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Research of Quantitative Indicators of Tightness of the Northern Sea Route (NSR)

Aleksandr Tezikov[1], Andrei Afonin[1], Vitaly Kljuev[2]
[1] Admiral Makarov State University of Maritime and Inland Shipping, Saint-Petersburg, Russia
[2] The Ministry of Transport of the Russian Federation, Moscow, Russia

ABSTRACT

The paper discusses the features of the Arctic shipping and the main sources of navigational accident risk in the Arctic seas in the Northern Sea Route (NSR).
The results of the analysis of risk assessment techniques of navigation accidents, based on the use of the global and regional statistics of marine accidents are considered. In addition, we used data from the Russian Northern Sea Route Administration. Statistical representativeness of navigational accidents related to the seas of the Arctic basin was estimated.
The study found an association between the frequency of incidents of navigation and tightness of aquatory.
The term "tightness of aquatory", which is usually used in connection with the navigation of vessels in narrow waters and in shallow water, is proposed to use as the generalized characteristics of the entire water area of the NSR and its individual parts including for seaports.
To determine the degree of tightness of aquatory we suggested to use a method, based on the theory of geometric probability.
The examples of the effective use of geometric probability theory to solve practical problems of hydrography and decoding images are presented.
The paper presents the basic scientific principles, formulas and ratios that allow to calculate the required probability analytically for two variants of the direction of flow of ship, including isotropic and anisotropic many routes.
All studies were conducted in the Arctic Faculty of the Admiral Makarov State University of maritime and inland shipping. In conclusion, the article gives a general evaluation of the prop osed method and the directions of its perfection.

KEY WORDS: Polar Code; FSA; Quantitative assessment; Geometrical probability; Navigational hazard.

INTRODUCTION

The principles of Formal Safety Assessment (FSA) stated in the Temporary manual were developed and approved by Maritime Safety Committee and Marine Environment Protection Committee of the International Maritime Organization (IMO) (Revised guidelines for formal safety (FSA) for use in the IMO rule making process, 2014) since 1997. The Polar Code, 2015 which is also in many respects based on the principles of FSA came into force in 2017.

The essence of the FSA concept is aprioristic risk assessment of marine navigational and environmental incidents and development of the actions directed at decreasing these risks (Chen, 2001). The world or regional statistics of accidents is used, as a rule, in case of risks assessment of navigation incidents (Pastusiak, 2016). Statistics allows to select some general reasons of accidents by their types, for example ecological - (Moe, 2000), on the frequency and conditions and to use the obtained data as the initial aprioristic estimates at FSA development.

The available statistics of navigation incidents on the water area of NSR (Federal state Institution “The Northern Sea Route Administration”, 2017) can't be objective for the existing and perspective year-round Arctic transport projects because generally it was created in the conditions of extremely low navigation intensity, only for the summer navigation period and as a rule, for vessels with insignificant draft and not having ice strengthening.

The traditional method of aprioristic assessments of probabilities of navigation incidents can be applied to the water area of NSR only partially because the conditions of the Arctic navigation and its risks substantially differ from the navigation conditions and the corresponding risks on not Arctic water area of the World Ocean.

DEFINITION OF RESEARCH PROBLEM

Aprioristic assessment of probability can be carried out on the basis of the general assumptions of adverse events in the absence of reliable statistical data. It is established (Kljuev, 2016) that navigation incidents happen on the "constrained" sites of water areas more often. At the same time degree of "tightness" of the water area is defined by sizes and quantity of its sites dangerous to navigation. It should be noted that the term "tightness" of the water area is usually used for vessels navigation in narrow waters and in shallow water where tortuosity of fairway and proximity to surface and underwater navigation hazards significantly influence maneuverable characteristics of the vessel.

Results of hydrographic research of the Arctic seas (Batalin, 2008; Federal State Unitary Enterprise "Hydrographic Enterprise", 2016; Kastner, 2015; Reshetnyak, 2006; Svahn, 2015) show that the water area of NSR is mainly shallow, abounds with a large number of underwater navigational hazards which are shallows, banks, reefs and rocks and therefore can be characterized as "constrained". Comparative assessment of "tightness" degree of the water area of NSR and its separate parts is required to perform for definition of areas potentially dangerous for navigation and implementation of the complex actions directed to decreasing of incidents risks (Revised guidelines for formal safety (FSA) for use in the IMO rule making process, 2014). It is expediently to carry out the comparative assessment using some generalized quantitative indicators of the water area. Obviously that the calculation method of such indicators and the indicators themselves have to be justified, realized in practice and objective.

The quantitative assessment of "tightness" degree of separate parts of the NSR water area is offered to perform by the methods developed in the theory of geometrical probabilities and corresponding the listed requirements. The example of use of the theory of geometrical probabilities at the solution of practical tasks is use during the performing of shooting of underwater relief and search of underwater objects and also recognition of the scanned images. Use of the theory of geometrical probabilities allows to reduce a task of quantitative assessment of the water area "tightness" to a task about crossing of straight lines with curves on the plane. At the same time the probability of crossing of straight lines (vessel way) with curves (contours of navigation hazards) P_o is accepted as a quantitative measure of "tightness" of the water area M_{TWA}.

DEVELOPMENT AND JUSTIFICATION OF METHOD OF QUANTITATIVE ASSESSMENT OF THE WATER AREA "TIGHTNESS"

Local rise of bottom which is dangerous to the vessel with draft *d* is given as

$$R_{hi}^{d} = R_{hi}\left[x, y, z < z_{ex}\left(d\right)\right], \tag{1}$$

where the lower index "h" designates "hazard"; *i* — the number of hazard; *x, y* — planned coordinates of a local rise; *z* — depths in the internal area of local rise of bottom; $z_{ex}(d)$ — extreme passing depths for the vessel with draft *d*.

Vessel routes are set by array of lines as

$$G = \{G(d)\}. \tag{2}$$

The consideration of draft *d* in models (1) and (2) is fundamental because passing depths and sizes of that part of local rise of bottom which has to be accepted as dangerous depend on her value.

The probability P_o of crossing of routes of the vessel G with danger R_{hi}^{d} represents a measure of undesirable event $M_{TWA}[G \cap R_{hi}^{d} \neq 0]$ that is written as

$$P_o = P\left[G \cap R_{hi}^{d} \neq 0\right] = M_{TWA}\left[G \cap R_{hi}^{d}\right]. \tag{3}$$

The probability of safe navigation P_S is defined by a condition under which any of routes G won't cross hazard R_{hi}^{d}. This condition is established by ratio

$$P_S = P\left[G \cap R_{hi}^{d} = 0\right]. \tag{4}$$

The events set by conditions (3) and (4) make full group of events, i.e.

$$P_o + P_S = 1.$$

Algorithms of probabilities (3) and (4) calculation depend on the choice of the direction of routes G for which the assessment of " tightness " of the water area is carried out. It is possible to allocate two main ways of setting of routes directions: isotropic and anisotropic. At the isotropic method the routes are arranged in all possible directions. At the anisotropic method the priority direction of routes, for example, "East" - "West" is allocated. The routes which are different from the routes set in the direction are considered forbidden at the anisotropic method of the routes direction.

ISOTROPIC SET OF ROUTES

We consider a part of the water area which is limited to a quadrate of the square *S* and perimeter *L(S)*. We consider that there is one local rise of bottom R_{hi}^{d}, where $i = 1$, on the water area

If we assume that routes G can cross the allocated part of the water area in any direction that corresponds to the isotropic set of straight lines, then the probability of undesirable event (3) equal to measure of "tightness" of the water area $\mathrm{M}^1_{\mathrm{TWA}}$ can be calculated on a formula

$$P_{\mathrm{o}} = \mathrm{M}^1_{\mathrm{TWA}} = \frac{L(R^d_{h1})}{L(S)}, \tag{5}$$

where $L(R^d_{\mathrm{o}1})$ — perimeter of contour of local rise R^d_{h1}; superscript "1" indicates the number of local rises on the water area.

The equation (5) implies the probability of undesirable event doesn't depend on the position of the local rise R^d_{h1} in the allocated part of the water area.

Let's consider more general case when on the allocated part of the water area there are two dangerous rises R^d_{h1} and R^d_{h2} removed from each other so that the safe route can be laid between them.

We will unite the rises R^d_{h1} и R^d_{h2} by the general contour which perimeter we will designate as $L(\oplus) = L\left(R^d_{h1} \oplus R^d_{h2}\right)$. The probability that routes at their isotropic arrangement will cross the general contour can be calculated by a formula

$$P_{\mathrm{o}} = \frac{L(\oplus)}{L(S)}. \tag{6}$$

The probability that any of routes won't cross the general contour will be equal

$$P_S = 1 - P_{\mathrm{o}}. \tag{7}$$

Expression (7) is received on the basis that probabilities P_{o} and P_S form full group of casual events.

The routes passing through the general contour are divided into four groups:

– $G \cap R^d_{h1} \neq 0$ — the routes crossing the rise R^d_{h1} (an adverse event);

– $G \cap R^d_{h2} \neq 0$ — the routes crossing the rise R^d_{h2} (an adverse event);

– $G \cap \left(R^d_{h1}, R^d_{h2}\right) \neq 0$ — the routes which are at the same time crossing both rises (an adverse event);

– $G \cap \left(R^d_{h1}, R^d_{h2}\right) = 0$ — the routes passing between rises R^d_{h1} and $R^d_{\mathrm{o}2}$ (a favorable event).

From the listed groups of routes the fourth group characterizes safe navigation whereas the first three define degree of "tightness" of the water area.

The measurement of length of the "twisted" contour encompassing rises R^d_{h1} and R^d_{h2} is required for determination of probability of each of the listed four events. The length of the contour is denoted as $L(\otimes) = L\left(R^d_{h1} \otimes R^d_{h2}\right)$.

Taking into account the designations presented above the probabilities of each of the listed four events are calculated by the following formulas:

$$P\left(G\cap R_{h1}^{d}\neq 0\right)=\frac{L(\oplus)-L\left(\otimes\right)+L\left(R_{h1}^{d}\right)}{L\left(S\right)}; \quad (8)$$

$$P\left(G\cap R_{h2}^{d}\neq 0\right)=\frac{L(\oplus)-L\left(\otimes\right)+L\left(R_{h2}^{d}\right)}{L\left(S\right)}; \quad (9)$$

$$P\left(G\cap\left(R_{h1}^{d},R_{h2}^{d}\right)\neq 0\right)=\frac{L\left(\otimes\right)-L\left(\oplus\right)}{L\left(S\right)}; \quad (10)$$

$$P\left(G\cap\left(R_{h1}^{d},R_{h2}^{d}\right)=0\right)=\frac{L\left(\otimes\right)-L\left(R_{h1}^{d}\right)-L\left(R_{h2}^{d}\right)}{L\left(S\right)}. \quad (11)$$

The sum of the probabilities calculated by formulas (8) – (11) is equal to the ratio $L\left(\oplus\right)/L\left(S\right)$, that corresponds to the probability calculated by formula (6).

Quantitative assessment of "tightness" of the water area at the isotropic arrangement of routes on the basis of formulas (6) – (11) for two local spaced dangerous rises, equal to the probability of crossing at least of one of hazards, is determined by formula

$$\mathrm{M}_{\mathrm{TWA}}^{2}=\frac{L\left(R_{h1}^{d}\right)+L\left(R_{h2}^{d}\right)}{L\left(S\right)}. \quad (12)$$

Generalizing the received result on *n* dangerous rises of bottom at the isotropic arrangement of routes, we will receive expression for quantitative assessment of " tightness " of the water area as

$$\mathrm{M}_{\mathrm{TWA}}^{n}=\frac{\sum_{1}^{n}L\left(R_{hi}^{d}\right)}{L(S)}. \quad (13)$$

The formula (13) shows that the indicator of "tightness" of the water area in the absence of any preferred direction of the chosen routes is defined by a ratio of the sizes of the water area and dangers.

ANISOTROPIC SET OF ROUTES

Let's consider the part of the water area limited to a rectangle with square *S* and perimeter *L (S)*.

We assume that there are no local rises of bottom on the water area. Routes belong to a set of straight lines which at the same time cross the right and left vertical framework of the area in any their point. At the same time any of them can't cross either the top horizontal frame, or lower. Each of horizontal frameworks, by analogy with (1), can be interpreted as some dangerous object therefore for their description we use following expression

$$R_{Ei}^{d}=R_{Ei}\left[x,y,z<z_{ex}\left(d\right)\right], \quad (14)$$

where the lower index «*E*» is border of forbidden area; index «*i*» is number of a framework which is forbidden to be crossed.

Replacement of object (1) on the object (14) allows the task of calculation of "tightness" indicator of the water area for the anisotropic set of routes to reduce to the task of calculation of "tightness" indicator for the isotropic set of routes considered earlier.

The full set of routes G crossing the allocated part of the water area is divided into four groups:

– $G \cap R_{E1}^{d} \neq 0$ — the routes crossing framework R_{E1}^{d};

– $G \cap R_{E2}^{d} \neq 0$ — the routes crossing framework R_{E2}^{d};

– $G \cap \left(R_{E1}^{d}, R_{E2}^{d}\right) \neq 0$ — the routes which are crossing both horizontal frames at the same time;

– $G \cap \left(R_{E1}^{d}, R_{E2}^{d}\right) = 0$ — the routes passing between frameworks R_{E1}^{d} and R_{E2}^{d}.

From the listed groups of routes the fourth group characterizes safe navigation whereas the first three groups define degree of "tightness" of the water area. Probabilities of each of the listed four groups are calculated by formulas:

$$P\left(G \cap R_{E1}^{d} \neq 0\right) = \frac{L(\oplus) - L(\otimes) + L\left(R_{E1}^{d}\right)}{L(\oplus)}; \tag{15}$$

$$P\left(G \cap R_{E2}^{d} \neq 0\right) = \frac{L(\oplus) - L(\otimes) + L\left(R_{E2}^{d}\right)}{L(\oplus)}; \tag{16}$$

$$P\left(G \cap \left(R_{E1}^{d}, R_{E2}^{d}\right) \neq 0\right) = \frac{L(\otimes) - L(\oplus)}{L(\oplus)}; \tag{17}$$

$$P\left(G \cap \left(R_{E1}^{d}, R_{E2}^{d}\right) = 0\right) = \frac{L(\otimes) - L\left(R_{E1}^{d}\right) - L\left(R_{E2}^{d}\right)}{L(\oplus)}. \tag{18}$$

In formulas (15), (16) and (18) the summand $L\left(R_{E1}^{d}\right)$ and $L\left(R_{E2}^{d}\right)$ representing perimeters of segments of straight lines, are equal to the doubled length of each of segments.

Based on the fact that the events connected with crossing by routes of all four borders of the allocated area make full group

$$P\left(G \cap R_{E1}^{d} \neq 0\right) + P\left(G \cap R_{E2}^{d} \neq 0\right) + P\left(G \cap \left(R_{E1}^{d}, R_{E2}^{d}\right) \neq 0\right) + P\left(G \cap \left(R_{E1}^{d}, R_{E2}^{d}\right) = 0\right) = 1, \tag{19}$$

the “tightness” indicator of the water area has the following form:

$$\mathrm{M}_{\mathrm{TWA}}^{2} = 1 - P\left(G \cap \left(R_{E1}^{d}, R_{E2}^{d}\right) = 0\right). \tag{20}$$

Taking into account the expression (18), we will receive calculated formula for the indicator of the water area constrained by two borders:

$$\mathrm{M}_{\mathrm{TWA}}^{2} = 1 - \frac{L(\otimes) - L\left(R_{E1}^{d}\right) - L\left(R_{E2}^{d}\right)}{L(\oplus)}. \tag{21}$$

The analysis of formula (21) shows that at the anisotropic choice of routes the "tightness" indicator of the water area depends not only on a ratio of the sizes of the water area and hazards, but also on their mutual arrangement.

The "tightness" indicator of the water area with other things being equal always has bigger numerical significance for areas where the priority direction of the vessels movement is allocated in comparison with areas where the priority direction of the movement isn't established. With use of the developed technique there is a possibility of laying of the most optimum routes on NSR, including and with use of the software developed earlier (Afonin, 2016).

CONCLUSION

It is offered to use probability of crossing of vessel routes with navigation hazards as a quantitative measure of "tightness" of the water area. The article presents the basic formulas and ratios allowing to calculate analytically the required probability for two options of the direction of the vessels streams including the isotropic set of routes and anisotropic set of routes. The general assessment of the offered method and the directions of his improvement:

1. The quantitative indicator of "tightness" of the water area can be used in FSA for polar and Arctic navigation.

2. Use of the theory of geometrical probabilities allows to receive the quantitative indicator of "tightness" of the water area having obvious geometrical interpretation of the events leading to collision with hazards.

3. Algorithm of calculation of "tightness" indicators of the water area is rather simple in realization because it is based on measurements of lines lengths on navigation charts and calculation of their ratios. The algorithm is characterized by sufficient simplicity.

4. "Tightness" of the water area, apparently, has to be estimated by some set of quantitative indicators because it depends on the main vessels sizes, the established directions of their movement, borders of the water area and other factors. The question of structure of such indicators needs additional justification.

5. The approach to assessment of "tightness" of the water area used in this work can be extended to the dynamic objects influencing risk of navigation incidents in the Arctic seas.

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