

N.M. Quay, J.K. Vrijling, P.H.A.J.M van Gelder and R. Groenveld

Delft University of Technology, Delft, the Netherlands.

Q.M.Nguyen@citg.tudelft.nl

J.K.Vrijling@citg.tudelft.nl

P.H.A.J.M.vanGelder@citg.tudelft.nl

R.Groenveld@citg.tudelft.nl

Methods to assess safety criteria of approach channels with respect to the acceptability of ship grounding risks

Abstract

This paper describes a method for assessing the safety of approach channels with respect to an acceptable probability of ship grounding. Available ship simulators are used to generate trajectory data on the ship motions by which necessary probability density distributions of the ship motions are derived as a function of the environmental conditions, ship characteristics and ship speeds. Using the Monte Carlo method, a computer model then determines the probability of ship grounding based on the mentioned distribution functions. The results of the probabilistic calculation are the downtimes that correspond to the assumed acceptable probabilities of grounding in advance. On the basis of these results and an analysis of the consequences of grounding, the final acceptability of ship grounding risks will be defined, which can be considered as the key criterion to assess a level of navigation safety.

1 INTRODUCTION

Navigation safety is one of the key issues in the design or operation of any approach channel. Once channel depth and width have been presupposed, it is necessary to relate them to the probability of accidents ships will encounter. The subject taken up in this paper is ship grounding over the lifetime of the project. Such accidents can be minor or major, depending on the impacts on human lives, the environment, port operations, downtime and economic loss.

In principle, safety criteria are designed and classified according to different levels of risk. The risk, in this context, is expressed by the degree or possibility of chance of touching the bottom and the consequences of this accident. Safety criteria are, therefore, indirectly and partially subject to the probability of ship grounding in the channel. On the other hand, the acceptable chance of touching the bottom of the channel will be strictly limited by the safety criteria. It is apparent from this philosophy that the more accurate the probability of ship grounding, the more practical the safety criteria improved.

Guidelines for an acceptable probability of the ship grounding in the approach channel are still lacking. Some studies were carried out and discussed [5,6,8,9,12], but they are not as comprehensive. This is mainly due to the following reasons: (1) a limited number of conditions can be investigated by simulation. The acceptable probability of the grounding under such conditions then depends very much on the probability of occurrence of the conditions tested. The number of traffic expected specifically of the design ship class becomes another important condition which determines an acceptable probability of the grounding; (2) probabilistic methods in the design or in the safe evaluation of requirements of channel width and channel depth, regarding to ship grounding, have been studied separately. These results in the fact that the actual probability of ship grounding is not yet known; (3) the acceptable probability criteria depend also on the consequences of grounding. Some damage is difficult to practically express in terms of money (loss of human lives, the environmental impacts); (4) rough assumptions of design conditions lead to some errors. Another more precise approach is necessary.

The most important matters concerning the assessment of approach channel safety in term of the grounding are related to: (1) determining the possibility of the ship grounding or collision with surrounding constructions (dikes, bridges, quay-walls); (2) optimization of channel dimensions in terms of cost-benefit analysis; and (3) establishment of the admittance policies which include the introduction of tidal windows adapted to the maneuvering conditions.

This paper relates to and discusses almost all the points listed above. However, only the methodology is described. No final numerical results are yet presented in this phase of the research.

2 THE PROPOSED METHODOLOGY

2.1 Development of a probabilistic model of ship grounding

Ships dynamically maneuver under certain environmental conditions and manual control. For different transits of the ships, they pass along different paths. By superimposing these swept paths into a combined single plot, an area of the ships maneuvering (swept path envelope) will be identified. Based on this area or envelope, a lane for ship maneuvering (or channel width) is defined. In fact, the channel width is mostly decided narrower than

the possible area of ships maneuvering in order to minimize not only the initial dredging investments but also the maintenance costs. However, it is obvious that grounding only happens to a ship when the underkeel of the ship touches the seabed. By combining these two conditions, an event tree of ship grounding can be distinguished into two cases as follows:

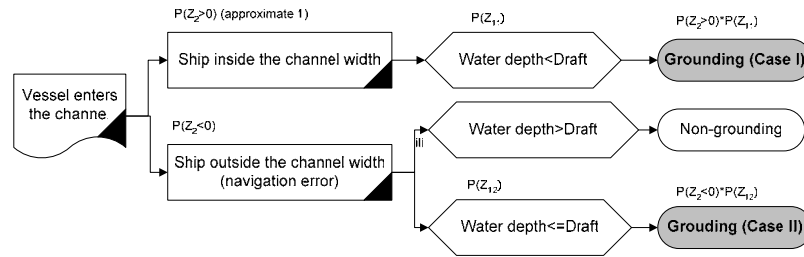


Figure 1: Event tree of ship grounding

Therefore probability that the ship may be grounded, P_g , is determined as:

$$P_g = P[Z_{11} \cup (Z_{12} \cap Z_2)] \text{ or:}$$

$$P_g = P(Z_{11}) + P(Z_2) \cdot P(Z_{12} | Z_2) - P(Z_{11}) \cdot P(Z_2) \cdot P(Z_{12} | Z_2) \quad (1)$$

Where:

$P(Z_{11})$: is the probability of ship grounding inside the channel; $P(Z_{12})$: is the probability of ship grounding during excursion from the borders of the channel; $P(Z_2)$: is the probability of ship excursion from the borders of the channel; $P(Z_{12}|Z_2)$: conditional probability of ship grounding during excursion.

Suppose that Z_{12} , Z_2 are independent events, and the third component of equation (1) is expected as a very small and may be neglected. So P_g in equation (1) is written as:

$$P_g = P(Z_{11}) + P(Z_{12}) \cdot P(Z_2) \quad (2)$$

2.2 Methodologies of Research

This new method has been developed in combination with Monte Carlo simulation and the probabilistic approach. The method consists of four categories. The whole calculation procedure is depicted in Figure 2, which has been discussed in the following sections:

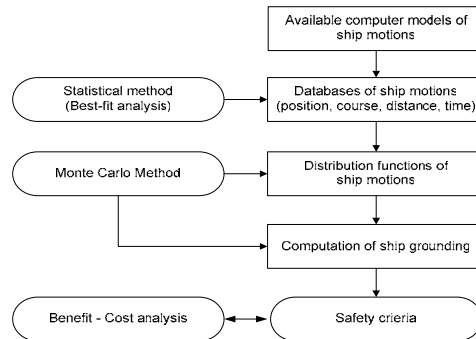


Figure 2: Calculation process of the new method

First, available ship handling computer models are used to generate data of ship trajectories for all possible maneuvering conditions. Real time simulation (RTS) is the most reliable way of building up databases of ship maneuvering (position, distance and

course), because real pilot behavior is incorporated in the simulation. However, the disadvantages of RTS are that it is expensive and time consuming. Therefore, only a few maneuvering conditions are tested. The reliability of these distributions depends very much on the number of maneuvering conditions that are tested. To overcome this limitation of RTS, probabilistic fast time simulation, which is under development by the Dutch institute MARIN, is considered as the best choice so far. The verification tests of the new probabilistic fast time simulation showed reasonable and acceptable results [3]. There are available numerical models such as SEAWAY [2] which can be used to establish databases of vertical motions of a ship. The program is a frequency-domain ship motion PC program, based on both the ordinary and the modified strip theory, to calculate the wave-induced loads and motions with six degrees of freedom of hull ships in a very shallow waterway [11].

Secondly, on the basis of these databases, characteristics of ship motions should be defined as a function of the environmental conditions, ship size and ship speed, including: probability density distributions of cross tracks of the ship as shown in Figure 3, and probability density distributions of off-track distances during ship excursion from the borders, which fitted well with Gamma distribution, as shown in Figure 4. These figures are created based on the data of the study case at the entrance channel of Coega Port, Republic of South Africa. Probabilistic fast time simulations were performed with the use of container vessel 4.500 TEU. Eighteen scenarios of environmental conditions which are grouped into three classes (extreme, normal and gentle conditions) were carried out. For each scenario, 99 runs were executed [3].

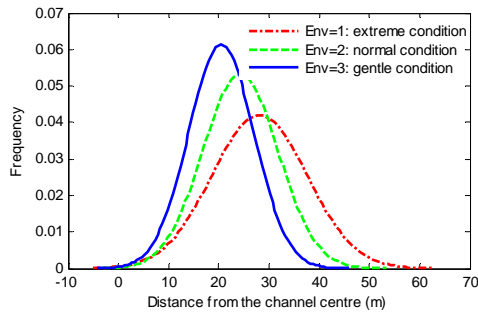


Figure 3: Density functions of distance from the center of the channel fitted with normal distribution for different environmental conditions

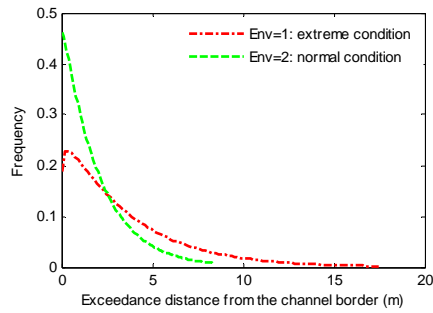


Figure 4: Exceedance (off-track) distances on the starboard side (channel width B=90m) fitted with Gamma distributions

The cross tracks of ship positions can be well described by normal distribution. The probability of ship exceeding from the channel borders can be determined as follows:

$$P(Z_2 < 0) = P(x > B/2) = \int_{B/2}^{\infty} f(x) dx \quad (3)$$

Where: B/2 is half of channel width; f(x) is density function of the ship position.

It can be realized from Figure 4 that probably 100% of the ship tracks are located inside the channel width in the gentle condition. Distributions of the off-track distances are closely related to the length of the tracks that exceed a given channel width during ship excursion. This phenomenon, shown in Figure 5, evidently explains that the further a ship moves away from the center of the channel, the longer the track length which a pilot needs to steer the ship back to a desired line.

The duration of the ship excursion from the channel width can, therefore, be derived as: $t_{DE}=y/V$; where: y is the length of off-track during ship excursion for a certain off-track

distance, which can be estimated by calculating the regression formula in Figure 5; and V is the ship speed. It is interesting to observe that this excursion duration appears to fit well with the Weibull distribution in Figure 6. One can see that the conservative time is not so long, about 80 seconds, and that even the ship goes 10m away from the border.

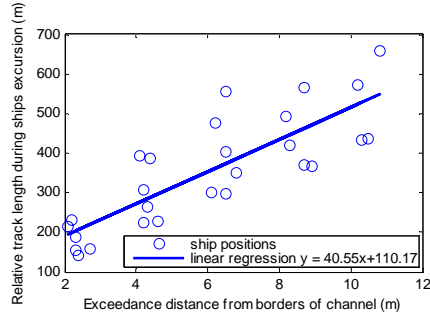


Figure 5: Linear regression between exceedance distances and ship track lengths during excursion

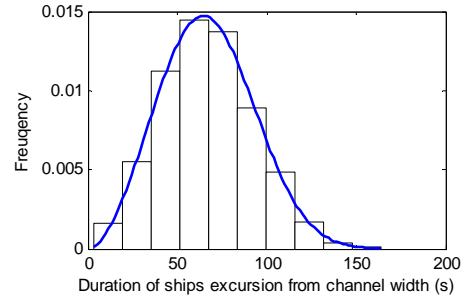


Figure 6: Duration of ship excursion fitted with Weibull distribution

The spectrum density of vertical motions concerning the underkeel level of ships induced by waves should be also established. Ships experience heave, roll and pitch motions which combine to produce vertical displacements of the hull. The magnitude of these dynamics, which is defined by a number of critical points on the hull, depends on many factors, including: wave spectrum, ship specifications and speed, and water depth. When all the factors are available, the characteristics of vertical motions of critical point k can be found as follows:

$$S_{Z_k}(\omega_e) = r_{Z_k}^2 S_{\zeta}(\omega_e) \quad (4)$$

$$m_{o,Z_k} = \int_0^{\infty} S_{Z_k}(\omega_e) d\omega_e \quad (5)$$

Where:

- $S_{\zeta}(\omega_e)$: the encounter spectrum of wave as a function of the encounter frequency ω_e ;
- $S_{Z_k}(\omega_e)$: the response spectrum of vertical motion of the critical point k ;
- Z_k : dynamic vertical motion of point k ;
- r_{Z_k} : is the amplitude characteristic of vertical motions of the critical point k ;
- m_{o,Z_k} : is zero moment of the motion spectrum of the critical point k .

Thirdly, using the Monte Carlo method a computer model accesses these distribution functions and simultaneously introduces more variables (tidal predictive errors, inaccuracy in dredging, ..) to calculate the probability of a ship grounding during a selected environmental condition, ship size and ship speed. The process can be repeated over a given time period. An overall loop of the Monte Carlo calculation has some components, including: (1) generating pre-defined weather condition and tidal; (2) generating pre-defined ship size and ship speed; (3) accessing the associated appropriate distributions of ship motions; (4) calculating the probabilities of ship excursion; calculating the probabilities of ship grounding; (5) calculating down times due to weather conditions and tide.

The final results of the probabilistic calculation are the downtimes, the possible accessibilities of the channel and the associated probabilities of grounding for each type of ship. Three these aspects are interdependently involved to provide an acceptable

probability of ship grounding. It can be essentially explained that the benefits of downtime reduction should be plotted against whether the ship is allowed to navigate in heavier environmental condition accepting, consequently, a higher probability of grounding (and higher risk) or increases channel dimensions, resulting in an increment of dredging costs. The total resultant costs of enlarging channel, downtimes and the risk of possible bottom touches for all possible accessibilities (or alternatives), are estimated. An acceptable probability of ship grounding should be selected by which net present value (NPV) of the total benefits and costs for the lifetime of the project are maximized. The equation is well known used as:

$$NPV = \sum_{t=0}^k \frac{(B-C)}{(1+r)^t} \quad (6)$$

Where:

- B: are the future annual benefits of downtime reduction (B_{dt}), transport increment (B_{ti}) and risk reduction (B_{rr}).
- C: are initial and annual costs to manage risk;
- r: is the discount rate; k: is the project life (years).

The benefit of the risk reduction can be expressed in terms of a probabilistic equation [13] as:

$$B_{rr} = C_o.P_r \quad (7)$$

Where: C_o is the consequence of the accident (ship grounding); P_r is the occurrence probability of the accident.

3 THE PROBABILITIES OF THE SHIP GROUNDING

The whole channel should be separated into several sections where variations in local maneuvering conditions for every transit can be neglected. The hydrodynamics and the response spectrum of ship motions for each section can, therefore, be seen unchangeable. Hence the ship motions in waves might be considered as the Gaussian, stationary and ergodic process [7]. These should, of course, be a non-stationary process for the whole channel. The probability of touching the bottom at critical point k on the ship hull during the time period t_i of a passage in section s_i with a water depth h_i and a length L_i can be defined by the following two approaches:

The Monte Carlo simulation (MCS)

A specific loop (inside overall loop) of the Monte Carlo simulation consists of the following steps: (1) determine a time period for a passage of section s_i : $t_i=L_i/V$; (2) generate the stochastic values of exceedance distance DE and the time period t_{DE} during the ship excursion from the probability density functions as defined in Figure 4 and Figure 6 respectively; (3) calculate the time period when ship progresses within the channel borders: $t_{IN}=t_i - t_{DE}$; (4) realization of the vertical motions, $Z_k(t)$, as a function of the time series (t_{IN} and t_{DE}) from the response spectrum $S_{Zk}(\omega e)$; (5) find maximum negative peaks for the samples of the motions, then check if (peak-max[t_{IN}]>KC) or (Peak-max[t_{DE}]>KC_{DE}) then grounding = 1; otherwise grounding = 0; here:

$$KC = h_i - DT_k - Sp \quad (8)$$

$$KC_{DE} = h_i - DT_k - Sq - DE / m \quad (9)$$

Where:

- KC: average static instantaneous under-keel clearance during ship progressing inside the channel (m);
- KC_{DE}: average static instantaneous under-keel clearance during ship excursion (m);
- DT_k: static draft at point k (m);
- Sq: squat of ship (m);
- DE: excursion distance of ship from the borders of the channel (m);
- m : slope angle of underwater dredging bank.
- V : average speed of ship (m/s)

Repeat the above process n times (n must be large enough), the probability of bottom touch of critical point k can be estimated as:

$$P_{i,k} = \frac{\text{Numbers}_{\text{grounding}=1}}{n} \quad (10)$$

Probabilistic approach

If the magnitude of KC is not so high, that the number of touching the bottom within disjunctive time intervals are considered as independent, which lead to the condition: $KC/\sqrt{m_0} \gg 1$, the probability of bottom touching of critical point k can be calculated by [10]:

$$P(Z_{11}) = 1 - e^{-\lambda(KC)} \quad (11)$$

$$P(Z_{12}) = 1 - e^{-\lambda(KC_{DE})} \quad (12)$$

$$P_{i,k} = P(Z_{11}) + P(Z_{12}) \cdot P(Z_2) \quad (13)$$

$$\lambda(KC) = \sqrt{\frac{m_2}{m_0}} e^{-\frac{KC^2}{2m_0}} \quad \text{and} \quad \lambda(KC_{DE}) = \sqrt{\frac{m_2}{m_0}} e^{-\frac{KC_{DE}^2}{2m_0}} \quad (14)$$

- $P(Z_{11})$, $P(Z_{12})$: are respectively the probabilities of ship grounding inside and during excursion from the borders of the channel as defined in the equation (2);
- $P(Z_2)$: probability of ship excursion from the borders of the channel as defined in the equation (3);
- $\lambda(KC)$ and $\lambda(KC_{DE})$: are respectively the expected numbers of the channel bottom touches during ship progresses inside and outside the channel borders;
- m_0 , m_2 : are respectively zero and second moments of the motion spectrum of point k .

Probability of ship grounding $P_i = \max(P_{i,k})$ can be considered as the probability of touching the bottom in section s_i . Probability of bottom touching, $\text{Pr}[\text{Env}(h)]$, during a given environmental condition h in whole channel is obtained as:

$$\text{Pr}[\text{Env}=h] = 1 - \prod_{i=1}^{ns} (1 - P_i) \quad (15)$$

The probability of touching the bottom during a given period, P_{life} , can be determined as:

$$P_{\text{life}} = N_{\text{ship}} \sum_{h=1}^{N_e} f[\text{Env}(h)] \cdot \text{Pr}[\text{Env}(h)] \quad (16)$$

- ns : the number of sections;
- N_{ship} : the number of ships presents in the channel during a given period;
- $f[\text{Env}(h)]$: occurrence frequency of environmental condition h .
- N_e : the number of environmental conditions.

4 FURTHER STUDY

Great effort should be made to introduce various types of distributions and characteristics of ship motions to the computer model. The complicated relations among environmental conditions, ship types and the response of ship motions could be filled up to make the method more comprehensible.

Before starting to implement a ship handling simulator, there should be carefully to select environmental conditions to be analyzed [1], considering these as a combination of winds, waves, currents and tide. One environmental condition selected in simulation must be ensured that it is reliable to cover all the possible and necessary combinations. Estimation of occurrence frequencies of these environmental conditions is another important condition to determine probability of ship grounding. Much attempt should be made to investigate this problem.

This paper describes the method used to assess the navigational safety of the designed channel. If all environmental condition factors are measured to enable them to be available in the computer model earlier ship's entry, it is probable that "near real time simulation" [4] can be carried out by using this method in which several scenarios of the channel's transit accessibility will be provided before near time ship's entry. By relating to the acceptable probability of grounding, an optimal scenario (ship speed and tidal window) is selected for ship access.

The probabilistic approach and the Monte Carlo method are merit tools translating "black box" outcomes from simulations into meaningful bases in the application of channel design. It is expected that the method would be further improved to provide the required reliability of accessing the probability of ship grounding when sufficient and reliable databases of ship motions are available.

References:

- [1] M.J. Briggs, L.E. Borgman, E. Bratteland, Probability assessment for deep-draft navigation channel design, *Coastal engineering* V. 48, pp 29-50, (2003).
- [2] J.M.J. Journee, User manual of SEAWAY, Technology University of Delft, (2001).
- [3] J. Lan, Probabilistic design of channel widths, International institute for infrastructural, hydraulic and environmental engineering, (2003).
- [4] T. Obrien, Experience using dynamic underkeel clearance system, *Pianc 2002*, 30th International navigation congress (2002).
- [5] PIANC, Approach channels. A guide for design, (1997).
- [6] PIANC, Capacity of ship maneuvering simulation models for approach channels and fairways in Harbors, *Pianc Bulletin* 77, (1992).
- [7] W.G. Price, R.E.D. Bishop, Probabilistic theory of ship dynamics, John Wiley and Sons. Inc., New York, (1974).
- [8] R.P.A.C. Savenije, Probabilistic admittance policy deep draught vessels, Ministry of Transport, Public Works and Water Management, Transport research Center, (1995).
- [9] R.P.A.C. Savenije, Safety criteria for approach channels, Ministry of Transport, Public Works and Water Management, Transport Research Centre, (1998).
- [10] J. Strating, T. Schilperoort, H.G. Blaauw, Optimization of depths of channels, *Delft Hydraulics*, (1982).
- [11] M. Vantorre, J. Journee, Validation of strip theory code SEAWAY by model test in very shallow water, *Flander hydraulics research*, Antwerp, Belgium (2003).
- [12] J.K. Vrijling, Probability of obstruction of the entrance channel, <http://www.waterbouw.tudelft.nl/public/gelder/citatie19.doc>, (1995).
- [13] J.K. Vrijling, P.H.A.J.M. van Gelder, Probabilistic Design, Technology University of Delft, (2004).