Identification and Estimation of Ship Navigational Limits for Waterway Designs Using Simulation

Quy N.M., Vrijling J.K., Pieter van Gelder, Groenveld R.

Delft University of Technology, Section of Hydraulic Engineering
Delft, Netherlands
Q.nguyenminh@tudelft.nl; J.K.Vrijling@tudelft.nl; P.H.A.J.M.vanGelder@tudelft.nl; R.Groenveld@tudelft.nl

Abstract

This paper presents a new method to evaluate the effect of environmental conditions on the ship's maneuverability by classifying the external forces acting on the ship using simulation approaches. The results of the evaluation could be useful for several aspects of the engineering design and navigation risk analysis, including:

- Identification and estimation of ship’s navigational limits;
- Probabilistic design of waterway widths with regarding to an acceptable risk of ship’s accidents, considered as the risk of the ship’s grounding or collision with a fixed object.
- Estimation of downtimes that amounts a straightforward optimal design use for entrance channels.

Keywords

Maneuverability; occurrence frequency; ship’s accident; safety criteria; simulation.

Introduction

Maritime simulation is a reliable and indispensable tool in the assessment of navigational safety of a ship in conjunction with harbors and waterways. The main application focuses essentially on channel design to indicate the ship’s maneuverability and possible accident occurrence in relation to the mariner’s behavior and environmental conditions. This approach usually consists of two-step process: application of a ship-handling simulator for generating the data of ship motions and assessment of navigation risk based on this data.

The most important data achieved from the simulation for waterway design are: ship’s track distances (center of gravity and extreme starboard and port points of ship) in respect to center of the waterway; ship courses; and of ship speed (horizontal, vertical and angular).

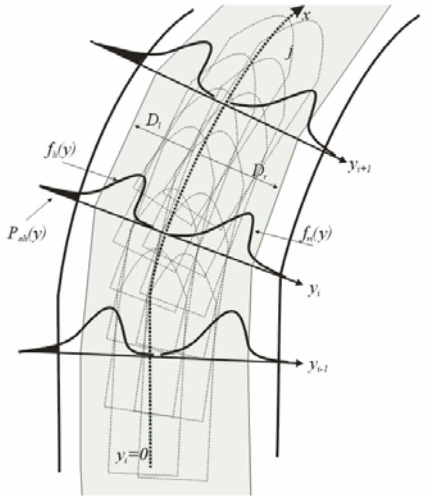

Fig. 1: **Distribution of ship’s position based on the simulation results (probability of ship’s accident denoted by black zone)** (Gucma, 06)

One of the most important measures for the risk assessment associated to the design of waterway width is the probability of ship’s accident in each of waterway sections. The probability of a ship exceeding from a certain waterway width can be determined as follows

$$P_{ex} = P(y > Dr \mid Env = i) = \int_{B/2}^{\infty} f(y)\,\mathrm{d}y \tag{1}$$

where Dr is half of the channel width; $f(y)$ is the density function, as shown in Figure 1, of the ship’s positions in the simulation of a maneuvering scenario, i^{th}.

The probability of ship’s accident from the waterway section borders during a given time period, P_{life}, can be determined as

$$P_{life} = N_{ship} \sum_{i=1}^{Ne} P_{ex} P_{oc}[Env = i] \tag{2}$$

where N_{ship} is the number of ships presents in the waterway during a given time period; Ne is the number of scenarios. $P_{oc}[Evn=i]$ is the occurrence frequency of the maneuvering scenario i^{th}.

Simulations are usually conducted in series, performed in different environmental conditions, each consist of several trials. In principle, the environmental conditions of wind, waves, and currents are divided into a number of regions or categories to facilitate the probability assessment of the navigation results. These environmental categories, reflecting the frequency of occurrence and severity, are selected to define the different combinations of the environmental conditions that might be present when the ship is transiting the approach channel. The different combinations of environmental conditions are divided into various classes (normally three or four), known here as "maneuvering scenarios", by ordering degree of affecting the ship's maneuverability. The first maneuvering scenario class involves combinations that are so extreme that the ship's passage into the harbor will not be attempted due to the steering and propulsion capacity of the ship. The second class considers the less extreme combinations under which the ship's passage might be attempted. The next scenario involves combinations that would always allow passage to be attempted.

To determine the frequency of the occurrence of each maneuvering scenario, a linear programming method proposed by Briggs et al. (2003) can be used. The essential limitation of this method lies in the fact that it generates some unrealistic combinations of environmental conditions. Moreover, unaccepted environmental combinations with regard to the ship's maneuverability for navigation safety are not identified.

Methodology of research

This new method has been developed in combination with Monte Carlo simulation and the probabilistic approaches. The method consists of categories, as depicted in Figure 2, which has been discussed in the following sections.

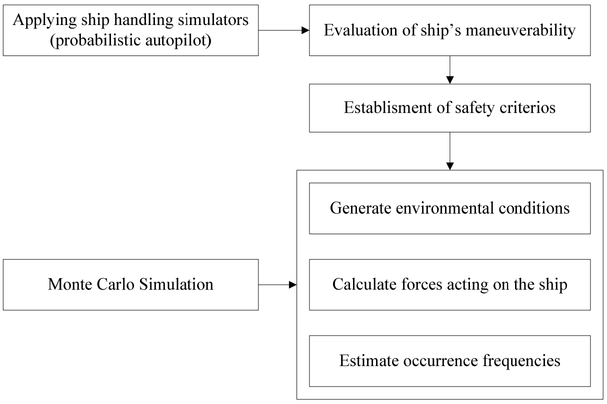

Fig. 2: **Methodology of research**

Ship's maneuverability

The new method has been developed based on the useful investigation of the two following studies.

- Risk analysis of vessels exceeding horizontal boundaries in a channel (Welvaarts, 2001), and
- Probabilistic design of approach channel width (Giang, 2003).

Both the studies were carried out for a bulk carrier of 65.000 DWT at the entrance channel of IJmuiden port, which is the third biggest port in the Netherlands. The IJmuiden channel is about 25 km west of Amsterdam and has an azimuth of 100.5^0.

In the first study, navigation safety criteria were laid down on the basis of the steering and propulsion characteristics of the ship, including the maximum rudder angle use, the drift angle and the power burst. These criteria are presented in Table 1.

Table 1: **Safety criteria relate the ship's maneuverability**

Criteria	Judgment		
	F	C	U
Rudder angle used when sailing with distances of	0-400m	400-550m	>500m
Drift angle	0-15°	15-20°	>20°
Power burst with sailing distance of	0-0.5L	0.5L-L	>L

- F: is Feasible, no problem for ship's maneuver;
- C: is Critical, ship's passage might be attempted;
- U: is Unacceptable, ship's passage will not be attempted;
- L: is half ship's length.

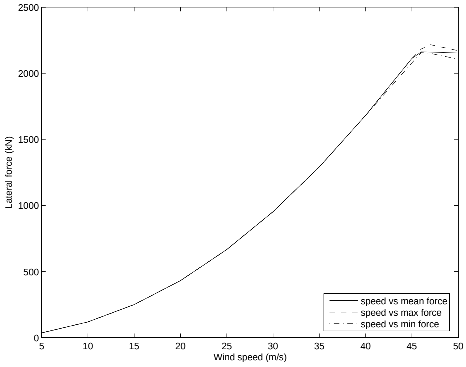

Fig. 3: **Relationship between lateral forces and wind speeds, in case ship speed 10 knots**

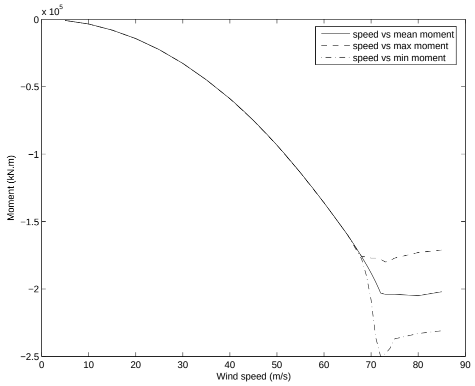

Fig. 4: **Relationship between moment forces and wind speeds, in case ship speed 10 knots**

Normally, to evaluate and distinguish the environmental conditions as well as maneuvering scenarios linked to the ship's maneuverability, extended maneuvering simulation runs should be carried out in real time scale, not only for the different environmental combinations in each maneuvering scenario but also for the several repetitions of the maneuver under the same conditions. The results of this simulation are the information on the use of rudder angle, drift angle and engine. Using this information, a level of the ship handling difficulty associated with a certain maneuvering scenario can be evaluated. However, it seems to be impossible because of time consumption. To reduce the extremely large number of simulation runs, the environmental conditions are considered as external forces and moments exerting on the ship. An investigation on the response function of the ship as a function of the external forces was carried out in the second research where the load limits that would prevent the ship sailing was defined. A probabilistic autopilot model of the ship-handling simulator, which has been under developing by the Dutch Institute MARIN (Giang, 2003), was used for this investigation. Some of the results are given in Figure 3, Figure 4, and Figure 5. It can be seen from these figures that the ship would be navigable only if the force acting on the hull is less than 2000 kN; or the moment is less than 180000 kN.m. By contrast, several lower couples of the force and moment result in the same effect.

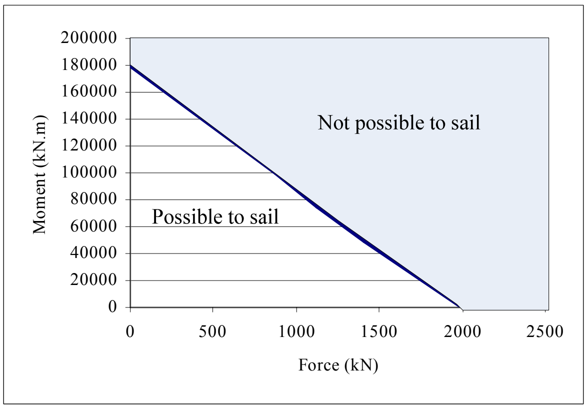

Fig. 5: **The navigation limits based on the forces acting on the ship for sailing speed of 10 knots**

Assumptions

Based on the above results, some assumptions for this study have been made as follows:

There is a boundary limit of the load acting on the ship, so that the ship cannot sail in the case of any couple of the force and moment lie on or upper this boundary (see Figure 3).

It can be seen from Figure 3 that the ship seems very strong resisting the moment impact. When the ship is progressing in a restricted channel, it is almost never the case that the resultant moment caused by environmental conditions is up to 50.000kN.m. For example, if wave height H_s=3.5m, wind speed 30m/s and current 3 knots act simultaneously in the same direction of 45 degree (the most dangerous angle for moment) on the ship, the total moment is about 49.000kN.m only. However, the above combination is never allowed in connection with the ship's transit in the restricted channel. The effect of the moment on the ship's maneuverability can, therefore, be excluded in this study.

The lower values around the boundary limits of the force are seen as the maneuvering scenario so that ship can attempt to sail.

Establishment of navigation safety criteria

Going on these assumptions and on the boundary limits defined in the above, the following criteria can be formulated to classify the maneuvering scenarios

Table 2: **Classifying safety criteria for bulk carrier 65.000DWT by force impact**

Maneuvering scenarios	Criteria (kN)	Remarks
Ao: not possible to sail	F≥1000	Safety factor = 2
A1: can attempt to sail	600≤F<1000	The safety margin depends mainly on mariner's competence
A2: no problem to sail	F<600	No problem for any mariner

Calculation Procedures

The calculation procedures consist of several steps as described in Figure 6.

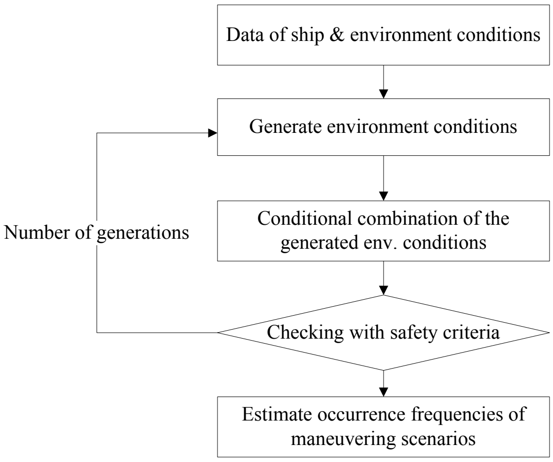

Fig. 6: **Calculation procedure**

Generating environmental conditions

Environmental conditions (wind, waves and currents) of the IJmuiden channel have been gathered for this study, which are presented in the Appendix B. Data of winds, waves and currents are the tables of frequencies distinguished by classes of different directions and values.

Generation of winds and currents

The frequencies of winds and currents in all directions (the last column of the frequency tables in Appendix B) can be fitted to a certain distribution function, as presented in Figure 7, where “Chi2” distribution has been found for the wind speed. Based on that, one may first generate stochastically a value of wind and current speeds according to the predefined distribution functions. Then, a uniform random number can be generated to obtain a desired direction by using the inverse transformation method (Wendy and Angel, 2002). To confirm the generated results, Chi-square test method could be useful. A Matlab Code has been developed for this purpose. It can be seen from Figure 8 that the generated frequencies of wind speeds compared well to those observed after the number of the generation, n, is 300.

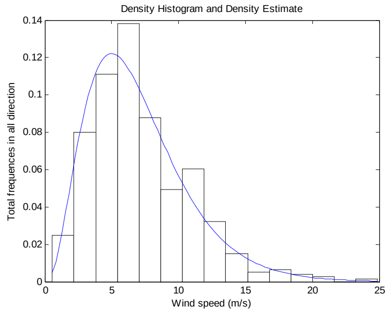

Fig. 7: Frequencies of wind speed fitted to Chi2pdf (x_wind, 7)

The Chi-square, λ, is estimated by

$$\lambda = \frac{\sum_{i,j}^{l,m}\left[f_o(i,j) - f_g(i,j)\right]^2}{f_o(i,j)} \qquad (3)$$

where $f_o(i,j)$ and $f_g(i,j)$ are the observed and generated frequencies of the wind and current in lass i and direction j, respectively; l, m: are respectively the numbers of the value classes and directions;

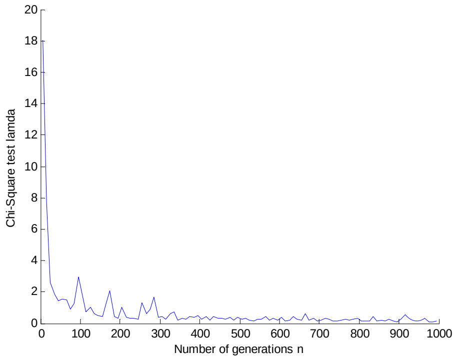

Fig. 8: Chi-square test versus number of generations

Conditional generation of waves from wind conditions

This procedure arms at rejecting as many as possible undesired combinations in the maneuvering scenarios, as remained in the former approach. For instant, the combination of very low wind speeds but very high waves, which are hardly ever occurred, should be removed. To overcome this shortcoming, the physical relations between the environmental conditions should be defined. Those relations are probably modeled by using probabilistic and mathematical tools.

Teng (2000) proposed a conditional probability function to examine the validity and accuracy of estimating the wave height from the corresponding wind speed distribution using long-term wind and wave data from five of the National Data Buoy Center (NDBC) buoy stations in the Pacific Ocean. The technique of estimating wave height distribution from wind distribution is to relate the marginal probability distributions of significant wave height, $P(H_s)$, and wind speed, $P(W_i)$, in terms of a parametric model of the condition probability of the wave height at given wind speeds, $P(H_s|W_i)$, as:

$$P(H_s) = \sum_{i=1}^{N} P(H_s \mid W_i) P(W_i) \qquad (4)$$

The conditional probability $P(H_s|W_i)$ can be assumed to be log-normal distribution such as:

$$P(H_s \mid W_i) = \frac{1}{H_s \alpha \sqrt{2\pi}} \exp\left(-\frac{\ln H_s - \beta}{\alpha}\right) \qquad (5)$$

In which the wind speed is divided into N equal intervals; α and β are the parameters that can be determined from empirical coefficients. These coefficients in the nonlinear function can be numerically estimated from values of the mean and standard deviation of the wave height for various wind speed intervals.

Figure 9, for example, presented the condition probabilities of the wave height with the wind speeds of 10m/s, 15m/s and 20m/s for the IJmuiden channel applying the above-mentioned technique.

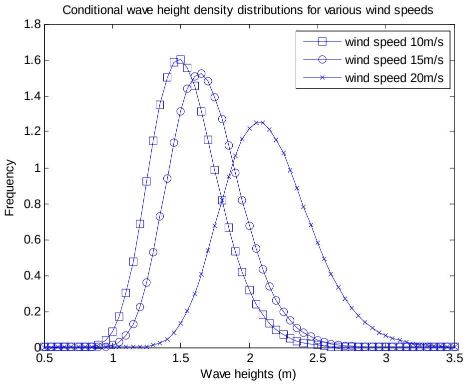

Fig. 9: Conditional wave height for various wind speed fitted to Log-normal distributions in the IJmuiden channel

Calculations of the forces and moments

The forces and moments acting on the ship for each ship's passage are estimated according to the generated environmental conditions (winds, waves, currents and their directions), ship size and ship speed. The total force exerting perpendicularly to the ship's hull will, then, be obtained by synthesizing the individual forces of winds, waves and currents from the different directions. The mathematic models of environmental forces on the ship's hull recommended by OCIMF (1997) was used, as described in Appendix A, in which the coefficients for wind and wave forces are derived from the Towing Tank Test Project at the Dutch institute MARIN (Giang, 2003) and coefficients for current forces are derived from the OCIMF.

Calculations of the occurrence frequencies of the maneuvering scenario

The occurrence frequencies of each maneuvering scenario is determined as

$$f_{Ao} = \frac{n_{Ao}}{N},\ f_{A1} = \frac{n_{A1}}{N},\ f_{A2} = \frac{n_{A2}}{N} \qquad (3)$$

$$n_{Ao} + n_{A1} + n_{A2} = 1$$

where N is the number of environmental combinations, which are grouped into three maneuvering scenarios (Ao, A1 and A2); n_{Ao} is the number of times that the calculated force, $F \geq 1000$ kN, n_{A1} is the number of times that F lies in $600 \leq F < 1000$, n_{A1} is the number of times that F is less than 600 kN.

Results

Table 3 shows the different results of the occurrence frequencies for the environmental conditions being calculated from the former approach and those from the conditional probability between winds and waves. A sample of environmental combinations in the scenario Ao for the conditional generation is given in Table 4.

Table 3: Frequencies of the maneuvering scenarios for the different approaches

Maneuvering scenarios	From the former approach	This study
Ao	0.0082	0.0010
A1	0.0804	0.1928
A3	0.9114	0.8062

Table 4: Environmental combinations in the scenario Ao for the conditional generation

Combi-nation	Environmental conditions		
	Wind (m/s)	Wave (m)	Current (m/s)
Ao_1	17.176	2.503	0.493
Ao_2	3.134	2.328	0.552
Ao_3	19.246	2.959	0.137
Ao_4	19.683	2.547	0.000
Ao_5	18.177	2.633	0.611

Conclusions

From the above results, some conclusions have been drawn as follows

- The environmental combinations can be established reasonably by applying the conditional generation between wind speeds and wave heights except the combination Ao_2 in Table 4. However it might be accepted with a certain small rate due to swell (developing wave after wind decayed). It is noted that swell wave can also be taken into account in the conditional probability in Eq. 5.
- Much attention should be focused on the combinations between wave heights from 2-3 m and wind speeds from 15-20 m/s. These combinations lie somewhere around the boundary line between maneuvering scenarios Ao and A1 and provide extremely important distribution functions concerning the ship's course and position, from which the probabilities of the ship's excursion from a predefined channel width will be estimated.
- The major part of the total forces in the maneuvering scenario Ao is contributed by waves. The minimum wave height must be more than 2.0 m in the maneuvering scenario Ao.
- Downtime due to the so extreme weather conditions making it impossible for ship to sail can be obtained in cases of the total calculated force exceeding the criteria defined in Table 2. It is obvious that the higher criteria the maximum force, the safer navigation for the ship's passage, but the higher downtimes will then have to be accepted.
- One thing we have to consider is how many hours should be allowed for the downtime when ship encounters the maneuvering scenario Ao. This depends very much on whether winds, waves or currents play a major part in producing high forces and on the duration of their effect. Individual forces of winds, waves and currents in each environmental combination have, therefore, to be sorted out and statistical analysis should be carried to define the time period of their impact on the basis of the recorded hydro-meteorology data. It should be remembered that downtimes might be not only due to the so extreme weather conditions but also an acceptable probability of ship's accidents (Quy et al., 2005). The latter has not been discussed in this paper.

Summary

The proposed method provides a rational and quantitative way for evaluating the effect of environmental conditions on the ship's maneuverability by which downtimes and probabilities of ship's grounding for lifetime of the channel are estimated. The results using this method obtained in this paper are more reasonably than those presented in the literature because unrealistic environmental combinations are mostly rejected. Advantage of the method is that a lot of simulation runs can be reduced and maneuvering scenarios will be distinguished by taking into account the behavior of ship's maneuverability.

References

Briggs, M. J., Borgman, L. E., & Bratteland, E. (2003). "Probability assessment of deep draft navigation channel," Coastal Engineering, Vol 48, pp 29-50.

Giang, H.H. (2003). “Probabilistic design of approach channel width,” Msc thesis, International Institute for Infrastructure, Hydraulic and Environmental Engineering (IHE), Delft, Netherlands.

Gucma, L. (2006). “The method of navigational risk assessment on waterways based on generalized real time simulation data,” Proc. of International Conference on Marine Simulation and Ship Maneuverability (MARSIM’06), Terschelling, Netherlands.

Oil Companies International Marine Forum (OCIMF), (1994). “Prediction of Wind and Current Loads on VLCCs,” London, England.

Quy, N. M., Vrijling J.K., Gelder van, and Groenveld R. (2005) “Methods to assess safety criteria of approach channels with respect to the acceptability of ship grounding risk,” Proc. of 6th International Symposium on Navigation, Gdynia, Poland.

Teng, C. C. and Liu, P. C. (2000), “Estimating wave height distributions from wind speed distributions,” Coastal Engineering, Vol 1, pp 310-319.

Welvaarts, W. (2001). “Risk analysis of vessels exceeding horizontal boundaries in a channel,” Msc thesis, Delft University of Technologies, Netherlands.

Wendy, L. M. and Angel, R. M. (2002). “Computational statistics handbook with MATLAB,” Chapman & Hall/CRC, Printed in the United States of America.

Appendixes

A. Equations of external forces acting on the ship’s hull and ship’s characteristics

Wind forces

$$
\begin{aligned}
X_{wind}(N) &= \frac{1}{2} C_x \beta_R \rho_w V_R^2 A_T \\
Y_{wind}(N) &= \frac{1}{2} C_y \beta_R \rho_w V_R^2 A_L \\
N_{wind}(N.m) &= \frac{1}{2} C_N \beta_R \rho_w V_R^2 A_L L
\end{aligned}
\tag{A.1}
$$

where X_{wind} and Y_{wind} are the transverse and longitudinal wind forces, respectively; N_{wind} is the moment force; C_x, C_y are the force coefficients and C_N is the moment coefficient, which are derived from the OCIMF recommendations by towing tank test; ρ_w is the density of air (kg/m^3); β_R is the wind angle which is formed between wind and sailing directions (degree); V_R is the average wind speed (knots); A_T and A_L are the transverse and longitudinal projected area of the ship (m^2); L is the overall length of the ship (m).

Current forces

$$
\begin{aligned}
X_{current}(N) &= \frac{1}{7600} C_{xc} \rho_c V_c^2 T_f L_P \\
Y_{current}(N) &= \frac{1}{7600} C_{yc} \rho_c V_c^2 T_f L_P \\
N_{current}(N.m) &= \frac{1}{2} C_{nc} \rho_c V_c^2 T_f L_P^2
\end{aligned}
\tag{A.2}
$$

where $X_{current}$ and $Y_{current}$ are the transverse and longitudinal current forces, respectively; $N_{current}$ is the moment force; C_{xc}, C_{yc} are the drag current force coefficients and C_{nc} is the drag moment coefficient, which are derived from the OCIMF recommendations by towing tank test and depend upon the current angle of incidence; ρ_c is the density of water (kg/m^3); V_c is the average current speed (m/s); T_f is the ship’s draft (m); L_P is the length of the ship (m).

Wave forces

$$
\begin{aligned}
X_{wave}(N) &= C_{xw} H_s^2 \mu \\
Y_{wave}(N) &= C_{yw} H_s^2 \mu \\
N_{wave}(N.m) &= C_{nw} H_s^2 \mu
\end{aligned}
\tag{A.3}
$$

where X_{wave} and Y_{wave} are the transverse and longitudinal wave forces, respectively; N_{wave} is the moment force; C_{xw}, C_{yw} are the wave force coefficients and C_{nw} is the wave moment coefficient, which are derived from towing tank test; μ is the wave angle of incident (degree); H_s is the significant wave height (m).

The ship’s characteristics

Characteristics of the bulk carrier 65000 DWT

Items	Units	Dimension
Overall length, L	m	245.3
Length between pp, L_P	m	233.6
Beam	m	32.2
Depth	m	19.0
Draft (loaded), T_f	m	13.0
Frontal wind area, A_L	m^2	740
Lateral wind area, A_T	m^2	2389

B. Environmental conditions of the approach channel at IJmuiden port used in this study

Table B.1: Occurrence frequencies of current speeds

Direction (degree)	Current speeds (m/s)												Total
	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	
15	0.000	0.000	0.083	0.083	0.000	0.000	0.083	0.000	0.083	0.083	0.000	0.000	0.415
190	0.083	0.000	0.083	0.000	0.000	0.000	0.083	0.083	0.083	0.083	0.000	0.083	0.581

Table B.2: Occurrence frequencies of wind speeds

Wind speed (m/s)	Wind direction (degree)												Total
	15	45	75	105	135	165	195	225	255	285	315	345	
2.5	0.00365	0.00376	0.00328	0.01001	0.01181	0.0074	0.00624	0.00583	0.00503	0.00463	0.00457	0.00418	0.07039
5.0	0.01549	0.01541	0.01945	0.0308	0.02917	0.03026	0.01362	0.01679	0.0187	0.01803	0.01498	0.01721	0.23991
7.5	0.01484	0.01491	0.0345	0.01647	0.01105	0.03213	0.02575	0.03552	0.02856	0.02151	0.01723	0.02326	0.27573
10.0	0.00795	0.00729	0.02181	0.00328	0.00129	0.01011	0.0244	0.05042	0.02865	0.01723	0.01385	0.01384	0.20012
12.5	0.00187	0.00238	0.00671	0.00102	0.00003	0.00243	0.01785	0.04477	0.01842	0.01186	0.00981	0.00625	0.12340
15.0	0.00044	0.00009	0.00158	0.00028	0	0.00053	0.00908	0.02175	0.00888	0.00671	0.00587	0.00248	0.05769
17.5	0.00004	0	0.00005	0	0	0.00015	0.0043	0.00805	0.00395	0.00474	0.00218	0.0008	0.02426
20.0	0	0	0	0	0	0	0.00094	0.00249	0.00196	0.00156	0.00046	0.00006	0.00747
22.5	0	0	0	0	0	0	0.00011	0.00023	0.00044	0.00004	0.00002	0	0.00084
25.0	0	0	0	0	0	0	0	0.00005	0.00008	0	0	0	0.00013
Total	0.04428	0.04384	0.08738	0.06186	0.05335	0.08301	0.10229	0.1859	0.11467	0.08631	0.06897	0.06808	0.99994

Table B.3: Occurrence frequencies of significant wave heights

Sig. wave height (m)	Wave direction (degree)												Total
	15	45	75	105	135	165	195	225	255	285	315	345	
0.2	0.05742	0.01264	0.00410	0.00290	0.00265	0.00230	0.00610	0.02049	0.02543	0.03323	0.11743	0.33645	0.62114
0.4	0.00899	0.00085	0.00005	0.00000	0.00000	0.00005	0.00005	0.00760	0.01174	0.00740	0.03043	0.16400	0.23116
0.6	0.00190	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00275	0.00385	0.00235	0.00755	0.05477	0.07317
0.8	0.00050	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00070	0.00180	0.00060	0.00395	0.02109	0.02864
1.0	0.00015	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00025	0.00070	0.00040	0.00220	0.00939	0.01309
1.2	0.00025	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00025	0.00010	0.00025	0.00110	0.00575	0.00770
1.4	0.00015	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00045	0.00005	0.00060	0.00420	0.00560
1.6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00035	0.00000	0.00075	0.00240	0.00365
1.8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00015	0.00010	0.00040	0.00200	0.00275
2.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00015	0.00010	0.00020	0.00190	0.00245
2.2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00000	0.00035	0.00165	0.00215
2.4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00005	0.00020	0.00150	0.00185
2.6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00005	0.00010	0.00005	0.00015	0.00080	0.00115
2.8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00005	0.00000	0.00010	0.00060	0.00075
3.0	0.00005	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00020	0.00065	0.00100
3.5	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00010	0.00010	0.00055	0.00030	0.00121
Total	0.06942	0.01349	0.00415	0.00290	0.00265	0.00235	0.00615	0.03274	0.04522	0.04478	0.16616	0.60745	0.99746