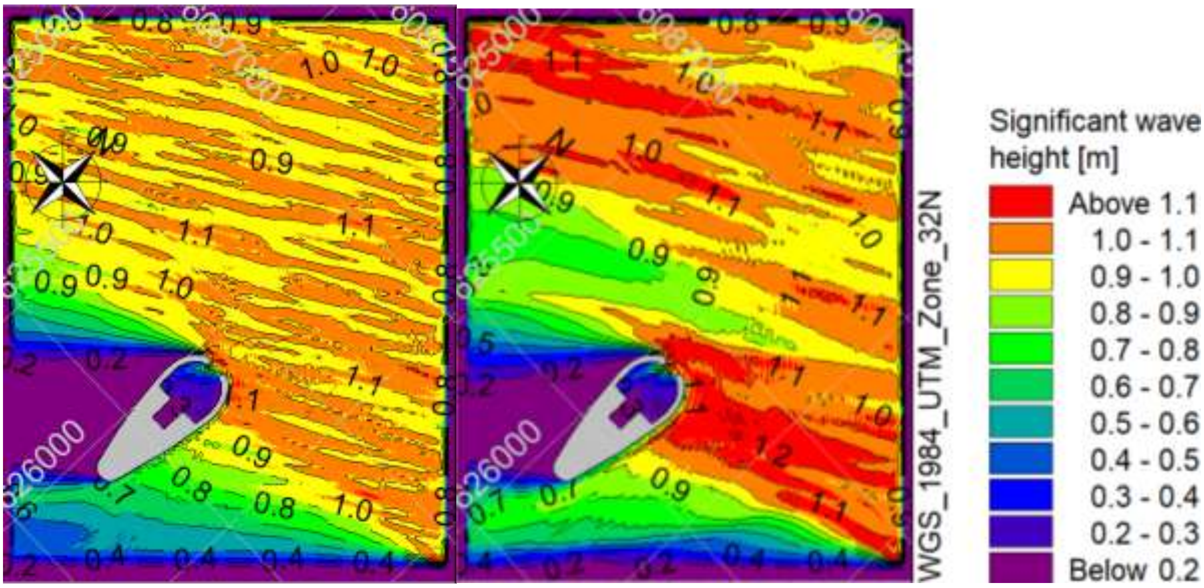


Figure F-4 Wave disturbance plot for wave direction =60°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

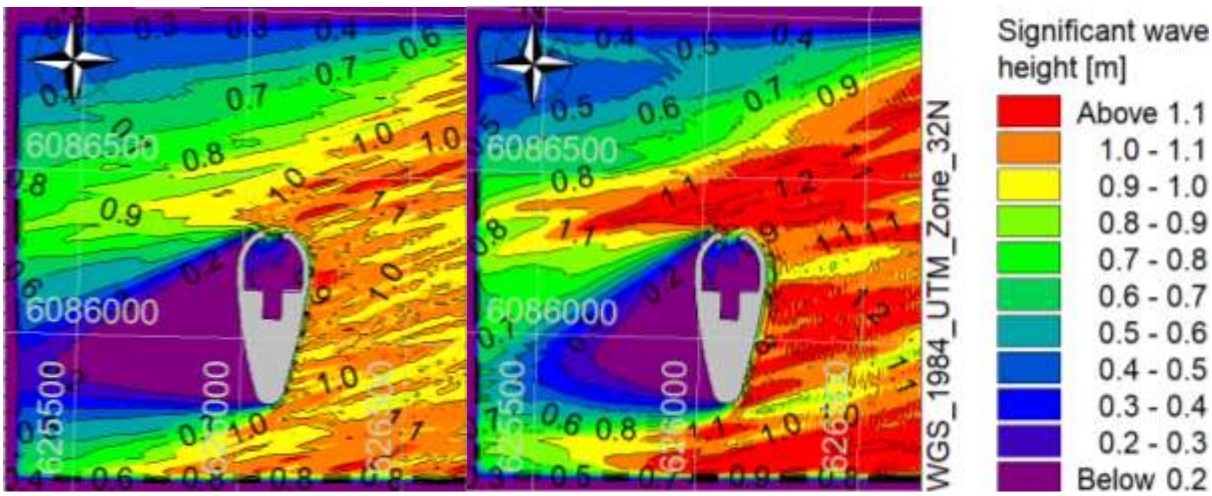


Figure F-5 Wave disturbance plot for wave direction =75°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

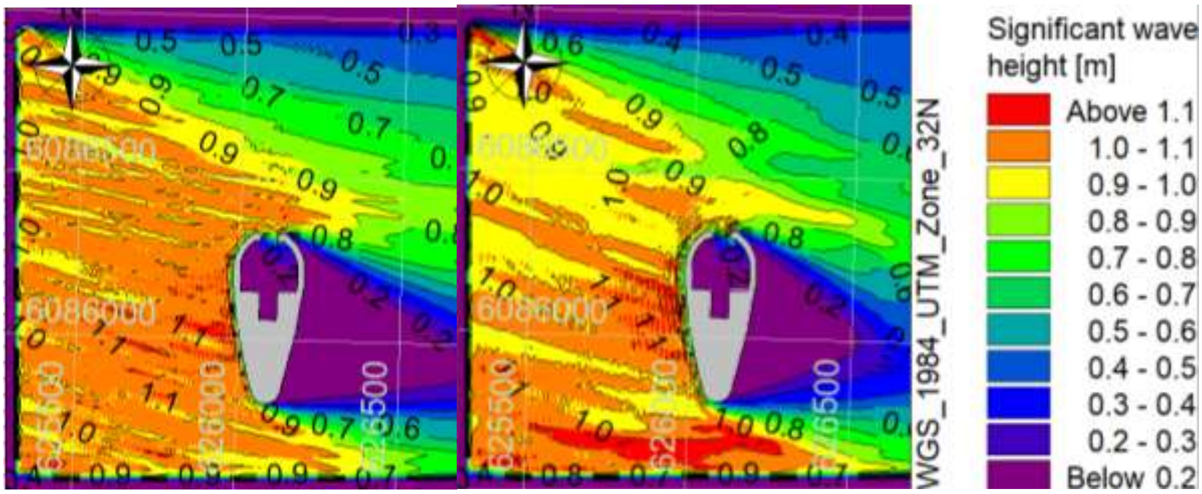


Figure F-6 Wave disturbance plot for wave direction =285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

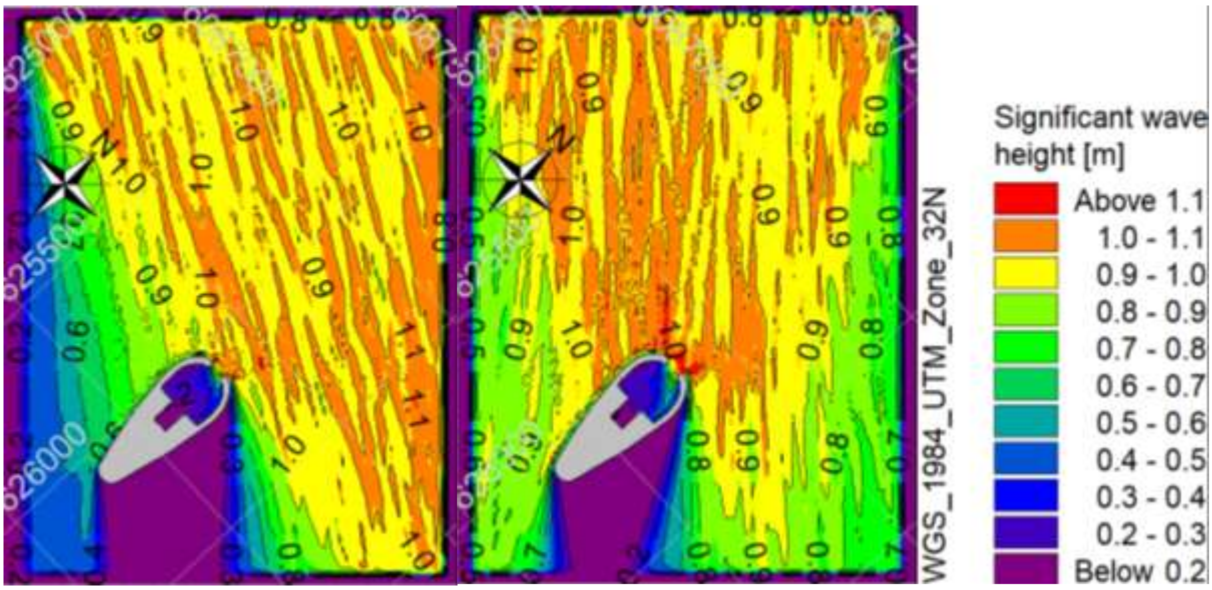


Figure F-7 Wave disturbance plot for Tp = 3.5 sec. Left: MWD= 300°N, Right: MWD=315°N

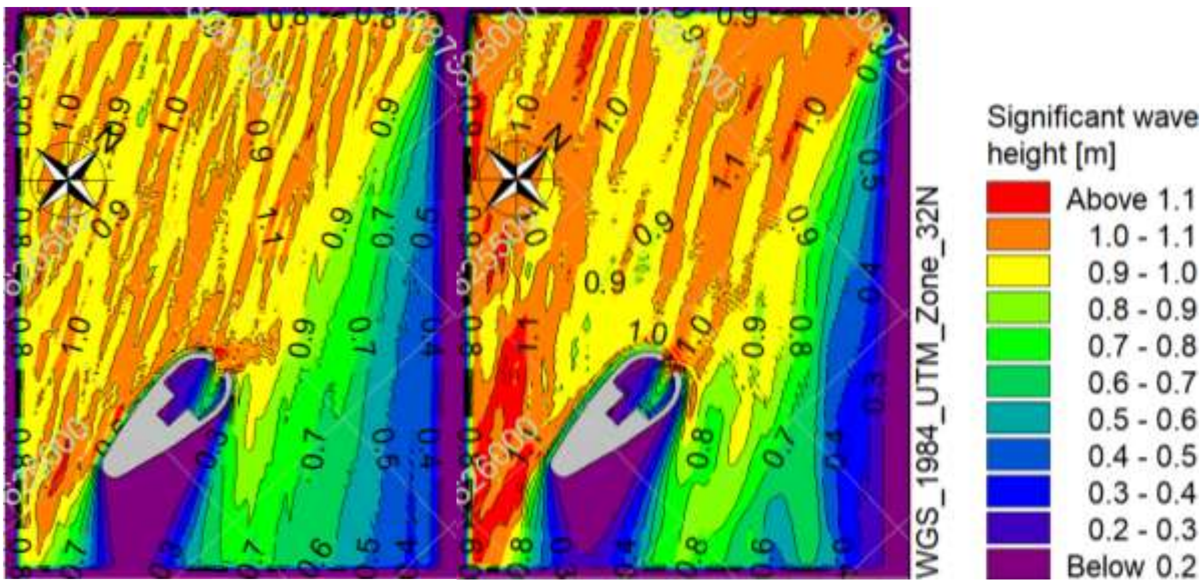


Figure F-8 Wave disturbance plot for wave direction =330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

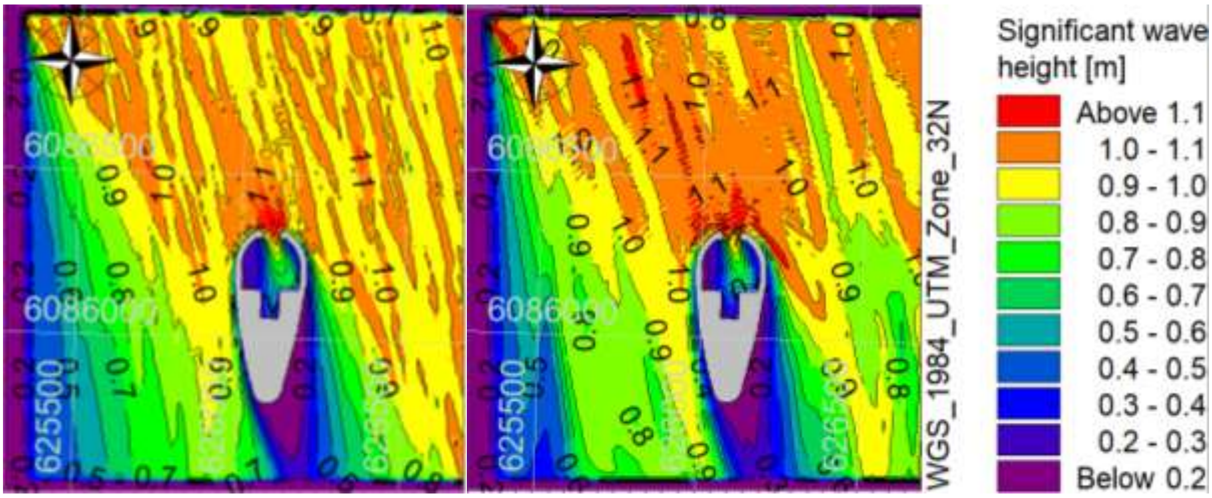


Figure F-9 Wave disturbance plot for wave direction =345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

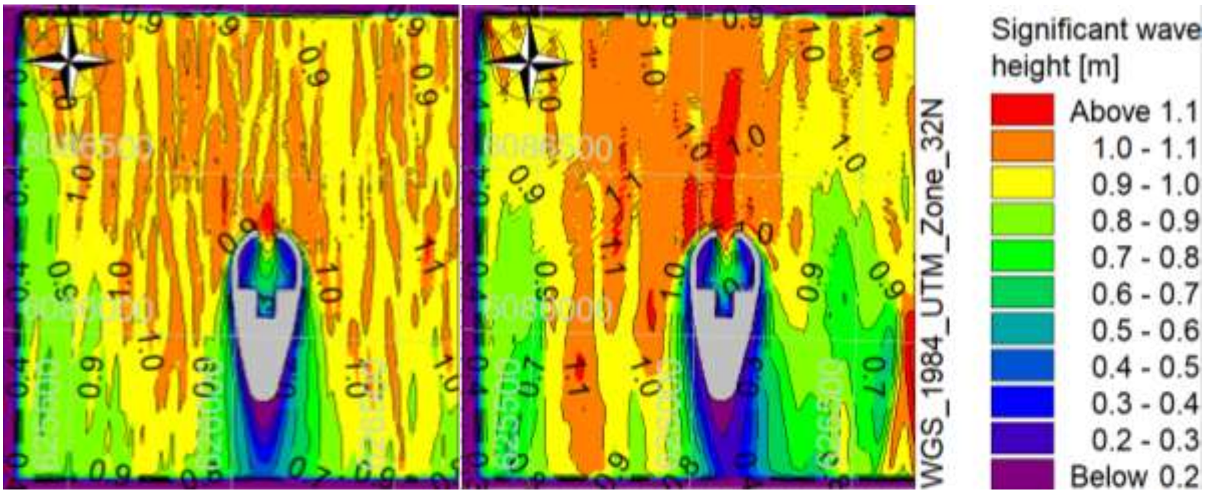


Figure F-10 Wave disturbance plot for wave direction =0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

F.2 Closeup of Wave Disturbance Maps for Layout 3b

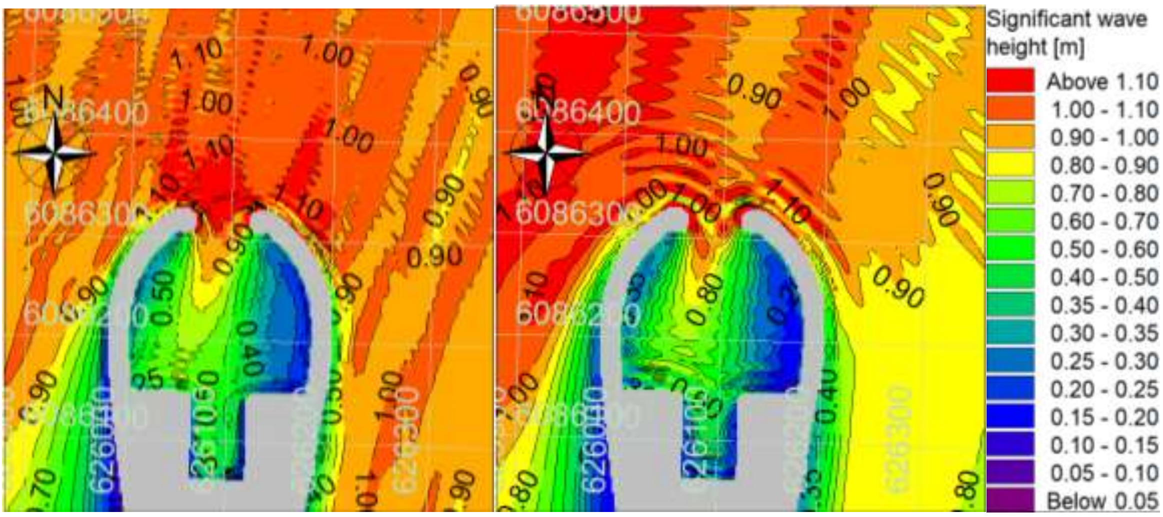


Figure F-11 Closeup of wave disturbance plot for wave direction = 15°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

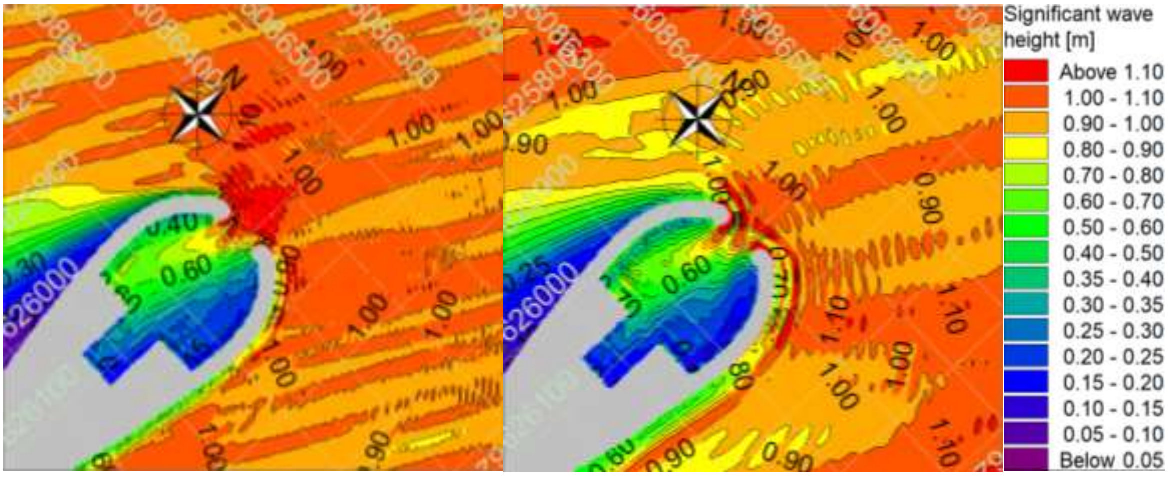


Figure F-12 Closeup of wave disturbance plot for wave direction = 30°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

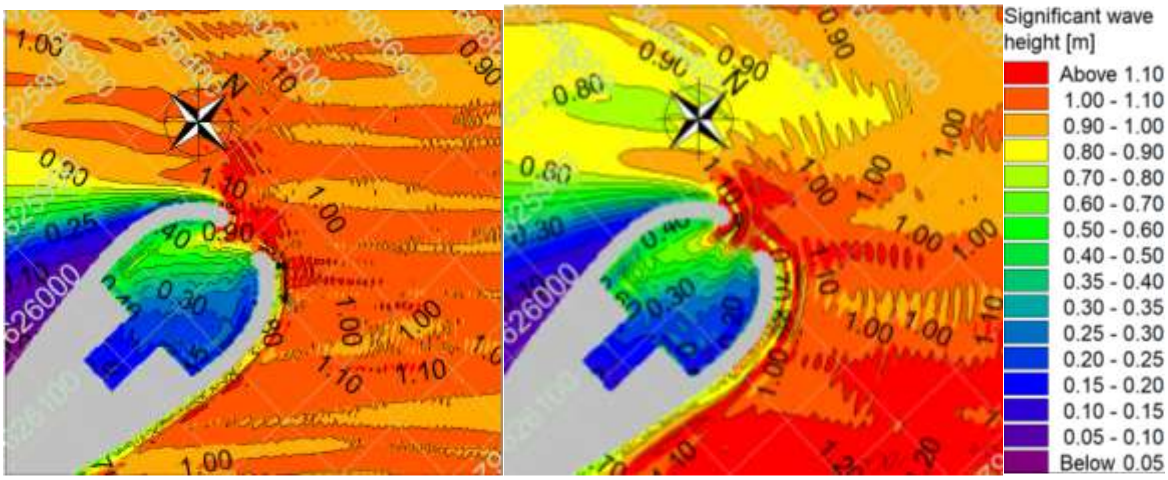


Figure F-13 Closeup of wave disturbance plot for wave direction = 45°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

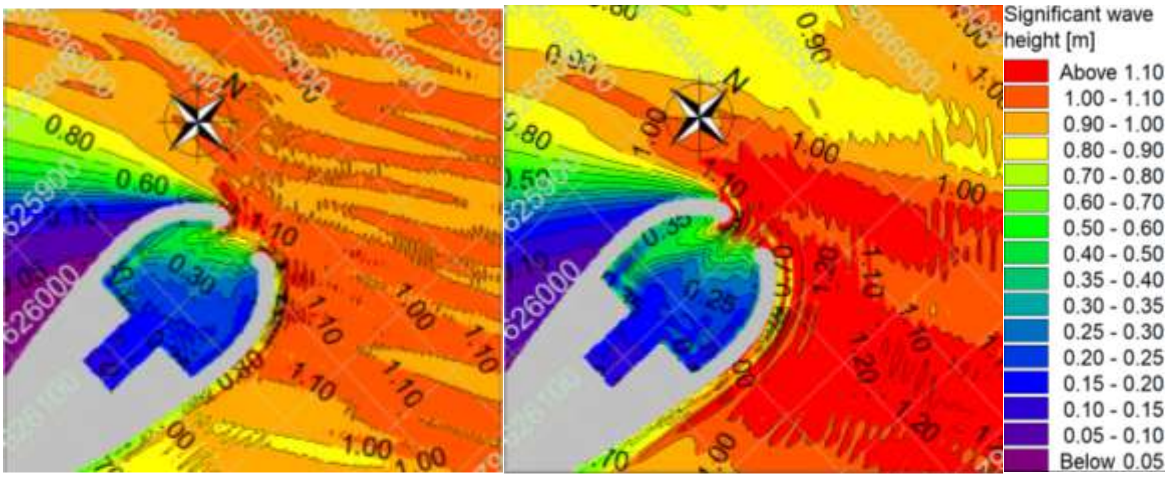


Figure F-14 Closeup of wave disturbance plot for wave direction = 60°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

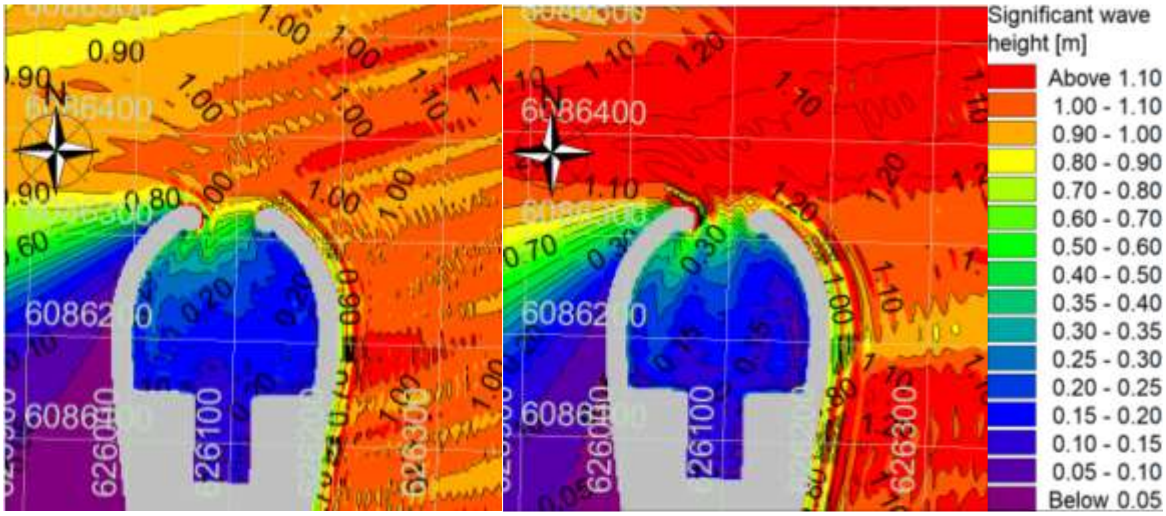


Figure F-15 Closeup of wave disturbance plot for wave direction = 75°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

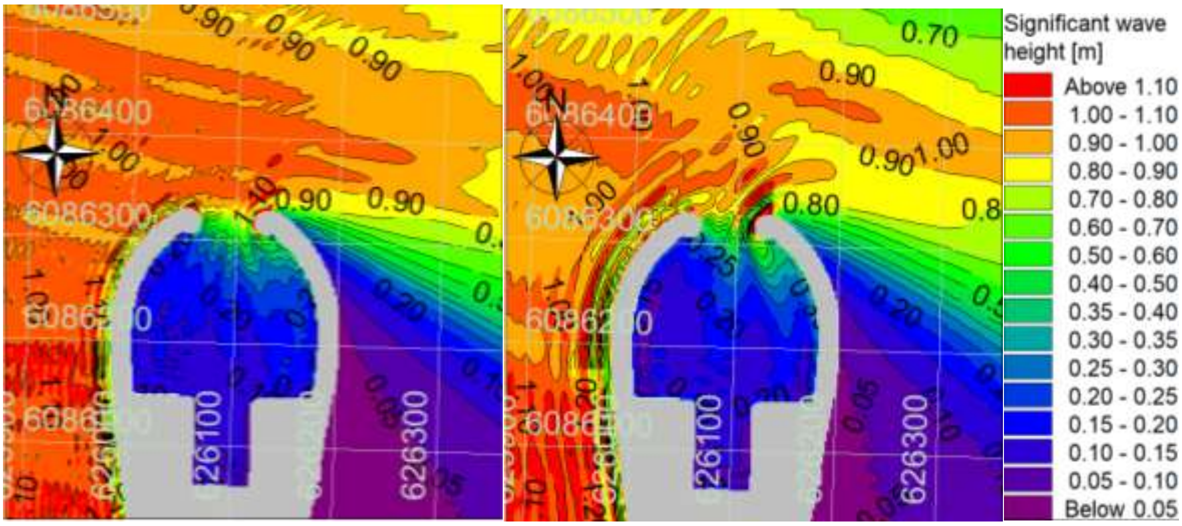


Figure F-16 Closeup of wave disturbance plot for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

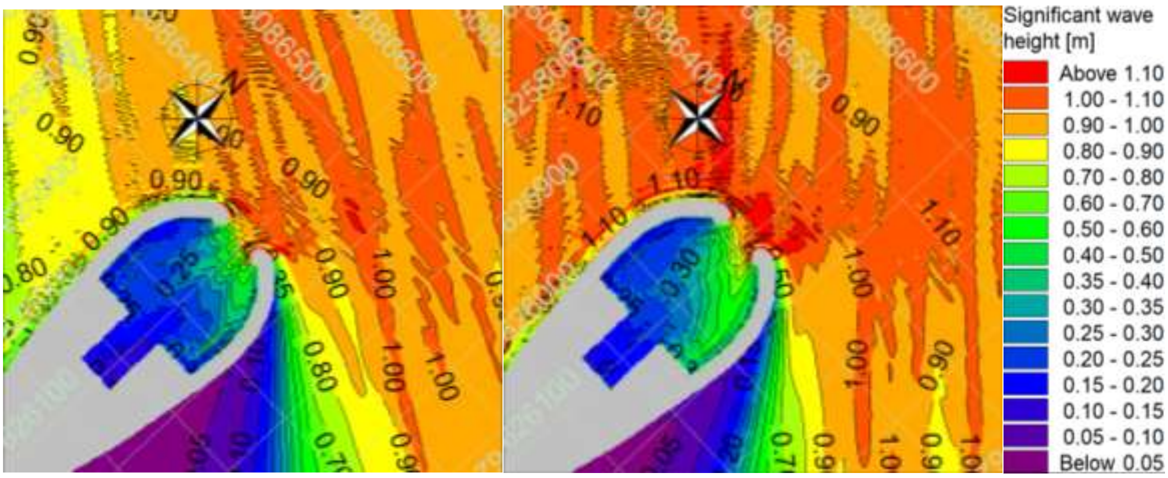


Figure F-17 Closeup of wave disturbance plot for Tp = 3.5 sec. Left: MWD = 300°N, Right: MWD =315°N

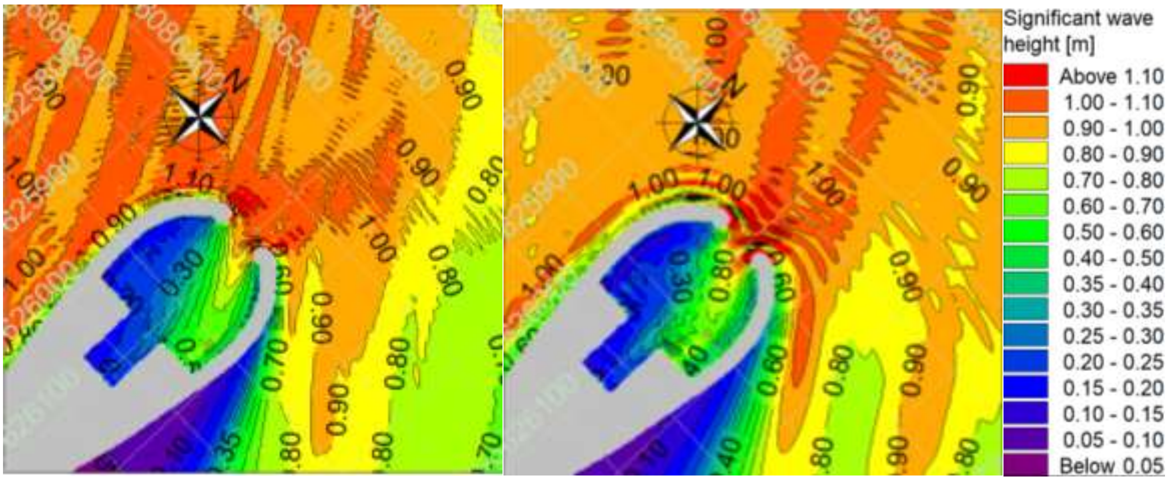


Figure F-18 Closeup of wave disturbance plot for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

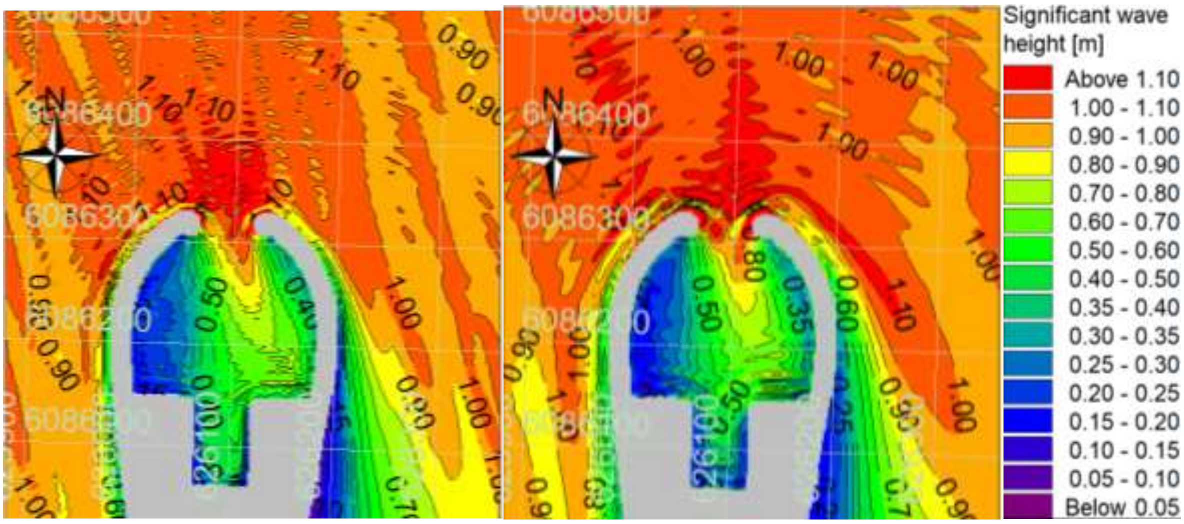


Figure F-19 Closeup of wave disturbance plot for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

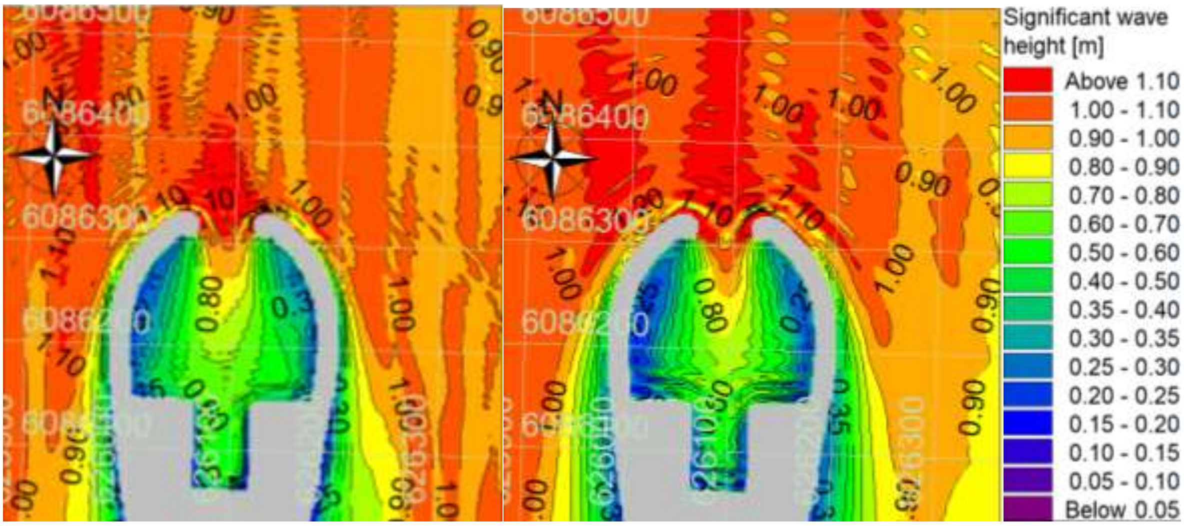


Figure F-20 Closeup of wave disturbance plot for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

F.3 Instantaneous Surface Elevation Maps for Layout 3b

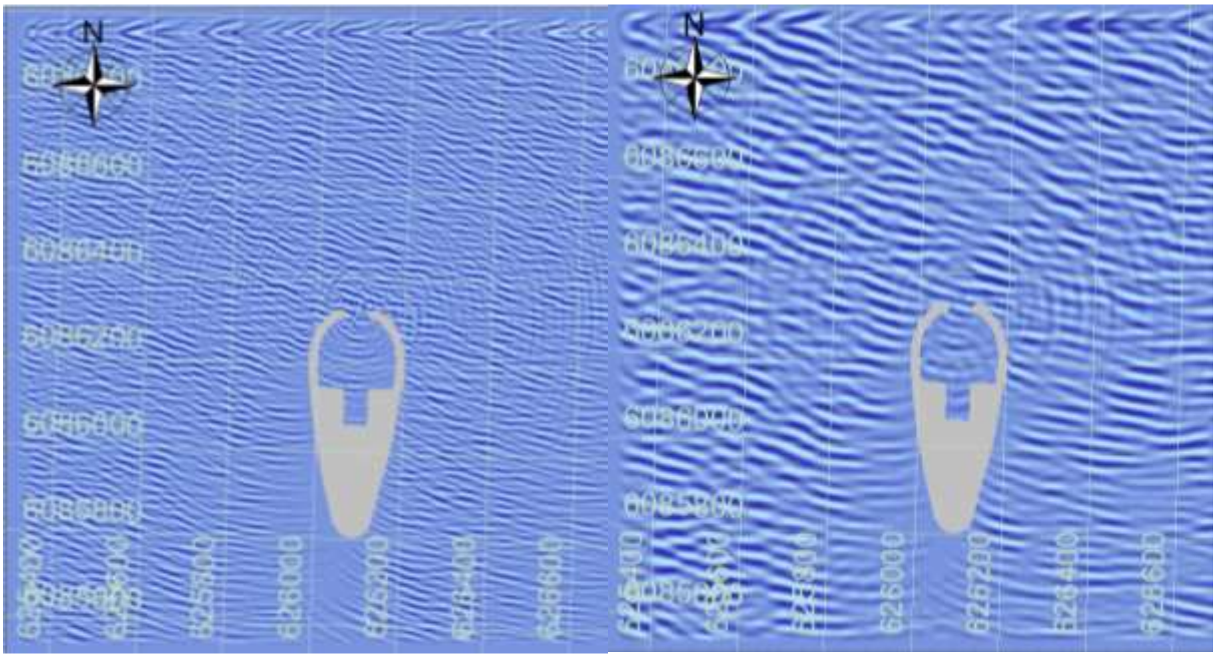


Figure F-21 Surface elevation map for wave direction = 15°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

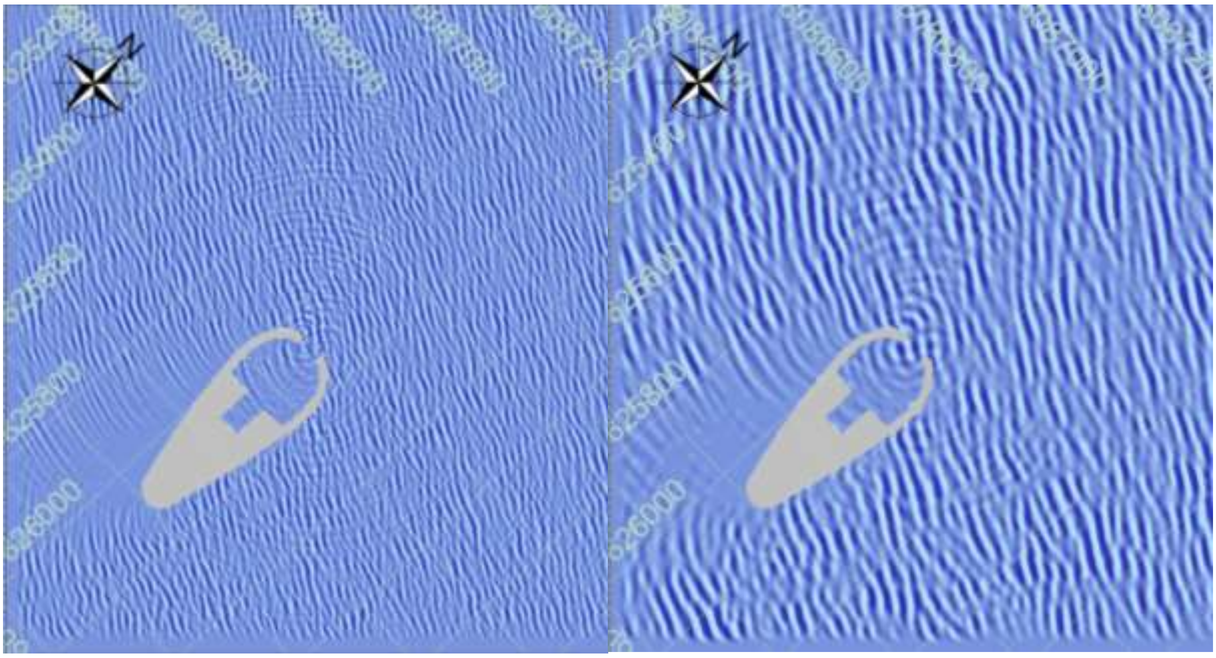


Figure F-22 Surface elevation map for wave direction = 30°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

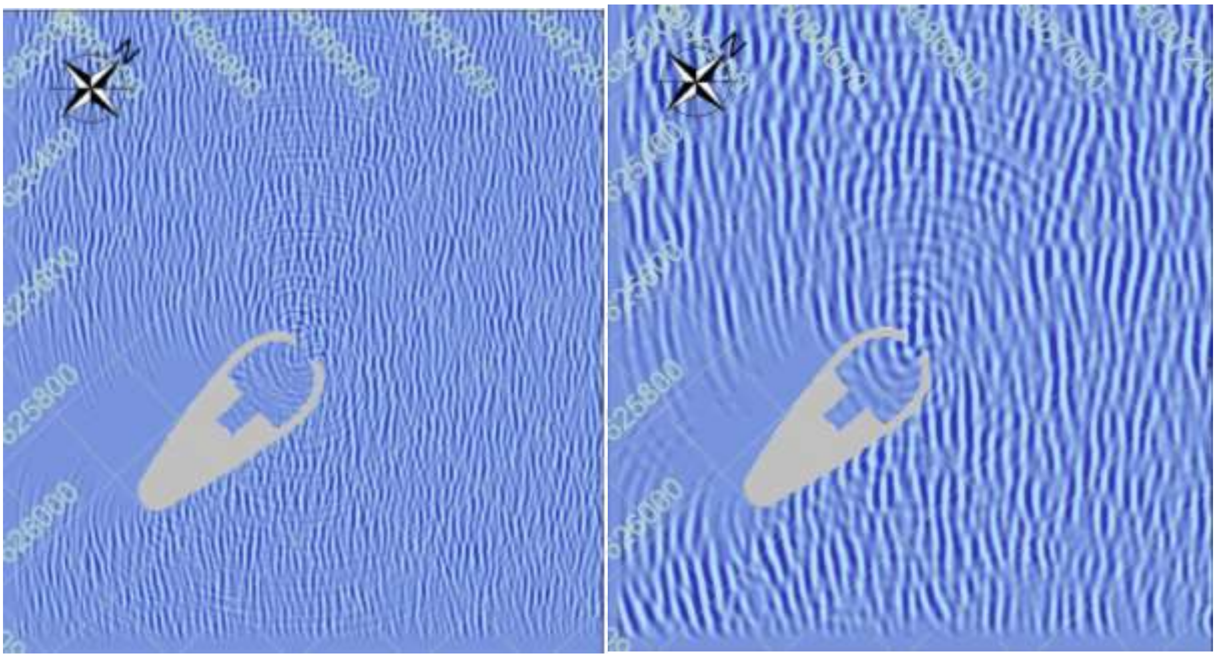


Figure F-23 Surface elevation map for wave direction = 45°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

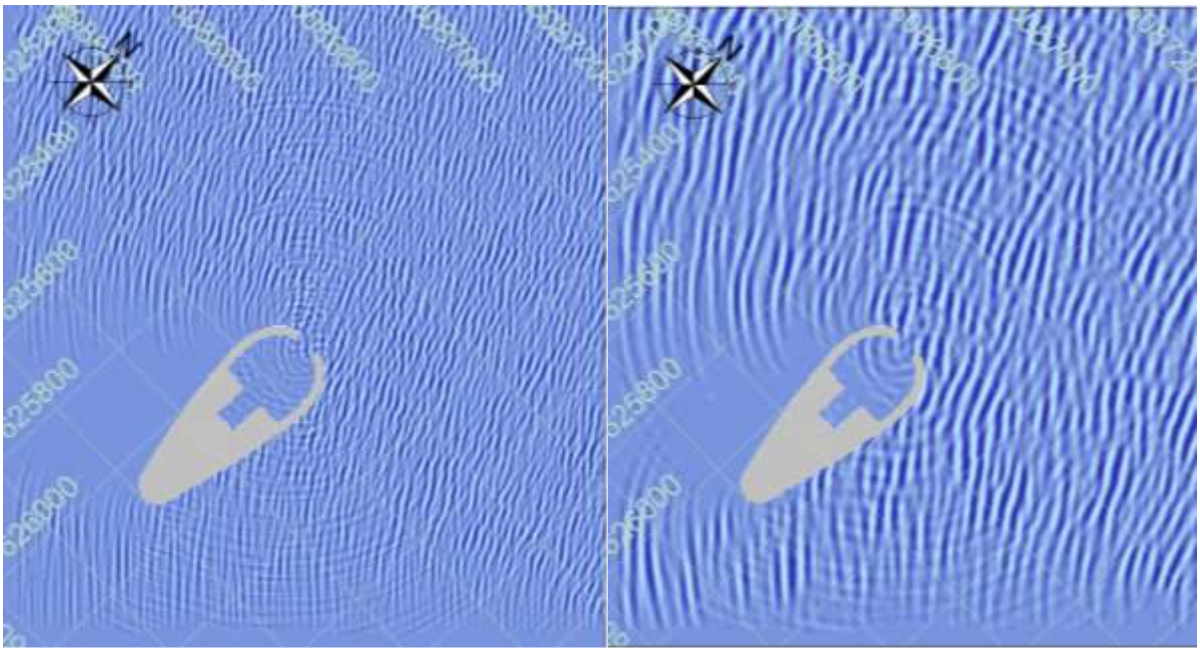


Figure F-24 Surface elevation map for wave direction = 60°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

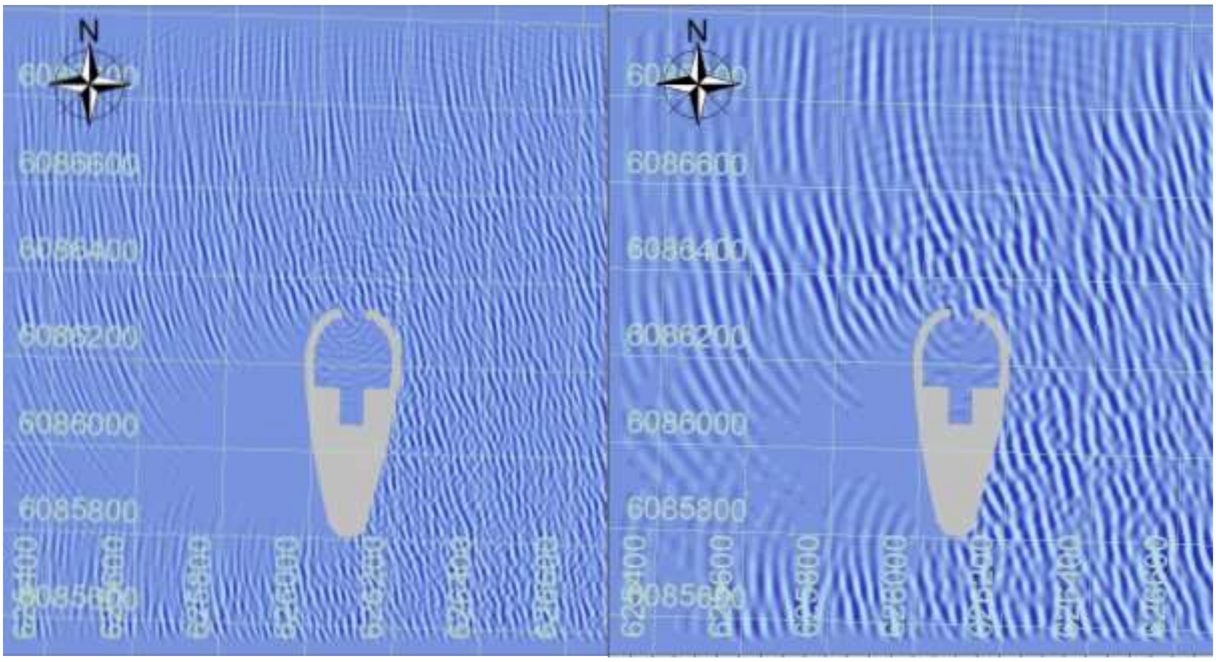


Figure F-25 Surface elevation map for wave direction = 75°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

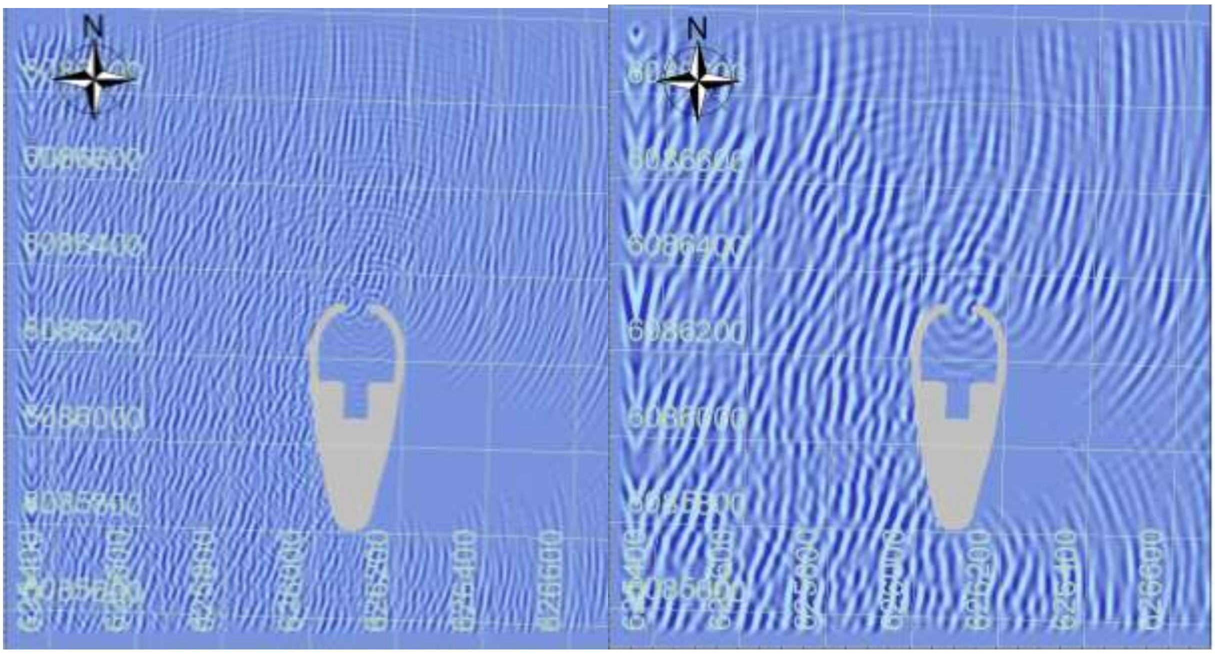


Figure F-26 Surface elevation map for wave direction = 285°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

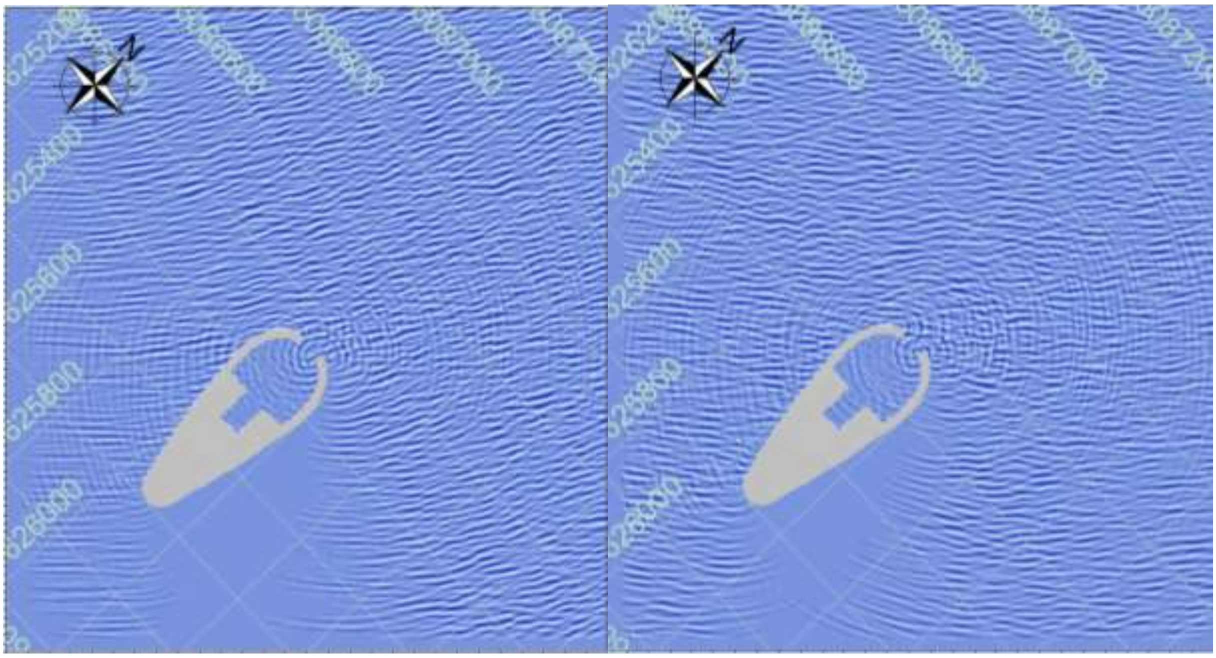


Figure F-27 Surface elevation plot for Tp = 3.5 sec. Left: MWD = 300°N, Right: MWD =315°N

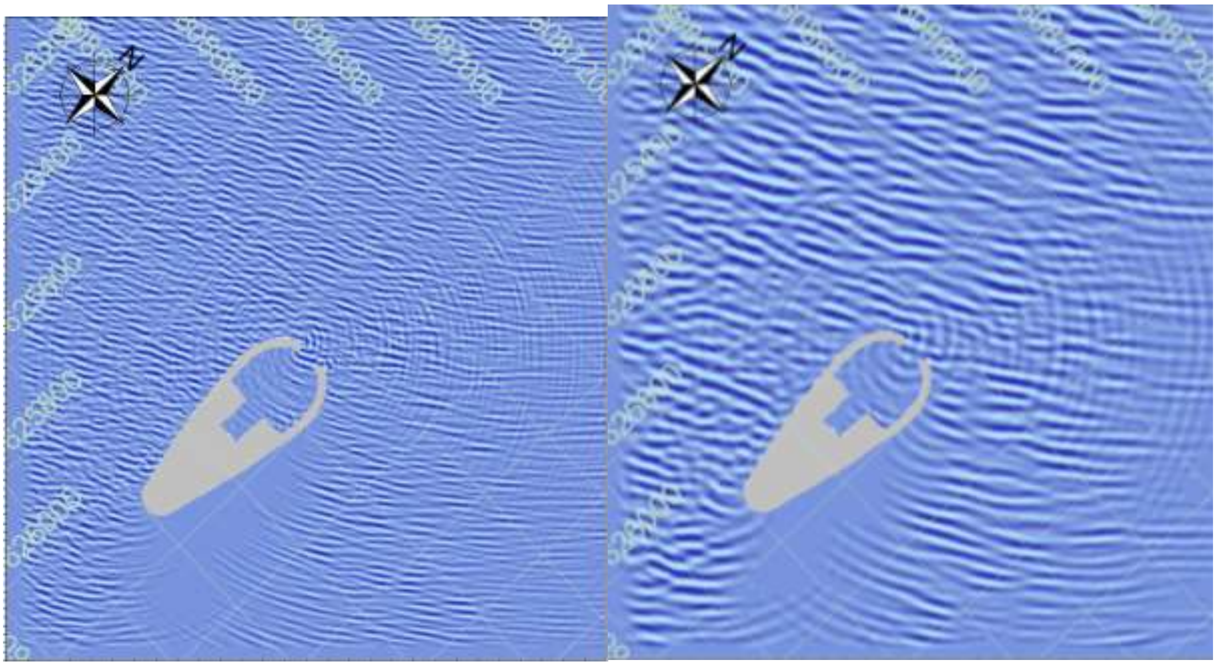


Figure F-28 Surface elevation map for wave direction = 330°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

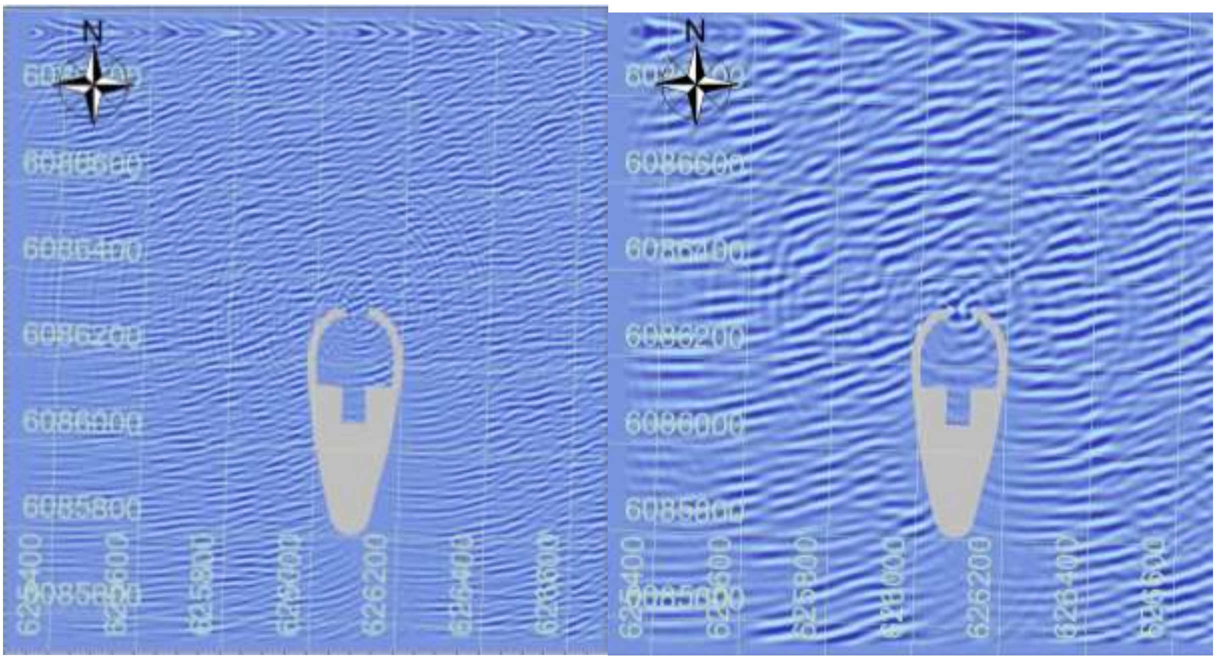


Figure F-29 Surface elevation map for wave direction = 345°N. Left: Tp = 3.5 sec, Right: Tp =5 sec

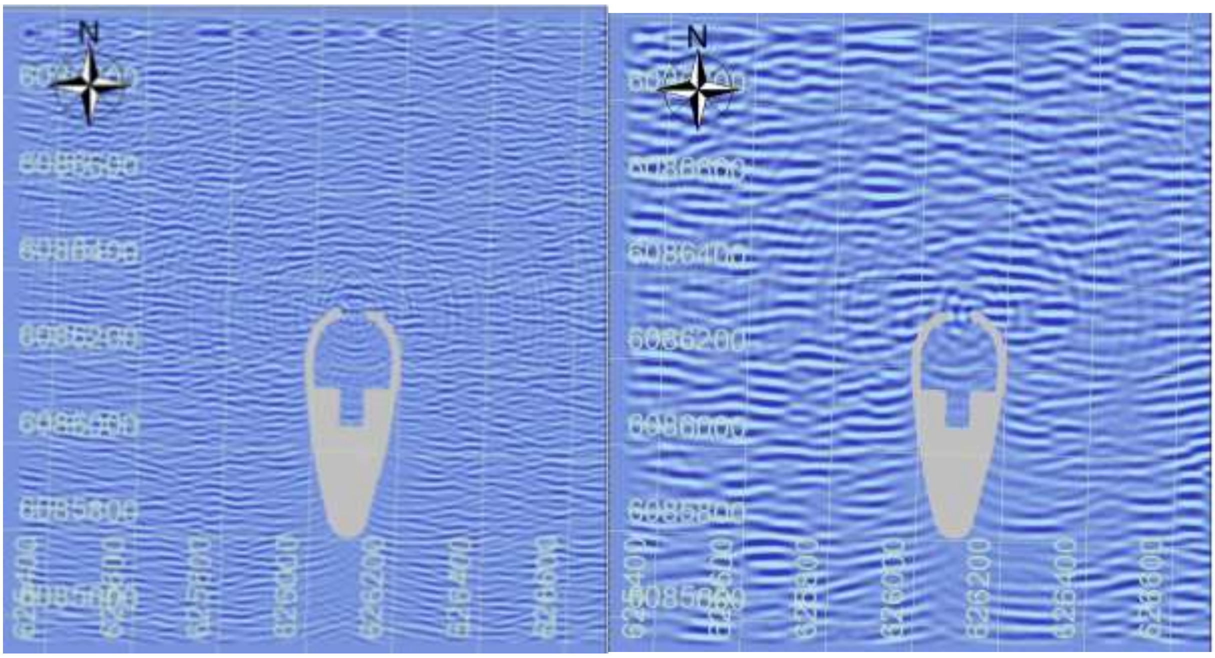


Figure F-30 Surface elevation map for wave direction = 0°N. Left: Tp = 3.5 sec, Right: Tp =5 sec