RISK AND SIMULATION-BASED OPTIMIZATION OF CHANNEL DEPTHS: A CASE STUDY AT THE ENTRANCE CHANNEL OF CAM PHA COAL PORT

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(November 07, 2007)

Abstract

This paper presents a new simulation model for long-term optimization of channel depths in which the risk of ship grounding due to wave impacts can be considered for every ship transit. This new model includes four main components: (1) an exponential probability law for a 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 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 downtime that correspond to an acceptable grounding risk for a specified ship and a generated environment condition. This new approach makes the simulation model more realistic as met in the real world port activities. So the results achieved from this model are more accurate than those from other methods. 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, AND OPTIMAL DESIGN

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 (PIANC, 1997). 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 (Demirbilek & Frank, 1999). A simple general guideline for minimum depth clearance requirements in channels influenced by waves is given by Permanent International Association Navigation Congress (PIANC, 1997). 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 unfavorable. This guideline gives rather unrealistically deep depth under moderate wave actions. Whereas U.S. Army Corps of Engineers (USACE, 1998) states that "net depth allowance for waves is $1.2H_s$ for deep-draft and $0.5H_s$ for shallow-draft channels". Briggs et al. (2003) 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 system to predict ship dynamic underkeel clearance (DUKC) along ship passage. The predicted results are implemented by using a numerical ship motion model and real time measures of wave climate data in combination with probabilistic computation (Moes et al., 2002). Based on these results, a minimum underkeel clearance allowance can be selected, which indicates a safety level of a particular channel transit. However, the costs for installation and operation of such systems are still prohibitively expensive; Moreover, this system cannot be applicable during design stage.

So the optimization of channel depths in long-term should be considered a two-stage process: (1) establishing an entrance policy that a simulation model can use it 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 the navigation safety; (2) optimizing channel depths in the long-term considering an acceptable probability of the ship grounding on the basis of the established entrance policy.

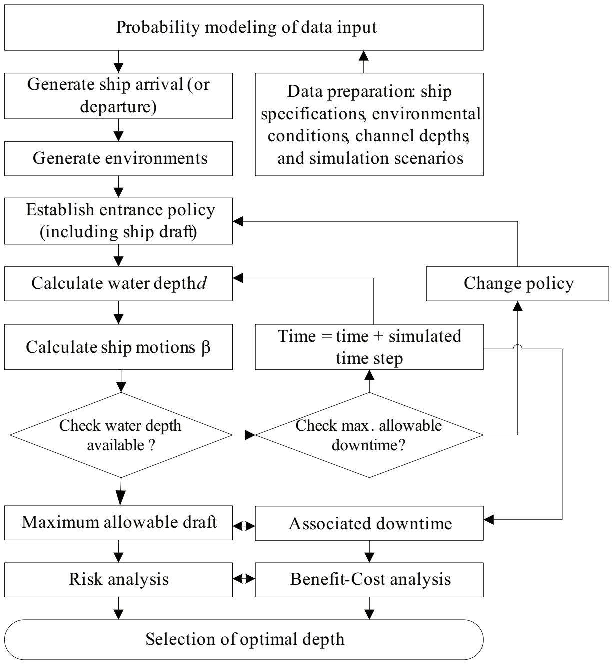

Figure 1: General procedure for the optimization of channel depths.

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. The simulation model structure has been described throughout out the following case study. In general, the optimal procedure is generally described in Figure 1.

2 Project description

Cam Pha Port in the North Sea of Vietnam is the largest specialized port serving export of coal to Europe, Japan and China. The Cam Pha approach channel is about 44.5 km long determined from the sea entrance to the port. The layout of the approach channel is highlighted in Figure 2. Presently, the entrance channel is being used by bulk carrier vessels of up to 40,000 DWT (partly loaded) with a single lane traffic. 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. Therefore, in 2001, Vietnam Coal Incorporation had initiated a feasibility project of the Cam Pha Port expansion (Quy, 2001) in which the entrance channel will be enlarged to allow 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 the outer entrance channel, named "Dong Trang channel", with the length of about 12 km is very shallow (only -10.0 m on average from the sea datum) and some parts of the seabed is hard soil, this results in a very high cost in dredging work. Hence, economic and environmental pressures have revealed the need to minimize the dredging when determining a 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 with the following objectives:

- Establishing an entrance policy by which the pilots can use it with a sufficient confident to decide the transit conditions before leaving the port;
- Optimizing the channel depth in the long-term with regarding to an acceptable probability of the ship grounding on the basis of the established accessibility policy.

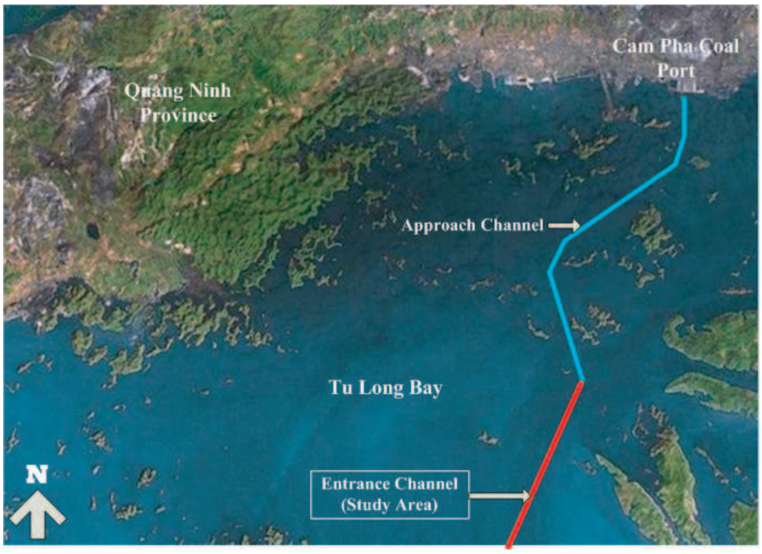

Figure 2: General layout of Cam Pha approach channel and studied area

2.1 Port facilities and location of water areas

The port consists four quays for ship loadings: a newly constructed quay for bulks carrier up to 65,000 DWT, the other side of this quay for coal barges of about 6000 DWT, and two quays for ships 10,000 DWT. There are two coal ship-loaders with capacities of 18,000 and 20,000 ton/hour for ships of more than 10,000 DWT; and two gantry crane loaders for barges and smaller ships.

The turning basin with diameter of 400 m is located in front of these quays. Nearby, one mooring water for ship accommodation before sailing if no possible navigational water level is found. In some circumstances due to a low water season, ship can not be loaded fully at the quay, the remaining amount can continue to be loaded on ship at the floating point, which located in the end of the outer entrance channel.

2.2 Present operational procedure

Since the port is solely for export of coal, all ships arriving the port are empty with a ballast draft. Such ballasted ships can use the channel at mean low water level without delay. 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 a berth availability, loading equipment and other delays, which can be considered in a port simulation model (Geert & Gerrit, 1998). The scheme of ship loading operation procedures is illustrated in Figure 3.

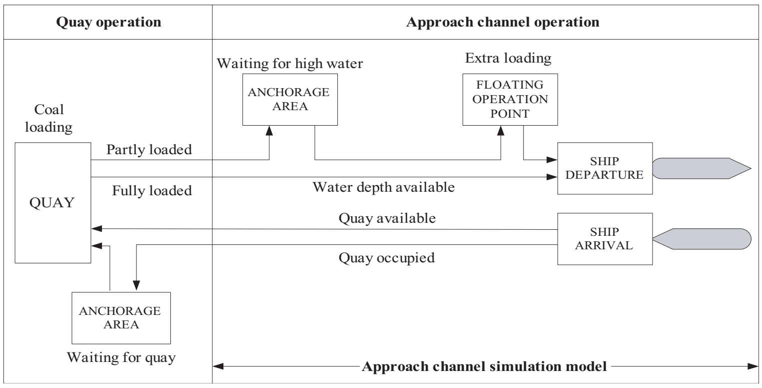

Figure 3: The scheme of ship operation sequence at Cam Pha coal port

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.

2.3 Deterministic method of existing admittance policy

So far a deterministic admittance policy has been used for Cam Pha coal port. The entrance admittance of ships based on a fixed underkeel clearance ratio as recommended by PIANC guideline. The relation 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 a bulk carrier 65,000 DWT using this channel should be 0.25. 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.

3 Risk-Based Model

The new simulation model 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 chance of touching the bottom during a transit. This therefore requires reliable estimation of the ship vertical motion response due to the wave effects.

3.1 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. 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 (Cramer & Hansen, 1994). 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. For this application purpose, a parametric model of the ship motion response has been developed and presented in the following.

For restricted entrance channels and shallow waterways, the wave climate is generally not excessive; and since the ship dimensions are usually large relative to the wave length, ship response problems can be treated with linear models (all directly proportional to wave height) (Journee, 2002). The response spectrum of the ship motion based on the linear model is directly given by the wave spectrum as:

$$S_r\left(\omega_e\right) = \left|H\left(\omega_e\right)\right|^2 S_\eta\left(\omega_e\right) \tag{1}$$

where ω_e is the encounter frequency; $|H(\omega_e)|$ is the encounter frequency transfer function, which depends on ship speed, sailing angle, loading condition and water depth (or underkeel clearance);

$S_\eta(\omega_e)$ is the wave spectrum in encounter frequency. For a given wave direction and a loading condition, Eq. (1) can be rewritten as:

$$S_r\left(\omega_e|H_s,T_z,V,kc\right) = \left|H\left(\omega_e|V,kc\right)\right|^2 S_\eta\left(\omega_e|H_s,T_z\right) \tag{2}$$

The encounter frequency for shallow waters is determined as:

$$\omega_e = \omega - kV\cos(\theta) \tag{3}$$

$$\mu = \frac{\omega^2}{g\tanh(\mu d)} = \frac{\omega^2}{g\tanh\left[\mu(kc+T)\right]} \tag{4}$$

where V (m/s) is the forward speed of ship; kc (m) is the average instantaneous underkeel clearance; d (m) is the water depth; θ (degree) is the angle between wave direction relative to the ship speed vector (θ=0 for waves from astern); T (m) is the ship draft depending on loading condition; ω (rad/s) is the wave frequency; μ is the wave number.

It can be seen from Eq. (2) that if the transfer function can be formulated as a function of the transit conditions (V and kc), the response spectrum of the motion, $S_r(\omega_e)$, can be determined for all possible sea states described by wave spectrum $S_\eta(\omega_e)$.

With the assumption that the wave-ship motion is a linear input-output system, whose transfer function is faithfully modeled by an "all-pole" model as:

$$H\left(z\right) = \frac{b(0)+b(1)z^{-1}+\ldots+b(n)z^{-n}}{1+a(1)z^{-1}+\ldots+a(m)z^{-m}} = \frac{\sum\limits_{k=0}^{n} b(k)z^{-k}}{1+\sum\limits_{k=1}^{m} a(k)z^{-k}} \tag{5}$$

Here, z is the angular frequency vector for which the transfer function $H(z)$ is determined by the (real or complex) numerator and denominator polynomials represented in the vectors b and a, respectively. For known $H(z)$ and z, nonlinear optimization to define $a(k)$ and $b(k)$ is generally realized in the iterative techniques proposed by Prony or Shank, both are available in the Matlab Signal Processing Toolbox (Matlab, 2005). For the problem under discussion, Eq. (5) can be rewritten as:

$$H\left(\omega_e|V,kc\right) = \frac{\sum\limits_{k=0}^{n} b(k|V,kc)\omega_e^{-k}}{1+\sum\limits_{k=1}^{m} a(k|V,kc)\omega_e^{-k}} \tag{6}$$

We assume the form of $a(k)$ and $b(k)$ are nonlinear polynomial functions of V and kc with the p- and q-orders respectively. They can be therefore expressed as:

$$a(k|V,kc) = \sum_{j=1}^{p+1}\left[\sum_{i=1}^{q+1}\alpha_{i,j}V^{q+1-i}\right]kc^{p+1-j}; k = 1 \div m \quad (7)$$

$$b(k|V,kc) = \sum_{j=1}^{p+1}\left[\sum_{i=1}^{q}\beta_{i,j}V^{q+1-i}\right]kc^{p+1-j}; k = 0 \div n \quad (8)$$

The idea given to define the response function is that a parametric modeling technique is applied to find the parameters a and b in the Eq. (6), which corresponds to define the coefficients α and β in the proposed mathematical model given in Eqs. (7) and (8). The estimation of the model parameters is achieved in two steps: the encounter frequencies and response functions considered as the data samples are obtained from either physical model tests or numerical ship motion model for at various values of V_i and kc_j, $(i = 1 \sim M, j = 1 \sim N)$, from which the corresponding parameters $ao(k)$ and $bo(k)$ can be estimated using Prony's algorithm (Jones, 2005). The estimated parameters are then used to define the coefficients α and β by doing a least square fit, which minimizes the sum of the squares of the deviations of the data from the model as:

$$\varepsilon_\alpha = \min_\alpha \sum_{i=1}^{M}\sum_{j=1}^{N}\left[a\left(\alpha|V_i,kc_j\right) - ao\left(V_i,kc_j\right)\right]^2 \quad (9)$$

$$\varepsilon_\beta = \min_\beta \sum_{i=1}^{M}\sum_{j=1}^{N}\left[b\left(\beta|V_i,kc_j\right) - bo\left(V_i,kc_j\right)\right]^2 \quad (10)$$

Thus, the parametric modeling problem for the model given in Eq. (6) is reduced to finding the minimum points of the function ε_α and ε_β in Eqs. (9) and (10), which is called a prediction error method. Minimizing ε_α and ε_β in Eqs. (9) and (10) leads to the error of the response function over the $(N \times M)$ samples is minimized, which is given by:

$$\varepsilon_H\left(\omega_e\right) = \sum_{i=1}^{M}\sum_{j=1}^{N}\left[H\left(\omega_e|V_i,kc_j\right) - H_0\left(\omega_e|V_i,kc_j\right)\right]^2 \quad (11)$$

where H_{oi} is the sample value of the transfer function; and H_i is the regression prediction value; and $\overline{H}_o$ is the mean of the sample values.

One might prefer to use a regression coefficient R^2, as given in Eq. (12), for assessment of the estimated response function, and thus we have to choose p and q that satisfy the condition $R > R_0$ (R_0 is an expected fitting coefficient). Hence, minimizing ε_H in Eq. (11) is equivalent to maximizing R in the following equation:

$$R^2 = 1 - \frac{\sum\left(H_{oi} - H_i\right)^2}{\sum\left(H_{oi} - \overline{H}_o\right)^2} \quad (12)$$

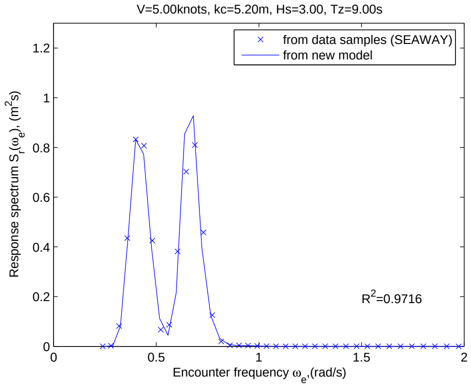

Figure 4: Comparison between the theoretical ship response calculations (SEAWAY) and the results from the parametric model

It was confirmed 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 and provides the results more accurate than those from the regression model (Vrijling, 2004). As an example, the estimated response spectrum from this model are compared very well to those obtained from the numerical ship motion model, named "SEAWAY" (Journee, 2001), as shown in Figure 4. The average fit coefficient is 0.991 and the smallest fit is 0.9716 for this case study.

3.2 Modeling Grounding Risk

Because of randomly nature waves, the resulting ship motions have to be treated as a random process in which the probability of contact with seabed during transit must be maintained at an acceptable minimum level. Probabilistic model is promising tool for calculating the chance of touching bottom. Subsequent to these studies safety criteria can be established in relation to use of the channel.

There are two commonly applied models to assessment of the grounding risk: first-passage failure model and extreme theory-based model.

First-passage failure model

A widely excepted assumption that the wave-induced vertical motion of a ship is a stationary random process and well described by the Gaussian distribution. The first-passage failure is an event that a stationary random process $Z(t)$ cross a level $z = \beta$ (m) at once during a period T_h (sec.). 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 the Poisson process . Under this assumption probability of the first-passage failure, $P(\beta, T_h)$ of a response $Z(t)$ is a stationary can be estimated by (Y. K. Lin, 1967):

$$P(\beta, T_h) = 1 - \exp(-v_\beta T_h) \tag{13}$$

where $P(\beta, T_h)$ is the probability of ship touching the bottom at once during a period T_h (sec.) with the average instantaneous underkeel clearance $kc = \beta$; and v_β is the mean rate of crossing with a level of β, v_β can be then expressed as:

$$v_\beta = \frac{1}{2\pi}\sqrt{\frac{m_{2z}}{m_{oz}}}\exp\left(-\frac{1}{2}\frac{\beta^2}{m_{oz}}\right) \tag{14}$$

where m_{oz} and m_{2z} represent zero and second moments of the vertical motion process, respectively; which can be determined by the following equations:

$$m_{oz} = \int_0^\infty S_r(\omega_e)d\omega_e \tag{15}$$

$$m_{2z} = \int_0^\infty \omega_e^2 S_r(\omega_e)d\omega_e \tag{16}$$

$S_r(\omega_e)$ is the vertical motion spectrum of the ship as defined in the previous section.

In engineering design, it is highly desirable to know a certain level of the underkeel clearance for which a probability of bottom touches 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 $P(\beta, T_h) = \alpha$, from Eqs. (13) and (14), a crossing level for which the probability of ship touching the bottom at once $= \alpha$ can be expressed by (Quy et al., 2006):

$$\beta = \sqrt{m_{0z}}\sqrt{-2\ln\left\{-\frac{\ln(1-\alpha)}{\frac{T_h{}^2}{2\pi}\sqrt{\frac{m_{2z}}{m_{0z}}}}\right\}} \tag{17}$$

Obviously if β is larger the available underkeel clearance, kc, the ship entrance will not be allowed. This condition is one of the most important conditions to establish the ship entrance policy.

Extreme theory

It can be realized in the fact that even with a number of the bottom touches during a transit; the ship can be still underway without grounding. The study (Savenije, 1998) indicated that the possibility that the vessel touches the bottom and penetrates 0.25m does not always resulting in the grounding and the major damage. It is, of course, only true for the soft bottom. The application of extreme value theory in evaluation of penetration is therefore meaningful. The definition of extreme value, $\bar{\eta}$, is shown in Figure 5. It means that for the probability of first-passage failure with a crossing level, β, with a corresponding extreme value, $\bar{\eta}$, a penetrated depth onto the bottom is thus defined by:

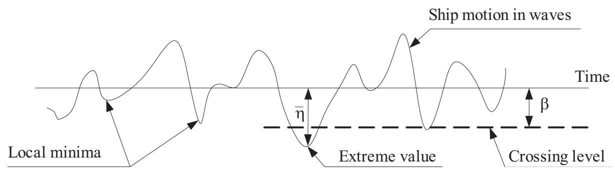

Figure 5: Definition of extreme value $\bar{\eta}$ and crossing level β

$$\Delta = \bar{\eta} - \beta \tag{18}$$

For the problem under discussion, consider $z_1, z_2, , z_n$ are negative minima values taken from a response $Z(t)$ of the vertical motion of a ship during period T_h. The response $Z(t)$ is as well-defined a stationary and Gaussian with zero mean. If the values of the sequence $(z_1, z_2, ..., z_n)$ are rearranged in an increasing order $\eta_1 < \eta_2 < ... < \eta_n$ of magnitude in which $\eta_j = |z_i|$, $i, j = 1 \sim n$. Then the r^{th} member of this new sequence is called "the r^{th} order statistic of the sample". Due to the fact that the maxima is the last order statistic, the following probability density function of maxima distribution is obtained by (Ochi, 1990):

$$g(\eta_n) = n \{F(\eta)\}^{n-1} f(\eta) \tag{19}$$

where $g(\eta_n)$ is the probability density function of the largest value in n observations; $f(\eta_n)$ and $F(\eta_n)$ are respectively probability density and cumulative distribution functions of the maxima in the new sequence.

Now, let $P(\bar{\eta}_n, T_h)$ be probability of the extreme value of n observations of the response process within the period T_h. We wish to obtain the extreme value $\bar{\eta}$ with the probability of being exceeded the value $= \alpha$ Thus, we have:

$$P(\bar{\eta}_n, T_h) = \alpha \tag{20}$$

If α is small and n is large, the solution of Eqs. 19 and 20 yields the value $\bar{\eta}$ as (Ochi, 1990):

$$\bar{\eta} = \sqrt{m_{oz}} \sqrt{2 \ln \left\{ \frac{T_h^2}{2\pi\alpha} \sqrt{\frac{m_{2z}}{m_{oz}}} \right\}} \tag{21}$$

Since the penetrated depth of ship hitting the bottom has been estimated, the grounding risk and ship damage can therefore be quantitatively assessed.

4 Simulation model

The model is a traffic simulation and runs in discrete time. First, stochastic variables of environmental conditions and ship arrivals are generated as the input data of the model. The risk-based model as presented in Eq. (17) is used to determine whether a ship entrance is allowed by comparing a calculated minimum safe underkeel clearance with an available underkeel clearance, kc. The core element is a calculation program that will provide various results of the simulation for the optimal process of channel depths.

The simulation model can be divided into three modules: input data module, a calculation program and an output data module. Some selected important elements have been explained in detail as follows.

4.1 Input data and and generation model

Comprehensive data about the channel environments and design ship should be available. The form of the input data can then be derived. The data are analyzed to find appropriate probability distributions, averages, and other input parameters which are later on used to generate the input for the simulation model.

Arrival pattern of ship at the quay

The model assumes that the ship arrival at the quay follows an exponential distribution function which has the following form:

$$f(t) = 1 - e^{-\lambda t} \tag{22}$$

where λ is the arrival rate. For a given λ a sequence of ship arrival time, t, can be generated as follows:

$$\begin{aligned} i &= rand(1, n) && (23) \\ t_i &= -log(i)/\lambda && (24) \end{aligned}$$

Here n is the number of ship arrivals. The simulation starts by generating a date and a time of the first ship after having permission for loading at the quay. On the basis of the possible maximum tidal window to be found available in the next few days, the model will calculate a value of the ship 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 the ship motion response. The ship speed is considered to be constant over the complete passage. In this study the bulk carrier 65,000 DWT often calls the port being used. Its main dimensions are: overall length (Loa) is 274m; beam (B) is 32m; full loaded draft (T) is 13m.

Table 1: Water level statistics

Items	Level (m)	Recorded time
The highest high water level	+4,67	17/08/1963
The lowest low water level	+0.07	12/01/1968
Mean water level	+2,30	
The mean highest water level ($P_{1\%}$)	+4,22	
The mean lowest water level ($P_{99\%}$)	+0,38	

Tide

Tide in the Cam Pha indicates a K_1 - O_1 regular diurnal component (a tidal period is about 24 hours and a complete tidal cycle of about 13.5 days) with mean sea level of 2.3m. The statistical analysis results of the water levels are shown in Table 1 . Tidal data for the study period have to be available in the model. There are two types of water level, astronomic and meteorology. The predicted astronomical water level for a given period of simulation 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 (S. Lin et al., 1998). A Gaussian distribution function of the predicted error, with parameters mean value is 22.3 mm and standard deviation is 13.2 mm, was found based on the statistical water level data recorded during the past 5 years. By relating to the channel bed profile, the water depth at any time and location of the channel can be calculated.

Local wave climate

The best way to obtain a local wave climate is to conduct measurements for a number of locations along the entrance channel. However, this is very costly work and impossible in the frame of this research. For the purpose of the feasibility study, wave characteristics at the area were studied by Vietnam Marine Hydrometeorologic Center in one part of the technical report on “Regional study of wind and wave characteristics of Vietnam Coasts” (Thuy et al., 1998). It was done by reviewing and analyzing all the existing long-term data of the waves at Bai Tu Long Bay, and by calculating the local wave climate at the area of the entrance channel. The most useful results of the wave analysis provided by Client for this application are:

- The local wave climate conditions were calculated by a numerical model (SWAN) based offshore wave database at the South China Sea obtained from satellite observations.
- The hindcast wave conditions by a computer program of spectral wave hindcast model based on the wind data of the Cam Pha station (two hour intervals for two years 1993 and 1994).

Due to lacking of on-site wave measurements of the wave for validation of the wave transform model, the accuracy and reliability of the wave condition are still questionable. It is strongly recommended that measurements of the wave must be conducted for detail design phase.

Sets of calculated wave condition values are grouped and arranged in such as that given in Table 2 for all wave directions. The number in each cell of this table indicates the chance 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.

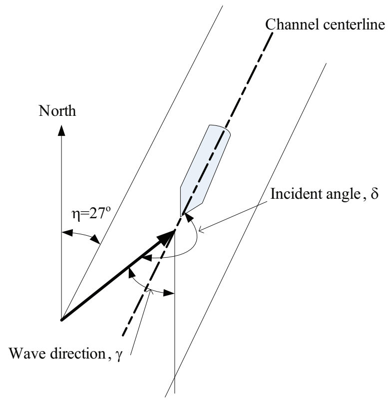

Figure 6: Angle of incidence of the wave relative to the outgoing ship

Since the wave angle used in the simulation is an angle relative to the ship these angles have to be defined for different wave directions. The ship is assumed to sail parallel to the axis of the channel. In reality this is not always the case. However, for determination of the ship motion response, this assumption needs to be made in order not to make the simulation extremely complex. The following wave is defined either 360^o or 0^o and the heading wave is 180^o. Because of the exporting coal port, only coming waves with directions ranging from ESE to WSW for outgoing ships are considered. An incident angle of the waves relative to the outgoing ship described in Figure 6 is determined as: $\delta = 180^o + \gamma - \eta = 153^o + \gamma$. All the concerned incident angles corresponding to the wave directions are determined and given in Table 3.

Two parameters, H_s and T_z, of Pierson-Moskowitz spectrum has been proposed to calculate the ship motions. It was found that the Gamma distribution fits fairly the significant wave heights in all direction classes (last column of Table 2). Based on this distribution we can first generate stochastically a value of significant wave height, H_s. Then a uniform random number can be generated to obtain a desired direction by using the inverse transformation method (Wendy & Angel, 2002). Finally, a wave period, T_z, can be determined using a conditional distribution between two these parameters, H_s and T_z (Memos & Tzanis, 2000). However, in this study, a wave period, T_z, is independently generated because of insufficient data of wave characteristics.

4.2 Calculation program

The core of this simulation model is a calculation program. Attention is paid to a successful approach by Vantorre and Laforce (2002), on which the calculation program described in this

Table 2: Frequency of wave height versus mean zero-crossing wave period for all wave directions

Wave height (m)	Wave period, T_z 0.00-4.99	5.00-5.99	6.00-6.99	7.00-7.99	8.00-8.99	9.00-9.99	10.00-10.99	≥ 11	Total
0.00-0.49	12.25	13.26	8.95	6.58	1.44	0.48			42.96
0.50-0.99	5.32	7.54	6.56	3.65	1.35	1.05			25.47
1.00-1.49	0.85	3.21	4.50	3.89	1.63	1.15	0.04		15.27
1.50-1.99	0.35	1.86	3.21	2.53	1.06	0.82	0.01	0.00	9.84
2.00-2.49	0.02	0.76	1.65	1.27	0.42	0.06	0.01	0.00	4.19
2.50-2.99	0.00	0.35	0.62	0.85	0.30	0.11	0.02	0.01	2.26
3.00-3.49	0.00	0.01	0.04	0.11	0.12	0.06	0.02	0.01	0.37
≥ 3.5	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Total	18.79	26.99	25.53	18.88	6.33	3.73	0.10	0.02	100.37

Table 3: Frequency of wave height versus wave direction and incident angle

Wave height (m)	Wave direction (estimated incident angle relative to outgoing ship) SE 108	SSE 130.5	S 153	SSW 175.5	SW 198	WSW 220.5	W 243	Others	Total
0.00-0.49	2.18	3.20	6.38	10.88	7.02	3.89	2.35	7.06	42.96
0.50-0.99	0.98	1.86	3.88	6.72	4.73	1.78	1.20	4.32	25.47
1.00-1.49	0.52	1.31	2.75	3.80	3.36	1.03	0.15	2.35	15.27
1.50-1.99	0.21	0.47	1.86	2.85	2.19	0.89	0.12	1.25	9.84
2.00-2.49	0.06	0.15	0.75	1.20	0.65	0.45	0.08	0.85	4.19
2.50-2.99	0.00	0.03	0.21	0.75	0.52	0.32	0.08	0.35	2.26
3.00-3.49	0.00	0.00	0.02	0.05	0.04	0.03	0.03	0.20	0.37
≥ 3.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Total	3.89	6.84	15.85	26.25	18.51	8.39	4.01	16.39	100.13

section is based. General calculation procedure of of the simulation is illustrated in Figure 7. The program consists of calculation steps as follows:

Determination of the depth: based on a generated time of the ship arrival at the quay for loading, the model will calculate the time of loading fully on the ship and determine available water depths along the channel, taking account of the local bottom depth and the tidal data. For a selected sailing speed, a maximum tidal window available in next few days will be defined. The whole passage should be divided into sub-passages by which the variations of tide and bottom profile in each segment can be neglected and the water depth can be 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.

Estimation of squat: when ship draft and water depth in each sub-passage are available, a database of the navigation (T, d and V) is formulated. The empirical expression, proposed by

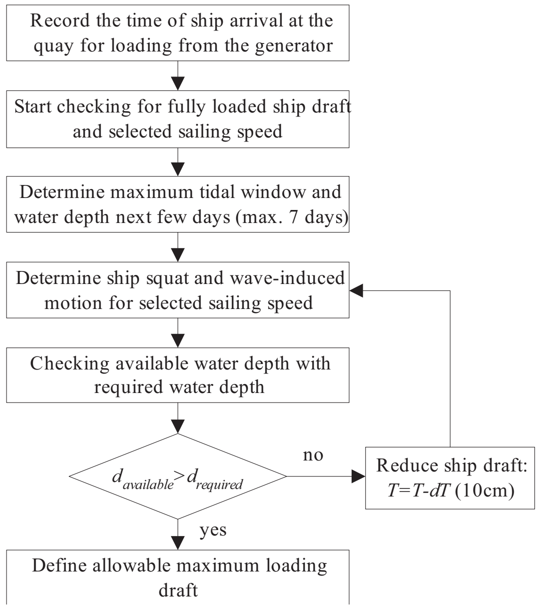

Figure 7: Procedure for determination of a maximum loaded draft

Barrass II (PIANC, 1997), has been used to estimate the ship squat of the critical point on the ship hull.

Calculation of the motion characteristics: for each sub-passage and generated wave parameters H_s and T_z, Pierson-Moskowitz spectrum density will be calculated. The motion characteristics of the ship response can therefore be defined using the developed parametric model. The calculation focused on the hull motion at stern; because the risk of touching the bottom is most critical for this part of the ship. The reason for this is the export function of the port where the outbound ships-loaded to full draft faces incoming waves (Quy et al., 2006). This allows computation of the amplitude characteristics of the vertical motion of the critical point as presented in Eqs. 13 and 14.

Calculation of a minimum safe underkeel clearance in each sub-passage: a value β_i, as defined in Eq 17, can be determined which is considered as "a minimum safe underkeel clearance" for ship entrance in sub-passage i. I should be noted that $P(\beta, T_h)$ is the probability of ship grounding estimated for the channel as whole, which is obviously different from one determined for each sub-passage. If the channel consists of n_s segments (sub-passages), $P(\beta, T_h)$ defined in Eq. 13 can be rewritten as:

$$P\left(\beta, T_h\right) = 1 - \exp\left\{-\int_0^{T_h} v_\beta(t)\mathrm{d}t\right\} \approx 1 - \exp\left\{-\sum_{i=1}^{n_s} v_\beta(i)\Delta t(i)\right\} \tag{25}$$

here $\Delta t(i)$ is the duration that a ship passes through sub-passage i; $v_\beta(i)$ is the mean rate of crossing with a level of β_i as defined in Eq. 14 for sub-passage i.

Now let P_i be the probability of ship grounding in sub-passage i. Suppose all sub-passages are independent each other. The probability of ship grounding for the channel as whole with an acceptable risk of α can be defined as:

$$P(\beta, T_h) = 1 - \prod_{i=1}^{n_s} (1 - P_i) = \alpha \tag{26}$$

Let P_i be equally for all sub-passages, from Eqs. 25 and 26, a minimum safe underkeel clearance in sub-passage i can be expressed as:

$$\beta_i = \sqrt{m_{oz,i}} \sqrt{-2 \ln \left\{ - \frac{\ln\left(\sqrt[n_s]{1-\alpha}\right)}{\frac{\Delta t(i)}{2\pi} \sqrt{\frac{m_{2z,i}}{m_{oz,i}}}} \right\}} \tag{27}$$

This value will be compared to an available underkeel clearance, kc_i, with the condition that $kc_i > \beta_i$. 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 Simulation output

The simulation output contains the following:

- The ship waiting time for each transit and the total waiting time for the period of simulation;
- The average number of times that ships have to be loaded at floating berths (when there is no available water depth for ships loaded fully at the quay);
- The average amount of coal has to be loaded at floating berths. If price units of the above items are available, all will be converted to money; and
- Channel utilization ratio which is defined by as the ratio of the time that ships occupy the channel to the period of simulation.

4.4 Model verification and validation

For purposes of verification, the data of wave and tide were generated from the generation models as formulated above; then the statistics for wave heights and tidal levels were calculated. Finally, probability density functions of the generated data were determined and compared with those from the observation. Goodness of fit tests was found to verify that the found fitted parameters fit reasonably with the generated data, as an example shown in Figure 8 the wave performed.

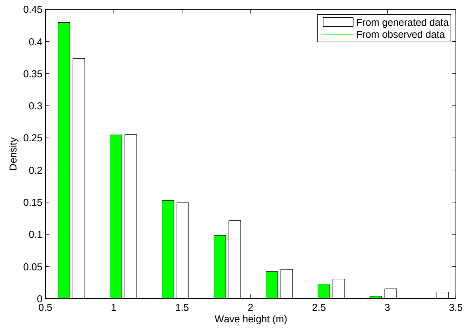

Figure 8: Comparison between the generated and observed wave frequency

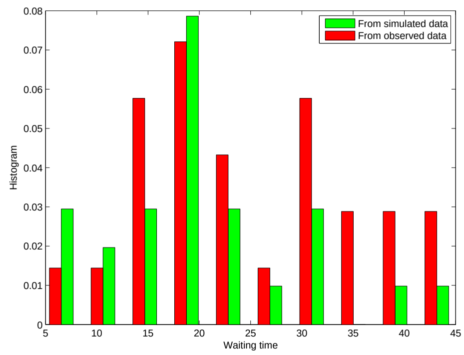

Figure 9: Histogram comparison of waiting times between the observed and simulated data

For purposes of validation of the simulation model, the historical data of waiting times for fifty of the ship arrivals during the past were gathered. It means that the simulation experiment should be conducted for the existing condition of the port. Figure 9 compares the histograms of waiting times taken from the simulated data, with the number of runs is 50, and the observed data. We expect that the model would be acceptable, although some differences were appeared from this comparison. The main reason of these differences was evaluated by the authors and a number of experts in the port authority as:

- The observed data were too limited, so the parameters of the statistics have not been approached to the “true” ones;

- The quality of the observed data of the downtime is considered low;

- The wave data acquired for this study may not reflect properly actual wave climate at the location.

Table 4: Simulation scenarios

Items	Unit	Data input	Remark
1. Simulation time, T_{sim}	hours	360x24	
2. Ship characteristics			
The expected number of ships per year, n	No.	10, 20, 30, 40 and 50	four options
Distribution of the departure time	type	exponential	
Average time between departure $1/\lambda$	hours	$=T_{sim}/n$	
Ship specification		see Table 5.1	
Ship speed, V	knots	5.0, 7.5 and 10	three options
3. Channel characteristics			
Channel length	m	12000	
Channel depth level			five options
Option 1(Existing condition)	m	-10	from chart datum
Option 2, 3, 4 and 5	m	-11, -12, -13 and -14	from chart datum
4. Cost parameters			
Waiting cost	USD/hour	25	
Dredging cost	USD/m^3	3.5	
Extra loading cost at the floating berth	USD/ton	20	the cost difference in comparison with loading at the quay

- The simulation model considers waiting times for high tidal level and acceptable weather condition only, while other factors with high uncertainty such as queuing, pilot and documentation delays are sometimes included in the data.

5 Simulation 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, of course, 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.

5.1 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, which amounted to 75 simulation scenarios to be investigated. The input details are presented in Table 4.

5.2 Safety criterion

Risk acceptance, α , is one of the key issues in the design or operation of any approach channel. The risk acceptance is defined for a particular to satisfy the condition that a calculated probability of bottom touch does not exceed this value. 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 (Briggs et al., 2003) 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 = 3×10^{-5} as observed in Northern European ports might be reasonably assigned for this case.

5.3 The number of simulation runs per scenario

The simulation execution method selected for the model is the replication method (Emrullah, 2003). This method requires a certain number of 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.

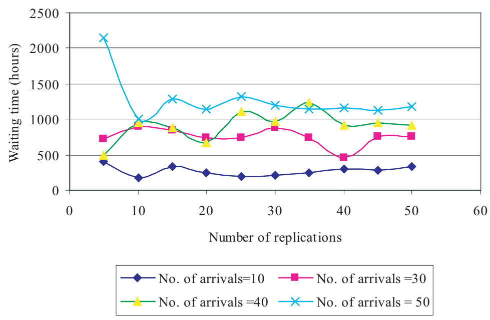

Figure 10: Effect of the number of replications on average waiting times

Figure 10 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 dispersion and sensitivity. After this period, the variations in the downtime become less and seem to be constant for the number of fifty repetitions. This means that fifty repetitions should therefore be made for each scenario.

5.4 Results

Based on the above data of environmental conditions and the established scenarios, various simulation results have been achieved.

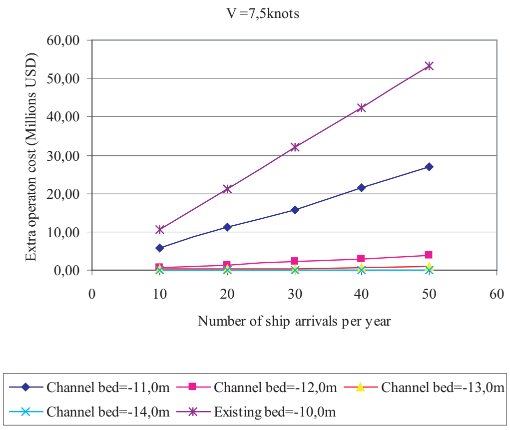

Figure 11: A linear relationship between operation costs and No. of ship arrivals for different channel bed levels

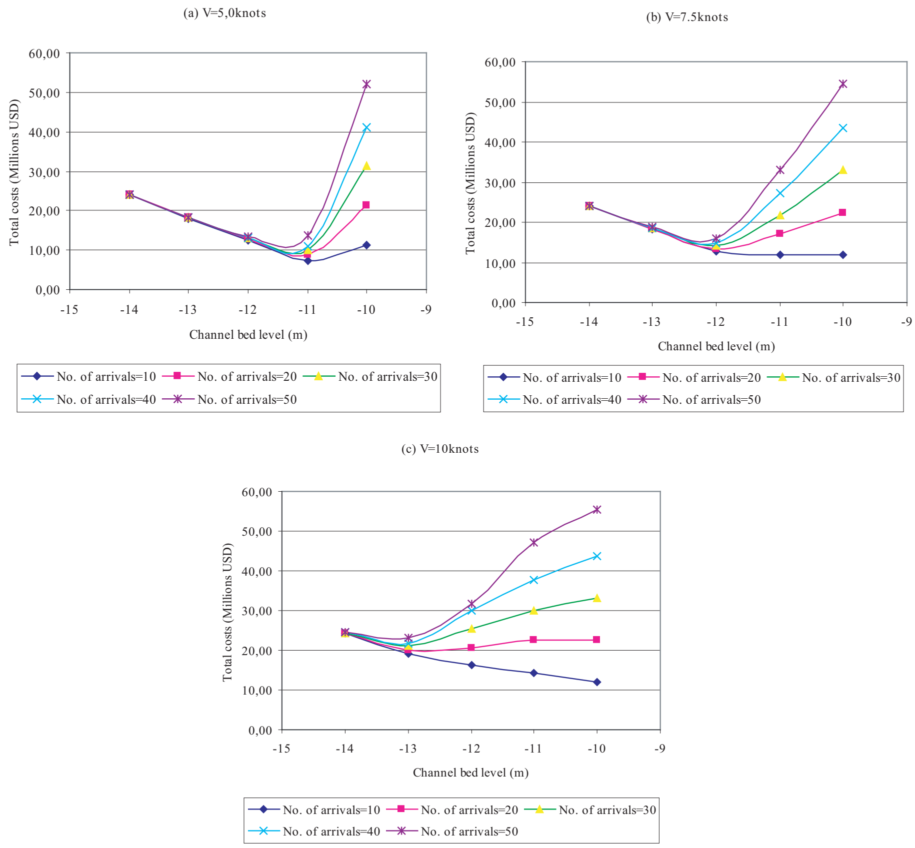

Figure 12: Total costs vs. bed levels for various ship speeds and No. of ship arrivals

Figure 11 shows the relationship between extra operation costs, which consist of 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 (i.e. lower bed level). However, they are much reduced and even approached to zero in the cases of the channel bed deeper than -12.0 m. It can be seen in this figure 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.

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 and channel bed levels for alternative sailing speeds, as shown in Figure 12. 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 12*a*). 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 12*b* and 12*c*).

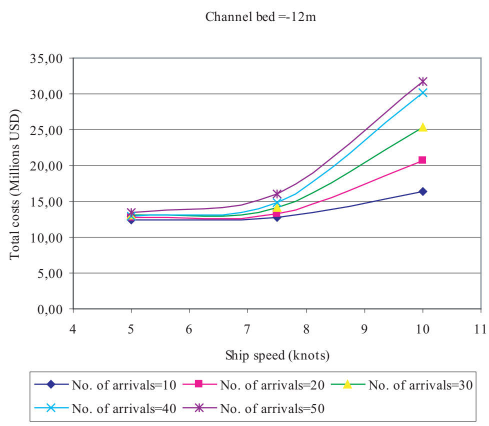

Figure 13: Relationship between total costs and ship speeds for various number of arrivals

The 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 13. 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

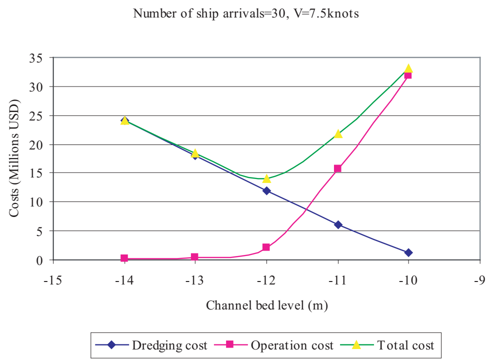

Figure 14: Cost details for the selected design

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.

It was preliminary concluded 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. Figure 14 shows the cost details of this alternative in case the number of ship arrivals is $n = 30$. It is interesting to observe that the operation cost will be increased quickly if the channel bed is shallower than -12 m.

6 Conclusions and Recommendations

This paper has demonstrated the application of a new simulation model for investigation of the channel performance in the Cam Pha coal port. The simulation have 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 (1) establish relationships between the number of ship arrivals and various performance measures; and (2) to determine the effect on these measures under alternative operating and investment policies.

Based on the simulation results, It was found that that the channel bed level of -12 m would be the best choice and a sailing speed of -7.5 knots would be moderately in the point of view of vertical motion.

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 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.

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