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THE RESULTS OF COMPUTER SIMULATION OF THE PROBABILITY OF ACCIDENTS DUE TO SHIP NIPS BY DRIFTING ICE ALONG THE NORTHERN SEA THROUGHWAY

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Results of testing of computer simulation model for assessment of probability of accidents with tankers due to pressure by drifting ice are presented. The testing was carried out for the navigation route «Sabetta Port – Kara Gate Strait – Murmansk Port» and for the first ten-days period of May, during the most difficult ice conditions of the navigation. The probabilities of the accidents were calculated. There was analyzed the model response to variations of its parameters values.

Keywords: simulation, accident probability, nips

Introduction

Modern civilization is hydrocarbon-based: energy sector and chemical industry are powered by oil, oil products and natural gas. Exhaustion of old fields forces the exploitation of new oil and gas fields in the Subarctic region and on the shelves of the Arctic seas. This fact requires the development of systems to transport hydrocarbons, in particular, sea transport systems of the Northern Sea Route (NSR) [1, 2, 3].

In accordance with the project Yamal LNG the third LNG (liquefied natural gas) train is already launched in the largest LNG plant located in Sabetta at the Yamal Peninsula. In the near future it is planned to increase its total capacity and come to level of production of 17.4 million tons of liquefied natural gas per annum [4]. Project is based on the resources of the Yuzhno-Tambeyskoye (South-Tambey) gas field which includes reserves of more than 1 trillion cubic meters of natural gas. Liquefied natural gas is exported by six modern carriers by standard navigation routes [5, 6]. Achieving the plant total capacity will increase traffic requirement. Besides, the Northern Sea Route is used for transporting large amount of oil. In the current time hydrocarbons are exported by tankers from the offshore Varandey oil terminal and ice-resistant oil platform Prirazlomnaya located in the Pechora Sea (south-eastern part of the Barents Sea), Kharasavey sea terminal located at the west of the Yamal Peninsula in the Kara Sea, ports of Sabetta and Novy Port at the east of Yamal Peninsula in the Gulf of Ob. Transportation is carried out by modern tankers and LNG carriers. Ice strengthening of vessel class Arc7 allows them to navigate independently stern first in ice up to 2.1 m thick [7, 8].

Operation of any transport system is accompanied by accidents resulting in oil and liquefied gas spills and environmental pollution [9, 10, 11]. During ice navigation an emergency situation may be caused by ship collision, stranding, docking impact by coastal terminal or platform, collision with icebergs and ice formations [12]. All reasons listed above are human errors, since abidance by the safety navigation rules and properly functioning radar facilities can reduce the risk of accidents caused by these reasons to near-zero values. Force majeure reason of accident is ship besetting under ice pressure. All wrecks of ships in the Arctic Ocean were caused by ship besetting, except war losses [13]. Ice cover is the major hazard to navigation along the Northern Sea Route and hindrance to business activities in the Arctic [14]. Computational modeling allows to predict the location, strength and probability of zones of possible ship besetting under ice pressure, but it can't entirely eliminate the possibility of besetting.

The study aims to test the computer model of evaluation of accident probability due to ice pressure on the route "Sabetta–Kara Strait–Murmansk" (Fig.1).

Materials and methods

To evaluate the probability of accident a Monte Carlo-based computer model was created and improved by V.Yu. Tretyakov. This method is used for simulation of random events in case of achieving critical values by some parameters (e.g., vessel under pressure in level ice of specified thickness, etc.)

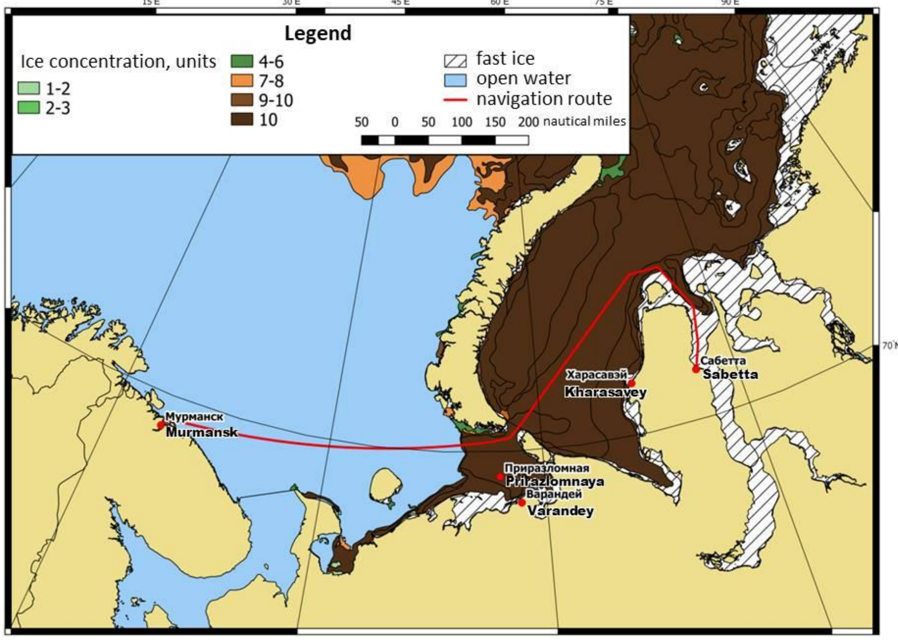

Figure 1. Map of the route. Ice conditions are of the period 10-20 of May, 2018

In the model an accident occurs if vessel is in the zone of ice pressure and ice strength is upper than an amidship. If ridge concentration is more than 2 units than ice strength is taken to be equal to the greater value between level ice strength and strength of consolidated layer of ridges. During the model numerical simulations ice cover characteristics are set as stochastic variables (not deterministic), and their statistical distributions are model parameters. The cumulative distribution functions are following: function of probability for vessel to get into zone under ice pressure;

summarized length of a route in very close floating ice; relative lengths of parts of route in very close floating ice of various age; area of homogenous ice zones; lengths of parts of the route under ice pressure and without ice pressure; thicknesses of ice of various age; ridge concentration; ratio of ridge concentration to total ridge and hummock concentration; lengths of linear ridges; widths of ridges; ratio of ridge width to ridge altitude; thickness of consolidated layer of ridges. In Monte Carlo simulation, a random number generator provides a decimal fraction in the [0,1] interval which is considered as value of cumulative distribution function of the given characteristic of ice cover. Based on this value the quantile is estimated which is a specific value of ice characteristic. In the model we take into account only static interaction between hull and ice. Strength of the hull's elements is estimated according to the requirements of the Russian Registry of Shipping. If randomly generated ice strength and its statistical distribution exceed the strength of a vessel, this cause hull destruction and emergency situation. Statistical distributions of ice characteristics are based on ice maps of the Arctic and Antarctic Research Institute (AARI) archive, data on AARI expeditions and literature sources. Ice compression strength depends on many factors. Study on ice compression strength in ice interactions with different structures are high-demand and carried out by Russian [15-19] and foreign [20-24] specialists.

Ice strength depends on its thickness. During the period from the beginning of sustainable ice formation to the beginning of summer thawing ice thickness is determined by its age. Ridging develop predominantly in young and thin first-year ice (FYI). Newly-formed ridges are made of single ice rubbles that have the same thickness as the parent ice floe. Thus new ridges don't pose a risk of ship besetting under ice pressure. The situation changes when the consolidation of part of single ice rubbles occurs and forms so called consolidated ice layer. It is supposed that navigators are able to avoid ridges if ridge concentration is up to 2 units according to Russian nomenclature (i.e. 2/5). In this case strength of level ice alone is taken into account; notably, both strength of deformation and strength of fracture are examined [25], and the lowest value is taken as the ice strength.

According to studies [26, 27] ridge concentration is 50% of total hummock and ridge concentration. Spatial orientation of ridges is random [27, 28], thus distribution of ridge orientations is set as proportional and mean angle between the direct course of a vessel and the ridge line is 45%.

Pre-processing of statistical distributions of summarized lengths of parts of the route characterized by specific parameters of ice cover is based on vector maps of ice conditions from AARI archive. These maps were made by the Centre of ice meteorological information of AARI on the base of remote sensing data [29].

Processing of vector map is made with use of ArcGIS as follows: polygonal objects of ice maps are crossed by linear object of navigation route. As a result a layer of linear objects is created that have the same sets of attributes as those of the crossed polygons. After that selection of objects according to their attribute values is done and lengths of the objects are calculated. Objects with total ice concentration not less than 9 units (9/10) with presence of ice older than young stage are identified, subsequently the selected objects are added to the new layer of parts of the route. Next step is to sort objects by age and to add them into separate layers. Lengths of individual objects and summarized lengths of objects that meet certain criteria are calculated. These result in ten-days series of lengths of the route segments in close ice, in close ice with presence of young (up to 10 cm thick), grey (10-15 cm thick), grey/white (15-30 cm thick), thin FYI (30-70 cm thick), medium FYI (70-120 cm thick), thick FYI (more than 120 cm thick). Besides, ten-days series of summarized lengths of parts of route in close ice with partial concentration of thick first-year ice of at least 5 tenths and summarized lengths of parts of route in close ice with sum of partial concentrations of thick first-year ice and medium first-year ice of at least 5 tenths are calculated.

The origin set of numeric variables for statistical distribution of parameter values of the model should be homogeneous. Thus the analysis of obtained numerical series for presence of interannual trend is made based on cumulative curves. Method of cumulative sums originally was applied in hydrology to examine the presence or absence of directed trends in the interannual dynamic of annual river discharges [30]. Afterwards it was applied for preliminary interannual variability analysis of any environmental parameters. Summary of this method is the following. A plot is made with years on the x-axis and cumulative sums of parameter values of specific years on the y-axis. In our case these are the values of the same within-year (intra-annual) ten-day interval of different years. Cumulative sum for particular year is the sum of values from the beginning of the time series to this particular year inclusive. For the first year it is the value itself, for the second year it is the sum of the values of both the first and the second year, etc. Data points of cumulative sums on the plot are connected with a line. The line must be close to the straight line in case of the absence of interannual variability. The kinked or broken-line curve show that there is a trend and the data is heterogeneous.

For curves that are close to straight line the original numerical series is divided into halves to examine its homogeneity. For kinked or broken-line curve the original numerical series is divided into parts in the points of inflection. If number of elements is not enough for statistical analysis, than original numerical series is divided into two parts in the point of the most significant inflection. Next step is testing the null hypothesis that two parts belong to one population, that means the absence of significant differences between these two samples. Verification is made in Mathcad with use of Mann-Whitney-Wilcoxon and Siegel-Tukey nonparametric tests.

Statistical distributions of model parameters were made in Mathcad based on methods of Hazen, Kritskiy-Menkel, Tchegodayev and Gringorten. Statistical distributions that were obtained by different methods varied inessentially. Therefore statistical distributions calculated by Gringorten method which combine three other methods were used in the model (Fig.2).

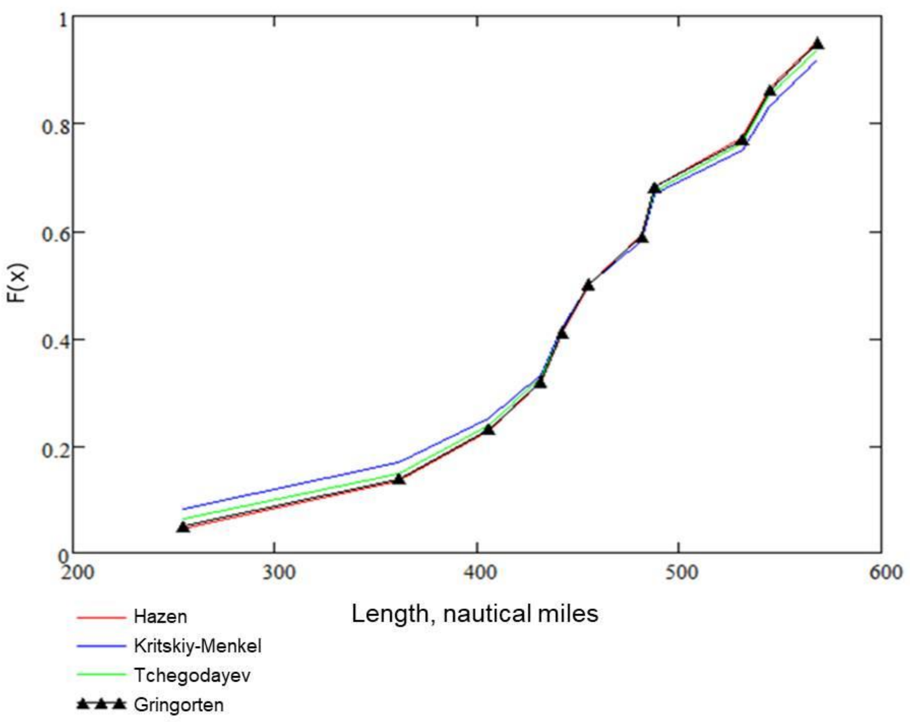

Figure 2. Cumulative distribution function of length of the route in close ice for the first ten-day period of May calculated by different methods.

Statistical distributions of parameters are put in txt-files which are multiply used for calculations during numerical experiments.

Model is built in Delphi algorithmic language. It provides for both automatic and forced end of individual numerical experiment (series of navigations). User sets number of simulations in one computer calculation. Statistical distributions of model parameters remain constant in an individual calculation. Automatic end of numerical experiment (series of navigations) occurs in case of stabilization of the ratio of number of accidents to number of navigations. If A is a ratio of number of accidents to number of navigations to the end of this simulation, B is a ratio of number of accidents to number of navigations in case of previous accident, than numerical experiment ends on condition that $| A – B | < (A*0.001)$. Numerical experiment also ends in case of 10001 accident-free navigations.

However, there is a possibility for maximal number of navigations per ten-days period to be substantially less than number of navigations which provides stabilization of the ratio of number of accidents to number of navigations. In this case in one numerical experiment (series of navigations) maximal number of navigations which is expected for a given ten-days interval throughout the entire period of operation of this sea transport system is set. The numerical experiment is forced to end after accomplishing of this number of iterations without regard for stabilization of accidents to navigations ratio. Both in automatic and forced end of numerical experiments user establishes a number of numerical experiments in one computer calculation. The ratio of number of accidents to number of navigations is regarded as probability of accident. Since one computer calculation consists of a series of numerical experiments, the probability of accident should be regarded as a random variable with mathematical expectation (E) and root-mean-square deviation (RMSD). According to central limit theorem, statistical distribution of a random variable will approximate a normal distribution since it is contributed by variety of factors. As an upper bound of accident probability we suggest to use sum of E and triple RMSD with running series of not less than 30 numerical experiments with forced end. In that case probability of greater accident rate according to three-sigma rule is only 0.15%. Thus this approach should be applied to estimate expected damage.

Results and discussion

The model was tested for the most difficult ice conditions of the first 10-days period of May. The ratio of number of accidents to total number of navigations in case of automatic end of numerical simulations for 70000-toner Arc7 vessel was 0.023. The most important stage of simulation modeling in scientific researches is model sensitivity testing to parameters varying. For this purpose we set a number of simulations with fixed maximum and minimum parameters according to their statistical distributions. For example, to learn model sensitivity to variation of total hummock and ridges concentrations we have compared results of simulations of situation of absence of ridges and situation of maximum ridge concentration of 4.5 units (i.e. up to 90% of ice area is covered by ridges). This procedure is necessary to verify the model: if changing the value of specific parameter is evidently supposed to cause accident but has no effect on simulation results, then there is an appreciable error in model algorithm or program code. Besides, this procedure reveals the most sensitive parameters of the model, which require additional field study and/or specific processing of previous data of expeditions, experiments, satellite data, etc. Results of simulations for determining the most important parameters are represented in Table 1. “Reference” scenario means that all values are based on files of statistical distributions and random numbers generation. Otherwise input values for testing model for sensitivity to a specific parameter are set by user. Processing and averaging of results is made using R.

Table 1 – Model outputs for different parameters.

Model parameters	Parameter minimum and maximum	Probability of accident (average for 30 simulations)
«Reference» scenario	-	0.023
Length of route in close ice	min – 255 nm (nautic miles)	0.016
	max – 567 nm	0.028
Ridge concentration	min – 0 units (0/5)	0

	max – 4.5 units (4.5/5)	0.030
Probability of ship besetting under ice pressure	min – 0	0
	max – 0.02	0.044
Length of parts of route under ice pressure	min – 2.9 m.miles	0.017
	max – 69.7 m.miles	0.027
Length of parts of route without ice pressure	min – 6.2 m.miles	0.441
	max – 1609.7 m.miles	0.009

Thereby, parameters that governed the probability of accident are following: length of the route in close ice, total ridge and hummock concentration, probability of ship besetting under ice pressure and length of parts of route under ice pressure.

The results of 450 numerical simulations with varying vessel ice classes and vessel displacements are presented in Table 2.

Table 2 – Simulation results of navigations of different vessel ice classes and displacements

Vessel ice class	Displacement, Thousand tons	Probability of accident (average for 30 simulations)
Arc5	45	0.025
	70	0.025
	85	0.024
Arc6	45	0.025
	70	0.024
	85	0.025
Arc7	45	0.024
	70	0.024
	85	0.023
Arc8	45	0.022
	70	0.024
	85	0.023
Arc9	45	0.022
	70	0.022
	85	0.020

The results are visualized on Figure 3. The data indicates that stronger ice class reduces probability of accident. Thus, the model simulates correctly the increasing strength of the hull in case of increasing ice class.

Furthermore, about 600 model simulations were made with forced setting a value of number of navigations in one experiment for ice classes Arc5, Arc6, Arc7, Arc8, Arc9 with displacement of 70000 tons. Number of navigations varied, setting equal to 30, 100, 500 and 1000 in one experiment. Simulation results are shown in Table 3.

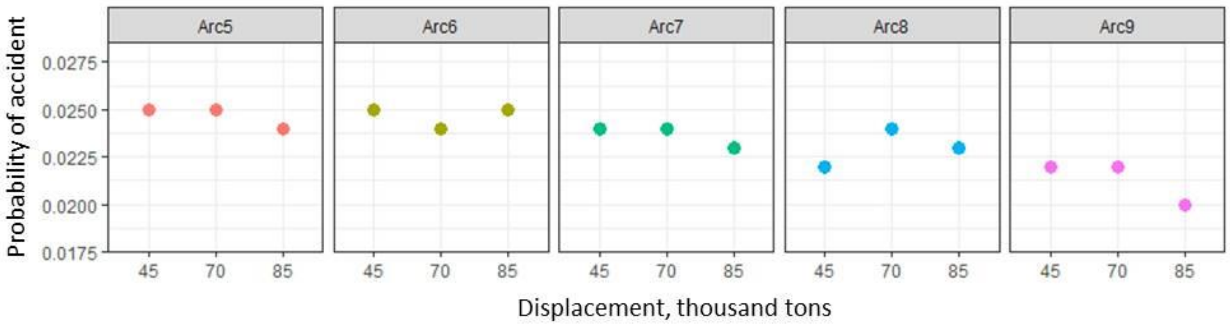

Figure 3. Simulation results for different ice classes of vessels

Table 3 – Simulation results with forced setting of number of navigations

Ice class	Number of navigations in one experiment	Probability of accident (average for 30 simulations)
Arc5	30	0.104
	100	0.040
	500	0.026
	1000	0.023
Arc6	30	0.091
	100	0.046
	500	0.025
	1000	0.024
Arc7	30	0.132
	100	0.051
	500	0.024
	1000	0.023
Arc8	30	0.257
	100	0.043
	500	0.023
	1000	0.023
Arc9	30	0.097
	100	0.039
	500	0.024
	1000	0.022

Conclusions

In this study the computer model of evaluation of accident probability due to ship besetting under ice pressure on the route “Sabetta–Kara Strait–Murmansk” was tested. To conduct numerical experiments the distributions of parameters of the model (i.e. characteristics of ice cover) are prepared, these are: thickness of consolidated layer of ridges, ratio of ridge width to ridge altitude, percentage of ridge concentration, total ridge and hummock concentration, lengths of parts of route without ice pressure, length of navigation route in close ice, relative length of route in close ice with presence of thick FYI, medium FYI, thin FYI and young ice. For data preparation ten-day interval vector maps of ice conditions on the route for the period 1997-2018 from AARI archive were processed. Obtained series of lengths were tested for having a trend based on method of cumulative curves and were tested for homogeneous by use of Mann-Whitney-Wilcoxon and Siegel-Tukey nonparametric tests. Statistical distributions were based on methods of Hazen, Kritskiy-Menkel, Tchegodayev and Gringorten.

The main conclusions from the results of simulations include the following:

1) Parameters that markedly affect the accident probability are length of the route in close ice, total ridge and hummock concentration, probability of ship besetting under ice pressure, lengths of parts of route under ice pressure;

2) Calculations with forced end of numerical experiments with small number of navigations show accident probability several times higher than those with more than 100 navigations or in case of automatic end;

3) Probability of accident due to ice pressure for ice class Arc7 is 0.023 on navigation route “Sabetta–Kara Strait–Murmansk” during first ten-day period of May which is characterized by the most difficult ice conditions on the route.

Risk assessment is crucial for strategic planning of logistic systems for production and transportation of hydrocarbons in the Arctic.

It is necessary to note that research activities in this field are in progress. For instance, lengths of parts of route in various types of ice have already been calculated for another high-demand navigation route “Sabetta-the Bering Strait”.

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