

MODELING RISK AND SIMULATION-BASED OPTIMIZATION OF CHANNEL DEPTHS AT CAM PHA COAL PORT

N.M. Quy; J.K. Vrijling; P.H.A.J.M. Gelder; R. Groenveld
Delft University of Technology

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 simulation-based method and a risk model of ship grounding for a long-term optimization of channel depths. The long-term optimization of channel depths should be considered a two-stage process: Firstly, establishing a ship entrance guidance to facilitate a required navigation safety with respect to an acceptable risk of ship grounding due to wave impacts. As basis for such guidance, ship motion responses are defined as a function of the sea state (described by significant wave height H_s and wave period T_2) and the transit condition (ship speed V and ship draft T). Secondly, using the Monte Carlo method and based on the established accessibility policy, a simulation model is developed to define a safe underkeel clearance allowance for ship entrance and simultaneously determine downtimes that correspond to an acceptable grounding risk for a specified ship and a generated sea state. The final results derived from the simulation model can be considered as the key parameters in analysis and selection of an optimal depth. The approach was applied to the entrance channel of Cam Pha Coal Port, Vietnam as a case study.

KEY WORDS

Ship grounding, risk modeling, simulation, and entrance channel.

1. Introduction

Simulation-based optimization technique is frequently used for many applications into the research of different systems such as urban, economic, transportation and so on. In the maritime field, simulation models have been used for port operations and ship traffic flow. Most of the existing traffic simulations place emphasis on the study of traffic rules and entrance regime on port capacity with very little attention on safety aspect of a particular transit [1]. 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 increased. 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 basis for a trade-off between cost and benefit. The optimization of channel depths therefore aims at determining 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 and practical [2]. A simple general guideline for minimum depth clearance requirements in channels influenced by waves are given by PIANC [1]. It is defined by ratios of water depth to ship draft, which should be 1.3 when H_s 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 unfavourable. This guideline gives rather unrealistically deep depth under moderate wave actions. Whereas U.S. Army Corps of Engineers [3] states that "net depth allowance for waves is $1.2H_s$ for deep-draft and $0.5H_s$ for shallow-draft channels". It should be noted that the wave period contributes a significant effect on ship motion. Hence, an adequate guidance for ship accessibility, so called "entrance policy", should consider wave conditions (both H_s and wave period, T_2) in association with transit conditions (sailing speed and minimum underkeel clearance) for the navigation safety.

So the objectives of this paper aim at (1) Establishing an entrance policy that pilots can use with sufficient confidence to decide the transit conditions before leaving the port; (2) Optimizing channel depths in the long-term considering an acceptable probability of the ship grounding on the basis of the established entrance policy. However, the study is confined to one failure mechanism, which is the event of ships touching the channel bottom induced by waves and being viewed as grounding.

2. Methodology

The optimization of channel depths should be considered a two-stage process, as generally described in Figure 1, consisting of: Firstly, establishing ship entrance guidance to facilitate a required navigation safety with respect to a possibility of touching the channel bed as discussed previously. To do that, 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 police for safe navigation.

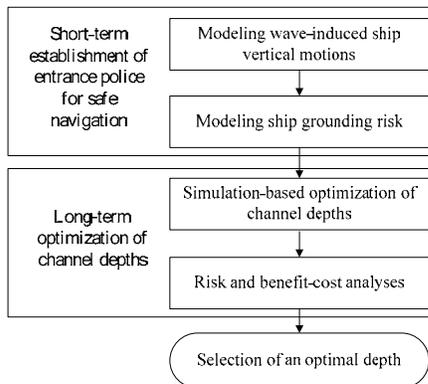


Figure 1: General Procedure for Optimization of Channel Depths

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, a stochastic model of the environmental conditions and ship arrivals has to be set up on the basis of historical records or forecasted data. The advance 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. The aforementioned approach was applied to Cam Pha Coal Port in Viet Nam and described in detail in the following.

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 in fully loaded state beyond the present capacity of the entrance channel of the port. Therefore, in 2001, Viet Nam Coal

Incorporation initiated an expansion project of the port [4] in which the entrance channel will be enlarged to allow the ships of up to 65,000DWT (fully loaded) using a tide up for leaving the port. But till now, the rehabilitation of the channel has not yet been commenced. The main reason of this delay is that a part of the channel with the length of 12 km is very shallow (only -10 m from the sea datum), this results in very high costs in dredging work. Hence, economic and environmental pressures have revealed the need to minimize the dredging when determining the depth of the entrance channel. Establishment of an appropriate and reliable policy for the ship entry also gives an opportunity to reduce the dredging depth requirement. This study, as a part of the mentioned project, deals with the rehabilitation of the entrance channel.

3.2 Present Operational Procedure

Since the port is solely 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.

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 next 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 wait 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 get a topping up of coal from a fleet of 500 DWT barges. The additional cost for this floating loading operation is 20 USD/ton in comparison with loading at the quay.

3.3 Deterministic Method of Existing Admittance

So far 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 guideline. 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 for should be 25 per cent of the maximum draft for a 65,000DWT bulk carrier using the outer area of this channel exposed to the open

sea, and 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. Simulation-Based Optimization

4.1 Probabilistic Method of Admittance Policy

The developed simulation model, which in this paper is based on a probabilistic approach, 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 probabilistic method is a determination of the chance 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.

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. The response spectrum is, however, only obtainable for a particular transit condition and a specified sea state. While 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 to be requested. Moreover, these two approaches cannot account for uncertainty present in these parameters in calculating the response spectrum, and later applying to performance of risk analysis. Hence, a demand is emerging for a high resolution and continuous description of the response spectrum for the problem [5-8]. In this paper, the parametric model [9] of the ship motion response developed in the latest paper [8] has been adopted.

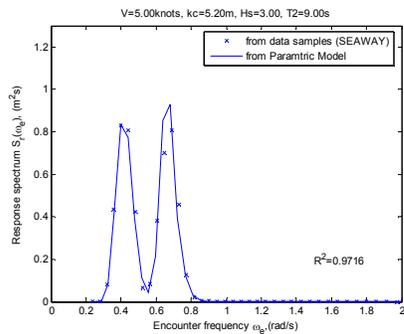


Figure 2: Comparison Between Theoretical Ship Response Calculations (SEAWAY) and Results From Parametric Model

For example, the response spectral estimations based on this model are compared very well to those obtained from the numerical ship motion model [10]. The average fit

coefficient is 0.991 and the smallest fit is 0.9716, as shown in Figure 2, for this case study.

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 $X(t)$ cross a level $x=\beta$ (m) at once during a period T_o (s). It is frequently used for estimating the chance of 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 [11]. Under this assumption the probability of the first-passage failure, $P(\beta, T_o)$, of a response $X(t)$ when is a stationary can be estimated by

$$P(\beta, T_o) = 1 - \exp(-v_\beta T_o) \quad (1)$$

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

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

where m_0 and m_2 represent zero and second moments of the response, respectively, which can be determined by the following equations

$$m_0 = \int_0^\infty S_r(\omega_e) d\omega_e \quad (3)$$

$$m_2 = \int_0^\infty \omega_e^2 S_r(\omega_e) d\omega_e \quad (4)$$

here $S_r(\omega_e)$ is the response spectrum as defined 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 . So let $P(\beta, T_o) = \alpha$, from Eqs (1) and (2), crossing level for probability of first-passage failure = α can be expressed by [12]

$$\beta = \sqrt{m_0} \sqrt{-2 \ln \left\{ \frac{\ln(1-\alpha)}{\frac{T_o^2}{2\pi} \sqrt{\frac{m_2}{m_0}}} \right\}} \quad (5)$$

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

4.2 Simulation Model

The present simulation model, as outlined in Figure 3, consists of several procedures. First, the data of ships 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 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 as follows.

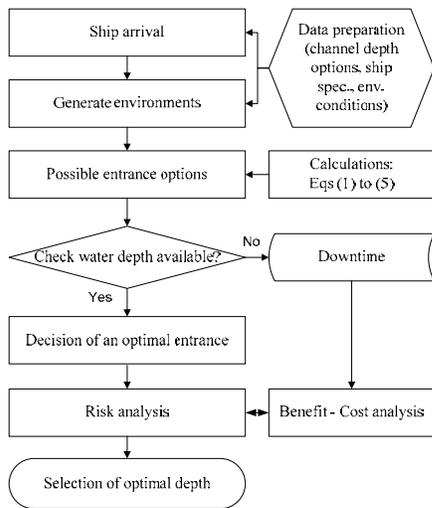


Figure 3: Calculation Procedure of the Simulation Model

Departure Pattern of the Ship

The model assumes that the ship departure follows an exponential distribution function which has the following form

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

Where μ is the arrival rate; and t is the time of ship departure. The simulation starts by generating a date and a time of the first ship after having permission for loading. 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, of course, have to be available in advance for definition of ship motion response. The ship speed is considered to be constant over the complete passage. Specifications of the design ship are presented in Appendix.

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 meteorology. 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 [13]. In this case study, a Gaussian distribution function of the predicted error, with parameters mean value is 22.3 mm and standard deviation is 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; and it can also be changed dynamically in the model during the ship transit along the channel.

Wave Generation

Two parameters, H_s and T_2 , of Pierson-Moskowitz spectrum has been proposed to calculate the ship motions. The frequencies of wave height in all directions can be fitted to a certain distribution function. One may first generate stochastically a value of the wave height and the wave period according to predefined distribution functions. Then, a uniform random number can be generated to obtain the desired direction by using the inverse transformation method [14].

Calculation Program

The core of this simulation model is a calculation program. Attention is paid to a successful approach [15], on which the calculation program described in this section is based. The program consists of calculation steps as follows:

- (1). Determination of the depth: based on a generated departure time and a selected ship speed, an instantaneous water depth at the ship position is calculated, 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 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, three speed values are selected to formulate a database of the navigation (T , d and V_j). The empirical expression, proposed by Barrass II [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_2 , Pierson-Moskowitz spectrum density will be calculated. The motion characteristics of the ship response can then be defined using the parametric model as developed in [8]. This allows the computation of the amplitude characteristics of the vertical motion of the critical point on the ship hull.

(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.

4.3 Results

Till now, due to the limited channel depth, only a small number of ships of 65,000 DWT or larger have called the port. However, it is expected that this number will increase after the channel is deepened. So the objective of this simulation is 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 with 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 out. So the throughput is equally for all alternatives of the design depths and sailing speeds; and this throughput is dependent on 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.

Simulation Scenarios

The study established five options of channel bed levels and three scales of the sailing speed (slow, moderate and normal speeds) with five options of the expected number of ship arrivals, as presented in Table 1.

Table 1: Simulation scenarios

Items	Data input
1. Simulation time, T_{sim}	360x24 (hours)
2. Ship characteristics	
- The expected number of ship arrival per year, n	10, 20, 30, 40 & 50 (5 options)
- Distribution of departure time	Exponential
- Average departure time, $1/\mu$	$=T_{sim}/n$ (hours)
- Ship speed	5, 7.5 & 10 (3 opts.)
- Ship specification	See Appendix
3. Channel characteristics	
- Channel length	12,000 (m)
- Channel depth level	
Option 1 (existing)	-10 (m)
Other options	-11, -12, -13 & -14
4. Cost parameters	
- Waiting cost	25 (US\$/hour)
- Dredging cost	3.5 (US\$/m ³)
- Extra loading cost at the floating point (a difference with the loading cost at the quay)	20 (US\$/ton)

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 to satisfy the condition that the probability of bottom touch does not exceed an imposed value. Therefore, an acceptable probability of ship

grounding should be compared with those from worldwide databases. PIANC reported a grounding probability for Northern European ports of 3 per 100,000 (i.e. 3×10^{-5}) ship movements. Statistics in the literature [16] provides 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 the bottom touch only, the risk acceptance $\alpha = 3 \times 10^{-5}$ as observed in Northern European ports might be reasonable.

The Number of Simulation Runs per Scenario

The simulation execution method selected for the model is the replication method [17]. 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 of course much more time of work.

Figure 4 demonstrates the variations in the downtime according to the number of repetitions. The first ten replications is the initial transient period. The results seem to be dispersion and sensitivity. After this period, the variations in the downtime become less and seem to be constant for the number of fifty repetitions. It is therefore recommended that fifty repetitions should be made for each scenario.

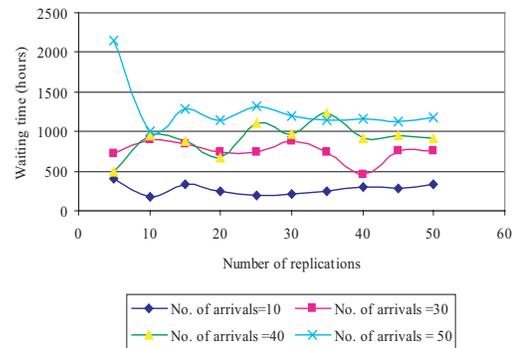


Figure 4: Effect of the Number of Replications on Waiting Times

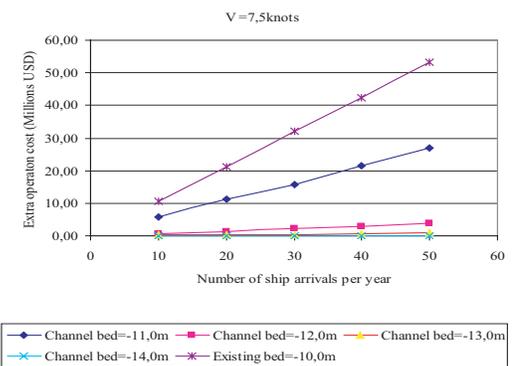


Figure 5: The Linear Relationship between Extra Operation Cost and Number of Ship Arrivals for Different Channel Bed Levels

Figure 5 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 of the channel depth. Moreover, they are much reduced and even approached to zero in the cases of the channel bed deeper -12.0 m. It can be seen in those figures that extra operation costs and waiting times seem as 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 case of larger numbers of ship arrivals considered in the future study.

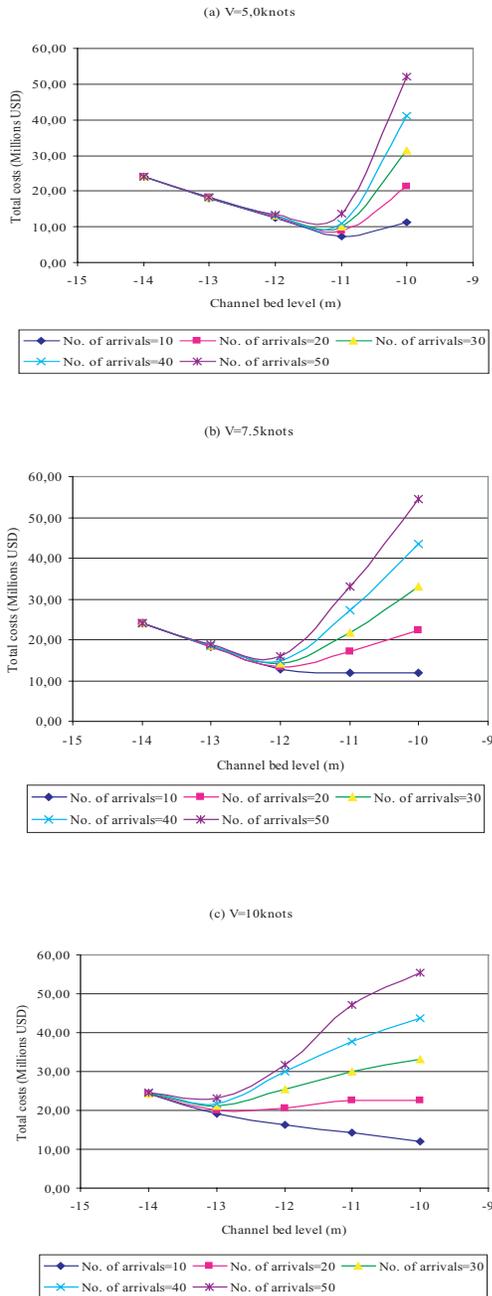


Figure 6: Total Costs vs. Bed Levels for Various Speeds and No. of Arrivals

The total cost, defined as a sum of the extra operation cost and dredging cost, is expressed in terms of the number of ship arrivals, channel bed levels for alternative sailing speeds, as shown in Figure 6. It is very interesting to observe that there was 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 6a). But this differed from the two other cases of ship speeds where the minimum total costs were found at the channel bed of -10 m (existing condition) for the number of arrivals was less than 10; and when the number of arrivals exceeds 10, the minimum total cost was moving to the channel bed of -12 m and -13 m with the ship speeds of 7.5 knots and 10 knots, respectively (see Figures 6b and 6c).

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 7. It can be seen that the effect of ship speeds on the costs 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 hereto, in cases of sailing speed exceeding 7.5 knots, the total costs are increases quickly and the effect of the number of arrivals on the total costs becomes larger with the incensement of sailing speeds. This can be explained that the reduction of underkeel clearance due to the squat becomes significantly 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 word, the fewer water levels are available during the channel service period. Subsequently, waiting time and extra operation costs are increased.

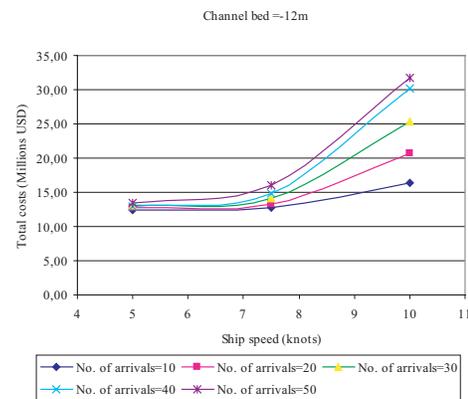


Figure 7: Relationship between Total Costs and Ship Speeds for Various Numbers of Ship Arrivals

5. Conclusion

This paper has demonstrated the application of an appropriate simulation model for investigation of the channel performance in the 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 generally developed and applied to all kinds of ship and entrance channel. A key component of this model is the application of 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. 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 grounding model in a single random ship departure.

Based on the simulation results is gained the confidence to conclude that the ship is navigated at a speed of 7.5 knots with the channel bed of -12 m will result in the best alternative when the number of ship arrivals is more than ten. It was observed that the operation cost will be reduced quickly if the channel bed is deeper -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. However, 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 altogether.

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.

References

[1] PIANC, *Approach channels - A guide for design*, in *Supplement to Bulletin no 95* (International Association of Ports and Harbors, 1997).
 [2]. Zeki Demirebilek and F. Sargent, *Deep-Draft Coastal Navigation Entrance Channel Practice*, in *Technical note I-63* (US Army Corp of Engineers: Washington, DC, 1999).
 [3]. USACE, *Hydraulic Design Guidance for Deep-Draft Navigation Projects*, E.M. 1110-2-1613 (U.S. Army Corps of Engineers: Washington, DC, 1998).
 [4]. Quy, N.M., *Feasibility study project of expansion of Cam Pha Coal Port* (Vietnam Coal Incorporation, 2001).

[5]. USACE, *Hydraulic Design Guidance for Deep-Draft Navigation Projects*, E.M. 1110-2-1613 (U.S. Army Corps of Engineers: Washington, DC, 2006).
 [6]. Savenije, R.P.A.C., *Safety criteria for approach channels* (Ministry of Transport, Public Works and Water Management, Transport Research Centre, the Netherlands, 1998).
 [7]. Cramer, E.H. and P.F. Hansen, Stochastic modeling of long term wave induced response of ship structure, *Marine Structure*, 7, 1994, 537-566.
 [8]. Quy, N.M., Vrijling, J.K., Gelder, P., Groenvelde, R., Parametric modeling of ship motion responses for risk-based optimization of entrance channel depths, *Proc. 11th World Conference on Transportation Research*, University of California, Berkeley, USA, 2007.
 [9]. Jones, D.L., *Prony's method* (Connexions Project, 2005). <http://cnx.org/content/m12762/latest>.
 [10]. Journee, J.M.J., *Introduction in ship hydro-mechanics* (Delft University of Technology, the Netherlands, 2002).
 [11]. Lin, Y.K., *Probabilistic theory of structure dynamics* (McGRAW-HILL, Inc., 1967).
 [12]. Quy, N.M., Vrijling, J.K., Gelder, P., Groenvelde, R., On the assessment of ship grounding risk in restricted channels, *Proc. 8th International Conference on Marine Sciences and Technologies* (Festival and Congress Center - Varna, Bulgaria, 2006).
 [13]. S. Lin, Kite Powell, and N.M. Patrikalakis. *Physical risk analysis of ship grounding* (Marine Police Center, Woods Hole Oceanographic Institution, 1998).
 [14]. Wendy, L.M. and R.M. Angel, *Computational statistics Handbook with MATLAB* (Chapman and Hall/CRC, 2002).
 [15]. Vantorre, M. and E. Laforce. Development of a probabilistic admittance policy for the Flemish harbours, *Proc. PIANC 30th International Navigation Congress* (Sydney, Australia, 2002).
 [16]. Briggs, M.J., L.E. Borgman, and E. Bratteland, Probability assessment for deep-draft navigation channel design, *Coastal Engineering Journal*, 48, 2003, 29-50.
 [17]. Demirci, E., Simulation modelling and analysis of a port investment, *SIMULATION*, 79(2), 2003, 94-105.

Appendix

The design ship is a bulk carrier 65.000 DWT with the main representative dimensions as:

overall length (<i>loa</i>):	274.000 m
beam (<i>b</i>):	32.000 m
fully loaded draft (<i>T</i>):	13.000 m
block coefficient (<i>C_B</i>):	0.8142
wetted surface hull:	3487 m ²

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

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

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