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CASE STUDY (Presented at 2023 GhIE Annual Conference & AGM)

Numerical modeling of wave penetration inside a harbour

Richard Asumadu[1, 2,*], Precious Mattah[1] and Donatus Angnuureng[1]

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Abstract
Wave penetration analysis is typically performed to ensure that the coastal structure at the harbour provides adequate shelter from waves and currents for ship berthing. Generally, wave penetration inside a harbour occurs through the entrance. The type of coastal protection (usually a breakwater) also has an impact on wave agitation within the harbour. In this research, wave penetration analysis has been done, mainly, by using MIKE 3 Wave FM software to model seven different scenarios as individual cases. From the seven different cases, the mean wave disturbance coefficient and mean significant wave height in the berthing area are determined. The model results showed that the wave penetration on the turning circle in the navigation channel is relatively unaffected by the wave disturbance in all seven cases. It is observed that 80 % of the time the significant wave height in the berthing area was less than or equal to 0.1 meters. The wave climate in the berthing area is therefore classified as good. Consequently, it can be concluded that the breakwaters are achieving their goal of reducing the impact of wave action and currents within the harbour.

Keywords: Wave Penetration, Mike 3 Wave FM, Berthing, Harbour, Waves

Introduction

Wave penetration in a harbour refers to the ability of ocean waves to enter and propagate inside the harbour. When waves enter a harbour, they interact with the harbour walls, seabed, and other structures, which can cause the wave energy to dissipate and the waves to lose their height and frequency. However, some waves may still be able to propagate deep into the harbour, causing disturbances to boats and other structures.

The amount of wave penetration in a harbour depends on several factors such as the size and shape of the harbour, the height and frequency of the waves, the depth and slope of the seabed, and the presence of any structures such as breakwaters or jetties. Designers and engineers often use numerical models and physical experiments to evaluate wave penetration in harbours and optimize the design of harbour structures to minimize the impact of wave action

This research considered the design and construction of a Forward Operational Base harbour for Ghana's Naval Force's ongoing construction in the western part of Ghana for the studies. Two breakwaters are constructed to protect the harbour basin from waves and currents. The breakwaters are hereafter referred to as the main and lee breakwater.

To make sure, that the two breakwaters provide sufficient shelter for the berthing of ships, a wave penetration study is carried out. The study examines the wave disturbance in the berthing area under the most critical wave conditions.

Materials and Methods

Case study

The project site is located in the western part of Ghana on the coastal stretch exposed to the Gulf of Guinea between Takoradi and Ivory-coast as shown in Figure 1. The coastal stretch is part of an approximately 200 km long uniform beach confined by Abidjan to the west and a rocky headland with sandy bays to the east. East of the headland, the city of Takoradi is located. The site has coordinates records latitude 5.0217060 and longitude -2.7007150 at Ezinlibo.

Figure 1 Overview of the project area (Source: Google Satellite)

In this research, a practical case study of an ongoing harbour development along the western coast of Ghana was chosen to investigate wave penetration. The current study area is in Ezinlibo, about 150 km from Takoradi. The current site for harbour was chosen based on morphological (erosion/

*Corresponding author's email: asumadur@yahoo.com

[1]ACECoR, Centre for Coastal Management, University of Cape Coast, Cape Coast 00233, Ghana

[2]Ghana Hydrological Authority, Division for Coastal Engineering, MB 501, Accra, Ghana

accretion), security, and economic considerations (Salauddin *et al*., 2015) .

Figure 2 depicts the layout of the harbour under consideration in this research. Regarding the guidelines provided in the harbour layout and design guidelines provided by Department of Boating and Waterways (2005), the berthing facilities, for this research area layout of the harbour, is been designed, see details in Salauddin *et al*. (2015) for further studies on berthing.

for 1 hour during the year. For 80 % of the time, the significant wave height in the berthing area will be less than or equal to 0.1 meters. The wave climate in the berthing area is therefore classified as “good”.

Methods

This research is carried out with the MIKE 3 Wave FM model by DHI, where the harbour is subjected to regular waves. The wave disturbance coefficient in the harbour is then calculated based on the model results. Since the har-

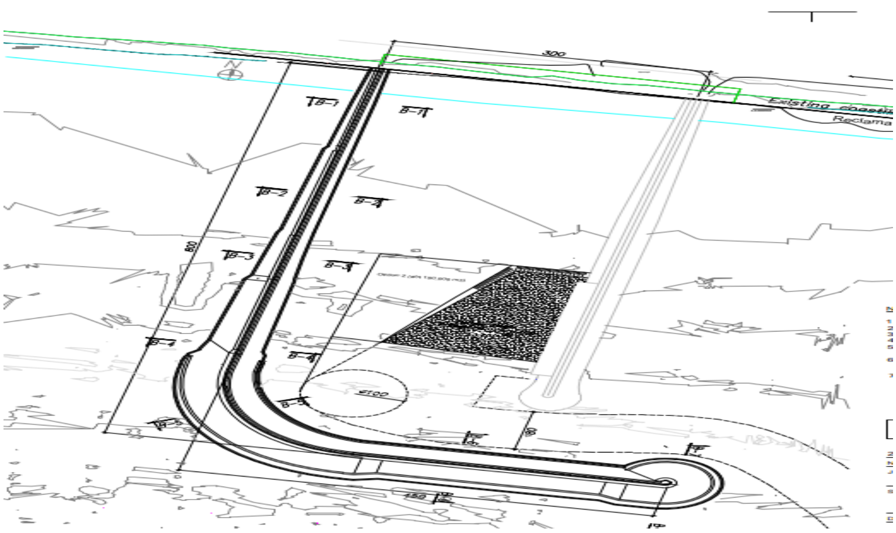

Figure 2 Schematic design of the harbour

Scenario

The seven worst-case combinations of wave direction and peak wave period are defined as shown in Figure 3. The seven different scenarios are modeled as individual cases. From the seven different cases, the mean wave disturbance coefficient and mean significant wave height in the berthing area are determined. To have a “good” wave climate in a small craft harbour, the significant wave height can only exceed 0.3 m once a year (Mercer *et al*., 1982). The results from the seven cases are summarized in Table 1.

By summing the yearly durations of the different cases, it is estimated how long time the mean significant wave height in the berthing area exceeds a given threshold during the year. The yearly cumulative time of exceedance for the different significant wave height thresholds is seen in Table 2. The mean significant wave in Table 2 shows that the height in the berthing area only exceeds the 0.3 m criteria

Table 1 Summary of wave direction, peak wave period and mean wave disturbance coefficient in the berthing area for the seven cases

	Incoming wave		**Berthing area**	
	Wave direction [Deg N]	Wave period [s]	Mean wave disturbance coefficient	Mean H_{m0} [m]
Case 1	145	8	0.05	0.05
Case 2	160	9	0.06	0.06
Case 3	170	11	0.08	0.14
Case 4	175	14	0.11	0.27
Case 5	180	17	0.11	0.33
Case 6	195	16	0.09	0.27
Case 7	180	11	0.06	0.11

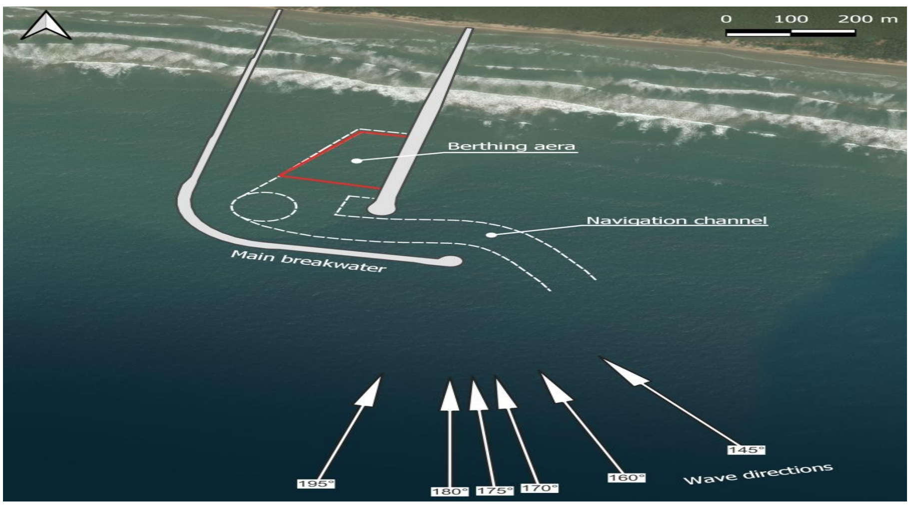

Figure 3 Overview of the project area and simulated wave directions.

Table 2 The time during the year where the mean significant wave height in the berthing area exceeds a given threshold

H_{m0} threshold [m]	Time exceeded [hr/yr]
0.30	1
0.25	59
0.20	650
0.15	677
0.10	1889
0.05	8591
0.04	8640

bour entrance is facing east, the most critical wave direction in terms of wave disturbance is east. Another factor that influences the wave disturbance in the harbour is the wave period. It is known that long periods of swell waves impose a greater risk of wave disturbance in the harbour. This is based on hindcast data from the previous Metocean study, the most eastern wave directions with the largest wave periods was identified.

The selection of wave directions and periods summarizes into seven different cases. The different cases are simulated with a regular unidirectional wave of 1 m. The calculated wave disturbance coefficient showed how much the incoming significant wave height is reduced in the harbour basin in each of the seven cases.

After the mean wave disturbance coefficient in the berthing area is calculated for all seven cases, they were multiplied by the incoming significant wave height of each specific case. The incoming significant wave heights for all seven cases were obtained from the hindcast data from the Metocean study. Based on this calculation the mean significant wave height in the berthing area is estimated. Finally, it is assessed to verify if the wave disturbance in the harbour basin is within an acceptable limit of 0.3.

Bathymetry Data
The bathymetry in the model is based on four different datasets; i.e., one bathymetric survey and three artificially produced datasets. The datasets are illustrated in Figure 4 and briefly described as follows:

a) Survey data covering the harbour basin and the area south of the main breakwater (Blebs Geo-Consult, 2022). The datum of the raw data is in National Level Datum (NLD) and is converted to meters of Mean Sea Level (mMSL).
b) Artificial extension of contours from survey data, which is a dataset is made by extending the bathymetric contour lines from the survey data. By doing so, a larger area of the model domain is covered by bathymetric data.
c) Artificial data for wavemaker region, which is another artificial dataset made in the wavemaker region. The MIKE 3 Wave FM model requires a uniform water depth in the wavemaker region. For this reason, an artificial uniform water depth of -20 mMSL is implemented in the model.
d) Artificial data for navigation area: once the Forward Operation Base is constructed, the navigational area where the ships are berthed is deepened to a minimum depth of -6.5 mNLD. Therefore, an artificial bathymetry of -6.85 mMSL is placed in the navigational channel where the water level is shallower than -6.85 mMSL.

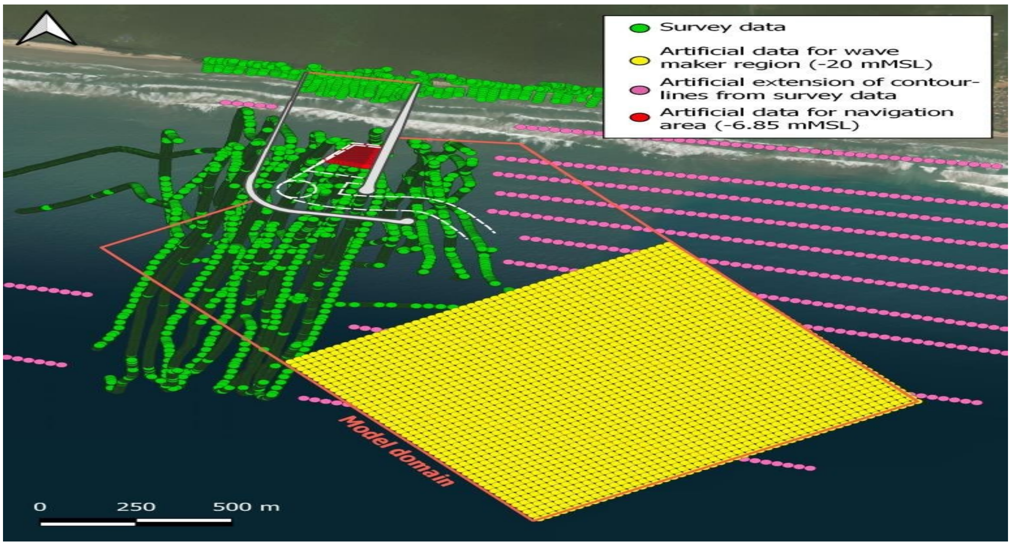

Figure 4 Types of bathymetric data used in the seven models (present figure show Case 1)

Waves
From the Metocean study, it is seen that the waves primarily come from the south. As previously mentioned, the orientation of the harbour inlet shows that the most critical wave direction in terms of wave disturbance is east (approximately 105 °N). The distribution of wave heights in wave directions is illustrated in Figure 5, and it shows how many hours during the year a given wave height and direction is expected to happen. From the Figure 5, it is seen that the most eastern wave direction is 145 °N. The harbour will be exposed to waves from this angle for approximately 1.2 hours yearly.

Besides the wave direction, the wave period influences the risk of wave disturbance. Increasing the wave period will increase the wave energy transport into the harbour basin. From the hindcast data generated in the Metocean study. The distribution of wave periods in mean wave directions is calculated and illustrated in Figure6, which is divided into different cases of peak wave periods and mean wave directions. The most critical combination of wave period and direction (marked with red crosses in the Figure 6) is used as representative values for the given case. The cases are therefore conservative estimates of the wave climate at the site. A total of seven cases covering the entire year are analyzed in the present study.

			Hm0 [m]													
	From		0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25
		To	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50
Mean wave direction	0	145	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	145	150	0.00	0.00	0.33	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	150	155	0.00	0.00	0.00	1.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	155	160	0.00	0.00	0.00	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	160	165	0.00	0.00	0.99	1.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	165	170	0.00	0.00	0.11	2.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	170	175	0.00	0.00	0.44	7.01	5.80	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	175	180	0.00	0.00	2.85	128.58	212.04	136.46	43.92	8.65	3.40	0.66	0.00	0.00	0.00	0.00
	180	185	0.00	0.00	15.55	371.50	588.79	367.89	191.77	78.42	10.40	3.40	0.00	0.00	0.00	0.00
	185	190	0.00	0.00	21.14	348.83	822.95	609.38	242.48	86.41	36.47	6.90	3.83	0.33	0.00	0.00
	190	195	0.00	0.00	7.89	243.14	901.81	768.74	303.05	128.69	37.02	10.62	3.94	0.00	0.00	0.00
	195	200	0.00	0.00	0.44	88.82	441.48	491.43	268.44	113.25	36.58	13.25	5.48	1.20	0.00	0.00
	200	205	0.00	0.00	0.00	22.12	124.86	92.22	55.20	25.30	13.80	8.98	1.64	1.64	0.00	0.00
	205	210	0.00	0.00	0.00	5.59	22.89	15.44	2.19	0.00	1.31	2.19	0.00	0.00	0.00	0.00
	210	215	0.00	0.00	0.00	0.22	6.68	5.80	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	215	220	0.00	0.00	0.00	0.00	0.66	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	220	360	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 5 Number of hours during the year that different and mean wave directions are occurring

			Tp [s]														
	From		0.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	
		To	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	
Mean wave direction	0	145	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	145	150	0.0	0.0	1.0	**0.2**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Case 1
	150	155	0.0	0.0	0.9	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	155	160	0.0	0.0	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	160	165	0.0	0.0	0.2	2.2	**0.1**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	case 2
	165	170	0.0	0.0	0.1	2.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	170	175	0.0	0.0	0.5	7.3	2.7	2.0	**1.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Case 3
	175	180	0.0	0.0	2.1	38.9	142.4	206.2	107.2	27.4	8.7	**3.7**	0.0	0.0	0.0	0.0	Case 4
	180	185	0.0	0.0	6.2	138.2	467.7	578.1	**282.6**	117.2	28.3	3.8	3.8	0.9	**1.0**	0.0	Case 5
	185	190	0.0	0.0	23.4	243.4	571.9	691.7	421.4	165.6	45.8	9.3	5.4	0.8	0.0	0.0	
	190	195	0.0	0.0	63.5	306.7	579.8	571.5	470.2	280.9	98.1	29.0	5.1	0.0	0.0	0.0	
	195	200	0.0	0.0	56.0	207.3	293.8	278.8	252.1	180.9	111.7	54.2	20.9	**4.5**	0.0	0.0	Case 6
	200	205	0.0	0.0	40.7	102.8	68.6	46.8	29.9	15.8	11.6	14.0	6.9	7.9	0.8	0.0	
	205	210	0.0	0.0	18.2	17.9	7.0	0.2	4.8	1.0	0.4	0.1	0.0	0.0	0.0	0.0	
	210	215	0.0	0.0	3.3	9.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	215	220	0.0	0.0	0.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Case 7
	220	360	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Figure 6 Number of hours in the year that different combinations of mean wave direction and Tp are occurring. The black boxes mark the seven simulation cases whereas the representative Tp and wave direction for each case are highlighted with red crosses.

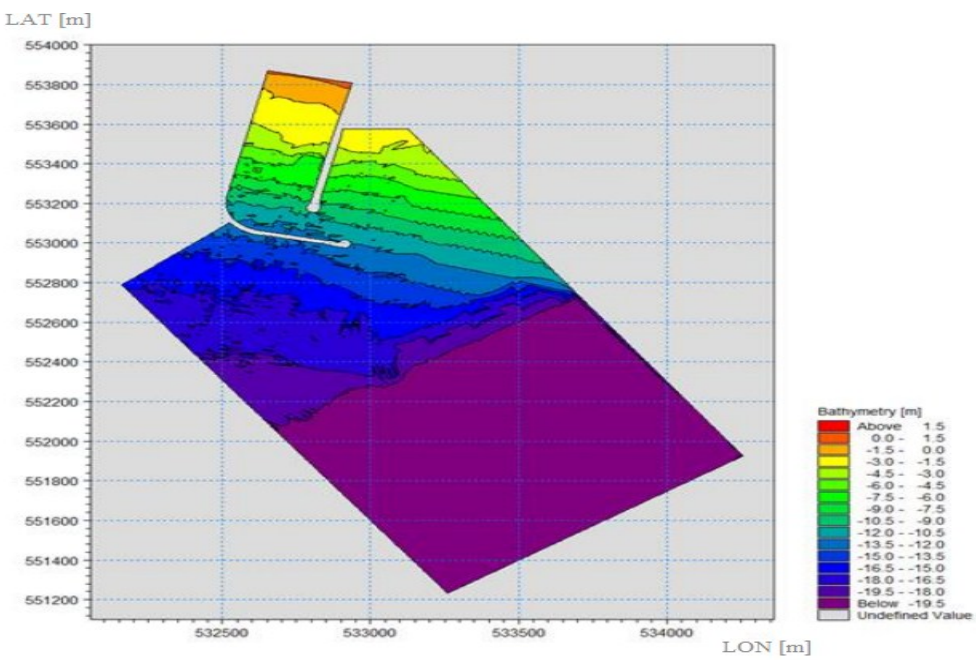

Figure 7 Example of the model domain and bathymetry for the three models (present figure depicts Case 1)

Table 3 Mesh in each of the models with wave period.

	Mesh size in harbour [m^2]	Mesh size outside harbour [m^2]	Wave period [s]
Case1	10	10	8
Case2	10	20	9
Case3	10	20	11
Case4	10	20	14
Case5	10	30	17
Case6	10	30	16
Case7	10	30	10

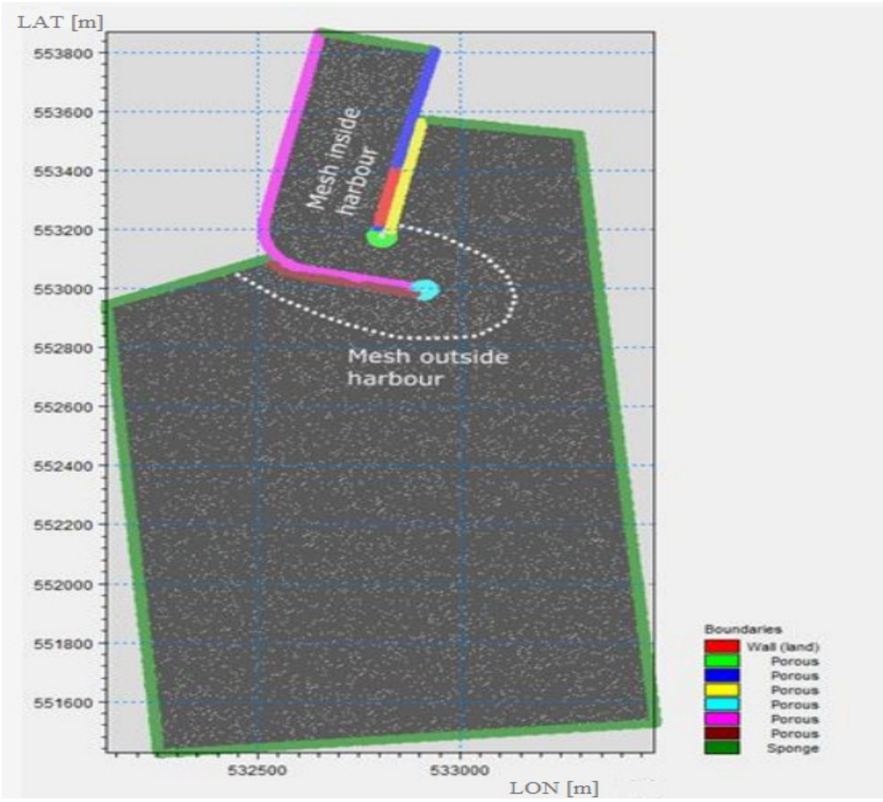

Figure 8 Example of model boundaries (present figure shows Case 4)

Model setup

Domain and Bathymetry

The model domain is oriented such that the waves are running parallel (or close to parallel) with the length of the model. The meshes and model domains are therefore different for each case. An example of the domain and bathymetry for one of the seven models (Case 1) is illustrated in Figure 7.

The resolutions of the mesh in each of the models are seen in Table 3. The size of the mesh elements varies from model to model since longer wave periods allow a coarser grid than shorter wave periods. However, the mesh inside of the harbour and near the harbour entrance is 10 m^2 in all the models. The boundary between the inside harbour region and outside harbour region referred to in Table 5 is illustrated in Figure 7.

Boundaries

A schematic sketch of the boundaries in the seven models is illustrated in Figure 8. As can be seen from the Figure 8, the outer model boundaries are sponges to absorb the incoming wave energy. The sponge boundaries are implemented to prevent undesired reflection of wave energy. The boundaries defining the two breakwaters are porosity zones.

The porosity zones allow some of the incoming wave energy to be dissipated and some of the energy to be reflected. The porosity (void over solid ratio) of the breakwater boundaries is set to 0.4. The width of the porosity zones varies according to the rock design. The cores of the breakwaters are impermeable. The 200 m wide berth wharf along the lee breakwater (the "Wall (land)") boundary from Figure 8 is a vertical concrete wall and it is modeled as a land boundary with full reflection.

Internal wave generation

The incoming wave is generated in an internal wave generation zone, which is 600 m wide and placed approximately 700 meters from the tip of the main breakwater as illustrated in Figure 9. In the wave generation zone, a regular 1 m wave is generated.

The incoming waves are simulated for 30 minutes. To check if the model has converged during this time, the wave heights of a random cell in the berthing area, in Figure 3 are plotted. The wave heights are illustrated in Figure 10, and it shows that the wave heights in the different models become constant during the simulation period indicating that the models are converged. In calculating the significant wave heights, the first 1000 time steps (out of the model's 1800 time steps) are disregarded to ensure that only the converged part of the model results is used to determine the wave disturbance coefficient.

Results and Discussion

Seven worst-case combinations of wave direction and peak wave period are defined from the Metocean study in Figure 3. The seven different scenarios are modeled as individual cases. From the seven different cases, the mean wave disturbance coefficient and mean significant wave height in the berthing area are calculated. To have a "good" wave climate in a small craft harbour, the significant wave height can only exceed 0.3

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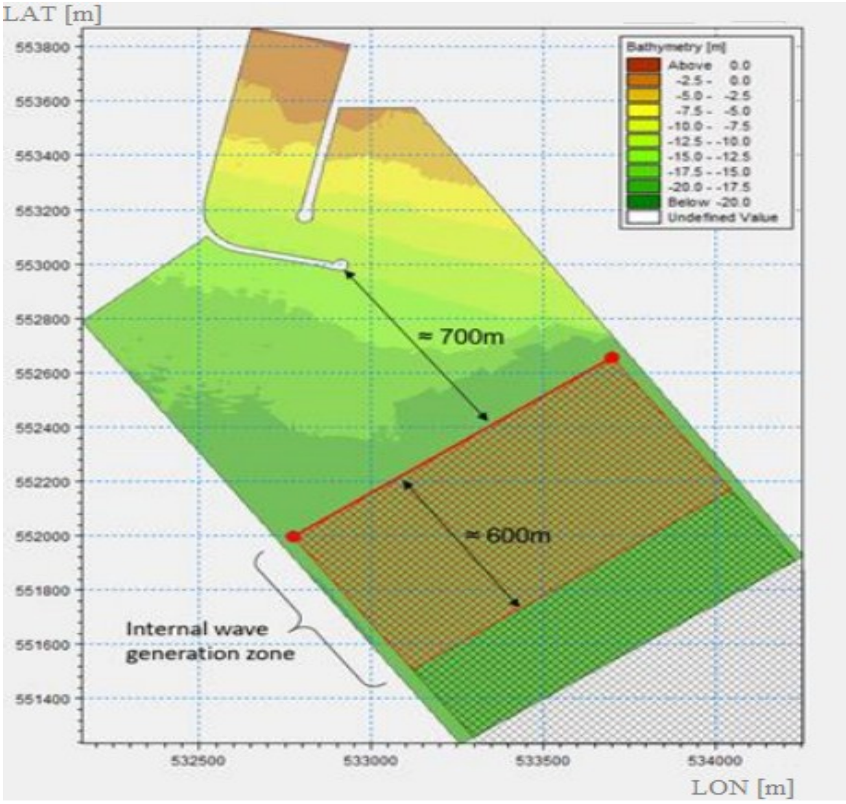

Figure 9 Example layout of internal wave generation zone (present figure shows Case 1)

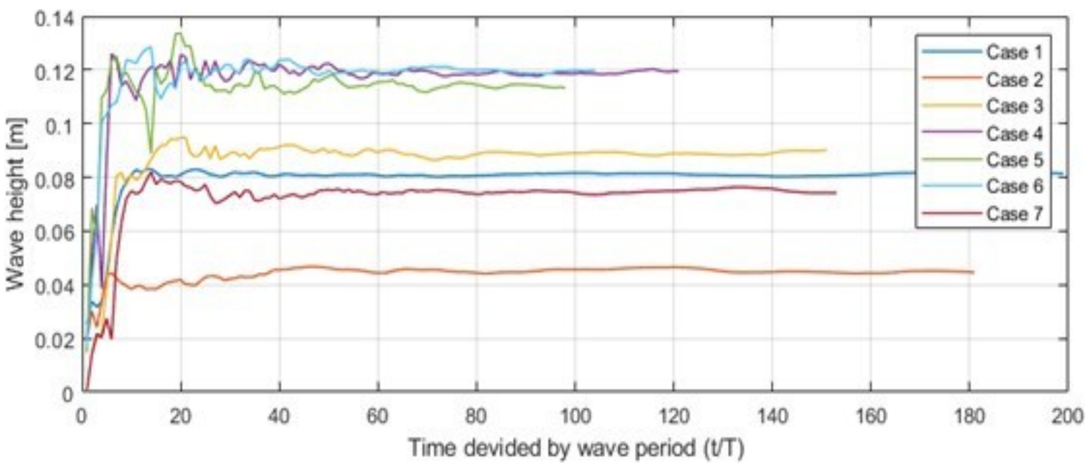

Figure 10 Model convergence

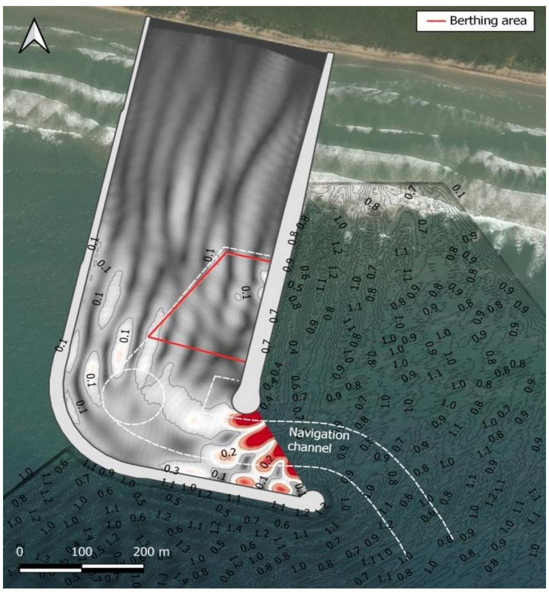

Figure 11 Case 1 wave disturbance coefficient

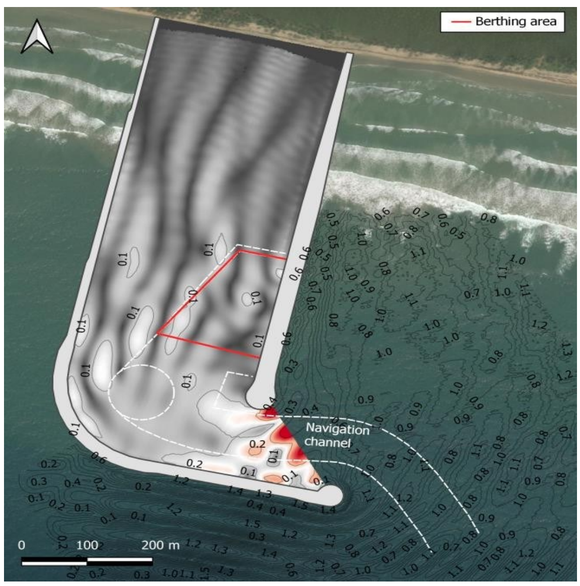

Figure 12 Case 2 wave disturbance coefficient

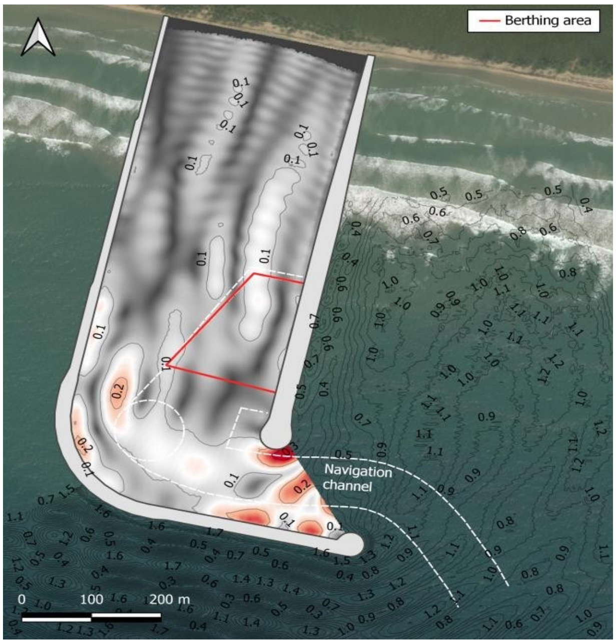

Figure 13 Case 3 wave disturbance coefficient

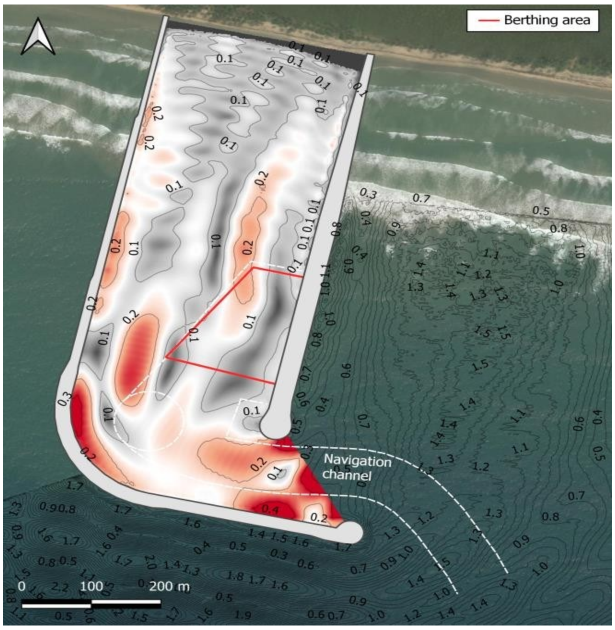

Figure 14 Case 4 wave disturbance coefficient

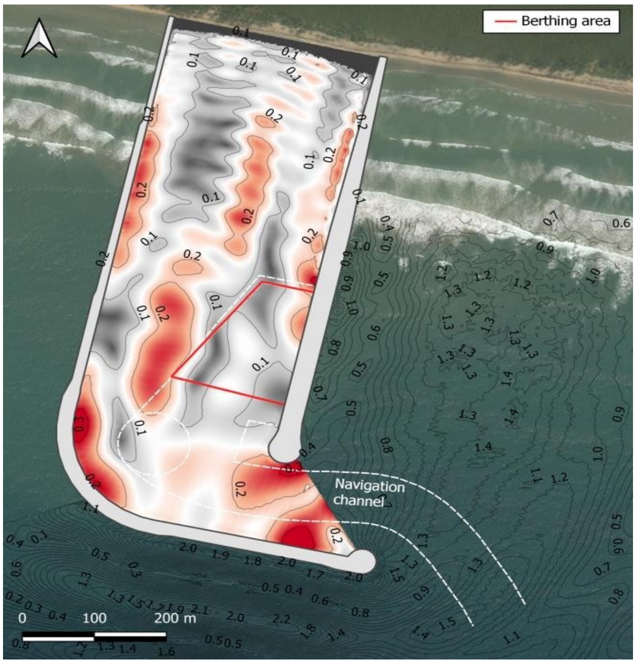

Figure 15 Case 5 wave disturbance coefficient.

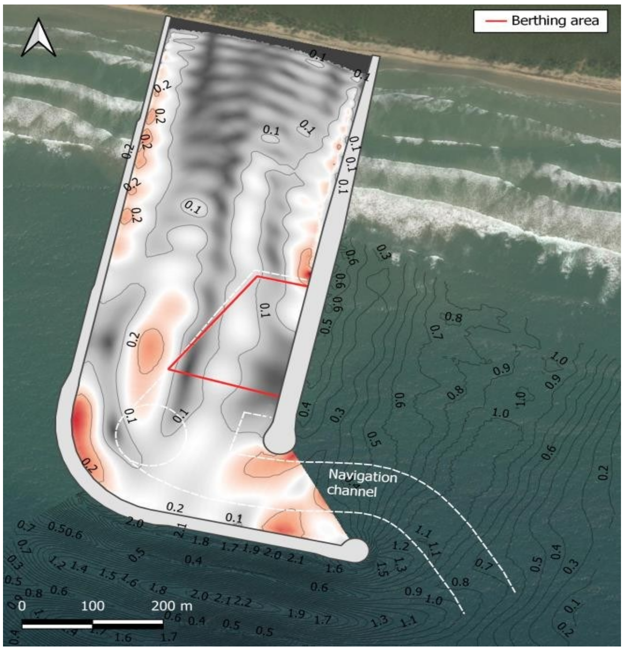

Figure 16 Case 6 wave disturbance coefficient

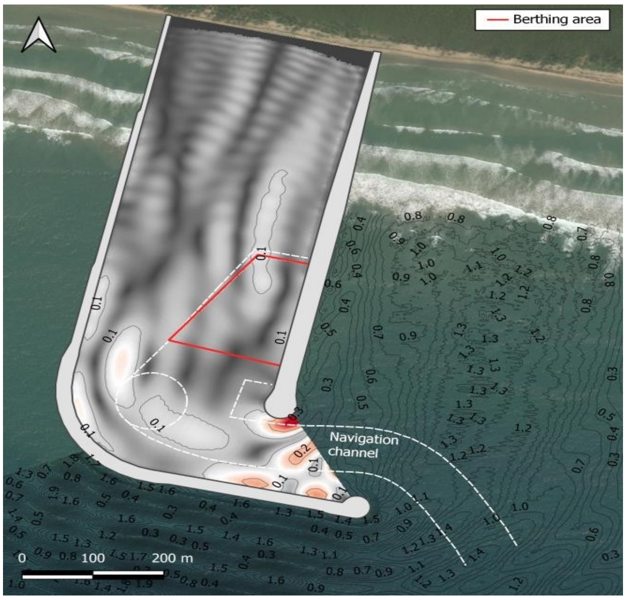

Figure 17 Case 7 wave disturbance coefficient

m once a year (Mercer *et al*., 1982).

A mean disturbance coefficient of 0.1 means that an offshore wave is reduced to 10 % wave height in the berthing area, e.g. 3 m is reduced to 0.3 m. By summing the yearly durations of the different cases, it is estimated how long time the mean significant wave height in the berthing area exceeds a given threshold during the year. The yearly cumulative time of exceedance for the different significant wave height thresholds is seen in Table 2.

Table 2 shows that the mean significant wave height in the berthing area only exceeds the criteria for 1 hour during the year. For 80 % of the time, the significant wave height in the berthing area will be less than or equal to 0.1 m. The wave climate in the berthing area is therefore classified as “good”.

Maps illustrating the wave disturbance coefficients in the harbour for the seven different cases are seen in Figures 11 to Figure 17, showing that the turning circle in the navigation channel is relatively unaffected by the wave disturbance in all seven cases.

Conclusions

In this study, a MIKE Wave FM numerical model software was employed to deal with real applications the development of an harbour. This paper investigated the wave penetration inside the small craft harbour for seven worst cases scenarios, in which the mean wave disturbance coefficient and mean significant wave height in the berthing area are determined for the design. The following observations are drawn on the rationale of the numerical results:

i. The wave penetration on the turning circle in the navigation channel is relatively unaffected by the wave disturbance in all seven cases.
ii. In 80 % of the time, the significant wave height in the berthing area was less than or equal to 0.1 m.
iii. The wave climate in the berthing area is classified as good.
iv. The breakwaters objective to decrease the impact of wave action and currents within the harbour was accomplished.

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Conflict of Interest Declarations

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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