Probabilistic Modelling of Icebergs in the Russian Arctic Seas

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Abstract. The paper aims at providing safe development of oil and gas deposits in the offshore area of the Kara and Barents seas where promising hydrocarbon deposits are located. For these water areas marine oil and gas structures construction projects are designed, primarily in connection with the plans for oil and gas fields’ development. Icebergs belong to such kind of drifting ice features, the action of which in most cases neither floating, nor stationary marine hydraulic structures can withstand.

The danger of a large drifting iceberg effect on exploration and production platforms, oil and gas pipelines is obvious, therefore, the iceberg – structure hit probability prediction is of great applied importance.

The aim of the paper is probabilistic modelling of icebergs to prevent their collision with structures, the Kara and Barents seas taken as an example.

1. Introduction
Continental shelf of Kara and Barents seas is the world’s largest source of unexplored hydrocarbon resources. Natural features of this region directly affect implementation of projects. Thus, in the Kara Sea water depth is 40–350 metres, ice conditions are as follows: ice holds up 10 months a year, its thickness reaches one and a half metres, and winter temperature is around 46˚C below zero. In addition, water areas of Barents and Kara seas feature hummocks, stamukhas and icebergs [1,3,8,13,16].

Ice features study is a necessary condition of design, construction and operation of structures in the arctic seas offshore area. However, so far ice features, including hummocks, multiyear ice floes, stamukhas and icebergs in the Russian arctic seas water areas have not been studied fully enough.

Icebergs are one of the most dangerous elements of natural environment both for navigation and for functioning of engineering structures and service lines located in the offshore zone of arctic and subarctic seas. Without taking into consideration this phenomenon the development of natural resources entails high risk both from the point of view of maritime safety and oil&gas production and from the point of view of limitation of damage caused to the natural environment by possible iceberg – structure collisions in sea [10]. Currently, in Russian practice [14] there are no techniques for calculating force impact of icebergs on marine hydraulic structures. Foreign design codes [7,9] contain only approximate methods of evaluating icebergs impact on structures based on probabilistic and statistical methods.
Thereby, it seems promising on the basis of field material obtained by several researchers in recent years to assess morphometric characteristics of ice features and their internal structure as well as to evaluate the danger for facilities in the offshore area of the Russian arctic seas caused by icebergs.

The aim of the paper is probabilistic modelling of icebergs to prevent their collision with structures, the Kara and Barents seas taken as an example.

The main tasks are: probabilistic analysis of morphological and kinematic parameters of icebergs in the promising areas of the deposits; tabular iceberg theoretical model development on the basis of CAD–technologies; probabilistic modelling of iceberg – structure collision for developing schemes of iceberg towing in the regions of promising hydrocarbon deposits in the offshore area of the Kara and Barents seas.

2. Background of problem

A common definition of iceberg is as follows: a massive broken off from a glacier fragment of an ice feature of random shape which, as a rule, is more than 5 m above sea level and can be either afloat or aground [2]. Icebergs are distributed on the territory constituting around 20% of World Ocean area; they have a great range of shapes and dimensions. In northern latitudes large icebergs are 200 m in diameter and 25 m above sea level; their underwater part has up to 200 m draught. Icebergs 1-5 m above sea level are called floebergs, icebergs less than 1 m is growlers. Depending on water density 87-90% of iceberg is underwater [16].

In the Kara Sea the main sources of icebergs formation are the Severnaya Zemlya and Novaya Zemlya archipelagos [2]. The length of the largest outlet glaciers is 50–56 kilometres; the area is more than 1000 square kilometres (Nordenskiöld Glacier on the Novaya Zemlya). It is known that the largest number of icebergs in the Barents Sea is registered near the sources of their formation – the Franz Josef Land, Spitsbergen and Novaya Zemlya archipelagos. But during certain years icebergs may spread far south and reach Norwegian and Russian coasts. The detailed description of such extreme cases based on the analysis of various sources is given in paper [3].

Figure 1 shows the scheme of icebergs repeatability and distribution lines in the Kara Sea [16].

![Figure 1. Icebergs repeatability lines in the Kara Sea (according to the data for the period from 1928 to 1991) and distribution of icebergs registered in 1% repeatability area.](image-url)
A significant parameter for designing is icebergs shapes repeatability in the region of promising deposits [2]. Foreign and Russian researchers from 1988 to 1992 in the Norwegian sector of the Barents Sea registered 8 varieties of icebergs shapes: floeberg, tabular iceberg, growler, pyramidal iceberg, dome-shaped iceberg, rounded iceberg, inclined slope-shaped iceberg and breaking iceberg [1,3,8]. Analysis reveals that the most common shapes of icebergs in the Kara Sea are floebergs and tabular icebergs.

Statistical characteristics of morphometric shapes of icebergs depending on year are given in tables 1–3 [13]. Characteristic calculated parameters of iceberg shapes are:
- iceberg height above sea level;
- iceberg waterline breadth;
- iceberg waterline length;
- iceberg’s keel draught.

As research results showed [13], empirical data of height, breadth and length of icebergs are well approximated by lognormal distribution with parameters given in tables 1-3. The data on iceberg’s keel draught are given in paper [3]. According to the definitions [3], the prevailing shape of icebergs in the Barents Sea is floebergs and growlers. The area along the waterline of such icebergs does not exceed 300 square metres, their height does not exceed 5 m, and their mass is 11 thousand tons. Therefore, the draught of floebers and growlers does not exceed 22 m. Mean draught of icebergs (except floebergs and growlers) is 50 m at standard deviation of 28 m, (interquartile range) is from 30 to 70 m.

**Iceberg height.** Statistical characteristics of yearly icebergs heights distributions are given in table 1.

| Table 1. Icebergs heights distribution, 2003–2009 |
|---------------------------------------------|
| Characteristic, metres | Year of observation |
| Mean value | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
| 9.4 | 4.3 | 11.1 | 7.7 | 11.2 | 16.2 | 12.5 |
| Minimum /maximum | 5/ | 1.6/ | 2/ | 2/ | 2/ | 9/ | 2/ |
| 20.8 | 13.2 | 33.8 | 25.3 | 30.0 | 45.0 | 27.2 |
| Standard deviation | 4.2 | 3.0 | 6.7 | 4.8 | 5.9 | 11.6 | 6.1 |

*Iceberg breadth.* Yearly icebergs breadths distributions are given in table 2.

| Table 2. Icebergs breadths distribution, 2003–2009 |
|---------------------------------------------|
| Characteristic, metres | Year of observation |
| Mean value | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
| 57.0 | 15.3 | 44.5 | 36.7 | 57.7 | 91.0 | 47.4 |
| Minimum /maximum | 10/ | 2/ | 5/ | 4/ | 5/ | 30/ | 10/ |
| 200 | 46 | 210 | 245 | 315 | 163 | 234 |
| Standard deviation | 50.4 | 11.1 | 35.5 | 41.7 | 49.2 | 67.2 | 39.0 |

*Icebergs length.* Yearly icebergs lengths distributions are given in table 3.

| Table 3. Icebergs lengths distribution, 2003–2009 |
|---------------------------------------------|
| Characteristic, metres | Year of distribution |
| Mean value | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
| 84.1 | 24.2 | 71.4 | 65.1 | 89.1 | 121.7 | 97.9 |
| Minimum | 10/ | 5/ | 5/ | 5/ | 40/ | 10/ |
| /maximum | 430 | 166 | 414 | 749 | 933 | 330 | 463 |
| Standard deviation | 85.6 | 23.2 | 64.9 | 83.6 | 105.3 | 96.1 | 78.5 |
3. Geometrical model

Actual iceberg shape consideration is one of the most complicated and formidable tasks while designing structures and navigation operations scheduling in the arctic seas. This is explained by the fact that icebergs have various and random shapes difficult to observe, predict and somehow take into consideration in engineering design. Besides, in spite of an almost 100-years long history of icebergs observations, there is still no reliable data base on icebergs shapes. Nevertheless, information on icebergs physical shapes and drift is of great applied importance, particularly, it is used for iceberg – offshore structures hit probability estimation as well as for prevention of such hits and development of sea operations on icebergs towing tactics [4].

In available literary sources icebergs shapes are described by idealized geometric figures and in most cases are far from the reality. Thus, for instance, in the paper [13] tabular icebergs are simulated as a prism, floebergs – as a cone, spherical segment or ellipsoid of revolution segment. As a rule, in these elementary iceberg models keel draught is unreasonably overestimated, while the wetted perimeter of the underwater part, the mass and volume of iceberg are, on the contrary, underestimated, which leads to substantial structural loads miscalculations.

The solution to the problem is seen in using up-to-date computer technologies, application software for modeling solid-state objects in CAD-systems, such as AutoCAD.

The improved iceberg models proposed by authors aim at correcting loads from these ice features on offshore structures and vessels; they can also be used for towing icebergs in other programs of ice management.

This calculation offers iceberg projections and shapes for calculating iceberg – platform hit probability and for iceberg towing. Figures 2 and 3 show tabular iceberg shapes models built with the aid of AutoCAD software. As the initial data for geometric modeling the statistical parameters of icebergs were chosen which are presented in tables 1-3 and in papers [3,16].

![Figure 2](image_url). Three-dimensional model of tabular iceberg shape (top view).

Figures 4 and 5 give geometric parameters of iceberg with dimensions 102.7×125.4×25.94m, accepted further for iceberg – structure hit probability calculation and subsequent iceberg towing in the water areas of the Barents and Kara seas.

4. Probabilistic model

One of the tasks is assessment of iceberg danger for platforms being installed in the water areas where icebergs occurrence is possible.

From the designing point of view iceberg – platform collision should be considered as a special load. Design codes [7] indicate that for collision prevention it is necessary to provide such activities as towing or stopping by a vessel.

Besides, collisions should be taken into consideration even in case of towing. Thus, iceberg towing is the most effective method of managing ice situation in the water area.
Figure 3. Three-dimensional model of tabular iceberg shape (side view).

Figure 4. Transverse section scheme of tabular iceberg shape (top view).
Currently more than 1500 towing operations have been registered in the waters of arctic offshore area [12].

The characteristics of iceberg danger can serve:
- platform – iceberg hit probability in the course of one year;
- hit probability in the course of year with the iceberg having dimensions or mass not less than specified value;
- hit probability in the course of year with the iceberg having kinetic energy not less than specified;
- probability for the iceberg approaching the platform to distance \( L \) to hit the platform;
- hit probability with the iceberg in the course of year when global load on the platform will be not less than specified, etc.

It should be noted that “probabilistic” design is referred to in the last definition from the above mentioned list describing possible factors of iceberg danger. Iceberg – platform contact interaction resultant load greatly depends on shape characteristics of the iceberg surface local segment directly coming in contact with platform body.

Paper [5] notes that hit probability with iceberg (or more exactly, estimated probability, calculated on the basis of available statistical information with the aid of one or another probabilistic model) cannot of itself give comprehensive information for offshore platform design implementation.

Indeed, if only small icebergs’ (or their fragments’) occurrence is possible in the offshore field zone, the corresponding calculated situation, apparently, will not be crucial for designing. If there are reasons to expect, though not very often, the occurrence of large icebergs, this design situation should be taken into consideration. For instance, in is possible to calculate such characteristics as platform – iceberg hit probability during the given period of time. The iceberg should have kinetic energy not less than the given value [9].

It should be mentioned that the design situation of platform – iceberg collision is a rare event. It means that an actual structure, whose service life in most cases is 25-50 years, will practically never be exposed to iceberg impact. Nevertheless, hit probability is more than zero.

In this paper the probability for the iceberg approaching the platform to the distance \( L \), to hit the platform is calculated. For modeling iceberg danger various probabilistic approaches can be used [5]. In most of them Monte-Carlo statistic modeling technique is applied.

For the probabilistic modeling the initial data of iceberg breadth given in table 2 were chosen [13]. At the first stage according to Monte-Carlo method a series of iceberg breadths amounting \( N=1000 \) values was modeled under lognormal distribution function (figure 6). As a result of modeling the following series statistical characteristics \( P_a(B) \) were obtained: breadth mean value \( m=30.8 \) m, standard deviation \( \sigma=41.9 \) m.
According to the authors’ calculation data, the breadth of tabular iceberg 1% probability in Kara and Barents seas makes up 240.5m. At the second stage iceberg – structure hit probability was calculated depending on its breadth. When values for all variables were determined, hit probability was calculated on the equation according to the «rain drop» model [11], and for \( N \) simulations it is defined by expression:

\[
p_h\left(\frac{F_k}{H}\right) = \frac{W + D_k}{\sum_{k=1}^{N}(W + D_k)} \times \frac{1}{W + D_a} \times N
\]  

(1)

where \( W \) is structure’s width, m; \( D_k \) is ice feature’s diameter, m; \( D_a \) is ice feature’s mean diameter, m. Equation (1) takes into account higher expectancy of hitting for large icebergs than for small ones. Iceberg – structure hit probability distribution bar chart is given in figure 7. For probabilistic analysis out of the series of \( N=1000 \) values 50 iceberg breadth values were selected as the most dangerous for structure in case of collision.

At the third stage joint event probability – the appearance of \( k \)-wide iceberg in the given water area zone, \( P_a(B) \), and its collision with the structure, \( P_{hit}(B) \), was determined on the basis of conditional probability theorem use [15]. The probability of the fact that \( k \)-wide iceberg occurs and hits the structure is determined according to probability multiplication theorem. It follows from the theorem that probability of joint events is equal to unconditional probability of the first event (in our case probability \( P_a(B) \)), multiplied by conditional probability of the second event (in our case probability \( p\left(\frac{F_k}{H}\right) \)), calculated on condition that the first event took place:

\[
P_{hit} = P_a(B) \times p\left(\frac{F_k}{H}\right)
\]  

(2)

The analysis of iceberg breadth probabilistic distributions (figure 6) and iceberg joint occurrence and structure hit probability (figure 8) showed good agreement with icebergs statistical data obtained by [13,16]. Hit probability of design iceberg with dimensions 102.7×125.4×25.94m with the structure made up 0.004 (figure 8). Data analysis of figure 8 shows that iceberg – structure hit probability grows as iceberg breadth increases. Consequently, we can draw the conclusion that icebergs more than 50m wide represent the greatest danger. Further, breadth values of 50-240m may be used for icebergs towing calculations and for ice management techniques development.

![Figure 6. Histogram of icebergs occurrence probability \( P_a(B) \) in the water area.](image-url)
Figure 7. Histogram of icebergs – structure hit probability $P_{hit}$. 

Figure 8. Histogram of joint event probability: icebergs occurrence and hitting the structure $P_{hit}$. 

5. Conclusions

The article presents morphological and kinematic parameters investigation analysis of icebergs in promising deposit areas of Russian Arctic. Icebergs shapes are described according to the classification met in paper of [16] and other researchers.

Theoretical model of tabular iceberg has been developed on the basis of AutoCAD software. The theoretical model was generated on the basis of statistical observations data of icebergs parameters such as breadth, height, length over the period of 2003-2009.

Iceberg – structure hit probabilistic modeling was carried out by Monte-Carlo method, and ice situation management techniques are presented. For probabilistic modeling icebergs breadth parameters were chosen. Iceberg breadth series of value number N=1000 was modeled by Monte-Carlo method under lognormal distribution law.

Data analysis has shown that iceberg – structure hit probability grows as iceberg breadth increases. Consequently, we can draw the conclusion that icebergs more than 50 m wide represent the greatest danger.

As a result, design sizes of icebergs have been chosen for calculating their towing and ice management operations.
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