On the assessment of ship grounding risk in restricted channels

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Abstract
The paper describes a procedure to assess the risk of ship grounding in restricted channels. The admittance policies (sailing speed and minimum safe underkeel clearance) for safe navigation will be established. First-passage failure and extreme theory of a stationary random process, which is considered as the ship motion response, are investigated. Due to the stochastic variation of the ship speed, V_s, and dynamic underkeel clearance, *KC*, the ship motion response characteristics are predefined and stored in a computer model as functions of V_s and *KC*, which have to cover a broad range of wave conditions. This makes it possible for a "closer" analysis in real time to refine the assessment. A numerical example is given and the procedure is therefore quantitatively described. The procedure can be used not only in the prediction of grounding risk some hours before the ship enters the channel but for the optimal design of channel depths with respect to an acceptable probability of ship grounding.

1 Introduction

Shipping fleets have been steadily increasing both in size and quantity over the last decades; how can these larger ships enter into present ports and maximize the loadings has drawn much attention to both port managers and designers. The technology [1-3] to enable deeper draft or minimize underkeel clearance, in other words, without compromising navigation safety is the most effective and economical. This approach essentially focuses on development of a system to predict ship dynamic underkeel clearance (DUKC) along ship passage. The predicted results are implemented by using a numerical ship motion model in combination with probabilistic computation [2, 4-7]. Based on these results, a minimum underkeel clearance allowance can be selected, which indicates a safety level of the particular channel transit.

The most important assumptions for assessment of the grounding risk in the probabilistic model are that the motions of ship in wave are considered as a stationary Gaussian random process, probability of ship grounding can be estimated by using the Poisson description, which is as a function of the tide, ship response characteristics (mainly depending on wave conditions and ship parameters) and ship speed. However, due to the stochastic variation of ship speed and dynamic underkeel clearance; and since ship response characteristics are also functions of these factors, estimating the risk of ship grounding for DUKC as well as predicting the changes in minimum safe underkeel clearance is still challenging. Furthermore, the assessment should also be refined in association with the ability for a closer analysis in real time during ship passage [1]. None of these studies have fully considered these conditions.

2 Theoretical background

First-passage failure
The first-passage failure is a event that a random process $x(t)$ cross a level $x=\beta$ (m) at once during a period T (sec). It is widely used for estimating the chance of ship touching the bottom, which is considered as the risk of ship grounding.

This method is based on the assumption that successive up-crossing of a specified level are independent and constitute the Poisson process [8]. Under this assumption probability of the first-passage failure, $P(\beta,T)$, of a response $x(t)$ when is a stationary can be estimated by

$$P(\beta,T)=1-\exp(-\nu_\beta T) \quad (1)$$

Where ν_β is the mean rate of crossing with level β, if $x(t)$ has the Gaussian distribution and zero mean, ν_β can be then expressed as

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

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

$$m_o = \int_{-\infty}^{\infty} S_{xx}(\varpi)d\varpi \qquad (3)$$

$$m_2 = \int_{-\infty}^{\infty} \varpi^2 S_{xx}(\varpi)d\varpi \qquad (4)$$

$S_{xx}(\omega)$ is the power spectral density function describes the distribution of the mean-square value of the response $x(t)$ over the frequency domain ω.

In the engineering design, it is highly desirable to know a certain level for which probability of first-passage failure is smaller than an acceptable value α. For example, before ship enters the approach channel we wish to know a specified level of the vertical motion corresponding to an acceptable probability of the ship grounding. So let $P(\beta,T)=\alpha$, from Eqs. (1) and (2), crossing level for probability of first-passage failure = α can be expressed by

$$\beta = \sqrt{m_0}\sqrt{-2\ln\left\{-\frac{\ln(1-\alpha)}{\frac{T60^2}{2\pi}\sqrt{\frac{m_2}{m_0}}}\right\}} \qquad (5)$$

The non-dimension of crossing level, denoted by β_0, is given by $\beta_0 = \beta/\sqrt{m_0}$. Figure 1 shows the non-dimensional crossing level β_0 for T=10 hours computed from Eq. (5) as a function of the first-passage failure α when β and $\sqrt{m_2/m_0}$ are independent each other. As can be seen in this figure that there is no significant difference in the values of β_0 for $\sqrt{m_2/m_0}$ up to 0.7, this is true for β_0 derived as a function of time T as shown in Figure 2 for first-passage failure α=10^{-4}.

It can be realized that β can be seen as average simultaneous underkeel clearance, KC, for which the probability of first-passage failure (grounding) is α. The problem become more complicated since the response characteristics, m_o and m_2, are also a function of KC and ship speed (i.e. time T), which vary along ship passage. This problem will be discussed in later sections.

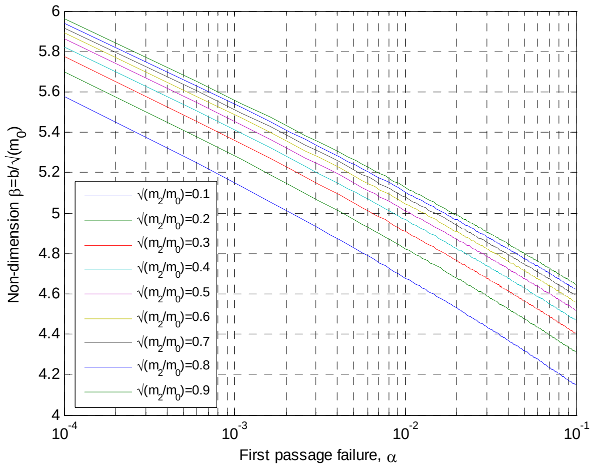

Figure 1: Non-dimensional β vs. α for T=10 hours

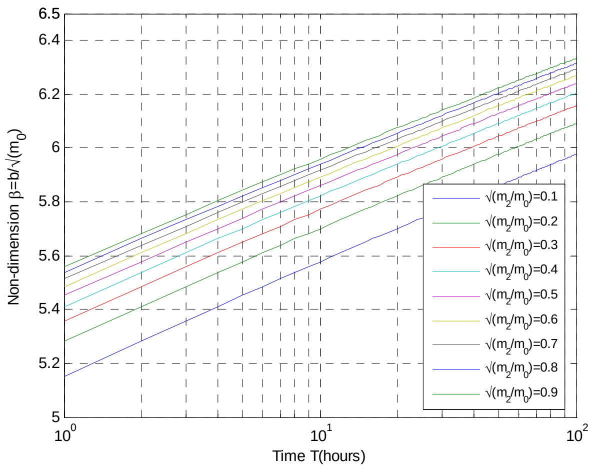

Figure 2: Non-dimensional β vs. T for $\alpha=10^{-4}$

Extreme values

Supposing the first-passage failure is viewed as ship grounding is somewhat pessimistically. 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 [4] 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 theory in evaluation of penetration is therefore meaningful. It means that for the probability of first-passage failure with the crossing level, β, with the corresponding extreme value, $\bar{\eta}$, a penetrated depth onto the bottom is thus defined by

$$\Delta = \overline{\eta} - \beta \quad (6)$$

For the study under discussion, consider $x_1, x_2, \ldots, x_n$ are negative minima values taken from a response $x(t)$ of the vertical motion of a ship during period T. The response $x(t)$ is as well-known a stationary and Gaussian with zero mean. If the values of the sequence $(x_1, x_2, \ldots, x_n)$ are rearranged in an increasing order $\eta_1 < \eta_2 < \ldots < \eta_n$ of magnitude in which $\eta_j = |x_i|$, $i, j = 1 \div n$. 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 [9]

$$g(\eta_n) = n\{F(\eta)\}^{n-1} f(\eta) \quad (7)$$

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, which are well-known that

$$f(\eta) = \frac{2}{1+\sqrt{1-\varepsilon^2}} \left[\begin{array}{l} \dfrac{\varepsilon}{\sqrt{2\pi}} \exp\left\{-\dfrac{\eta^2}{2\varepsilon^2}\right\} + \eta\sqrt{1-\varepsilon^2} \ldots \\ \times \exp\left\{-\dfrac{\eta^2}{2}\right\} \left\{1 - \Phi\left(-\dfrac{\sqrt{1-\varepsilon^2}}{\varepsilon}\eta\right)\right\} \end{array} \right] \quad (8)$$

$$F(\eta) = \frac{2}{1+\sqrt{1-\varepsilon^2}} \left[\begin{array}{l} -\dfrac{1}{2}\left(1-\sqrt{1-\varepsilon^2}\right) + \Phi\left(\dfrac{\eta}{\varepsilon}\right) - \sqrt{1-\varepsilon^2} \ldots \\ \times \exp\left(-\dfrac{\eta^2}{2}\right) \left\{1 - \Phi\left(-\dfrac{\sqrt{1-\varepsilon^2}}{\varepsilon}\eta\right)\right\} \end{array} \right] \quad (9)$$

Where

$$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}}, \text{ and } \Phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{u^2}{2}} du$$

$$m_4 = \int_{-\infty}^{\infty} \varpi^4 S_{xx}(\varpi) d\varpi$$

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

$$\mathrm{P}(\overline{\eta}_n, T) = \alpha \quad (10)$$

if α is small and n is large, the solution of Eqs (7)-(10) yields the value $\overline{\eta}$ as [10]

$$\overline{\eta} = \sqrt{m_0} \sqrt{2 \ln\left\{\frac{T60^2}{2\pi\alpha} \sqrt{\frac{m_2}{m_0}}\right\}} \quad (11)$$

The non-dimension of is defined as $\eta_o = \overline{\eta} / \sqrt{m_0}$. From the Eqs (5) and (11), the difference, Δ, between crossing level of the first passage failure and the corresponding extreme value can be defined as a function of the time period T, the response characteristics m_0 and m_2, and α. Since the penetrated depth of ship hitting the bottom has been determined, the grounding risk and ship damage can therefore be quantitatively assessed. Figure 3 shows the non-dimension of Δ_0-value, defined as $\Delta_0 = \Delta / \sqrt{m_0}$, for T=10 hours as a function of period α for various values $\sqrt{m_2 / m_0}$. As can be seen that there is almost no difference in the values Δ_0 for all values of $\sqrt{m_2 / m_0}$ with small values of α. The values Δ_0 and the differences between these lines increase with increasing of α and $\sqrt{m_2 / m_0}$.

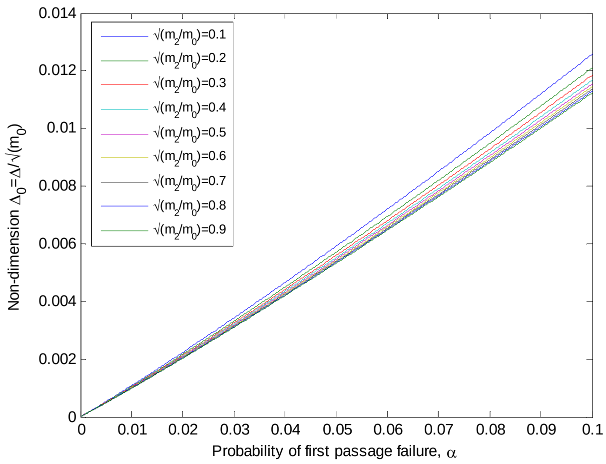

Figure 3: Non-dimensional Δ_0 vs. α for T=10 hours

3 Methodologies

As revealed in the previous section, definitions of the crossing level and extreme value in Eqs. (5) and (11) are no longer valid since the response characteristics m_0 and m_2, are also subject to the period T (i.e. ship speed) and average instantaneous underkeel clearance KC, which can be seen as a crossing level with a specified value α.

A solution to this problem is that response characteristics m_0 and m_2 can be predefined and stored in a computer model as functions of ship speed v_s and KC, which have to cover a broad range of wave condition and ship parameters. In near time ship arrival, the information on environmental condition should be provided and based on that extrapolating this forecast along approach channel.

Partitioning the whole channel into segments by which the variations of tide and bottom profile in each segment can be neglected. The Eq. (1) must be rewritten as

$$P_g = 1 - \exp\left\{ -\int_0^T v_b(t)\mathrm{d}t \right\} \tag{12}$$

$$\int_0^T v_b(t)dt \approx \sum_{i=1}^{n_s} v_b(\Delta t_i)\Delta t_i \tag{13}$$

Where n_s is the number of segments; Δt_i is the duration that a ship passes through segment *i.* Let P_i be the probability of ship grounding in segment *i*, we consider all the segments as members in a series system and suppose they are equally correlated, the probability of ship grounding for the channel as whole can be defined as [11]

$$P_g = 1 - \int_{-\infty}^{\infty} \prod_{i=1}^{n} \Phi\left[\frac{\sigma_i + \sqrt{\rho u}}{\sqrt{1-\rho}} \right] \varphi(u)\mathrm{d}u \tag{14}$$

Where σ_i can be calculated from $\sigma_i = -\Phi^{-1}(P_i)$

Φ and φ denote the standard Gaussian distribution and density functions, and ρ is the correlation coefficient. If the segments are independent each other (ρ =0), Eq (14) converges to

$$P_g = 1 - \prod_{i=1}^{n_s}(1 - P_i) = \alpha \tag{15}$$

Now let P_i be equally for all segments and ρ =0, from Eq (15) we can obtain other form of Eqs (5) and (11) for each segment as

$$\beta_i = \sqrt{m_{0,i}} \sqrt{ -2\ln\left\{ -\frac{\ln\left(\sqrt[n_s]{1-\alpha}\right)}{\frac{\Delta t_i 60^2}{2\pi}\sqrt{\frac{m_{2,i}}{m_{0,i}}}} \right\} } \tag{16}$$

$$\bar{\eta}_i = \sqrt{m_{0,i}} \sqrt{ 2\ln\left\{ \frac{\Delta t_i 60^2}{2\pi\left(1-\sqrt[n_s]{1-\alpha}\right)} \sqrt{\frac{m_{2,i}}{m_{0,i}}} \right\} } \tag{17}$$

From Eqs (16)-(17) and the computer model of the response characteristics, various values of β, $\bar{\eta}$ and Δ can be quickly determined for all possible ship speeds v_s, the underkeel clearances *KC* and a predefined value of α. To maximize the loading, the values of v_s and $KC_{\min}$ can be selected (which are considered as a part of decision support information before ship entry) for which the following condition must hold

$$KC_{\min} - \bar{\eta} \geq 0 \tag{18}$$

During a passage the average instantaneous *KC* and ship speed v_s should be automatically measured and updated in the computer model. For a mariner making decision, these data should be extended some time near future during ship progress and the predicted results should be visually supervised by displaying them on the screen. The prediction process can be illustrated in Figure 4.

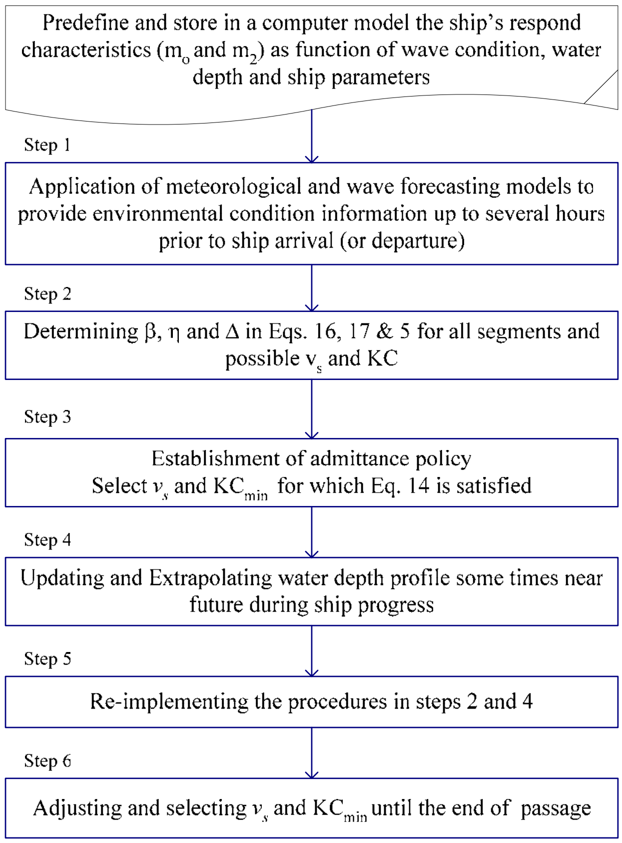

Figure 4: the prediction process with regarding to an acceptable probability of ship grounding

The foregoing procedure is used to study, as an example, the vertical motion of a critical point at stern of the bulk carrier 65.000 DWT sailing under heading wave with significant wave height H_s = 3,8m and wave period T_I=16sec. The spectral density functions of the motion are computed for various forward ship speeds and underkeel clearances (i.e. water depths). On the basis of these results and using nonlinear regression method, the response characteristics are defined as function of v_s and *KC* as

$$m_o = \left(2,9020.10^{-6} KC - 1,2384.10^{-4}\right) v_s^3 + 0,0021 v_s^2 + \left(0,0201 - 9,1538.10^{-04} KC\right) v_s + 0,0550KC + 0,4179 \quad (19)$$

$$m_2 = -\left(3.9093.10^{-7} KC + 7.7445.10^{-5}\right) v_s^3 + 0,002 v_s^2 + 0.0005 v_s + 0.0087KC + 0.0416 \quad (20)$$

The regression coefficients are found as 0.998 and 0.996 respectively. Figure 5 shows the values of m_o are calculated from Eq (19) at various v_s and KC. The points, denoted by symbols, are obtained from the numerical ship motion model [12], which has been validated for very shallow waterway. The values of m_2 can also be quickly obtained from Eq (20).

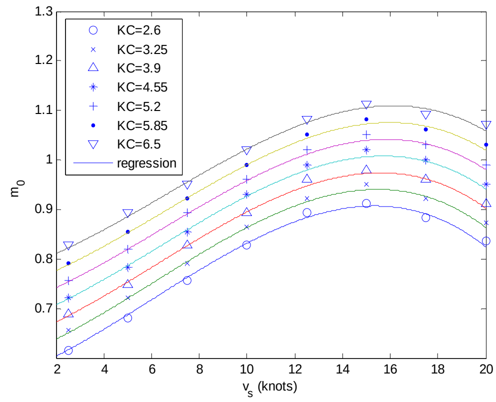

Figure 5: the values of m_0 for various KC and v_s derived from Eq.19

Substituting m_0 and m_2 from Eqs (19) and (20) into Eqs (1) and (2) we can define the probability of touching the bottom as function of v_s and KC as shown in Figure 6.

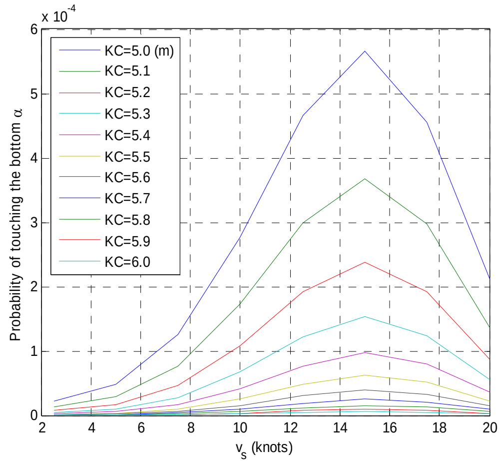

Figure 6: The values of α as a function of KC and v_s for $L_{channel}$=10km

We can obtain some information from this figure for the prediction as well as for mariner making the decision on navigation condition before ship entry as follows:

The ship speed is most critical within the range of 12-18 knots because it results in the highest probability, α, of touching the bottom. The values of α at lower and upper bounds outside this range are quickly dropped with decrease and increase in the ship speed respectively. On the other hand, the values of α increase rapidly with the decrease in the value of KC.

The figure provides several options of KC and v_s to facilitate a predefined value of α. An optimal one with maximum of ship draft (i.e. the maximum loadings or minimum value of KC) adapting a "possible tide window" available at certain time of ship entry can be then defined.

Because ship speed and KC vary along ships passage, the prediction should be refined during ships progress and be provided as soon as possible some time before that moment. For convenient, moreover, the change in average instantaneous underkeel clearance in comparison with crossing level should be visually observed in real time to assure that the condition in Eq. (18) is confidently satisfied.

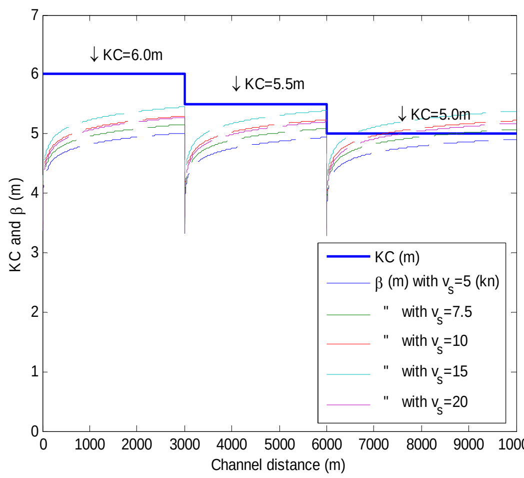

Figure 7: KC and β as function of channel distances with $\alpha=10^{-4}$ for various ship speeds v_s

Extending the condition for foregoing example, it is assumed that using the data on meteorology and topographic measured simultaneously near real time along the channel, the change of KC can therefore be instantaneously forecasted and extrapolated during ship progress as shown in the horizontal lines of Figure 7. In which the whole channel is divided into three segments with the length of 3000m, 3000m and 4000m and KC=6.5m, 5.5m and 5m respectively. Suppose that these segments are uncorrelated the crossing levels can be defined as a function of KC and v_s given in Figure 7 in the dotted lines for $\alpha=10^{-4}$. As can be seen that in the first two segments, the transit will be safe for all the values of ship speed because the estimated crossing levels, β, are under available forecasted underkeel clearances, KC; while the ship speed, v_s, is not allowed to exceed 5,0 knots in the third segment to satisfy the condition in Eq (18). The penetrated depth, Δ, onto the bottom along the third segment as defined in Eq. 6 can also be found.

4 Conclusions

Since the response characteristics, m_0 and m_2, can be defined as a function of ship speed and underkeel clearance, the assessment can be carried out not only real time before ship entry but also continuously refined along the ships passage by taking the data which are measured into consideration.

Ship speed is an important factor; the probability of touching the bottom can be decreased by either speed up or speed down within the specified ranges as indicated in Figure 6. In some circumstances, high speed may be chosen because it is more difficult to maintain ships track in cross current or wind with low speed. It can primarily be concluded that underkeel clearance affects rather greatly possibility of touching the bottom than the response characteristics, m_2 and m_0.

As indicated in the literatures [4, 13] acceptable probability of touching the bottom, α, is very small, the penetrated depth onto the bottom is thus extremely low. This means that for a soft soil foundation bottom, the ship damage due to one touch is insignificantly. It is therefore recommended that acceptable probability of grounding can somewhat be increased.

Stochastic squat of ship due to the sailing speed has not been considered in the paper. For a specified ship, however, the stochastic squat can be estimated in the reduction of the instantaneous underkeel clearance KC by using an empirical formula.

Using a parametric estimate method, the wave parameters can be introduced into the regression equations to enhance the assessment process. However, this work requires much more effort.

The correlation coefficient ρ can not be easily determined for all environmental and transit conditions. Fortunately, the probability of ship grounding is rather insensitive to ρ. The present study has been extended for three last points, as will be reported in a future publication.

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References:

1. Howell, R. *Predicted under keel clearance*. in *PIANC 30th International Navigation Congress*. 2002. Sydney.
2. Moes, J., et al. *Minimum safe underkeel clearance in port entrance channels*. in *PIANC 30th International navigation congress*. 2002. Sydney.
3. O'brien, T. *Experience using dynamic underkeel clearance systems*. in *PIANC 30th International navigational congress*. 2002. Sydney.
4. Savenije, R.P.A.C., *Probabilistic admittance policy deep draught vessels*. 1995: Ministry of Transport, Public Works and Water Management, Transport research Center.
5. Strating, J., T. Schilperoort, and H.G. Blaauw, *Optimization of depths of channels*. 1982: Delft Hydraulics. 24.
6. Vantorre, M. and E. Laforce. *Development of a probabilistic admittance policy for the Flemish harbours*. in *PIANC 30th International Navigation Congress*. 2002. Sydney.
7. Briggs, M.J., L.E. Borgman, and E. Bratteland, *Probability assessment for deep-draft navigation channel design.* Coastal engineering, 2003. **48**: p. 29-50.
8. Lin, Y.K., *Probabilistic theory of structure dynamics*. 1967: McGRAW-HILL, Inc. 366.
9. Vrijling, J.K. and P.H.A.J.M.v. Gelder, *Probabilistic Design*. 2004: Technology University of Delft.
10. Ochi, M.K., *On prediction of extreme values.* journal of ship research, 1973. **2**(1): p. 29.
11. Thoft-Christensen, P. and M. Baker, *Structural Reliability Theory and its Application*. 1982: Berlin Springer.
12. Journee, J.M.J., *User manual of SEAWAY*. 2001: Technology University of Delft.
13. Vrijling, J.K., *Probability of obstruction of the entrance channel*. 1995, Delft university of technology: http://www.hydraulicengineering.tudelft.nl/public/gelder/citatie19.htm.