Navigational risk in methods of assessing the safety of the vessel’s mooring manoeuvre

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Abstract

The article presents a new method of assessing the safety of the vessel’s mooring manoeuvre, which uses the theory of risk. Navigational risk is determined when using probabilistic methods to establish the probability of accident, and energetic methods to estimate its results. Examples have been presented of applying this method for the determination of optimal parameters of waterways and conditions for operating them, and for assessing the safety of the vessel’s mooring manoeuvre performed in various navigational conditions.

1 Introduction

At the present time, one of the most urgent problems of navigational safety is the ability to estimate navigational risk in restricted water areas [1]. There are two concepts of risk: technological and economic, and they depend on the method of describing the results of navigational accident. In the applications of marine traffic engineering it has been assumed that the technological risk is called navigational risk. In the navigational risk the assessment of accident results consists in a mathematical description of the dynamics of the vessel’s collision. In the economic risk the assessment of results consists in an assessment of the costs of the accident results.

In the course of performing a specific vessel manoeuvre in restricted water areas it may come to accidents resulting from these units’ movement. They are called navigational or manoeuvring accidents and classified as follows:
1. Running aground (understood as unintentional contact of the hull, rudder, or propeller with the water area’s bottom).
2. Damage of the hull during contact of the vessel with the bottom (arisen during the ship’s unintentional striking against a bottom element, when the
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3. Damage of hydrotechnical or port constructions due to the vessel’s immediate contact or to the indirect effect of propeller stream.
4. Damage of the tug participating in the manoeuvre.
5. Damage of the navigational floating mark.
6. Collision with another vessel in the water area (ships made fast to the quay, at anchor or making way).

The considerations presented concern only accidents of the first, second and fifth type entirely, the third in its part concerning the vessel’s immediate contact with the quay, and the sixth concerning ships made fast to the quay.

Navigational accidents are divided into two types, depending on the results of the accident [1):
- light (incident) – results \( S \leq 1 \),
- serious (accident) – results \( S > 1 \).

Removing the results of light accident does not require special rescue actions, and frequently the Maritime Administration is not informed about them, not even the shipowner. Removing the results of accidents, on the other hand, requires rescue actions. Research conducted shows that the relation of accidents to the total number of them in a given area does not exceed 10% [1].

Dutch criteria of navigational safety on fairways (in restricted water areas) permit the occurrence of maximum one accident in 237 years [3], which corresponds to the occurrence of maximum 0.004 accidents (running aground) in one year. English criteria, on the other hand, allow maximum 0.001 accidents (running aground) in one year [3].

Waterways are usually designed for 50 years of operation time, whereas vessels are designed for 15 years. Attention should be paid, however, to the following facts:
- in its fifty years of operation time waterways are modernised several times, which is connected with, among other things, ever better navigational systems and methods of manoeuvring the ship,
- each successive generation of ships (after 15 years) is closer to perfection with respect to manoeuvrability, navigational, technical reliability, etc.

Taking into consideration the above-mentioned facts it was found out that safety criteria should not be overstated in an artificial way. Because of this, the following criteria of navigation safety in restricted water areas have been accepted:
- waterways with tides, maximum 0.004 accidents in a year or maximum 0.04 total number of accidents [1],
- waterways without tides, maximum 0.007 accidents in a year or maximum 0.07 total number of accidents [1].

2 Methods of assessing navigational risk

Navigational risk is defined as the product of probability of accident occurrence and the results it effects. The definition of risk has been supplemented by the relative frequency of performing the assigned manoeuvre. Assuming that the
accident and its results are independent occurrences, navigational risk $R$ can be presented in the form of a product:

$$R = I_R \cdot P_A \cdot S$$

(1)

where:
- $I_R$ - accident annual intensity (frequency) of performing the given manoeuvre,
- $P_A$ - occurrence probability of a specific accident,
- $S$ - results effected by the accident.

Assessing navigational risk can be reduced to the determination of the two following parameters:
- occurrence probability of a specific accident $P_A$,
- results caused by specific accident $S$.

### 3 Probability of accident occurrence

The occurrence probability of a specific type can be calculated by the following methods:
- simulation,
- statistical,
- indirect.

**Occurrence probability of accident established by the simulation method** is determined by the following factors:
- navigational reliability of performing a given manoeuvre in specific conditions,
- the human factor in the anthropo-technical vessel – navigator system (navigator’s reliability),
- technical reliability of the vessel.

The navigational reliability of performing a given manoeuvre in a specific water area should be understood as the probability of avoiding collision with fixed objects (vertical wall, bottom of the water area) by a vessel of a given type in specific hydrometeorological and operational conditions with reliable working of all appliances of the vessel. In the methods presented, navigational reliability of the manoeuvre performed will be joined with the navigator’s reliability. The human factor will be taken into consideration by the participation in real research of navigators with qualifications corresponding to reality.

Technical reliability, on the other hand, should be understood as the probability of reliable working of the vessel’s systems and appliances that determine the performance of a given manoeuvre without failure.

Technical reliability and navigational reliability that includes the human factor are practically independent, so the probability of performing a given manoeuvre $P_B$ without failure can be written down in the following form:

$$P_B = P_n \cdot P_t$$

(2)

where:
- $P_n$ - probability that a ship of specific parameters and conducted by a navigator of specific qualifications will not have a collision when
performing a given manoeuvre in specific navigational and hydrometeorological conditions,

\( P_t \) – probability of reliable working of the vessel’s systems and appliances determining the performance of a given manoeuvre without failure.

The probability of performing a manoeuvre by a ship of a given type without failure, in specific navigational and hydrometeorological conditions, conducted by a navigator of specific qualifications at a certain time and place, amounts to:

\[
P_n = P(X_j \mid d_j)
\]

(3)

where:

\( X_j \) - maximum distance from the vessel’s extreme point to the left or right from the fairway axis in the \( j \)-th lane of the waterway (random variable).

The distribution parameters of random variable \( X_j \) are calculated on the basis of simulation research of a given manoeuvre carried out, aimed at determining the width of the traffic lane.

Technical reliability has been identified as the performance of a specific manoeuvre without failure. It depends on the reliable working of: the main engine, auxiliary engines with generators, the steering gear, the tugs and, in case of bad visibility, the radar. For the probability calculation of the above-mentioned appliances, the damage intensity function \( \lambda(t) \) in time \( t \) is used, which is a function of the damage occurrence density, on the condition that there has been no damage so far.

Two types of simulation models are used to determine the width of traffic lanes:

- the non-autonomous model,
- the autonomous model.

Non-autonomous simulation models applied in traffic engineering are models of the inter-active type working in real time (Fig. 1) [1]. They are based on the man-computer dialogue principle. ‘Man’ is here the navigator of specific professional qualifications; in most cases they correspond to his real qualifications. A computer of specific parameters is equipped with specialist modules of depicting information and steering the ship’s movement; its working is based on a simulation model of the vessel’s movement in the water area researched.

For many years there have been intensive efforts in the world to use simulation autonomous models in sea traffic engineering in order to determine the waterway parameters. Simulation autonomous models working in accelerated time have a number of merits as compared with non-autonomous models working in real time. These are:

- a considerably shorter time of research due to working in accelerated time,
- considerably lower research costs, as there is no need to employ in the research highly qualified and highly paid navigators (pilots, captains etc.),
- more possibilities to research a wider range of navigational conditions.
At present, however, autonomous models are far from being universal and their application is usually restricted to the initial stage of research, which concerns the determination of waterway parameters.

In simulation autonomous models working in real time the working out of the navigator’s decision-making process model is the most essential problem (Fig. 2). In most situations making a decision about a given manoeuvre is a process aimed at coastal conditions, which are variable and hard to define, and the individual perception of threat plays a big role in the navigator’s decision-making [1].

The probability of accident occurrence determined by statistical method can be defined as follows [2]:

![Diagram 1: Simulation non-autonomous model of vessel traffic in restricted water areas][1]

![Diagram 2: Simulation automatic model of vessel traffic in restricted water areas][2]
\[
P_{ai}(t) = \frac{n_{ij}(t)}{m_j(t)}
\]  

(4)

where:

- \(P_{ai}(t)\) - occurrence probability of accident of specific type \((i)\) in assigned conditions \((j)\) in researched time period \(t\),
- \(n_{ij}(t)\) - number of accidents of specific type \((i)\) in specific conditions \((j)\) in researched time period \(t\),
- \(m_j(t)\) - number of manoeuvres performed in specific conditions \((j)\) in researched time period \(t\).

This method consists of determining the number of accidents in the researched time period \((t)\). It concerns a specific type of navigational accidents handled in assumed navigational conditions (e.g. various visibility, wind force etc.). The time researched is usually a period of 5–25 years. It should be underlined here that a too short period causes errors due to a small number of trials; lengthening of the time period, on the other hand, causes errors resulting from consideration to old organisational methods, ship construction and its equipment.

**Direct method of determining the probability of accident** is based on the assumption that most of the navigational accidents considered belong to incidents, the results of which do not exceed 1 \((S < 1)\). Incidents of this type do not require special rescue actions and are removed with the forces of the vessel affected by the incidents, very frequently without the knowledge of the Maritime Administration and the shipowners.

Accidents have results exceeding one \((S > 1)\). They require special rescue actions entailing costs. It causes the fairway to be closed for a time and damage to the ship that needs to be repaired. The total number of accidents in a year is determined on the basis of the following dependence:

\[
a_r = P_A \cdot I_R
\]  

(5)

The proportion of accidents to the total number of accidents and incidents can be established by using simulation data concerning the total number and statistical data of accidents in a given waterway. Assuming the Maritime Administration to be the source of information on statistical data, at the same time we assume that these data concern accidents exclusively. Taking the above-mentioned assumptions into consideration, we can express the proportion of accidents to the total number of accidents and incidents by the dependence:

\[
c = \frac{a_{st}}{a_r}
\]  

(6)

where:

- \(a_{st}\) - statistical annual number of accidents on the researched section of the fairway in a given class of ships,
- \(a_r\) - total annual number of accidents and incidents on the researched section of the fairway in a given class of ships calculated by simulation methods.
The proportion of accident $(c)$ differs in dependence on the size of vessel; thus, on the section $0.0 \text{ km} + 18.8 \text{ km}$ of the \winouj cie – Szczecin fairway it is equal to [2]:

1. Ships of length $L_c > 160 \text{ m}$ $c \sim 6.0\%$.
2. Ships of length $L_c \leq 120 \text{ m}$ $c \sim 2.5\%$.

The statistical data concern here the period from 1987 to 1999.

Knowing the value of coefficient $c$ and the statistical annual number of accidents in the researched water area we can determine the total number of accidents and incidents.

### 4 Consequences of accident

When assessing navigational risk the calculation of accident consequences consists in a mathematical description of the collision dynamics of the vessel on the basis of which the physical indexes are calculated which characterise the consequences. When assessing economic risk the defining of consequences consists in the evaluation of costs. There are methods that make it possible to determine the economic consequences on the basis of navigational consequences [1]:

$$S_E = f(s)$$  \hspace{1cm} (7)

where:
- $S_E$ - economic consequences (evaluation of costs),
- $S$ - navigational consequences (physical index characterising the consequences).

Considering this fact, only methods of assessing navigational consequences will be presented in the article.

The consequences of accident are calculated by using the following index:

$$S = \frac{E(t)}{E_d}$$  \hspace{1cm} (8)

where:
- $E(t)$ - maximum energy of the vessel striking against an element of the bottom,
- $E_d$ - allowable energy of the ship striking a specific element (bottom).

The concept of maximum energy of the ship striking against a bottom element $E(t)$ should be understood as the kinetic energy the ship may have at the moment $(t)$ of striking against an element of the bottom in the least favourable navigational conditions during the performance of a specific manoeuvre. This energy is determined by simulation methods on the basis of research on a given ship manoeuvre in a specific water area in the navigational conditions researched.

The allowable energy of a safe \textbf{striking of the vessel against a bottom element} should be interpreted as the maximum contact energy that will not cause any damage to the hull, rudder or propeller, and that will not cause any damage...
to a given hydrotechnical structure or its fender devices. At the same time, the following condition must be fulfilled:

$$\begin{align*}
E_d &\leq E_{ds} \\
E_d &\leq E_{ds}
\end{align*}$$

where:

- $E_d$ - allowable energy of striking against an element of a specific type that does not cause damage to the ship’s hull,
- $E_{ds}$ - allowable energy absorbed by the system ‘fender device - hydrotechnical structure’ that does not cause its damage.

The allowable energy of the ship’s striking the bottom should be interpreted as the maximum contact energy with the bottom that will not cause any damage to the hull, rudder or propeller, and at which it will still be possible for the vessel to refloat with her own forces without the need of a rescue action. At the same time, the following condition must be fulfilled:

$$\begin{align*}
E_d &\leq E_{dk} \\
E_d &\leq E_{dm}
\end{align*}$$

where:

- $E_{dk}$ - allowable energy of contact with the bottom not causing any damage to the hull,
- $E_{dm}$ - allowable energy of the ship’s refloating with her own forces,

at the same time, in the process of running aground the kinetic energy of the ship $E(t)$ changes into working of the friction force of the hull against the ground and the increase of potential energy bound with raising its gravity centre when running aground, that is:

$$E_d = E_d + \Delta E_p$$

where:

- $E_d$ - allowable kinetic energy changed into the working of friction force of the hull against the ground,
- $\Delta E_p$ - increase of potential energy of the ship bound with raising its gravity centre when running aground.

5 Examples of applying navigational risk

Navigational risk understood as a theoretical concept along with methods of its assessment has been applied for:

1. The construction of a method of optimising waterway parameters with one limitation [1]. It has replaced the multi-limitation methods of optimising waterway parameters applied so far. The method has been applied for de-
2. Modernising waterways by the method of assessing economic risk was presented on the previous Risk Analysis II Conference [2].

3. Determining safe navigational conditions for entering the port. Simulation methods of risk assessment have been applied. This risk, determined for various navigational conditions, was the basis for calculating the allowable (maximum) intensity of performing the researched manoeuvre of entering by using the dependence:

$$I_{R_{dop}} = \frac{R_{dop}}{P_A \cdot S}$$  \hspace{1cm} (12)

where:

- $I_{R_{dop}}$ - allowable annual intensity of performing a specific manoeuvre in assigned conditions,
- $R_{dop}$ - allowable navigational risk.

![Diagram showing minimum safe width at the bottom of entry to the Piastowski Canal from the Szczeci ski Lagoon of the vessel $L_C = 250m$ $T = 11.0m$ in dependence of the accident results ($S$) and traffic intensity ($I$)]

This method was applied for determining the maximum vessels able to enter the port of winoujcie, obtaining the results presented in Table 1 [1].
Table 1. Results of researches concerned with maximum vessel entrance to winoujcie.

<table>
<thead>
<tr>
<th>Current port regulations</th>
<th>Results obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual entry intensity</td>
<td>Allowable navigational conditions</td>
</tr>
<tr>
<td>no limitations</td>
<td>wind up to 10 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Navigational back-up for the mooring ship. This is a newly worked out method serving the captain and the pilot to back up navigationally the safe performance of the mooring manoeuvre. It consists in determining and presenting the safe area around the vessel, dynamically changing during the ship’s movement, on the vessel’s ECDIS system (electronic chart). This area can be described as follows (Fig. 4):

\[ F = f(R_{dep}, R(t)) \]  

where:

- \( F \) - safe mooring area,
- \( R_{dep} \) - allowable navigational risk,
- \( R(t) \) - navigational risk at moment t.

Figure 4: The vessel’s safe mooring area

References