General models of ship risk during port manoeuvres

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Abstract

This paper presents the concept of a general model of ship risk in restricted areas. The paper is focused on the probabilistic side of risk assessment, without complete consequence analysis. Two prevailing kinds of accidents are included in the model. The main problem described in the paper is in the treatment of ships behaviour on restricted areas as a stochastic process. The necessary data for building such general models can be obtained from real experiments or simulation experiments like those presented in this paper. Several methods of accident modelling are proposed, especially for accidents of exiting safety horizontal borders of a waterway. The general models of risk can be used in risk assessment methods, decision support systems and safety evaluation of marine systems.

1 Introduction

The ships passage through the approach channels, waterways, and port basins can be considered as a stochastic process with changing probability and the consequence of an accident. The main aim of this paper is to build a general safety model of ship passage through restricted water areas. This model takes into account two prevailing kinds of accidents with the use of different accident probability distributions and the time of the ships performing a given maneuver. These kinds of accident are:

- accidents when a ship exceeds the horizontal boundaries of manoeuvring area such as grounding in channel, collision with embankments or breakwater, collision with moored ships or quay etc.
- accidents when a ship hits the bottom due to insufficient clearance under the ship’s hull (exceeding the available water depth).
The method applied to the first type of accidents aims to build a general risk model based on a previously performed series of real time simulations by the captains and pilots. In the next step, the data obtained in simulations are processed to obtain general models of ship accident probability in given restricted water areas. To find a general models it is proposed to use regression models where independent parameters are the ship position distribution and dependent parameters are size, the kind of ships, and environmental conditions during passage. This group of accidents is mainly due to human (navigator) error and technical failures of the main ship’s equipment. The distribution of this accidents group are estimated from real time interactive ship manoeuvring simulations, real experiments conducted with use of GPS, other land survey methods and historical accident data.

The second type of accidents investigated is modelled by a pure probabilistic method with the use of Monte Carlo simulations. This method, quiet differently from the previous one, has a significant limitation of the influence of the human factor, especially after the decision of the beginning of ship passage. The human influence is only significant in the passage planning phase. Experts are helpful for defining types and parameters of given distribution used in Monte Carlo simulations. Such kinds of accident are related with many factors, like sounding and dredging errors, squat and draft estimation errors, roughness of the bottom, tide and waves calculation errors, etc. All of these errors are included with the use of error distributions and expert opinion. A typical process of a ship’s passage in a restricted area is presented on Fig.1. The ship moves through the elements of water area from the sea to the quay. There are different navigational conditions in each stage of ship voyage and the times the ship remains in different stages are defined by distributions of times.
2 Process of ship movement in restricted area – first type of accidents

Modelling accidents due to ships exceeding horizontal boundaries of manoeuvring area needs the assumption that the process of ship movement is stochastic with changing probability of accidents and its consequences during passage to the berthing place (Fig.1).

It should be also noted that the accident consequences would also be changing during the passage. Four methods could be used to define such a process. The theoretical model is exampled by simulation researches conducted by a 250m length gas carrier. The area layout consists of a S-shape stretch of waterway (Fig.2). The simulations obtained by safe passage probability for every 5m in length section is presented on Fig.3. The simulations consist of 45 passages performed in different meteorological conditions.
2.1 Markov process

The first kind of accidents are modelled with the use of Markov chains theory with the assumption that the process of ships passage through a restricted area could be divided onto several nodes with certain accident probability distribution and time of ship passing through given node (Fig.4). Then with the assumption that accidents are distributed randomly during single node, the accident probability can be expressed with Poisson distribution with mean intensity $\lambda$.

There are several, consequently followed one by one up-states. Each up-state can be changed with intensity of $\lambda_i$ to down-state. With the simplified assumption that all down states are equal $S_1=S_2=...=S_i$ which is quite idealistic, especially in the case of consequences analysis; the time $\tau$ of reliable ship operation during passage in restricted waters can be defined as [1]:

$$
\tau = \sum_{i=1}^{n} [1 - F_i(\lambda_i)] \prod_{j=1}^{i-1} F_j(\lambda_j)
$$

where:

$$
F_i(\lambda_i) = \int_{0}^{\infty} e^{-\lambda_i t} dF_i(t)
$$

Laplace transform of distribution of ship time in given state $F_i(t)$,

and with the assumption that the distribution of ship time in a given state $i$-th is defined by single point distribution:

$$
F_i(t) = \begin{cases} 
0 & \text{for } t < L_i \\
1 & \text{for } t > L_i 
\end{cases}
$$

which Laplace transform equals:

$$
F_i(\lambda_i) = e^{-L_i \lambda_i}
$$

where:

$L_i$ - time of ship passage through the $i$ th stage,

$\lambda_i$ - intensity of failure during passage of $i$ th stage.

the time of reliable operation of ship during whole passage equals [1]:

$$
\tau = \sum_{i=1}^{n} [1 - e^{-L_i \lambda_i}] \prod_{j=1}^{i-1} e^{-L_j \lambda_j}
$$

Figure 4: Process of ship passage through restricted area.
2.2 Non-stationary Poisson process

Another approach is based on the assumption that all the safety of ship passages through restricted waters can be described by non-stationary Poisson process with changing accident intensity. The probability function of such a process can be written as follows:

\[ f_n(\tau, t_0) = \frac{a^n}{n!} e^{-a} \]  

(5)

where \( a \) is mean intensity of accidents during time interval between \( t_0 \) and \( \tau \) and defined as:

\[ a = \int_{t_0}^{t_0+\tau} \lambda(t) dt \]  

(6)

The example function of accident intensity on the waterway obtained from simulations is presented in Fig. 4. In the case when the function \( a \) is not available in analytic form the process of ship movement can be divided in small time intervals \( t_0 \) to \( \tau \) where the process of accidents can be regarded as stationary with \( \lambda \text{=const} \). Then equation (6) can be written as:

\[ f_n(\tau, t_0) = \prod_{i=1}^{k} \frac{a_i^n}{n!} e^{-a_i} \]  

(7)

where:

\[ a_i = \int_{t_0}^{t_0+i\Delta t} \lambda(t) dt = \lambda_i \Delta t \]  

(8)

2.3 Monte Carlo method

The third possible approach is based on the Monte Carlo method. After execution of simulation trials in different conditions the distributions of ship positions in given waterway sections are determined (Fig. 7).
If we denote that $P_0(t)$ means that in time $t$ when no accident will take place, the limit value of accident intensity $\lambda$ with assumption $t \to 0$ can be evaluated by:

$$\frac{1 - P_0(t)}{t} \approx -\frac{\ln P_0(t)}{t} = -\frac{\ln P_0(t)s}{v}$$  \hspace{1cm} (9)

where:

- $s$ - length of the section,
- $v$ - transit speed of vessel.

Figure 6: Distribution of real ships speed on the investigated area fitted to lognormal distribution.

The accident probability $(1 - P_0)$ can be evaluated from the results of simulation trials for each section of the waterway (Fig.7) Usually the normal distribution is used as a model of ship positions in simulation experiments. In such a case we obtain:

$$1 - P_{0i}(t) = \int_{d(i)\text{min}}^{\infty} f_i(y)dy$$  \hspace{1cm} (10)

where:

- $P_{0i}(t)$ - probability of safe passage in i-th section
- $d(i)\text{min}$ - distance to the safe waterway border in i-th section
- $f_i(y)$ - density function of ships position.

The problem of calculation of the time a ship sails through a given section for evaluation of accident intensity can be solved by two methods. The first method uses data from simulation and secondly, data from real experiments. In the present paper the second method is utilised due to its accuracy. The distribution of ships’ speed are given in Fig.6. We see that lognormal distribution fits well in the tail area of speed, but much worse in the mean area. With the use of them the time distribution of the ship sailing time in i-th section can be evaluated.
After the calculation of accident intensities the Monte Carlo method can be developed on the basis of Poisson process with changing intensity of accidents. For detailed researches the 200 meter long section (from 12050m to 12250m) of waterway have been chosen (Fig.2). The reason of choosing this part of waterway is the highest accident probability in this section (Fig.3). The results of 10000 Monte Carlo simulated passages through the investigated section has shown that accident probability in single passage equals $2.1 \times 10^{-3}$. The mean number of safe passages between accidents equals 470. The distribution of safe passages between accidents number on investigated area is presented on Fig.8. Due to the Poisson process assumption this distribution is similar to exponential distribution with mean equals 470 passages.

Figure 7: Distributions of ship positions on the waterway.

Figure 8: Cumulative density of safe passages between accidents fitted to exponential distribution.
3 Modelling the accidents caused by exceeding of the available water depth

The accidents caused by insufficient clearance under the ships hulls (exceeding the available water depth), concluded by ships hitting the bottom, can be characterised by the significant limitation of human factor influence during ship passage [4, 5]. Human error is critical here during voyage planning stage. Experts are necessary in this method for defining types and parameters of given distribution used in simulations.

The method applied for this kind of accident is a strict probabilistic method based on sampling from several distributions related with under-keel clearance. This kind of accident is related with many factors like sounding and dredging errors, squat and draft estimation errors, roughness of the bottom, wave influence on the ship, tide and water level calculation errors, etc. All of these parameters are included into the Monte Carlo model with use of its distributions (Fig. 9).

In the real case two distributions should be considered. The distribution of the deepest point of the ship in vertical plane $f_s(s)$ and minimal depth distribution $f_h(h)$ (Fig. 9). Then the density function of distribution $\Delta = H - S$ can be presented as a combination of two distributions $H$ and $S$. Under the assumption that $H$ and $S$ are independent it can be written:

$$f_{H-S}(\delta) = \int_{-\infty}^{+\infty} f_h(h) f_s(h - \delta) ds$$

and probability of accident is given by:

$$P_{AS} = P_{AC} \int_{-\infty}^{R_{min}} f_{H-S}(\delta) d\delta$$

where:

- $R_{min}$ – minimal under keel clearance,
- $P_{AC}$ – severe accident probability (Heinrich ratio).

Figure 9: Distributions related with under keel clearance of ship.
To build a Monte Carlo model of a ship’s underwater keel clearance the uncertainties should be divided into epistemic (model uncertainties) and aleatory (data uncertainties). The first of them can be reduced but the second cannot. To build a MC model first it should be performed with detailed analysis of every kind of distribution in the model. In the following there are presented some of the uncertainty sources and the distribution used for its modelling:

- squat (4 empirical models are used) – normal distribution with mean and variance obtained from results of 4 available methods,
- increase of draught due to roll (2 models are used) – uniform with limits of two available methods,
- error of draft reading – normal,
- error of sounding – normal,
- water level determination error – normal,
- distribution of available depth \( f_d(h) \) – discrete, obtained from sounding diagrams: shifted gamma, lognormal or exponential distribution,

The Fig. 10 presents the results obtained by MC simulation. Three different draughts of ships were taken into account. Draught 9.15m is presently the maximum allowable in Swinoujscie-Szczecin waterway. It should be noted that on the bases of Fig.10, higher draughts could possibly fulfil the safety criteria.

![Cumulative distribution of under keel clearance of three ships with different draught.](image)

**Figure 10:** Cumulative distribution of under keel clearance of three ships with different draught.

### 4 Conclusions

The presented model of general risk includes two most important accidents prevailing on restricted water areas such as grounding, due to exceeding horizontal boundaries, and grounding due to insufficient water depth. As it was proven, the Monte Carlo method with non-homogenous Poisson process is the most suitable for modelling the first kind of accidents. Presented in the paper are general models of risk that can be used in risk assessment methods, decision support systems and safety evaluation of marine systems.
References


