

Numerical wave penetration modelling and comparison with physical model and field measurements for the harbour of Zeebrugge

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Abstract

To prevent coastal flooding via the port of Zeebrugge, storm retaining walls need to be designed for which hydrodynamic boundary conditions are required. The wave conditions during an extreme storm event in particular were determined by doing numerical wave penetration modelling. Comparison between both a linear (MILDwave) and a non-linear (Mike 21BW) wave penetration model and comparison with field measurements shows that the influence of a long navigation channel and short crested waves cannot be neglected. Comparison with the regular wave physical model results shows the importance of including an accurate bathymetry.

1. Introduction

The port of Zeebrugge is located on the Belgian coast and extends 3.25 km into the North Sea (cf. Figure 1). It is an important economic port with a LNG-terminal. As determined by the Belgian master plan for coastal safety, safety measures (e.g. storm retaining walls) are needed in some parts of the harbour to prevent coastal flooding during severe storms with a return period of 1000 years. Especially next to the large sea sluice, called the “Vandamme” sluice (cf. circle in Figure 1), there is danger for wave overtopping due to wave penetration. For an offshore wave direction of approximately NNW, this dock is exposed to direct wave penetration and the quay wall heights are too low to prevent excessive wave overtopping.



Figure 1. Zeebrugge harbour (Port of Zeebrugge, 2012). The “Vandamme” sluice is encircled.

The wave penetration is modelled using two types of numerical models: MILDwave (Troch, 1998) and Mike 21BW (DHL, 2009). The effect of the long navigation channel leading up to the port and the effect of short crested waves on the wave penetration is investigated. A comparative analysis is done with the results of a physical model and with field measurements as a validation.

2. Numerical wave penetration modelling

2.1 Selection of the numerical models

The most important physical processes in a harbour are diffraction, depth refraction/shoaling, (partial) reflection, transmission and – to a lesser extent – non-linear wave-wave interactions. Phase-resolving numerical models are used for the modelling of wave penetration because they can simultaneously account for diffraction and reflection (and standing waves) as opposed to phase-averaged wave models such as SWAN (TUDelft, 2011). Both a linear model MILDwave and a non-linear model Mike 21BW are applied. MILDwave is a linear time dependant wave model based on the mild-slope equations of Radder and Dingemans (1985) and Mike 21BW is a more complex non-linear time dependant wave model based on the enhanced Boussinesq equations of Madsen et al. (1991, 1992).

The same models have been previously employed for the harbour of Ostend (Stratigaki *et al.*, 2010; Gruwez *et al.*, 2011). For the case of Ostend very good agreement between the numerical models and the physical model was obtained. The same method is therefore used for the port of Zeebrugge, which allows investigation of its robustness for different configurations.

As a side note, it is mentioned that in addition to the wave penetration modelling, the phase-averaged model SWAN was also used to model separately the local wave generation by extreme wind speeds. This was done to ultimately obtain the total wave climate (wave penetration and locally generated waves) in the harbour following the method discussed by Gruwez et al. (2011). However, it will not be further discussed here.

2.2 Set-up of the models

The bathymetry used for the numerical models is shown in Figure 2. The bottom levels are based on the prescribed dredging depths and field surveys. The influence of the navigation channel leading to the harbour on the wave climate in the harbour is investigated. The bathymetry was therefore made without (cf. Figure 2, left) and including (cf. Figure 2, right) the navigation channel.

The grid spacing is 5.0 m in both x and y direction and a time step of 0.125 s was used complying with the CFL-criterion. A minimum (positive) water depth was assumed to avoid having to include wave run-up. Wave breaking was included in both models. Transmission of wave energy over the harbour dams was neglected, since the limited transmission that could occur in case of a severe storm is not important for the inner harbour.

To model the partial reflection in the harbour, a thin sponge layer of one grid cell in front of each partially reflecting boundary was used. This was shown by Brorsen (2000) to be an effective and practical numerical partial reflection method for wave propagation models. Appropriate reflection coefficients were determined for each structure in the harbour (e.g. (flooded) quay walls, dikes, rubble mounds,...). The corresponding sponge layer coefficients were calculated iteratively with a 1DH-model of a cross section of the considered structure and a reflection analysis.

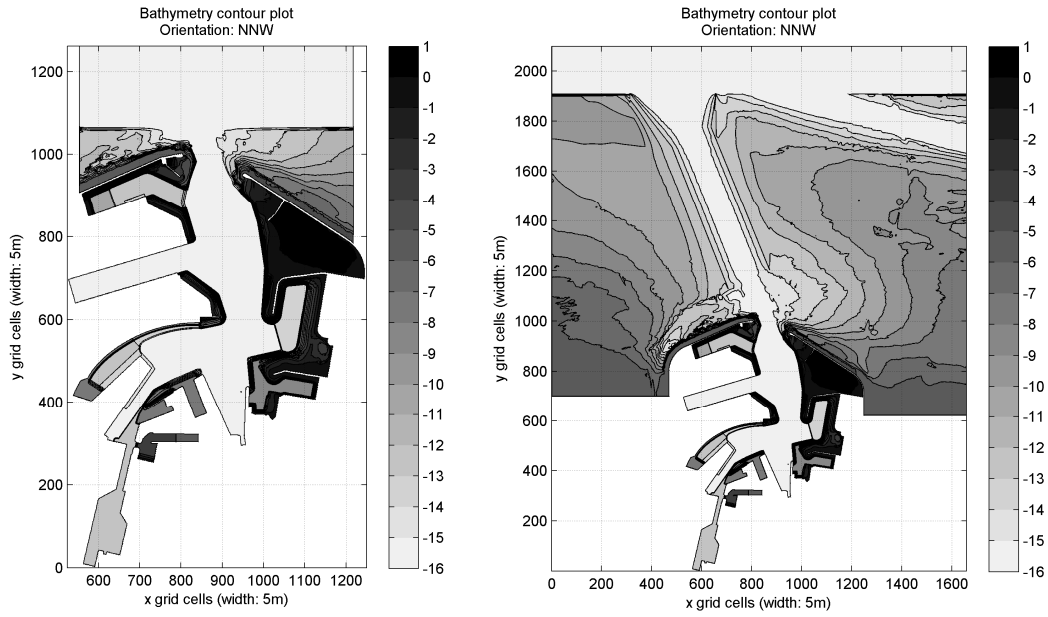


Figure 2. Left: bathymetry [m TAW] of the port of Zeebrugge for the numerical models. Right: bathymetry [m TAW] for the numerical models including both the port and the navigation channel leading up to the harbour.

Simulated conditions include $H_s = \sim 5.9$ m, $T_p = \sim 12.0$ s, SWL = +6.40 m TAW to +7.90 m TAW,^a for wave directions N, NNW, NW and a JONSWAP spectrum. Both long and short crested waves have been modelled, with a directional spreading of 0° and 20° respectively. The results and comparative analyses in §2.3 are limited to the conditions given in Table 1.

Table 1. Hydrodynamic boundary conditions, for a return period of 1000 years, imposed on the wave penetration models. Long crested (LC) and short crested (SC).

	H_s	T_p	SWL	DIRECTION	σ
	[m]	[s]	[m TAW]	[°N]	[°]
LC	5.9	12.0	7.30	337.5	0
SC	5.9	12.0	7.30	337.5	20

2.3 Results and comparative analysis

A very good correspondence of the wave disturbance coefficient K_d ($=H_{s,location}/H_{s,at\ the\ wave\ generation\ boundary}$) between both phase resolving models is found in case of the model without navigation channel (cf. Figure 3). This is also shown in Figure 5 where the wave disturbance is compared at some locations in the harbour. Note that locations ZBG_A, B and C are of main interest in this paper; they are the locations of the field measurements (cf. §4). Especially the result at ZBG_A is important, because it is located next to the “Vandamme” sluice (cf. Figure 10).

^a TAW = Tweede Algemene Waterpassing; Belgian standard datum level.

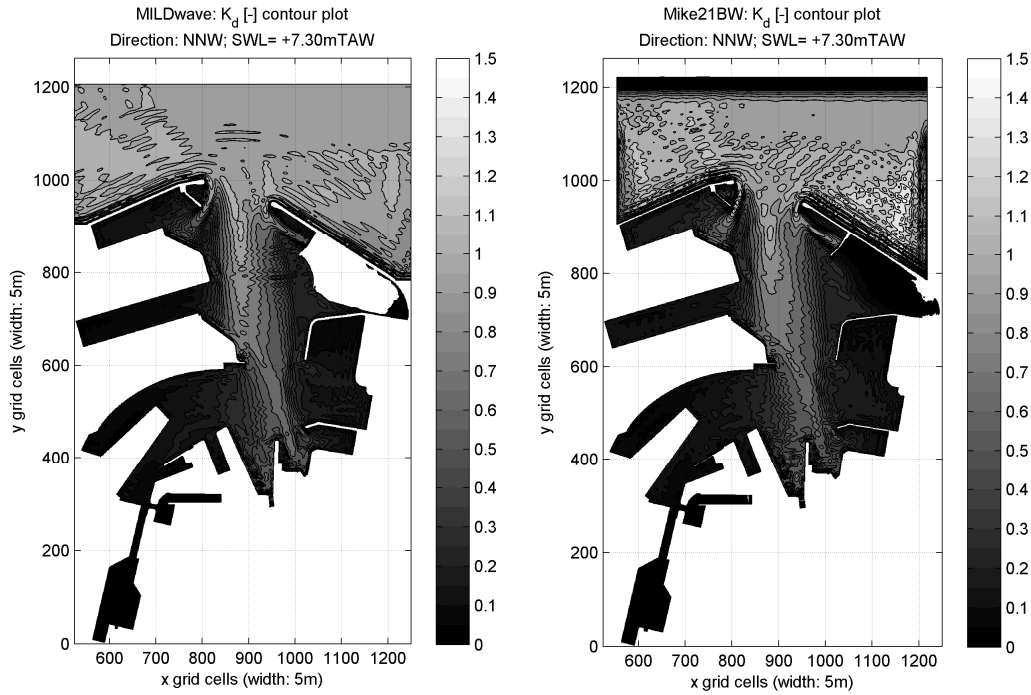


Figure 3. Contour plot of the wave disturbance coefficient K_d of the numerical results using the bathymetry without navigation channel. Left: MILDwave. Right: Mike 21BW.

In Figure 4 the result of the models including the navigation channel are shown. It appears that the navigation channel greatly affects the wave climate inside the harbour. A comparable effect of a navigation channel was first discussed and observed in the physical model of Zwamborn and Grieve (1974). It is a result of:

- Diffraction due to a difference in wave celerity in and next to the channel due to the water depth difference;
- Refraction on the side slopes of the navigation channel.

These diffraction and refraction effects cause a wave concentration on one side of the channel and a wave attenuation on the other when the angle between the channel and the incoming wave direction reaches a critical value between 20° - 30° . The wave concentration is clearly visible in the results of both models (cf. Figure 4). However, it seems that the navigation channel also introduces a non-linear effect, evident from the more severe wave focussing on the eastern flank of the channel in the result of the non-linear model Mike 21BW ($K_{d,max} = \sim 1.9$ compared to ~ 1.5 for MILDwave). The different effect of the navigation channel in each model causes more differences in the wave disturbance in the port itself. This is especially apparent in the dock to the “Vandamme” sluice (cf. ZBG_A in Figure 5, right) where at location ZBG_A a difference of 0.2 in K_d -value exists between both models.

Up until now only long crested waves were imposed. Figure 6 (right) shows the influence of the navigation channel when instead short crested waves with a directional spreading of 20° are generated. The wave focussing on the eastern flank – although still present – appears to be severely diminished. In fact, the influence of the channel on the wave climate seems to be evened out overall. This is primarily because in case of short crested waves not all wave

energy is concentrated in one direction and therefore not all waves make the critical angle of $20^\circ - 30^\circ$ with the channel.

Because the navigation channel has a possible non-linear effect and only Mike 21BW is able to model short crested waves,^b the numerical results in the following chapters will be limited to Mike 21BW.

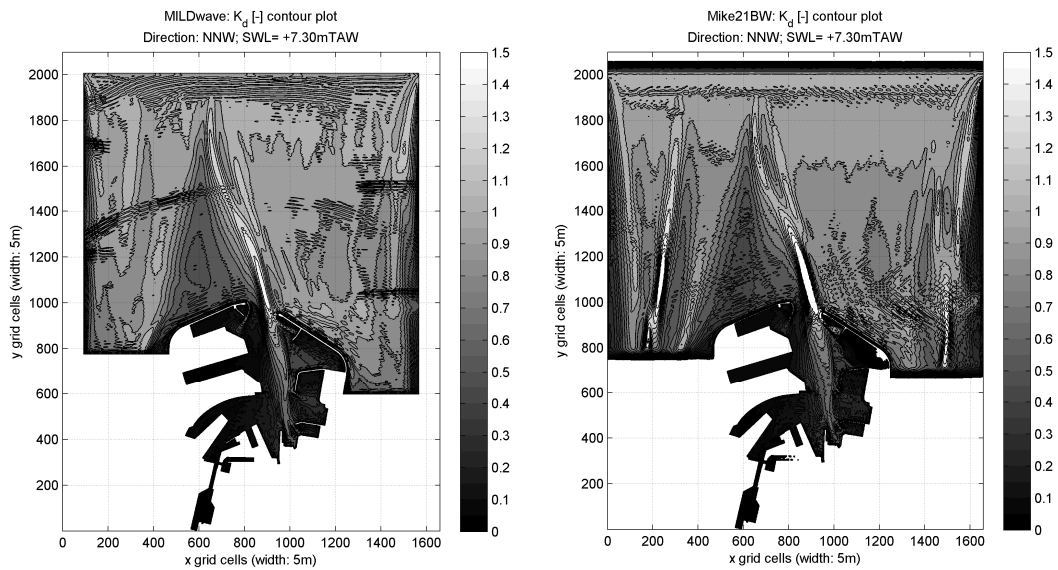


Figure 4. Contour plot of the wave disturbance coefficient K_d of the numerical results using the bathymetry including the navigation channel. Left: MILDwave. Right: Mike 21BW.

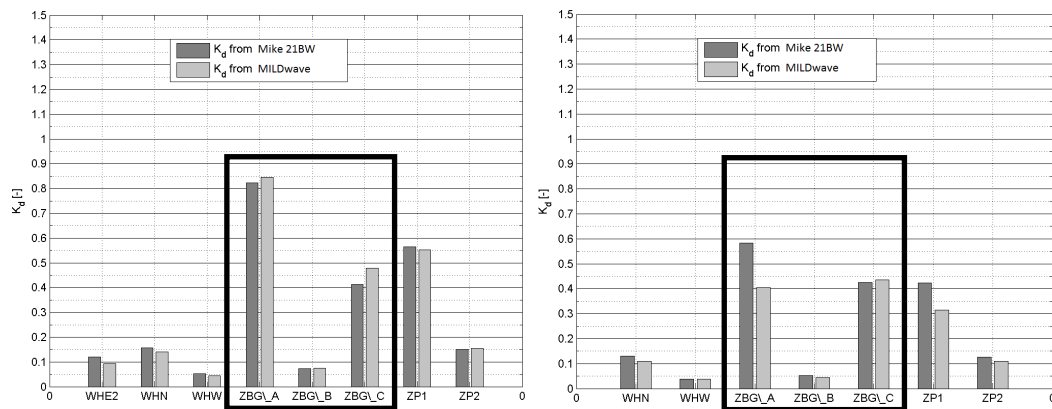


Figure 5. Wave disturbance coefficients K_d at specific locations with indication of the locations of interest. Left: bathymetry without navigation channel. Right: bathymetry including the navigation channel.

^b Short crested wave generation in MILDwave is in development by the University of Ghent (Comm. Troch P., 2010).

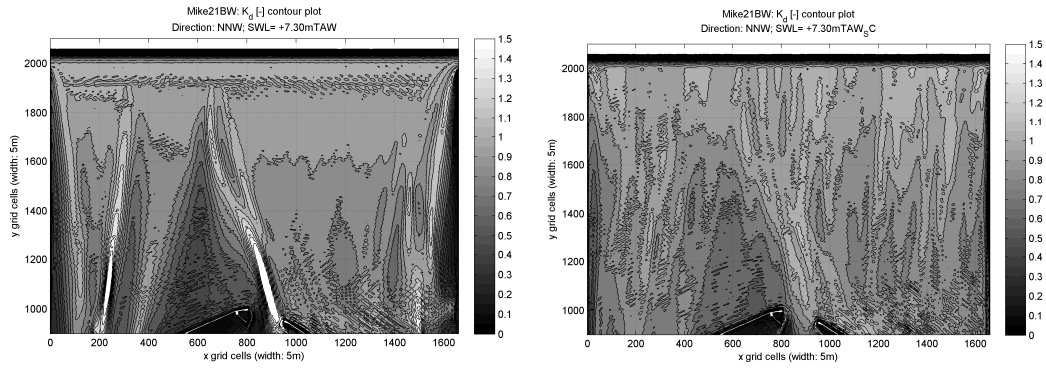


Figure 6. Contour plot of the wave disturbance coefficient K_d of the numerical results imposing long crested waves (left) and short crested waves with $s = 20^\circ$ (right), Mike 21BW results. Plot limited to the navigation channel up until the entrance of the harbour.

3. Physical wave model

A physical model was built by Flanders Hydraulics Research (Wens and Verbist, 1985) for wave agitation studies in the outer harbour of Zeebrugge (cf. Figure 7). Scaling was done according to the Froude law with a geometric undistorted scale ratio of 1:150. Wave measurements were performed inside the model harbour on a 1 m x 1 m grid (on the scale of the model) with non-directional wave gauges. Several zones of wave gauges are also defined in Figure 8 (Zone I to Zone XI). The results are given as K_d -values with reference to the average of all wave gauges at the entrance (Zone I).

Long crested and monochromatic waves with a wave height H , of 3.0 m and a wave period T , of 9.0 s have been modelled for a still water level SWL, of +4.60 m TAW. The following wave directions were simulated in the wave basin: WNW, NW, NNW, N, NNE and NE. The same boundary conditions were modelled in the Mike 21BW model with bathymetry including the navigation channel and also imposing monodirectional regular waves.

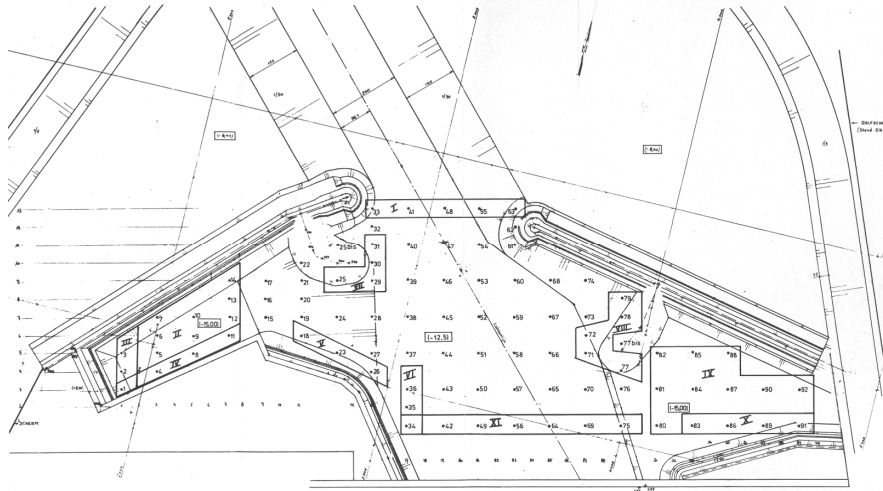


Figure 7. Overview of the physical model built by Flanders Hydraulics Research (Wens and Verbist, 1985).

Because the numerical model was made to correspond with reality as accurately as possible, no additional effort was made to make it correspond better with the physical model which deviates much more from reality. The area to which the physical model was limited, is indicated on the bathymetry of the numerical model in Figure 8.

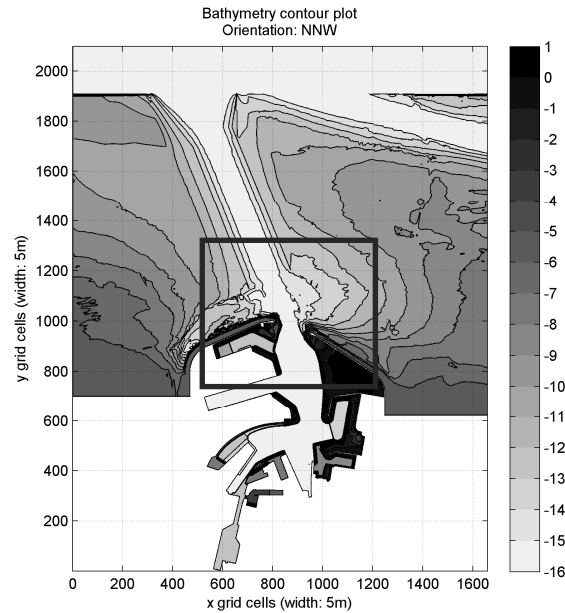


Figure 8. Bathymetry of the numerical model with indication of the area to which the physical model was limited.

The main geometric differences between the physical and numerical model are:

- Only part of the navigation channel outside the harbour was included in the bathymetry of the physical model (1.3 km of 4.5 km in total);
- The slope of the sides of the navigation channel were 1/50 in the physical model, but is 1/100 in the numerical model which corresponds better with the morphological equilibrium;
- The bottom level of the harbour in the physical model was constant at -15.10 m TAW;
- Slight differences in the configuration of the harbor dams and quay walls.

Despite these differences a similar result is obtained in Zone II (the western dock) or at least a comparable evolution over the different wave directions is observed (cf. Figure 9). However, in Zone XI (wave gauge locations at the southern physical model limit) the difference is very big for directions WNW, NW, N and NE. According to the physical model wave direction NW causes the most wave energy to penetrate into the inner harbour, whereas the numerical model predicts this to be more between NNW and N. These large differences are mainly explained by the use of long crested and monochromatic waves for which the refraction is very sensitive to the bathymetric differences between the two models.

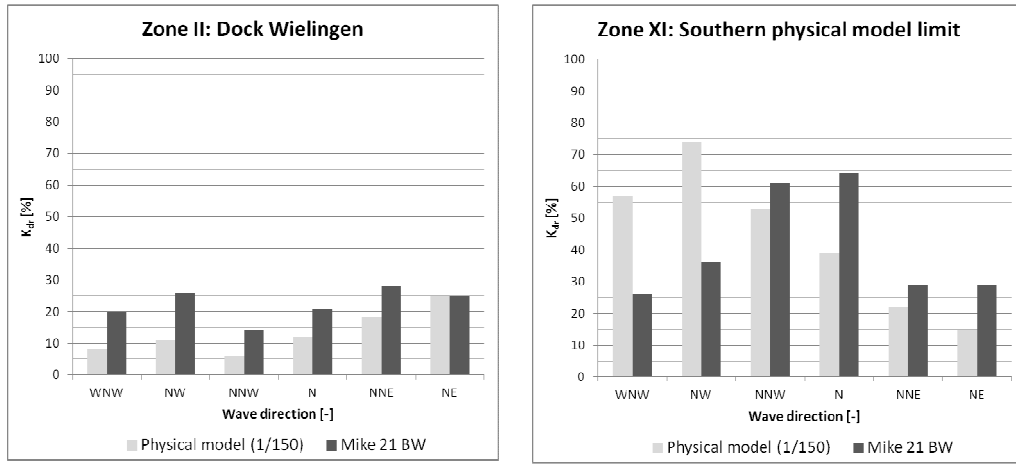


Figure 9. Average wave disturbance K_d -values of all wave gauges in Zone II (left) and Zone XI (right) for both the physical and numerical model for each imposed wave direction.

4. Field measurements

Because the numerical model is made to correspond with the actual bathymetry as accurately as possible, a comparison with field measurements should be better suited. Field measurements were performed in the harbour of Zeebrugge during the period between February 2010 and April 2011 (excluding the summer months June, July and August) (IMDC, 2011). Pressure sensors of the type PDCR 1830 were placed at three locations in the harbour (cf. Figure 10, left). Furthermore, wave measurements are being done continuously by the Coastal Division of the Flemish government with a wave buoy (ZOK) on a location just inside the harbour. The measurement of a directional wave buoy located outside the harbour (not pictured) is used as the reference for the wave disturbance coefficient K_d ($=H_s/H_{s, \text{buoy outside of harbour}}$). The K_d -values of the numerical model also use the significant wave height result at the location of this buoy as the reference value.

The highest measured significant wave height at location ZBG_A was 1.00 m on 25/09/2010. The offshore hydrodynamic conditions at this time were determined from the data of the wave buoy outside the port (cf. Table 2).

In total three Mike 21BW models are compared with the field measurements:

1. NM_{LC} : the numerical model with long crested waves;
2. NM_{SC} : with short crested waves;
3. NM_{SC+NC} : with short crested waves including the navigation channel.

The hydrodynamic boundary conditions employed for these models are also given in Table 2. Note that for the third model a significant wave height of 3.0 m was imposed at the boundary, which was necessary to obtain the 2.4 m value at the buoy location.

The third Mike 21BW model including the navigation channel in the bathymetry and applying short crested waves (NM_{SC+NC}) shows the best correspondence with the field measurements (Figure 10, right), especially at the location of interest ZBG_A. However, due to lack of storms during the field measurement period, only one wave condition was modelled. More storms need to be measured and simulated to obtain a more extensive and conclusive validation.

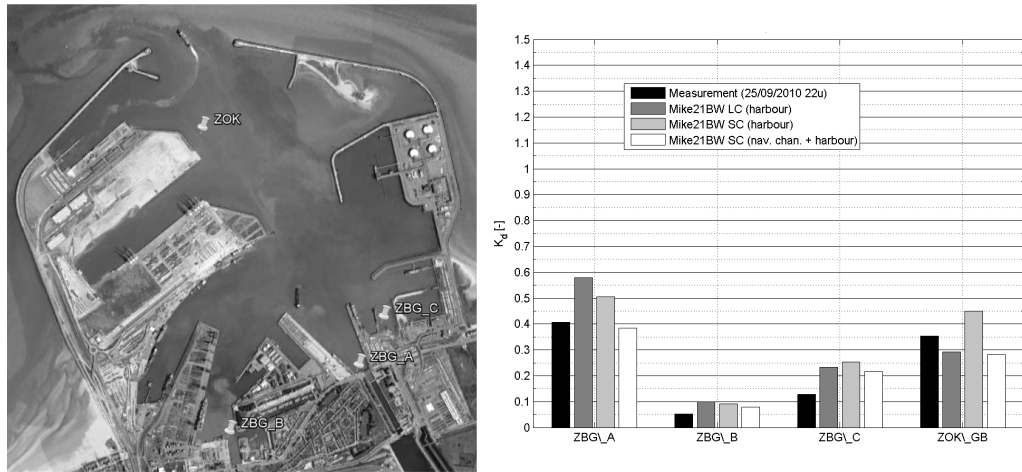


Figure 10. Left: location of wave buoy ZOK and pressure sensors ZBG_A, B and C (image courtesy of ©Google Earth 2010). Right: comparison between numerical model and field measurements of the wave disturbance K_d at the field measurement locations.

Table 2. Hydrodynamic conditions measured by the wave buoy outside the port (Buoy). Boundary conditions for the numerical model Mike 21BW with long crested waves (NMLC), short crested waves (NMSC) and short crested waves including the navigation channel (NMSC+NC).

	H_s	T_p	SWL	DIRECTION	σ
	[m]	[s]	[m TAW]	[°N]	[°]
Buoy	2.4	8.3	2.00	337.5	N/A
NM _{LC}	2.4	8.3	2.00	337.5	0
NM _{SC}	2.4	8.3	2.00	337.5	20
NM _{SC+NC}	3.0	8.3	2.00	337.5	20

5. Conclusions

The port of Zeebrugge has some weak areas where excessive wave overtopping could occur in case of extreme storms (with return period of 1000 years). Especially the dock leading to the “Vandamme” sluice is vulnerable to almost direct wave penetration attack for certain offshore wave directions.

Both a linear (MILDwave) and non-linear (Mike 21BW) phase resolving wave model was deployed to simulate the wave penetration into the harbour. Simulations were done using a bathymetry without the navigation channel as well as including it. For the simulations without navigation channel, the linear and non-linear model showed a very good correspondence. However, introducing the navigation channel caused more differences between the models to appear. This possibly indicates a non-linear effect of the navigation channel. The wave focussing effect created by diffraction and refraction on the slopes of the navigation channel was also found to be less severe in case of short crested waves than long crested waves.

A validation with pre-existing physical model results was attempted, but large differences in bathymetry and the use of monodirectional regular waves caused too much differences with the numerical model. Nevertheless, in some parts of the harbour a similar evolution of the

wave disturbance over the several modelled wave directions was observed. The large differences emphasise the importance of the accuracy of the bathymetry, although it should be noted that the effect of an inaccurate bathymetry is overly enlarged by imposing monodirectional and monochromatic waves.

Finally, three different numerical models were compared with a field measurement: the Mike 21BW model with long crested waves, with short crested waves and with short crested waves including the navigation channel. The latter model showed the best correspondence with the field measurement, which indicates that the effect of directional spreading and a navigation channel is best not neglected. However, more storms need to be measured and simulated to obtain a more conclusive validation.

Acknowledgments

The Flemish government (Coastal Division) is acknowledged for funding this research and providing the field measurement data.

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