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We present a simulation model for long-term optimal design of channel depths in which the risk of ship grounding due to wave impacts can be assessed for every ship transit. This new model includes four main components: (1) an exponential probability law for the number of ship departures; (2) a parametric model of the wave-induced ship motions; (3) modeling effects of tidal variations on the channel performance; and (4) a Poisson probability law for the grounding model in a single random ship departure. A key procedure of the simulation process is to define a minimum underkeel clearance allowance for ship entrance and simultaneously determine downtimes that correspond to an acceptable grounding risk for a specified ship and a generated environment condition. The final results derived from the simulation model can be considered as the key parameters in analysis and selection of an optimal depth. The model has been applied to the entrance channel of Cam Pha Coal Port, Vietnam, as a case study.

Keywords: Ship grounding, risk modeling, simulation model, entrance channel, underkeel clearance

1. Introduction

Simulation-based optimization techniques are frequently used for many applications in different systems, including urban, economic and transportation areas. In the maritime field, simulation models have been used for port operations and ship traffic flow. Most of the existing traffic simulations place the emphasis on the study of traffic rules and the entrance regime on port capacity, with very little attention on the safety aspect of a particular transit [1–3]. The environmental conditions for which a ship transit is considered safe or unsafe are referred to as the 'channel entrance policy'. If the channel is designed to allow ship navigation in more severe environmental conditions, waiting time (downtime) will be reduced but dredging cost will be rise. Alternatively, starting from a maximum acceptable waiting time and an investment policy with a level of navigation safety, the simulation can estimate a maximum channel capacity as the basis for a trade-off between cost and benefit. The optimization of channel depths therefore aims to determine a depth to balance between the benefit of transport increment, downtime reduction and increase in costs of initial/maintenance dredging for a long-term channel project.

It should be realized that the optimization of channel depths requires guidance for minimum underkeel clearance allowances for the entrance accessibility to facilitate a required navigation safety. The safety for the entrance accessibility, in this context, can mainly be expressed in terms of probability of ship grounding.

However, the present design guidelines for underkeel clearance allowances for coastal entrance channels and shallow waterways are not comprehensive or practical [4]. A simple general guideline for minimum depth clearance requirements in channels influenced by waves is given by the Permanent International Association of Navigation Congress (PIANC) [1]. It is defined by ratios of water

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depth to ship draft, which should be 1.3 when H_s (significant wave height) is not higher than 1 m and at least 1.5 when H_s is higher than 1 m and wave periods and directions are unfavorable. This guideline gives a rather unrealistically large depth under moderate wave actions. Alternatively, the US Army Corps of Engineers [5] states that "net depth allowance for waves is 1.2 H_s for deep-draft and 0.5 H_s for shallow-draft channels". Briggs et al. [6] applied this simplistic relation to the probability assessment of the ship grounding risk at the entrance channel of Barbers Point Harbor.

Recent efforts have focused on developing a model for prediction and assessment of ship grounding risk using either physical models or real time-measured wave data in combination with a numerical model of ship motion [7, 8]. However, both approaches cannot be used for a long-term study of the channel project because only a limited number of navigation conditions can be investigated.

There are two objectives of this paper. The first is to establish an entrance policy that a simulation model can use to check whether a transit condition is allowed before leaving the port. This entrance policy can not only be used for the optimal design but also for the operation of navigation depth by pilots. It should be noted that the wave period contributes a significant effect on ship motion. Hence, an adequate guidance for ship accessibility should consider wave conditions (both H_s and wave period T_z) in association with transit conditions (sailing speed and minimum underkeel clearance) for navigational safety. The second is to optimize channel depths in the long term considering an acceptable probability of the ship grounding on the basis of the established entrance policy. The study is however confined to one failure mechanism, which is the event of ships touching the channel bottom induced by waves (viewed as grounding).

2. Methodology

The optimization of channel depths should be considered a two-stage process, as described in Figure 1. The first part involves establishing an entrance guidance to facilitate required navigation safety with respect to the possibility of touching the channel bed, as discussed previously. To do this, the model of ship vertical motion responses due to wave effects should be defined. This step is the so-called short-term establishment of accessibility policy for safe navigation.

Secondly, using the Monte Carlo method and based on the established entrance policy, a simulation model is developed to define a minimum underkeel clearance allowance and simultaneously determine downtimes that correspond to an acceptable grounding risk for a specified ship and a generated sea state. The process can be repeated for a given time period and for all possible alternatives of the channel depths. To enable this, stochastic models of the environmental conditions and ship arrivals have to be set up on the basis of historical records or forecast data. The advantage is that since the ship motion response is defined as a function of the transit conditions and sea states, the model uncertainties can be assessed and included in the simulation. The final results derived from the simulation model can be considered as the key parameters in analysis and selection of an optimal depth. This approach was applied to Cam Pha Coal Port in Vietnam, and is described in detail in the following.

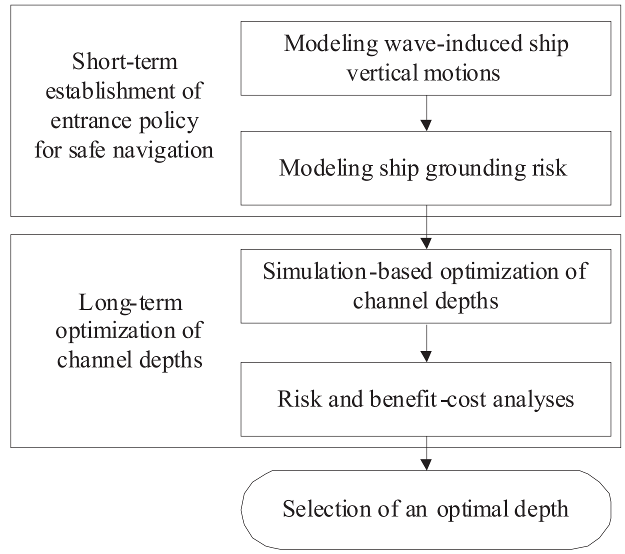

Figure 1. Two-stage process of channel depth optimization

3. The Case Study

3.1 Project Description

Cam Pha Coal Port in the North Sea of Vietnam is the country's largest specialized port serving export of coal to Europe, Japan and China. In recent years, the demand on coal export to Europe and Japan has increased rapidly and ships entering the port are becoming larger and are in a fully-loaded state beyond the present capacity of the entrance channel of the port. Therefore, in 2001, Vietnam Coal Incorporation initiated an expansion project of the port [9] in which the entrance channel was to be enlarged to allow ships of up to 65 000 DWT (fully loaded) using a tide up for leaving the port. However, at the time of writing, the rehabilitation of the channel has not yet commenced. The main reason for this delay is that a part of the channel of length 12 km is very shallow (only –10 m from the sea datum), resulting in very expensive dredging work. Hence, economic and environmental pressures have acknowledged the need to minimize the dredging when determining the depth of the entrance channel. Establishment of an appropriate and reliable policy for the ship entrance also provides an opportunity to reduce the dredging depth requirement. This study, as a part of the previously-mentioned project, discusses the rehabilitation of the entrance channel.

3.2 Present Operational Procedure

Since the port is solely used for export of coal, all the ships entering the port are empty with a ballast draft. Such ballasted ships can use the channel at mean low water level. On arrival at berth, the ship anchors or secures and waits for permission to load. For the study of the channel dimensions only, the model does not include the downtime due to waiting for berth availability, loading equipment and other delays, which can be considered in a port simulation model [10].

There are two possible options of loading the ship: fully loaded and partly loaded. The port authority will determine a maximum possible tidal window available during the following few days, taking into account the loading time at berth to decide how much coal should be loaded into the ship. After the completion of the loading (fully or partly), the ship may have to remain at the waiting area, located in front of the berth, before it can sail out. In case of no tidal window being available for full loading at the berth, the ship can continue to an anchorage area near buoy No. 0 at the end of the outer entrance channel to receive a topping up of coal from a fleet of 500 DWT barges. The additional cost for this floating loading operation is US $20 per ton, in comparison with loading at the quay.

3.3 Deterministic Method of Existing Admittance Policy

Until now, a deterministic admittance policy has been used for Cam Pha Coal Port. The entrance admittance of ships is based on a fixed underkeel clearance ratio as recommended by PIANC guidelines. The relations between the minimal underkeel clearance and the maximum draft have been calculated by adding the squat, wave allowance and other effects to establish the clearance. As a rule, the ratio between the gross underkeel clearance and the maximum draught should be 25% of the maximum draft for a 65 000 DWT bulk carrier using the outer area of this channel exposed to the open sea, where the bottom is composed of soft soil. Using this ratio the accessibility of the channel can be determined, adapting to a certain water level. Obviously, this entrance policy considered water level deviations and the ship draft, but does not make any distinction regarding other ship characteristics and wave conditions.

4. Risk-Based Model

The simulation model developed in this paper is characterized by the inclusion of modeling the wave-induced ship motions and its effect on the risk of ship grounding. The key element of the risk model, which is based on a probabilistic method, is a determination of the probability of touching the bottom during a transit. This therefore requires reliable estimation of the ship vertical motion response due to the wave effects, as has been discussed in the following.

4.1 Modeling of Ship Motion Response

The response of the wave-induced motions (or motion spectrum) $S_r(\omega_e)$ can be achieved either from towing tank experiments or by numerical models based on the ordinary or the modified strip theory [11]. The response spectrum is, however, only obtainable for a particular transit condition and a specified sea state. For a long-term assessment of a ship response, much broader sea states and continuous variation of the parameters V (ship speed) and T (ship draft) are required [12]. Moreover, these two approaches cannot account for uncertainty in these parameters in calculating the response spectrum and in application to performance of risk analysis.

A demand is therefore emerging for a high resolution and continuous description of the response spectrum for the problem at hand. At least three studies with different application purposes could be found. A simple linear regression model of the response spectrum related to the frequency wave spectrum was presented by Savenije [2]. The regression coefficients of the model depending on the transit conditions are defined by minimizing the mean squared error between the observed data and the predicted model values. This model is currently used in the computer program HARAP (HARbourAPproach) [13] for optimal design and operation of navigation channel depths in the port of Rotterdam [14]. Recently, US Army Engineer (USACE) Research and Development Center have been developing a ship motion response model to use on the ship simulator [15]. However, as pointed out, this model is still considered a research tool and needs further verification. Moreover, no numerically measured error for the qualification of these models has been found in the published papers.

The more advanced model used in this article has been developed by the authors applying a parametric modeling method [16]. The model can allow us to determine the ship motion directly, from any wave spectrum, for a certain navigation condition. Obviously, this approach provides the results more accurately than from the regression model, as can be seen in Figure 2.

It was confirmed [16] that this new model with its parameters expressed by polynomial functions represents well the behavior of the ship motion response in the linear wave motion system. As an example, the estimated response spectrum from this model is comparable to that obtained from the numerical ship motion model, SEAWAY [17], as shown in Figure 3. The average fit coefficient of determi-

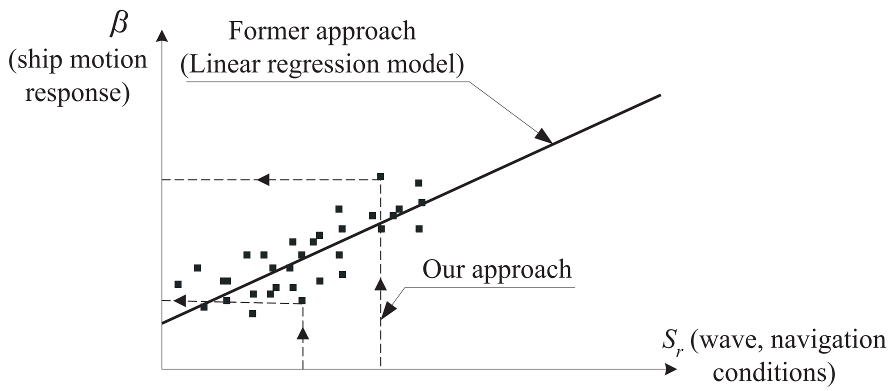

Figure 2. Determination of ship motion response from wave and navigation conditions

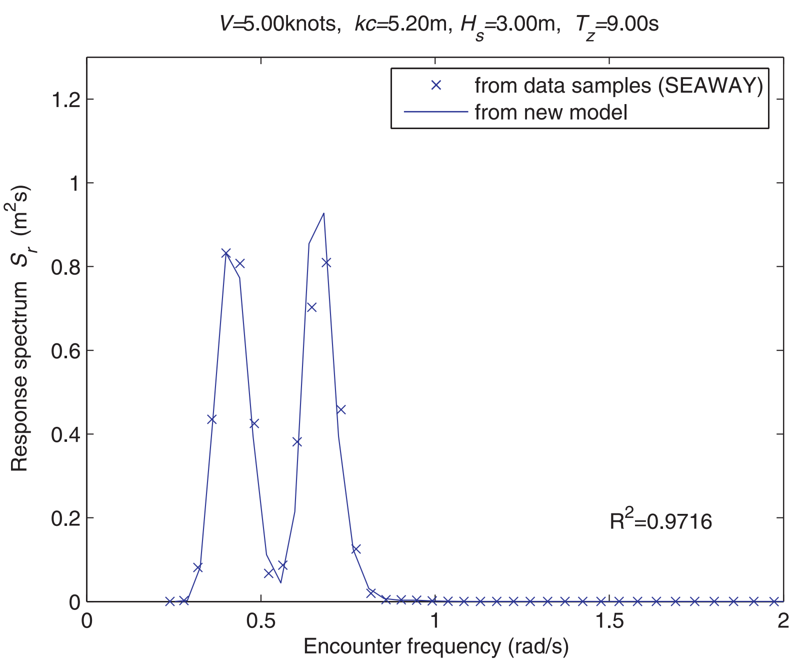

Figure 3. Comparison of estimated response spectrum with numerical model (SEAWAY)

nation is 0.988 and the smallest coefficient is 0.9716 for this case study.

4.2 Modeling Grounding Risk: First-Passage Failure

A widely accepted model of ship grounding risk is first-passage failure. The first-passage failure is an event that a random process $X(t)$ crosses a level $x = \beta$ (m) once during a period T_0 (s). It is frequently used to estimate the probability of the ship touching the bottom, which is assumed as a measure of the risk of ship grounding. This method is based on the assumption that successive up-crossings of a specified level are independent and constitute a Poisson process [18]. Under this assumption the probability of the first-passage failure $P(\beta, T_0)$ of a response $X(t)$ when is a stationary can be estimated by:

$$P(\beta, T_0) = 1 - \exp(-\upsilon_\beta T_0) \qquad (1)$$

where ν_β is the mean rate of crossing with a level β. If the response $X(t)$ has the Gaussian distribution and zero mean, ν_β can then be expressed as:

$$\upsilon_\beta = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}\exp\left(-\frac{1}{2}\frac{\beta^2}{m_0}\right) \tag{2}$$

where m_0 and m_2 represent zero and second moments of the response, respectively, determined by:

$$m_0 = \int_0^\infty S_\mathrm{r}(\omega_\mathrm{e})\mathrm{d}\omega_\mathrm{e}, \tag{3}$$

and

$$m_2 = \int_0^\infty \omega_\mathrm{e}^2 S_\mathrm{r}(\omega_\mathrm{e})\mathrm{d}\omega_\mathrm{e}. \tag{4}$$

In Equation (4), $S_\mathrm{r}(\omega_\mathrm{e})$ is the response spectrum introduced in the previous section.

In engineering design, it is highly desirable to know a certain level of underkeel clearance for which probability of first-passage failure is smaller than an acceptable value α. For example, before the ship entrance we wish to know a specified level of the vertical motion corresponding to an acceptable probability of the ship grounding, α. From $P(\beta,T_0) = \alpha$ and Equations (1) and (2), crossing level for probability of first-passage failure α can be expressed [19]:

$$\beta = \sqrt{m_0}\left[-2\ln\left(-\ln(1-\alpha)\Big/\frac{T_0^2}{2\pi}\sqrt{\frac{m_2}{m_0}}\right)\right]^{\frac{1}{2}}. \tag{5}$$

For navigational safety, β must be smaller than available average instantaneous underkeel clearance, kc.

5. Simulation Model

The simulation model has been designed in the MATLAB programming language by the authors. This model is a discrete-event and compressed-time-stepping traffic simulation for the navigation channel exposed to the open sea where the safety of ship navigation is threatened by wave impacts. Stochastic variables of environmental conditions and ship arrivals are generated as input data for the model.

The simulation model, as outlined in Figure 4, consists of several components. First, the data of ships, tidal and wave conditions are generated as the input of the simulation. The risk-based model described in Equation (5) is used to determine whether a ship entrance is allowed by comparing a calculated β with the kc for a level of the risk acceptance, α. The core element is a calculation program that will provide various results of the simulation for the optimal process of channel depths. Some selected important elements have been explained in detail in the following sections.

5.1 Departure Pattern of the Ship

The model assumes that the ship departure follows an exponential distribution function of the form

$$f(t) = 1 - e^{-\mu t} \tag{6}$$

where μ is the departure rate calculated from the historical data and t is the time of ship departure. The simulation begins by generating a date and a time of the first ship after receiving permission to load. On the basis of the possible maximum tidal window to be found available in the next few days, the model calculates a value of the draft to which the ship shall be loaded. The other dimensions of the ship have, of course, to be available in advance for definition of the ship motion response. The ship speed is considered to be constant over the complete passage. Specifications of the design ship are presented in the Appendix in Table A.3.

5.2 Tide Generation

Tidal data for the study period have to be available and stored in the model. There are two types of water level: astronomic and meteorological. The predicted astronomical water level for a given period of calculation should be available as a function of date and time. Meteorological water level is defined as the difference (predicted error) between astronomical water level and real water level measured during the same period. A certain water level regarded as the real water level is determined by adding astronomical water level and a predicted error [20]. In this case study, a Gaussian distribution function of the predicted error with parameter mean value 22.3 mm and standard deviation 132 mm was found based on the statistical water level data recorded during the past 30 years. A certain tidal level will be defined and assigned to the ship transit based on the date and time of the ship departure. It can also be changed dynamically in the model during the ship transit along the channel.

5.3 Wave Generation

Two parameters of the Pierson-Moskowitz spectrum, H_s and T_z, have been proposed to calculate the ship motions. Sets of characteristic wave data values can be grouped and arranged as in Tables A.1 and A.2 for all wave directions. The number in each cell table indicates the probability that a significant wave height is between the values in the left column and in the range of wave periods listed at the top of the table.

The Gamma distribution has been found to fit fairly well with the frequency of the significant wave heights in all direction classes (last column of Table A.1), as shown in Figure 5. Based on this distribution we can first generate stochastically a value of significant wave height, H_s.

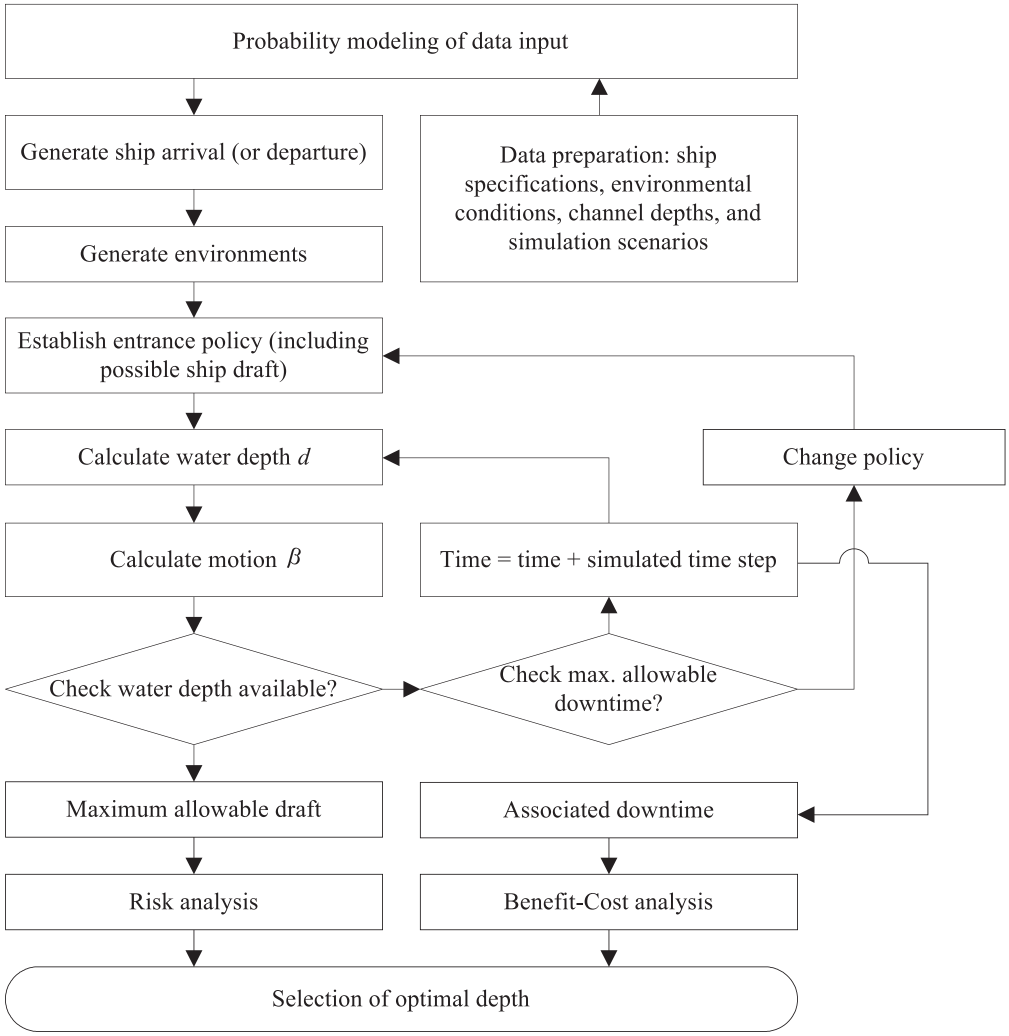

Figure 4. Main components of the simulation model

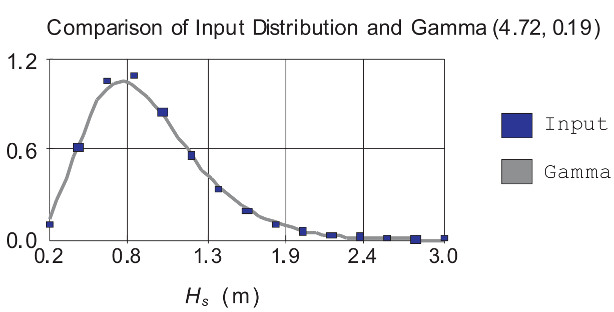

Figure 5. Frequency of the wave heights fitted with Gamma distribution

A uniform random number can then be generated to obtain a desired direction class by using the inverse transformation method [21]. Finally, a wave period T_z can be determined using a conditional distribution between the parameters H_s and T_z [22, 23].

5.4 Calculation Program

The core of this simulation model is a calculation program. Attention is paid to a successful approach [7] on which the calculation program described in this section is based. The program consists of the following calculation steps.

(1) *Determination of the depth* An instantaneous water depth at the ship position is calculated based on a generated departure time and a selected ship speed, taking account of the local bottom depth and the tidal data. For practical use in the grounding model, the whole passage should be divided into

Table 1. Matrix form of the encounter frequency transfer

Loading conditions (ship draft)	Wave direction relative to the ship speed					
	θ_1	θ_2	...	θ_i	θ_{i+1}	θ_n
T_1	$H_{1,1}$	$H_{1,2}$	...	$H_{1,i}$	$H_{1,i+1}$	$H_{1,\mathrm{n}}$
T_2	$H_{2,1}$	$H_{2,2}$	...	$H_{2,i}$	$H_{2,i+1}$	$H_{2,\mathrm{n}}$
!	!	!	...	!	!	!
T_3	$H_{i,1}$	$H_{i,2}$	...	$H_{i,i}$	$H_{i,i+1}$	$H_{i,\mathrm{n}}$
T_4	$H_{i+1,1}$	$H_{i+1,2}$	...	$H_{i+1,i}$	$H_{i+1,i+1}$	$H_{i+1,\mathrm{n}}$
T_m (fully loaded)	$H_{\mathrm{m},1}$	$H_{\mathrm{m},2}$	...	$H_{\mathrm{m},i}$	$H_{\mathrm{m},i+1}$	$H_{\mathrm{m,n}}$

sub-passages in which the water depth is approximately constant. The difference between the deepest and shallowest point of each sub-passage should not exceed a limiting value. The actual water depth h in each point of the passage is replaced by a certain minimum depth h_j of the sub-passage.

(2) *Estimation of squat* When ship draft and water depth in each sub-passage are available, a speed value is selected to formulate a database of the navigation (T, d and V). The empirical expression, proposed by Barrass II in PIANC [1], has been used to estimate the ship squat of a critical point on the ship hull.

(3) *Calculation of the motion characteristics* For each sub-passage and generated wave parameters H_s and T_z, the Pierson-Moskowitz spectrum density will be calculated. The response spectrum of the wave-induced motions can then be defined for a given generated wave direction and a loading condition as [16]:

$$\begin{aligned} & S_\mathrm{r}(\omega_\mathrm{e}|H_\mathrm{s}, T_z, V, kc) \\ = \; & |H(\omega_\mathrm{e}|V, kc)|^2 S_\eta(\omega_\mathrm{e}|H_\mathrm{s}, T_z) \end{aligned} \tag{7}$$

where $S_\mathrm{r}(\omega_\mathrm{e})$ is the response spectrum of the wave-induced motions, ω_e is the encounter frequency; $|H(\omega_\mathrm{e})|$ is the encounter frequency transfer; $S_\eta(\omega_\mathrm{e})$ is the wave spectrum at the encounter frequency; V (m/s) is the forward speed of ship; kc (m) is the average instantaneous underkeel clearance.

The encounter frequency transfer is determined as the function of a given generated wave direction and a loading condition with the matrix form as presented in Table 1.

Since the transfer response functions have been formulated into the parametric model in advance, the response spectrum can therefore be computed for any generated wave and certain navigation conditions during the simulation process. This allows computation of the amplitude characteristics of the ship vertical motion, as expressed in Equations (3) and (4). The computation focused on the hull motion at stern; the risk of touching the bottom is most critical for this part of the ship where the outbound ships loaded draft faces incoming waves [19].

(4) *Calculation of a minimum safe underkeel clearance* A value β can be determined, considered as a minimum safe underkeel clearance for ship entrance. This value will be compared to the available underkeel clearance, kc, with the condition that $kc > \beta$. If this is not satisfied, the ship has to wait at the anchor area. The model will accumulate the downtime until achieving a higher tidal level and tidal window to meet the condition.

5.5 Simulation Output

The simulation output contains: ship waiting time for each transit and the total waiting time for the period of simulation; average number of times and the average amount of coal (m^3) loaded onto ships at the floating point (when there is no available water depth for ships loaded fully at the quay); channel utilization ratio, the ratio of the time that ships occupy channel to the period of simulation; and conversion of all of the above to monetary units if prices are available.

5.6 Model Verification and Validation

For purposes of verification, the data of wave, tide and ship arrival were generated from the generation models as formulated above. The statistics for wave heights, tidal levels and ship arrival times were then calculated. Finally, probability density functions of the generated data were determined and compared with those from the observation. Goodness-of-fit tests were found to verify that the parameters fit reasonably well with the generated data. Figure 6 displays an example for the wave performed.

For purposes of validation of the simulation model, waiting times for 25 of the ship arrivals during the past were gathered. This means that the simulation experiment should be conducted for the existing condition of the port. Figure 7 compares the relative histograms of waiting times taken from the simulated data (number of runs 50) and the observed data. The authors expect that the model would be

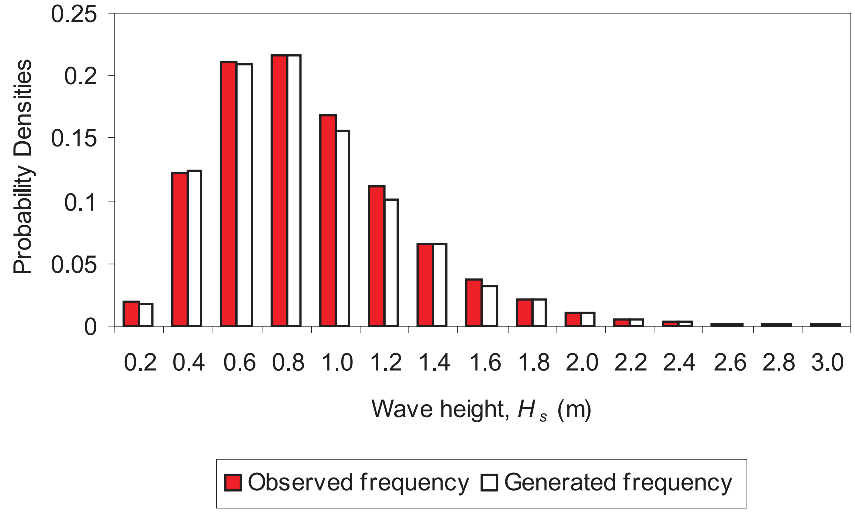

Figure 6. Comparison between the generated and observed wave frequencies

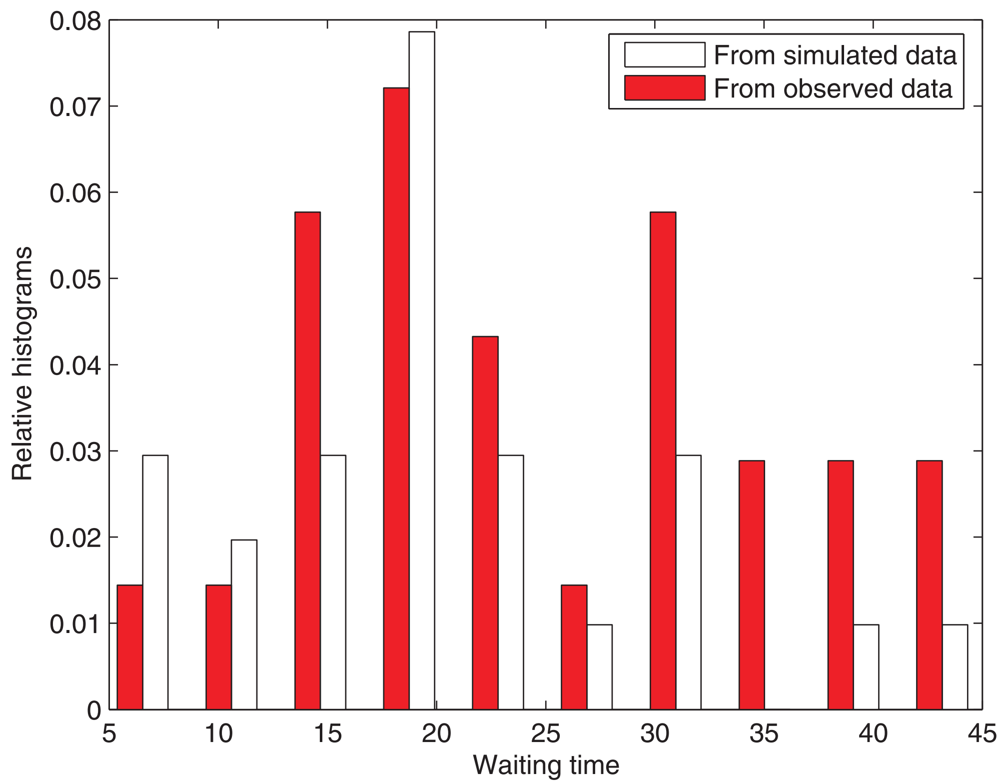

Figure 7. Relative histogram comparison of simulated waiting time with observed data

Table 2. Simulation scenarios

Items	Unit	Data input
1. *Simulation time*, T_{sim}	hours	360×24
2. *Ship characteristics*		
– The expected number of ship arrivals per year, *n*	–	10, 20, 30, 40, 50
– Distribution of departure time		exponential
– Average departure time, $1/\mu$	hours	$= T_{sim}/n$
– Ship speed	knots	5, 7.5, 10
– Ship specification		See Appendix
3. *Channel characteristics*		
– Channel length	m	12 000
– Channel depth level	m	
Option 1 (existing)		–10
Other options		–11, –12, –13, –14
4. *Cost parameters*		
– Waiting cost	US$/hour	25
– Dredging cost	US$/m^3	3.5
– Extra loading cost at the floating point (difference from the loading cost at the quay)	US$/ton	20

acceptable, although some differences were evident from this comparison. Reason for these differences, evaluated by the authors and a number of port authority experts, include the following.

- The observed data are too limited, so the parameters of the statistics have not approached the 'true' data.
- The quality of the observed data is considered low.
- The simulation model considers waiting times for high tidal level and acceptable weather conditions only, while other factors with high uncertainty such as queuing, pilot and documentation delays are sometimes included in the data.

6. Simulation Results

Until now, due to the limited channel depth, only a small number of ships of 65 000 DWT or larger have called at the port. However, it is expected that this number will increase after the channel is deepened. The objective of this simulation is therefore to investigate the effect of changes in the channel bed level and in the expected number of ship arrivals on the channel performance measures (waiting time, extra operation cost and dredging cost) in comparison to the existing condition. The simulation is based on the assumption that all ships are fully loaded either at the quay or at the floating point before leaving. The throughput is therefore equal for all alternatives of the channel depths and sailing speeds, and this throughput is dependent upon the expected number of ship arrivals only. The operation and dredging costs are certainly different between alternatives. These results will be used to determine the best design for the channel depth associated with acceptable navigation conditions.

6.1 Simulation Scenarios

The study established five options of channel bed levels and three scales of the sailing speed (slow, moderate and normal) with five options of the expected number of ship arrivals, which amounted to 75 simulation scenarios to be investigated. The input details are listed in Table 2.

Risk acceptance α is one of the key issues in the design or operation of any entrance channel. The risk acceptance is defined for a particular transit to satisfy the condition that the probability of touching the bottom does not exceed an imposed value. Therefore, an acceptable probability of ship grounding should be compared with those from worldwide databases. PIANC [1] reported a grounding probability for Northern European ports of 3 per 100 000 (i.e. 3×10^{-5}) ship movements. Statistics in the literature [6] provide accident probabilities ranging from a low of 4 per 100 000 (i.e. 4×10^{-5}) to a high of 83 per 100 000 tanker movements. These figures should, of course, include all types of accidents. From the safety point of view and the fact that the study concerns one failure mechanism of bottom touch only, the risk acceptance $\alpha = 3 \times 10^{-5}$ per ship movement as observed in Northern European ports might be reasonable.

6.2 The Number of Simulation Runs per Scenario

The simulation execution method selected for the model is the replication method [24]. This method requires a certain number of the experiments (simulation runs). Logically, more repetitions of the simulation will give more exact information on the channel performance; this requires more computational effort.

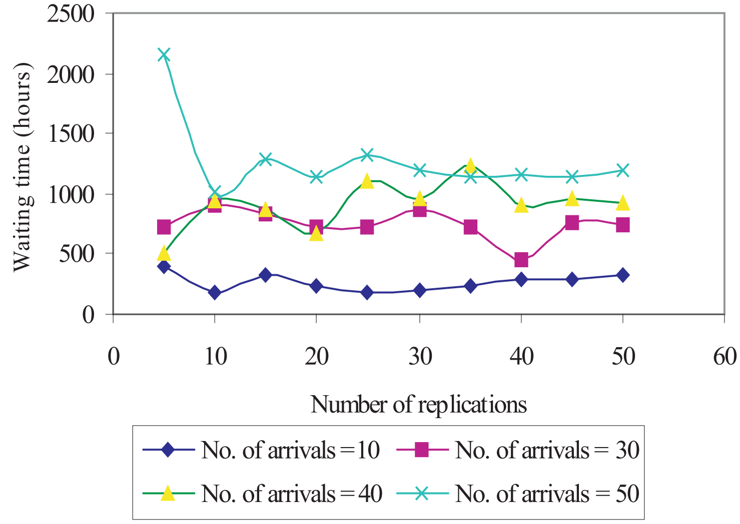

Figure 8. Effect of the number of replications on simulated waiting times

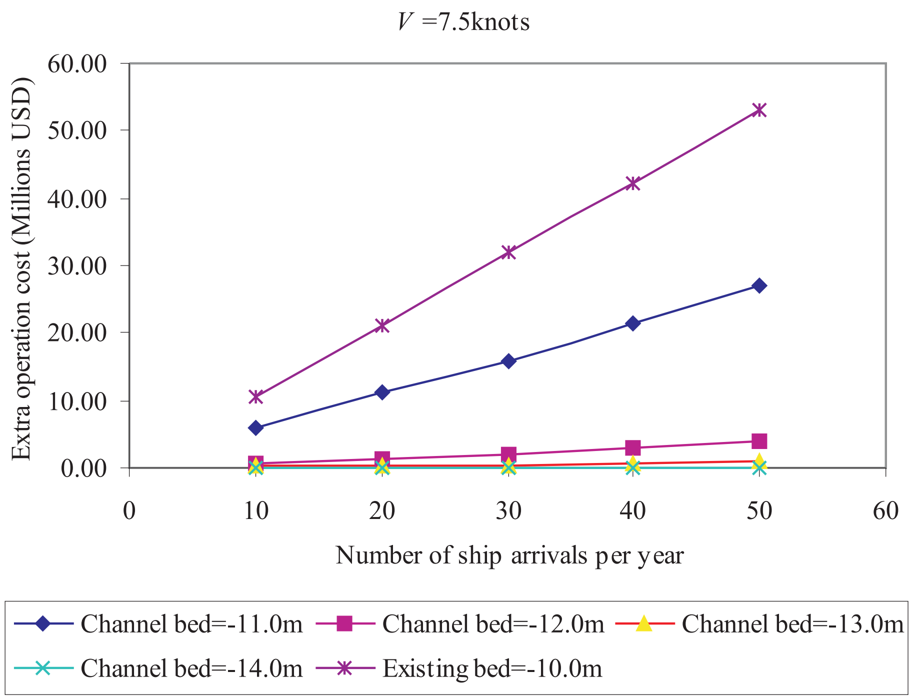

Figure 9. Linear relation between extra operation cost and number of ship arrivals for different channel bed levels and V = 7.5 knots

Figure 8 demonstrates the variations in the downtime according to the number of repetitions. The first ten replications are the initial transient period. The results seem to be dispersive and sensitive. After this period, the variations in the downtime become less and seem to be constant for 50 repetitions. It is therefore recommended that 50 repetitions should be made for each scenario.

6.3 Result Analysis

Figure 9 shows the relationship between extra operation costs, which comprise the waiting cost and the extra loading cost at the floating point, and the number of ship arrivals for different channel bed levels. The extra operation cost increases quickly with decreasing channel depth.

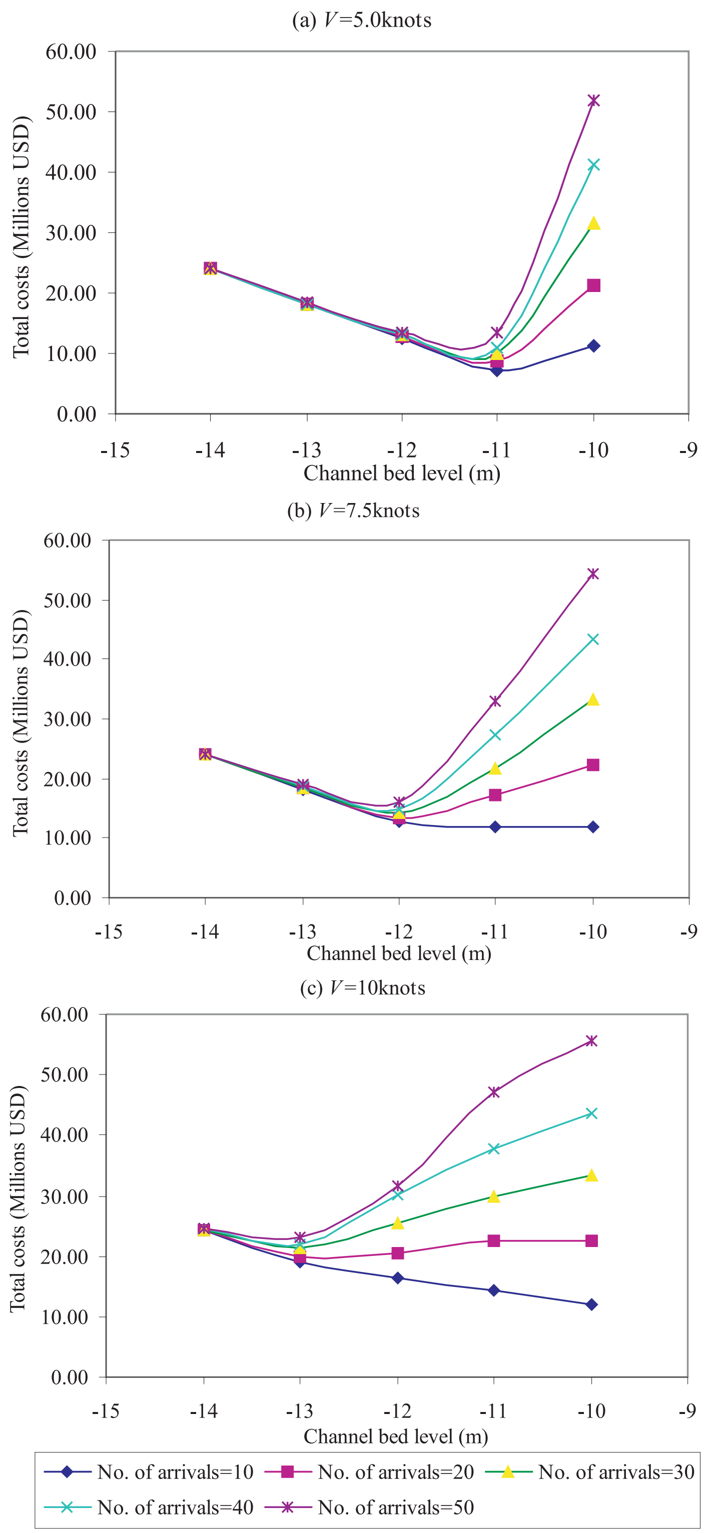

Figure 10. Total costs versus channel bed levels and number of ship arrivals for various speeds (a) V = 5 knots; (b) V = 7.5 knots; and V = 10 knots

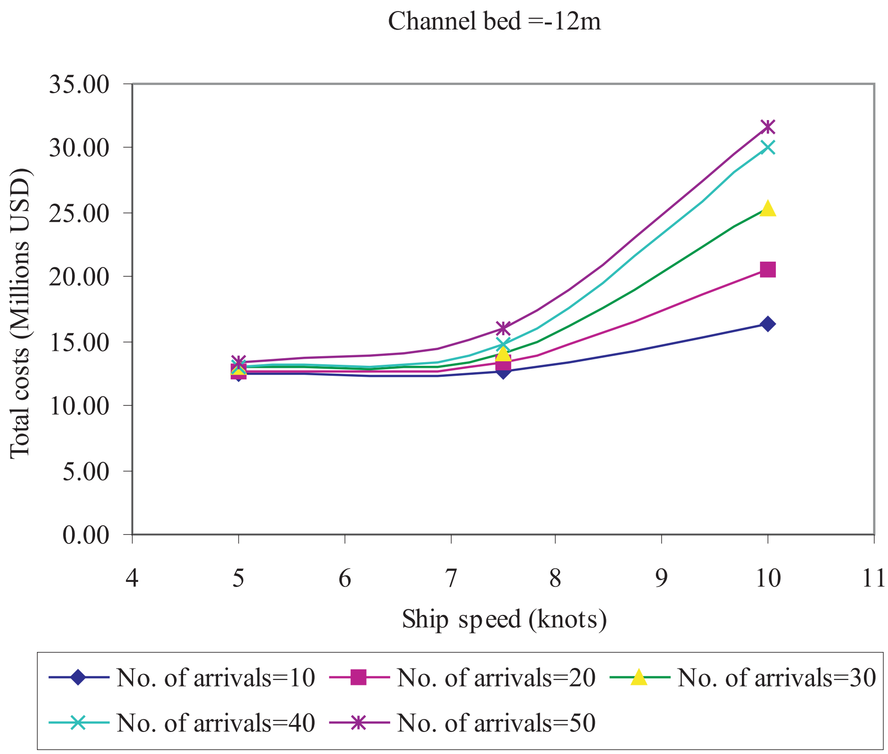

Figure 11. Relationship between total costs and ship speeds for various numbers of ship arrivals

Moreover, they are much reduced and even approach zero in the cases of a channel bed deeper than –12.0 m. It can be seen that extra operation costs and waiting times are almost a linear function of the number of ship arrivals. This observed fact enables an extrapolation of the results and a reduction of simulation time in the case of larger numbers of ship arrivals considered in the future study.

The total cost, defined as a sum of the extra operation and dredging cost, is expressed in terms of the number of ship arrivals and channel bed levels for alternative sailing speeds, as shown in Figure 10. It is interesting to observe that there is only one point of the minimum total cost given at the channel bed of –11 m and the speed of 5.0 knots with any number of ship arrivals (see Figure 10a). However, this differed from the two other cases of ship speeds where the minimum total costs corresponded to channel bed of –10 m (existing condition) as the number of arrivals was less than 10. When the number of arrivals exceeds 10, the minimum total cost corresponded to a channel bed of –12 m and –13 m with ship speeds 7.5 knots and 10 knots, respectively (see Figures 10b and 10c).

The minimum total costs for the channel bed of –12 m are presented as a function of the ship speed and the number of arrivals, as shown in Figure 11. It can be seen that the effect of ship speed on the cost varies in a certain pattern. When sailing speed is less than 7.5 knots, the total costs seem equally and only slightly dependent on the number of ship arrivals. In contrast, in cases of sailing speed exceeding 7.5 knots, the total costs increase quickly and the effect of the number of arrivals on the total costs becomes larger with the increase in sailing speeds. This can be explained as the reduction of underkeel clearance due to the squat becomes significant when the ship speed exceeds 7.5 knots. Hence, higher water levels are needed to satisfy the required safety of the ship navigation; in other words, the fewer water levels are available during the channel service period. Subsequently, waiting time and extra operation costs are increased.

7. Conclusions

This paper has demonstrated the application of an appropriate simulation model for investigation of the channel performance in Cam Pha coal port. The simulation has been executed for a bulk carrier of 65 000 DWT, which is the most common ship calling the port. However, the approach can be developed and applied to all kinds of ships and entrance channels, especially for the channel which is exposed to open seas. A key component of this model

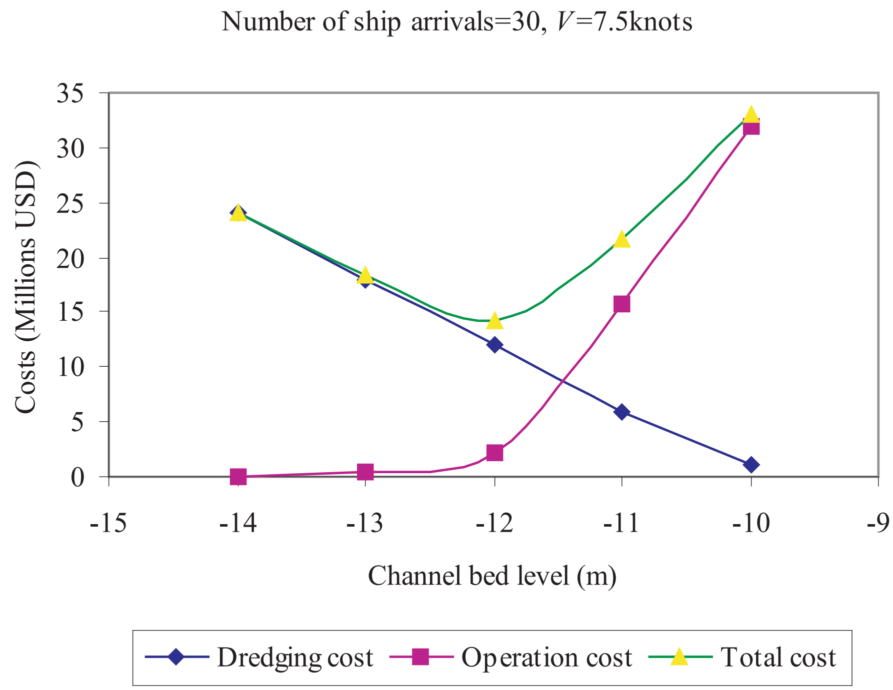

Figure 12. Cost details for the selected design

is the application of a wave-induced ship motion model to determine accurately a minimum underkeel clearance with acceptable navigation conditions for a safe transit. A significant part of this study relates to analyzing the effect of water depth fluctuations (the changes in tidal and channel bed levels) and navigation conditions on the channel performance measures such as downtimes, operation and investment costs. The channel simulation model developed for this application has been used to determine the effect on these measures under alternative operating and investment policies. The simulation model includes four main components: (1) an exponential probability law for a number of ship departures; (2) a parametric model of the wave-induced motion response; (3) modeling effects of tidal variations on the channel performance; and (4) a Poisson probability law for a grounding model in a single random ship departure.

Based on the simulation results, we are confident in concluding that a ship which is navigated at a speed of 7.5 knots with a channel bed of –12 m will result in the best strategy when the number of ship arrivals is more than 10. It can be observed in Figure 12 for the selected design that the operation cost will be reduced quickly if the channel bed is deeper than –12 m.

However, sailing speed is an important factor which is strongly interactive with the ship maneuvering and steering behavior. The probability of bottom touches decreases with decreasing speed. In many situations, the lower the sailing speed the wider the channel width required due to the effect of cross wind or current. Further effort needs to be made to incorporate an optimal study of the channel width, so that the whole channel can be optimized in an integrated manner. Moreover, the research should also combine both the channel and quay operation modes.

Finally, it is believed that this approach will provide a more accurate estimate of the required underkeel clearance and the long-term navigation safety or likelihood of a vessel accident than the standard design guidelines when sufficient physical data are available; the accessibility policy for ship entrance as well as the long-term optimization of channel depths will therefore be more accurately and practically achieved.

8. Acknowledgements

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9. Appendix

Table A.1. The frequencies of wave height in relation to wave period

Sig. wave	Wave period, T_z (s)											Total
height (m)	5	6	7	8	9	10	11	12	13	14	15	16	
0.2	0	0	0.0004	0.0033	0.00813	0.00586	0.0016	0.00022	0.00002	0	0	0	0.0195
0.4	0	0	0.0001	0.0027	0.02329	0.04785	0.03454	0.01156	0.00221	0.00028	0.00003	0	0.1225
0.6	0	0	0	0.0007	0.01344	0.05686	0.07728	0.04503	0.01397	0.00273	0.00038	0.00004	0.2104
0.8	0	0	0	0.0002	0.00502	0.03473	0.07403	0.06483	0.02897	0.00781	0.00144	0.0002	0.2172
1.0	0	0	0	0	0.00159	0.01576	0.04708	0.05636	0.03355	0.01171	0.00273	0.00047	0.1693
1.2	0	0	0	0	0.00047	0.00619	0.02408	0.03695	0.02771	0.01197	0.00339	0.00069	0.1115
1.4	0	0	0	0	0.00014	0.00227	0.01097	0.02063	0.01872	0.00967	0.00322	0.00077	0.0664
1.6	0	0	0	0	0.00004	0.00082	0.00472	0.01054	0.01125	0.00676	0.00259	0.0007	0.0374
1.8	0	0	0	0	0.00001	0.0003	0.002	0.00516	0.00632	0.00433	0.00188	0.00057	0.0206
2.0	0	0	0	0	0	0.00011	0.00085	0.00249	0.00344	0.00265	0.00128	0.00043	0.0113
2.2	0	0	0	0	0	0.00004	0.00036	0.0012	0.00158	0.00158	0.00084	0.00031	0.0059
2.4	0	0	0	0	0	0.00002	0.00016	0.00059	0.001	0.00093	0.00054	0.00022	0.0035
2.6	0	0	0	0	0	0.00001	0.00007	0.00029	0.00054	0.00055	0.00035	0.00015	0.0012
2.8	0	0	0	0	0	0	0.00003	0.00015	0.00029	0.00032	0.00022	0.0001	0.0011
3.0	0	0	0	0	0	0	0.00003	0.00015	0.00036	0.00047	0.00037	0.0002	0.0016
Total	0	0	0.0005	0.0069	0.05213	0.17082	0.2778	0.25615	0.14993	0.06176	0.01926	0.00485	0.9999

Table A.2. The frequencies of wave height in relation to wave direction

Sig. wave	Wave direction relative to the ship speed (degree)											Total
height (m)	15	45	75	105	135	165	195	225	255	285	315	345	
0.2	0.00574	0.00126	0.0004	0.00029	0.000265	0.00052	0.00061	0.00105	0.00141	0.00187	0.00253	0.00350	0.0195
0.4	0.00899	0.00085	0.0001	0	0	0.00005	0.00190	0.00680	0.01174	0.02010	0.03043	0.04160	0.1225
0.6	0.01780	0.01000	0.0052	0	0	0	0.00460	0.01300	0.02390	0.03480	0.04530	0.05580	0.2104
0.8	0.01900	0.00870	0	0	0	0	0.00920	0.01780	0.02520	0.03300	0.04100	0.06328	0.2172
1.0	0.01500	0.00780	0	0	0	0	0.00430	0.01090	0.02000	0.02650	0.03730	0.04748	0.1693
1.2	0.01090	0	0	0	0	0	0	0.00742	0.01419	0.02240	0.02930	0.02725	0.1115
1.4	0.00528	0	0	0	0	0	0	0.00246	0.00822	0.01177	0.01568	0.02298	0.0664
1.6	0	0	0	0	0	0	0	0.00150	0.00350	0.00610	0.00958	0.01674	0.0374
1.8	0	0	0	0	0	0	0	0.00100	0.00150	0.00387	0.00670	0.00750	0.0206
2.0	0	0	0	0	0	0	0	0.00100	0.00150	0.00174	0.00200	0.00501	0.0113
2.2	0	0	0	0	0	0	0	0	0.00015	0.00165	0.00150	0.00261	0.0059
2.4	0	0	0	0	0	0	0	0	0.00010	0.00056	0.00130	0.00150	0.0035
2.6	0	0	0	0	0	0	0	0	0.00010	0.00035	0.00071	0.00080	0.0020
2.8	0.00001	0	0	0	0	0	0	0.000032	0.00007	0.00015	0.00032	0.00053	0.0011
3.0	0.00005	0	0	0	0	0	0	0.000092	0.00017	0.00029	0.00045	0.00052	0.0016
Total	0.06942	0.01349	0.00415	0.0029	0.00265	0.00235	0.00615	0.03274	0.04522	0.04478	0.16616	0.60745	0.9999

Table A.3. Ship specification of bulk carrier 65 000 DWT

Items	Data input
Overall length (*loa*)	274 m
Beam (*b*)	32 m
Fully loaded draft (T)	13 m
Block coefficient (C_B)	0.8142
Wetted surface hull	3487 m^2

Note: The ship squat has also been taken into account to reduce the underkeel clearance. The empirical expression, proposed by Barrass II in PIANC [1], has been used as follows:

$$S_{\max} = \frac{C_{\mathrm{B}} S_2^{2/3} V^{2.08}}{30}$$

where C_{B} is the block coefficient; V is the ship speed (knots); and S_2 is the blockage factor defined as a ratio of midship section area to wetted cross-section area of waterway.

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