Navigation risk assessment for vessels manoeuvring in various conditions

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Abstract

The navigation risk is usually estimated by means of simulation researches. The appropriate numbers of simulation trials are executed for probability of accident calculation. Later on, navigational risk can be assessed with additional information about consequences of given accidents. Usually the simulations are executed in given meteorological conditions and all subsequent risk analyses are performed separately for such simulation cases. Until now there are no practical methods for total risk analysis with consideration of possible change of vessels parameters, meteorological conditions, type of performed manoeuvre and navigation marking used in analysed area. All these problems can be considered by presented method, which is based on statistical sampling from accident probability distributions obtained from simulations performed in different conditions. The practical application of presented method is exampled by simulation researches carried out at the entrance to Świnoujście Port.

1 Introduction

The most hazardous stage of the vessel’s voyage is concerned with navigation on restricted waters, in ports and on the waterways. From the other hand the consequences of such accident will not lead to human fatalities but mainly to economic loses due to closing the port or environmental impacts because of possible oil spills.

In such cases, the main engineering problem is to estimate properly the probability of vessel grounding due to exceeding horizontal boundaries of manoeuvring area. To solve this problem the real time simulations are usually applied for navigation risk and probability of accident evaluation. There are three main reasons of such procedure:
statistical data concerns grounding are not available for example when the waterway is on design stage, or is going to be modernised,
the period of waterway service was too short to collect serious and reliable statistical data,
some minor incidents are usually not reported to accident databases.
The simulations are usually performed in different meteorological conditions. In each kind of conditions, there is adequate number of trials executed by human navigators. After simulations, each trial is processed statistically in order to obtain probability density function of ship’s maximum distances from the centre of the waterway and accident probability calculation in given conditions. Later on the safe water area can be obtained and plotted on the area map with consideration of previously set up admissible risk level.
Several methods of risk assessment on the waterways have been already worked out [1], [5], [7]. The most serious lack of these methods is problems with describing total accident probability for different meteorological conditions, different vessels, kind of manoeuvres and changes in navigation marking.

2 Navigation risk assessment at the entrance to Świnoujście Port

Świnoujście is located at the southern Baltic Sea near western Polish border (Fig.1). Presently there can be served ships up to 250m of length and 12.8m draught. The main aim of performed simulation researches was to prove that the length of maximal ships could be increased up to 260m with unchanged risk level. The increase of ship’s dimensions is possible due to dredging works, which were carried out near Western Bank (Mielizna Zachodnia) close to western head of Świnoujście breakwater. It was a reason of widening the manoeuvring area for ships and consequently safety level increase. The results of simulation researches, which applied acceptable risk criterion proved hypothesis of vessel’s length increase possibilities.
The real time computer simulation models of ships were applied for researches. The real navigators controlled ship’s models in researches (captains, pilots). Usually the simulation researches are conducted in series each in different meteorological conditions. In each series, the simulation trials carried out with number, which guarantee the former set up level of confidence. Later on, the distributions of maximum distances from the centre of the waterway of ship points are determined. Two such distributions are analysed (right and left side of the waterway) for each section of the waterway (Fig. 2). The entire waterway was divided on perpendicular sections with appropriate length (in presented research 680 sections of 5m length).
After execution of simulation trials in each section for each meteorological condition two distributions were analysed – maximal distances left and right side of the centre of the waterway with sample number equal to the number of simulation trials performed (15 in presented researches). Each such obtained data sample was later on fitted to theoretical probability distributions. Usually normal
distribution well describes analysed variates [3]. However, due to relatively small sample size the fit results are sometimes not satisfactory. Estimated mean (m) and variance (σ) of normal distribution can be used for the probability of collision with canal banks (Pa) calculation (Figure 2). The following formula was used:

\[
P_a(d) = P(X \geq d_{\text{max}})
\]

where:
- \(d_{\text{max}}\) - distance from the centre of the waterway to the fairway bank (maximum allowable without collision with canal bank),
- \(X\) - variate with normal distribution of parameters \(X \sim N(m, \sigma)\).

Figure 1: Entrance to Świnoujście Port.
ship passages in simulation trials

Figure 2: Distributions of ship’s maximum distances from the centre of the waterway and probability of grounding calculation.

Consequently, the grounding probability while performing a specific manoeuvre during passage through limited water area can be presented as a vector:

$$P_a = [P_{a1}, P_{a2}, \ldots, P_{an}]$$  \hspace{1cm} (2)

where:

- \(P_{ai}\) - probability of collision occurrence in \(i\) section of the waterway,
- \(n\) - number of sections on the analysed part of the waterway (680 in this research).

The above probability of collision with bank was calculated twice one for right and one for left side of the waterway.

The risk may be defined as a product of accident (collision with bottom or canal bank) occurrence and its consequences with consideration of traffic intensity:

$$R_a = P_a I_s C$$  \hspace{1cm} (3)

where:

- \(P_a\) - probability of specific accident occurrence,
- \(I_s\) - mean annual intensity of performing a given manoeuvre,
- \(C\) - consequences of accident.

The effects of vessel’s collision with the sea area bottom can be presented in the following form [1,2]:

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\[
C = \frac{E_m}{E_p}
\]  

(4)

where:

\(E_m\) - maximum energy of the vessel at the moment of a contact between hull and bottom,

\(E_p\) - permissible energy of a safe contact between the vessel and bottom.

In this model, when value \(C\) is between zero and one, the collision does not cause any important outcomes and the vessel is able refloat by herself (or with assistance of the tugs manoeuvring with her) without an special salvage operation and damage to the hull. When value \(C\) is more than zero, the collision causes damage to the hull, or, to help the vessel afloat, it is necessary to undertake a special salvage operation involving economical consequences (stopping the traffic, closing the port, using tugs etc.). The energy can be evaluated on the basis of simulation series with consideration of average speed, rate of turn, drift angle, position, kind and slope angle of the bank friction coefficient between hull and the bottom etc. On the investigated part of the waterway the bottom is usually sandy with considerable mud layer. In such cases touching the bottom does not always result in major damage to the hull [6]. Environmental danger due to oil spill is also minor especially for double hull tankers.

As it appeared in presented researches the consequences of ship touching the bank of canal are nearly constant due to:

- ship's speed during the passage are almost constant,
- drift angles are relatively small,
- the kind of bottom is almost the same along the entire part of the waterway.

Admissible risk level was estimating with assumption that accidents are Poisson distributed. Probability of \(n\) incident occurrences during \(N\) passages of ships through the waterway is defined as:

\[
P_n = \frac{(NP_a)^n e^{-NP_a}}{n!}
\]  

(5)

where:

\(P_n\) - probability of \(n\) accident occurrence in \(N\) passages,

\(P_a\) - grounding probability in single passage.

Probability of incident free period (no occurrences \(n=0\)) in given time, for example one year can be calculated with help of following formula:

\[
P_0 = e^{-NP_a}
\]  

(6)

where:

\(P_0\) - probability of no accident occurrence during one year,

\(P_a\) - grounding probability in single passage.

\(N\) - number of passages per year.

The admissible risk level \(R_a\) is defined as the probability that at least one grounding occur throughout the life of the waterway. In this researches there
have been assumed that fairway is designed for the period of 15 years, and after that time it will be modernized or equipped with more effective navigation aids such as Vessel Traffic System, more accurate positioning systems etc. In other works the period from 15 to 100 years are mentioned depending mainly of national regulations in this matter [6].

It was assumed that during 15 years one grounding would occur. In the next step, it would be calculated the intensity of ship’s passages through the waterway during 15 years of time. Later on, the probability of grounding in one single passage would be calculated.

According to formula (8) maximal admissible risk level is $R_a=0.064$, which means that, there is only 6.4% probability for more than one accident per year.

The following simulation series of loaded bulk carrier of 260m total length and 12.8 draught were executed:

S1. entrance to Świnoujście - no wind; no current,
S2. entrance to Świnoujście – wind: N 10 rnls; current: 1.4 rnls incoming,
S3. entrance to Świnoujście – wind: N 5 rnls; current: 0.8 rnls incoming,
S4. departure from Świnoujście - no wind; no current,
S5. departure from Świnoujście – wind: S 10 rnls; current: 1.0 rnls outgoing,
S6. departure from Świnoujście – wind: S 5rnls; current: 0.5 rnls outgoing,

In each simulation condition 15 passages of ship’s model were executed. As a result, in each simulation condition the probabilities of accident were determined (Figure 3, 4) and on the basis of probability distribution function the manoeuvring area on given confidence level was determined (Figure 5).

Figure 3: Manoeuvring area of loaded 260m long bulk carrier entering to Świnoujście. Conditions: wind N 10rnls; current 1.4rnls incoming (S2 simulation series).
Later with use of previous presented energetic consequence model, the navigation risk can be estimated and compared with admissible risk level (Table 1). The risk was estimated only for most dangerous place in considered area - the head of eastern breakwater (Figure). Based on simulation results the linear and angular velocities of vessel in simulations were estimated.

Table 1: Consequence of accident estimation of loaded 260m long bulk carrier near the east head of Świnoujście breakwater (section no 190).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Entrance</th>
<th>Departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean linear speed</td>
<td>1.7 m/s</td>
<td>1.8 m/s</td>
</tr>
<tr>
<td>Mean transverse speed</td>
<td>0.1 m/s</td>
<td>0.1 m/s</td>
</tr>
<tr>
<td>Maximal energy of collision with bank</td>
<td>29000 kNm</td>
<td>15000 kNm</td>
</tr>
<tr>
<td>Admissible energy</td>
<td>6000 kNm</td>
<td>6000 kNm</td>
</tr>
<tr>
<td>Mean consequences</td>
<td>2.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

In case when the estimated risk level is higher in compare to admissible, some precautions should be made to reduce it. According to formula (3) only one element can be used to control the risk - intensity of vessel’s traffic. The appropriate intensity ($I_{\text{max}}$) can be calculated with use of following formula:

$$I_{\text{max}} \leq \frac{R_d}{P_a C}$$ (7)
Mean annual admissible intensity of given manoeuvre performing by analysed size of ships was estimated as:

- entrance: 20 manoeuvres,
- departure: 10 manoeuvres.

The frequency of hydro-meteorological conditions in simulations was estimated to 25%, which gives consequently more admissible manoeuvres of ships in these conditions.

Most of accidents occur due to human error. In such cases prevent action is usually being initiated and scale of consequences might be decreased. In regard to above, it can be assumed that the consequences of particular ship's grounding on the waterway have mostly deterministic character.

3 The method of navigation risk assessment in various meteorological conditions

The main disadvantage of presented methods of risk and probability of accident assessment is concern with the fact that each simulation series is analysed separately from each other. Usually simulation series are executed in different meteorological (wind and current) conditions. In presented researches, simulations was performed in six different conditions (S1, S2, S3, S4, S5, S6) three series for entrance of vessels to Świnoujście and three for departure. It is obvious that in further analyses the worst condition (with biggest probability of accident) is taken into consideration. To find distribution that describes all simulation conditions the following method is proposed:

1. fitting all data from analysed simulation series to theoretical statistical distributions,
2. random sampling from each obtained distribution for general model estimation,
3. fitting obtained samples to statistical distribution that taking into account all analysed series.

The above procedure should be performed for each section of the waterway. Obtained according to above method distribution for all meteorological conditions and for entrance and departure of vessels can be used in further analyses for finding safety water area and for probability of accident calculation and risk level assessment. The Figure 4 presents best-fitted distributions for six analysed simulation series. Chi Squared and Kolmogorov-Smirnoff tests were used as a goodness-of-fit criterion.

In researches concerned with ship passage on restricted area, usually normal distribution can be applied for practical purpose but it is often observed the positive skewness in distribution of ship’s maximum distances from the centre of the waterway at he bends of the waterways.
At the next step, the large numbers of random samples from each of distribution were taken. The total distribution for six analysed simulation series obtained according to such method is presented on Figure 6. The distribution that describes six analysed simulation series can be also fitted to normal distribution on confidence level 0.05 but due to kurtosis logistic distribution is more appropriate in analysed case.

4 Conclusions

The paper presents probabilistic method of navigation risk assessment and probability of accident estimation for different meteorological and manoeuvring conditions based on real time ship simulations. Random sampling and methods of determining distributions from data were applied in the paper. With use of presented method, the risk can be assessed for different meteorological conditions, different manoeuvres and different vessels with assumption that consequences are constant. Further researches should be concentrated on verification if presented method with different simulation data especially in tail area of distributions.

Figure 5: The best-fitted distribution for six analysed simulations series performed in different conditions. Section no 190.
Figure 6: Total distribution of vessel’s positions for six analysed simulation series. Section no 190.

References


