Complex Study of Large Ice Features and Assessment of Morphometric, Physical-strength and Age Characteristics of a Composite Ice Ridge

Roman B. Guzenko[1], Yevgeny U. Mironov[1], Victor V. Kharitonov[1], Ruslan I. May[1], Viktor S. Porubaev[1], Stepan V. Khotchenkov[1], Sergey M. Kovalev[1], Konstantin A. Kornishin[2], Yaroslav O. Efimov[3]

[1] Department of Sea Ice and Ice Forecasts, Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia
[2] R&D and Technical Regulations Department, Rosneft Oil Company, Moscow, Russia
[3] Department of Marine Operations, Arctic Research Centre, Moscow, Russia

ABSTRACT

The article describes a complex approach to the study of ice ridges and stamukhi, including methods: water thermal drilling, total station and sonar surveys, video filming with help of a submersible vehicle, determining the physical and strength properties of ice. The result of this study is the assessment of the morphometric, strength and age-related properties of the ice feature, as shown by the example of the old composite ice ridge of the East Siberian Sea.

KEYWORDS: complex study, morphometry, physical-strength characteristics, consolidated layer, old ice ridge, composite ridge

INTRODUCTION

Ice ridges and stamukhi are large ice features that have a significant mass and are typical of freezing water areas. To determine the possible ice load on marine objects, it is necessary to know the morphometric and physical strength characteristics of ice features. To obtain all necessary characteristics, it is advisable to use several methods.

During the joint expeditions of the AARI and Rosneft Oil Company in 2013-2017, more than 150 ice features were investigated in the seas of the Russian Arctic. In most cases, a set of methods was used, including determination of the morphometry and internal structure of ice features using water thermal drilling, total station survey of the surface, sonar and video of the underwater surface of the ice feature, determination of the local ice strength using a borehole jack, taking ice samples to determine the physical (temperature, salinity, density) and strength (compressive and bending strength) properties of ice.

The purpose of this article is to demonstrate a comprehensive study of the morphometry and physical-strength properties of ice feature using the example of an old composite ice ridge, to discuss the results, as well as a comparative analysis of the morphometric characteristics of a composite ice ridge with similar parameters of first-year ridges studied during the same period in the same region.

On May 9, 2015, as a result of the landing from the Atomic icebreaker "Yamal" on drifting ice north of Bennett Island in the East Siberian Sea, an investigation of the old ice ridge was carried out using various methods. The ice station at which the old ice ridge was studied was located on the ice breccia of first- and second-year ice at a point with coordinates 77º05,1′ N and 149º12,6′ E. During the work, the following hydrometeorological conditions were observed: air temperature –12.1 °C; northeast wind 7 m/s, clear; seawater temperature under ice –1.48 °C; salinity of seawater 26.83 ‰; the depth of the sea is 43 m. The old ice ridge was a complex ice feature, in which two crests could be distinguished (see Fig. 1).

Fig. 2 shows the relief of the upper surface of the old ice ridge according to the total station survey (TS). The profile of thermal drilling, points of sonar (SS) and video filming using an underwater remotely operated vehicle (ROV) are also marked there. The first crest is higher and straighter, extended in Fig. 2 from the lower right to the upper left; the second crest has an arched shape and is located in Fig. 2 to the left. According to the total station survey, the length of the surface part of the old ice ridge was 153 m and the width was 95 m. The surface part of the ice ridge was smooth without visible separate blocks.

RESEARCH METHOD

A comprehensive study of ice feature involves several methods that complement each other and together allow to get the true picture. We used the following methods in this study.

Water thermal drilling method. It is based on the technology of thermal drilling developed in the AARI under the guidance of V. Morev, it also includes a recording of the drilling speed on an electronic medium (Mironov et al., 2003).

Fig. 1 – Study of an old ice ridge in the north-west of the East Siberian Sea (visible points of drilling on the profile are marked by red)

The technology is carried out using the UVBL-2M water ice drilling system, which involves the simultaneous operation of two posts, each of them is equipped with drilling, measuring and recording set. The basic idea of the technology is that the drilling speed is determined by the condition of the medium penetrated by the drill, which is divided into three types: hard ice, soft ice, and a void. In the process of drilling, the drill hose rotates the measuring wheel of the transducer and the speed of immersion of the drill in the borehole is recorded to the logger. At the same time, a special electronic detector measures the excess of ice above sea level in the borehole. When processing thermal drilling data, the surface and underwater parts of the ice feature are determined, as well as the boundaries of voids and ice of various densities in the borehole within an accuracy of 1 cm. This technology allows to determine the external parameters of the ice feature and study the internal structure in the borehole, including the assessment of the boundaries of the consolidated layer (CL, the part of the ridge in which the ice blocks were frozen into a monolith), determine porosity (a relative content of voids in the ice feature; hereinafter: porosity is macroporosity), void sizes, hard ice content, etc. Detection of the boundaries of a consolidated layer is a special task when processing thermal drilling data. It is understood that there are no voids in CL (excluding small cavities inside a layer of hard ice) and thick layers of soft ice. As a rule, there should not be significant changes in the position of the boundaries of the consolidated layer between neighboring points. When determining CL, a curve of the drilling speed in the zone of the proposed layer and its neighboring areas is taken into account. In controversial points, for a more reliable determination of the CL boundaries, we used data on the local strength if it was measured at the same points using a borehole jack.

The total survey (TS) was carried out using the M3 DR Trimble Access total station. TS included drilling profile points, as well as all the most significant relief fragments of the upper surface of the ice feature.

The sonar survey (SS) of the lower surface of the ice feature was carried out with an Imagenex 881A azimuth search sonar equipped with an Azimuth Drive and a steering tool. SS results allow to get a three-dimensional image of surfaces within an accuracy of several centimeters. Typically, the SS of the underwater surface is carried out from two to three points depending on the size and configuration of the ice feature, as well as the available working time. The sonar is lowered into the lane (mynah) from a tripod using a manual winch to the depth necessary for optimal coverage. SS is performed in the mode of profiling by sectors with a certain step, which can be increased to speed up scanning and reduced for more detailed shooting.

Video filming of the ice ridge keel was carried out using the ROV "Gnom". Usually, its immersion takes place alternately with a sonar into the same lanes (mynahs). Three prepared lanes were used to shoot the keel of the old ice ridge: one lane was only for sonar surveys, one for video filming and one for both surveys (see Fig. 2).

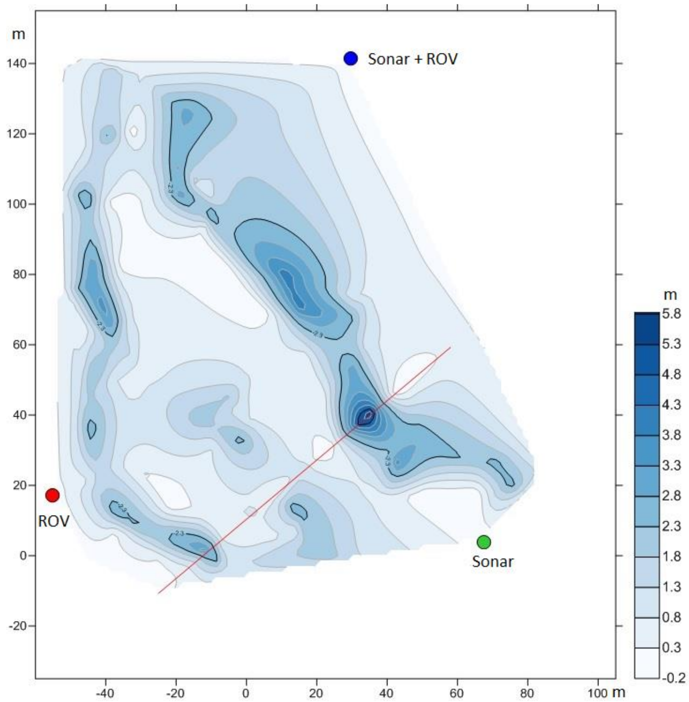

Fig. 2 – Top surface relief of the old ice ridge by the total station survey. The colored circles show the points for sonar survey and video filming by «Gnom» underwater ROV. The red line is the drilling profile

The physical and mechanical properties of ice were determined as follows. Using a "Kovacs Enterprise" core sampler with an internal diameter of 141 mm, an ice core was drilled and its texture was described. To measure the ice temperature, holes with a diameter of 3 mm and a depth of 70 mm were drilled every 10 cm in the selected core, where the probe of the GTH 175 / MO thermometer was placed. To measure the density, a sawing machine cut the core into individual cylinders so that the ice in the cylinder was homogeneous in texture. The height of the cylinder ranged from 10 to 15 cm. The sawn-off cylinder was measured with a caliper within an accuracy of 0.1 mm and weighed on an electronic balance. The ice density was calculated from the obtained values of the cylinder mass and volume. To take salinity samples, the ice core was cut by a sawing machine into discs of 2-3 cm thickness every 10 cm, which were placed into airproof plastic bags. Under laboratory conditions, the conductivity of melted ice was measured using a HI 8733 HANNA conductivity meter, based on which salinity was calculated.

The local strength of ice was investigated using a borehole jack manufactured at AARI (Smirnov et al., 2019). A borehole in the ice cover for testing the local strength was prepared using a portable drilling rig with a diameter of 250 mm. The local strength was determined every 30 cm throughout the depth of the borehole The indenter penetration was accompanied by a brittle-ductile failure of ice. During the tests, the indenter displacement and pressure in the system were recorded. At the same time, the pressure in the probe system was monitored by a test pressure gauge. Based on the obtained data on loading time, pressure in the system, and indenter penetration depth, the local ice strength was determined for each test.

Using a PIM – 200M field testing machine (press), the bending strength of ice discs was measured. For this, researchers used disks with a thickness of approximately 19 mm sawn by a circular saw. At the beginning and at the end of the series of measurements, the press was calibrated using a reference dynamometer. The duration of the deformation of the ice disk from the applied moment to the destruction of the ice disk was 0.7-1 s. The maximum force at the moment of sample failure was measured by the readings of a dynamometer with an indicator equipped with an arrow fixing the maximum value. In some cases, in addition to bending strength, the compression strength of the samples was determined using a hydraulic press.

MAIN RESULTS

Morphometric characteristics

Typically, for morphometric studies of a large ice feature, at least three profiles are drilled. However, the available working time allowed us to drill only one profile. Lower drilling performance was associated with the natural features of the old ice ridge such as low porosity and large thickness of CL. In addition, the initially short time limited by the expedition program to conduct this ice station was further reduced by the appearance of polar bears in the area of work (as a result, the total drilling time was about 3 hours).

A transverse drilling profile (Fig. 1-3) crossed both crests of the ice ridge, passing through the point of maximum sail height (point No. 18 on the profile) - 5.7 m. The predominant measurement resolution on the profile was 5 m, only in the area of the first ridge with the aim to capture its maximum excess, an intermediate point (No. 5) was marked, the distance from points No. 4 and No. 6, respectively, was 3 and 2 m. But if the point of maximum sail excess can be qualitatively assessed visually and, laying a drilling profile through this point, measure the excess with an electronic level gauge in a borehole or with a total station, it is almost impossible to catch the maximum value of keel draft on a drilling profile. To do this, it is necessary to use the data of the sonar sounding of the keel. According to the SS results, the maximum draft of the keel of the old ice ridge was 17.5 m, which is significantly larger than the maximum depth of the keel on the drilling profile (13.21 m). Thus, the maximum keel /sail ratio of the old ice ridge was 3.07. This is slightly less than the average values of the keel/sail ratio given for old ice ridges in the works (Kovacs, 1983, Timco and Burden, 1997, Sudom et al., 2011) and estimated from 3.22 to 3.55. In the context of the keel/sail ratio, a significant maximum sail height of our ice ridge (5.7 m) should be noted. Among 139 ice ridges studied in the seas of the Russian Arctic in 2013-2017 (Guzenko et al, 2019), it was the height of the old ice ridge (the remaining 138 ice ridges were first-year ones) that turned out to be the greatest.

The morphometric characteristics of the old ice ridge were compared with eight first-year ice ridges studied in the same area and in the same period (from May 6 to 15, 2015). Table 1 shows the values of the main morphometric characteristics of the old ice ridge, as well as the average and maximum values of similar parameters for eight first-year ice ridges. As you can see, almost all values of the parameters of the old ice ridge exceed the corresponding values of first-year ice ridges. Only the keel/sail ratio has traditionally been (Timco and Burden, 1997, Sudom et al., 2011) higher in first-year ice ridges.

The difference in horizontal and vertical sizes between the old and first-year ice ridges is most indicative of volume estimates; the volume of the old ice ridge is 5.6 times greater than the average volume of the first-year ice ridge, and 3.3 times greater than the maximum volume of the first-year one. TS and SS data were used to determine the volume. Based on the survey data, the horizontal area of the ice ridge was determined, and the average total thickness of ice in the ice ridge was estimated by the total volume/area ratio, which amounted to 6.33 m, which is quite close to the average ice thickness in first-year ice ridges (6.30 m). Figure 4 shows 3D images (3D model) of an old ice ridge obtained according to TS and SS. Figure 5 shows a single picture of the video filming. Most of the keel was large monolithic smoothed fragments characteristic of old ice ridges.

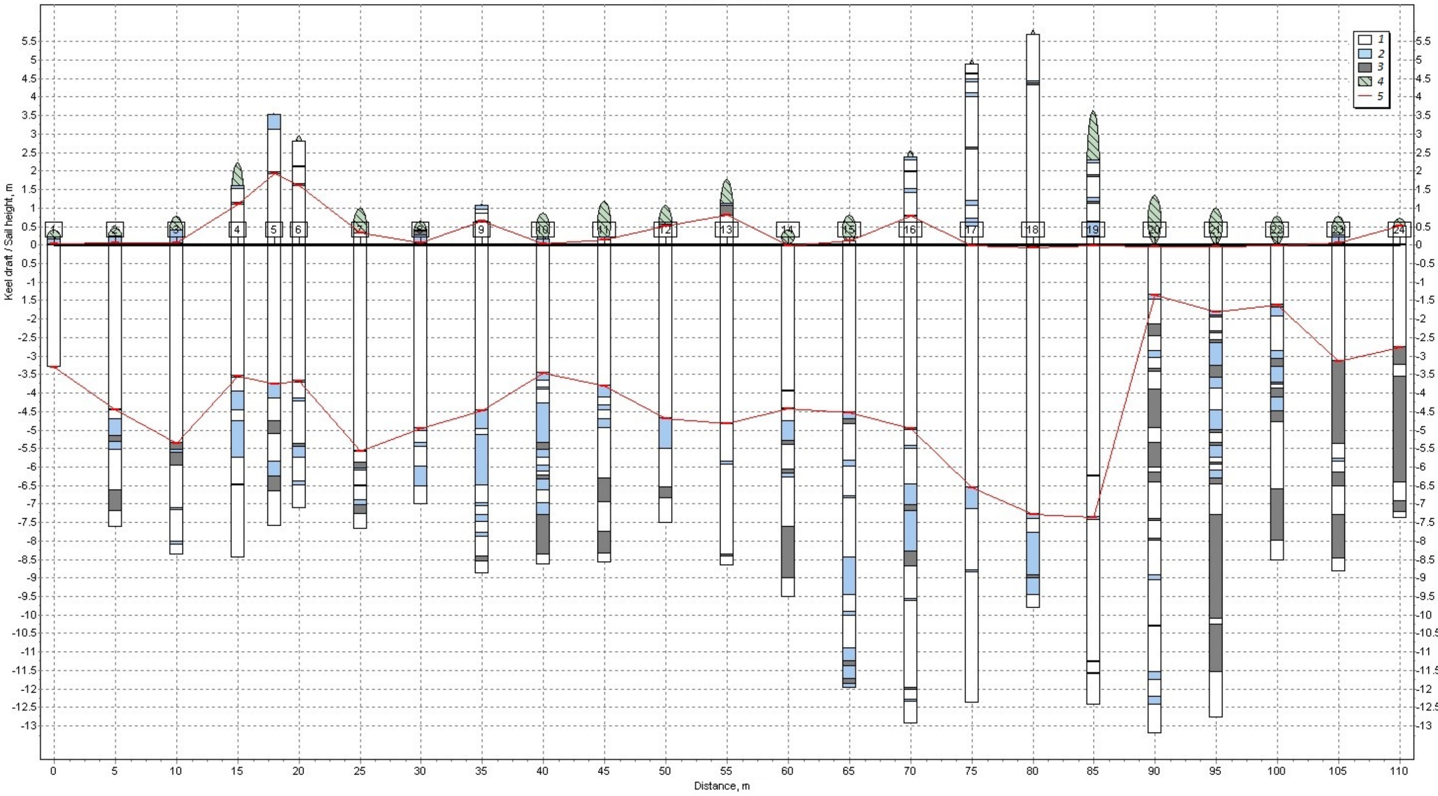

Fig. 3 - Cross-sectional profile of thermodrilling of old ice ridge. 1 – hard ice, 2 – soft ice, 3 – void, 4 – snow, 5 – boundaries of CL

Table 1. Basic morphometric characteristics of old and first-year ice ridges

Parameter	Old ridge	8 first-year ice ridges	
		avg	max
Sail height (max.), m	5.7	3.82	5.4
Keel draft (max.) according to drilling, m	13.21	11.44	12.98
Keel draft (max.) according to SS, m	17.5	12.62	16.29
Ratio max. keel / sail	3.07	3.46	4.41
Total ice thickness (avg.), m	6.33	6.30	9.79
Ridge length (on keel), m	170	97	150
Ridge width (on keel), m	130	49	61
Sail volume, thous.m^3	13.7	2.7	5.5
Keel volume, thous.m^3	169.8	29.8	49.3
Total ice ridge volume, thous.m^3	183.5	32.5	54.8
CL thickness (avg.), m	4.60	2.33	3.27
CL / total thickness ratio	0.73	0.37	0.56
Sail porosity, %	1	15	28
Keel porosity,%	12	15	18
Porosity of the rubble,%	19	25	33
Total ice ridge porosity, %	11	15	18
Ice ridge mass, thous. tons	146.1	25.3	43.7

Internal structure

Significant differences between ice ridges of different ages also appear in the key characteristics of the internal structure: the thickness of the CL and porosity. The average thickness of the CL of the old ice ridge is almost 2 times greater than the average thickness of the CL of first-year ridges, studied at the same time in the same area. Considering the approximately equal values of the total ice thickness in the old and averaged first-year ice ridges, the relative thickness of the CL of the old ridge (CL thickness/total thickness ratio) is also almost 2 times higher. The total porosity in the old ice ridge is expectedly lower. If the average porosity of the keel is comparable to the porosity of first-year ice ridges, then almost zero porosity of the sail is a typical sign of an old ridge. (Kovacs, 1983, Kharitonov and Morev, 2009, Strub-Klein et al., 2009, Kharitonov, 2013). Given the values of volume and porosity, it remains to clarify only the density of ice in the ice ridge in order to determine its mass. Measurements of ice density carried out at different horizons in first-year ridges give an average value of 917 kg/m3. In the old ridge, density was measured in the upper 135-centimeter section of the sail. It ranged from 524 to 783 kg / m³. But the ice density in the upper part of the sail of old ridge is usually lower than the average value over the entire ice ridge. Knowing the density of water (1021 kg/m3), the volumes of the surface and underwater parts of the ice ridge, the porosity of the sail and keel, the average thickness of the snow cover in the ice ridge (50 cm), we tried to analytically determine the average density of ice in the ice ridge using the following formula:

$$\rho_i = \rho_w \frac{V_k}{V_r + V_{s(ice\,eq.)}} \quad (1)$$

In formula (1): ρ_i is the density of ice, ρ_w is the density of seawater, V_k is the volume of the keel taking into account porosity, V_r is the volume of the entire ice ridge taking into account porosity, $V_{s(ice\ eq.)}$ is the volume of snow on the surface of the ice ridge in ice equivalent (with a snow density of 350 kg / m^3). According to our estimates, the average density of ice in the ice ridge was 896 kg/m3. The average ice densities given in the works (Kovacs et al., 1973, Kovacs, 1983, Strub-Klein et al., 2009, Richter-Menge and Cox, 1985, Cox and Richter-Menge, 1986) in old ice ridges range from 843 kg/m3 to 940 kg/m3. Kovacs et al. calculate the ice density in an old ice ridge in the Beaufort Sea, also based on the law of isostatic equilibrium, and obtain a value of 910 kg/m^3 (given snow density of 450 kg/m^3), which is in good agreement with the average value measured by the authors - 900 kg/m^3 (Kovacs, 1973). Using our calculated density value (896 kg / m^3) in determining the mass of the old ice ridge, we found that the mass of the old ice ridge is 5.8 times greater than the average mass of first-year ridge (at a density of 917 kg/m^3), and 3.4 times greater than first-year ridge maximum mass.

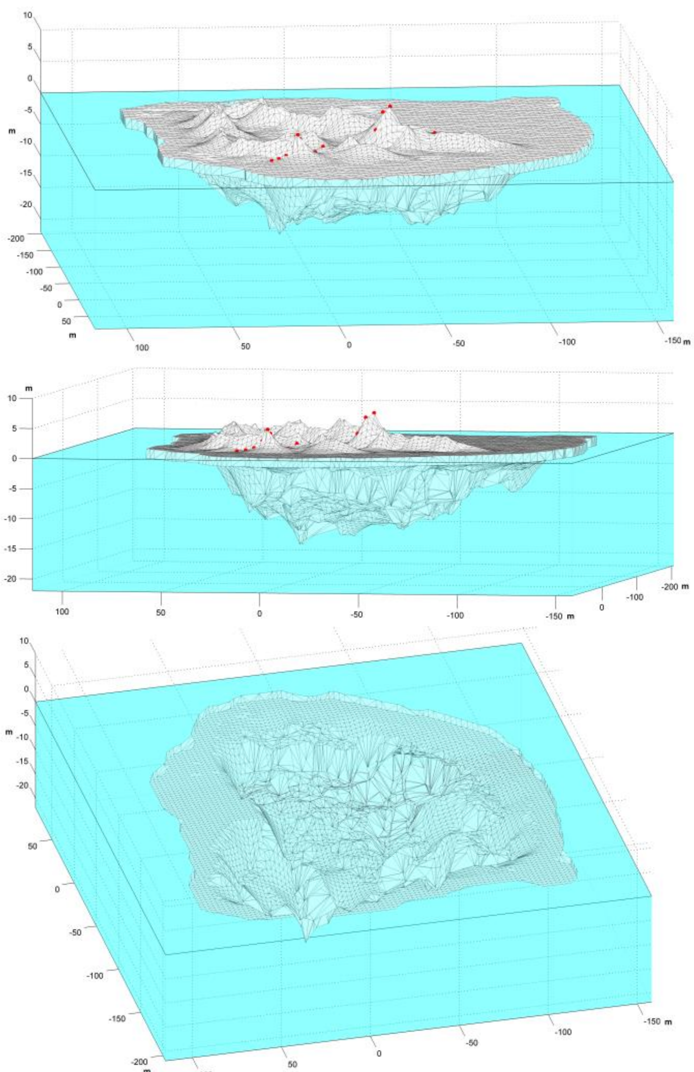

Fig. 4 - 3D-model of old ice ridge, views from above (a), side (b) and bottom (c). Visible points of drilling on the profile are marked by red

Fig. 5 - Video filming of the ice ridge keel using the ROV "Gnom"

Physical and strength properties of ice

A 135-cm ice core was taken in a sail of smaller crest one and a half meters from point No. 5 of the drilling profile. Further core sampling at this point was difficult due to the fragility of the underlying ice layer. The texture of the taken ice core was described as follows. The upper 0.17 m consisted of white opaque ice formed as a result of the complete recrystallization of the primary crystals Air inclusions had an irregular shape and a diameter of 0.5-3.0 mm. The ice from 0.17 m to 1.0 m had horizontal and vertical stratification, formed by sinuous inclusions of a vertical arrangement, which appeared as a result of freezing of meltwater in a small runoff channel. The diameter of inclusions is 1.0–5.0 mm, and the height is from 1.0 to 10.0 mm. Ice from 1.0 to 1.35 m retained air inclusions similar to the upper layers, but in some areas, inclusions appeared, formed from the combination and transformation of small bubbles of capillary primary inclusions characteristic of ice composed of fibrous crystals. That is, in this area, we observed partial preservation of the signs of the initial crystalline structure.

In the selected ice core, temperature, salinity, and ice density were measured every 10 cm. The average ice core temperature was –10.0 °C. The minimum temperature –11.9 °C was observed on the ice surface, and the maximum temperature –9.4 °C in the 0.2–0.3 m layer. The average salinity of the ice was 0.04 ‰. The maximum salinity of 0.07 ‰ was found on the horizon of 0.1 m and the minimum salinity of 0.01 ‰ on the horizon of 0.2 m. Basically, the ice core was completely desalinated. The average density of ice in the core was 704 kg / m³. The minimum density of 524 kg / m³ was observed in the upper 9-cm layer, and the maximum density of 783 kg / m³ was in the 0.25–0.38 m layer. The ice salinity in neighboring first-year ridges was 3.53–4.94 ‰, and the ice density was 897–925 kg / m³.

The bending strength of core ice disks was in the range 0.69-1.05 MPa with a 95% probability. The average strength was 0.87 MPa. This value exceeds the strength of first-year level ice, but less than the strength of second-year level ice in this region. Eleven measurements of local strength were performed in three boreholes in an old ice ridge: Seven measurements in the ice ridge sail to a depth of 2.2 m near the point No. 5 of the thermal drilling profile, as well as 3 measurements (to a depth of 90 cm) in the area of thermal drilling points No. 1 and 2. The values of local strength averaged over the depth of the borehole range from 5.09 to 18.85 MPa, the average value is 8.88 MPa. This is significantly less than the average strength values in first-year ridges (15.72 MPa), the strength of first-year level ice (16.73 MPa) and the strength of second-year level ice (19.38 MPa). When analyzing local strength data in an old ice ridge it is necessary to take into account that most of the values were obtained in an ice ridge sail, the zone most exposed to thermo-metamorphism for several years as a result of exposure to solar radiation. The average local strength in the sail was 6.23 MPa. Also, a low average strength value of 5.09 MPa was obtained in the area of point No. 1. The highest average borehole value of 18.85 MPa was determined in the area of point No. 2, while the highest values of 23.78 and 25.47 MPa were obtained at horizons of 60 and 90 cm, respectively.

Table 2 shows the values of salinity, density and local ice strength obtained in our old ice ridge, as well as in old ice ridges according to publications of various researchers. Comparing our data with the given publications information, we can note the following points. The salinity of the upper part of the sail of our ice ridge is close to zero and corresponds to the lower limit of the salinity of old ice. The average measured ice ridge density is even lower than the density range of other researchers. The local ice strength is several times lower than the values given in (Johnston, 2017) . However, Johnston used data of local strength, determined by means of instruments different from the borehole jack developed at AARI, and using a different method. In addition, it should be considered that our values of salinity, density and local ice strength were obtained on the basis of measurements taken mainly in the upper part of the large ice ridge sail, where these characteristics in old ice ridges usually have minimum values. This is due to the fact that during the life of such an ice ridge, the saltwater manages to drain from the surface down almost completely, respectively, with the desalination, the ice density decreases, and the low strength in the upper layers is associated with the process of thermo-metamorphism.

Table 2. Comparison of some physical and strength characteristics of ice in the sail of old ice ridges according to literature sources

Authors	Salinity, ‰	Density, kg/m3	Local ice strength, MPa
Authors of the article	0.01-0.07 avg. 0.04	524-783 avg. 704	5.1-18.9 avg. 8.88
Kovacs et al. (1973)	0.0-0.2(in upper 1.5 m)	825-900	
Kovacs (1983)	0.0-1.0	825-831	
Cox and Richter-Menge (1986)	0.76±0.66	854±37	
Høyland et al. (2008)	0-127 avg. 0.52	710-890 avg. 830	
Strub-Klein et al. (2009)	0.10-0.84	720-790	
Johnston (2017)	0.5-2.6		25-34*

* depth-averaged data are given for ice temperature –10 ° C

Assessment of the ice ridge age

The definition of “old ice ridge”, used in relation to the studied ice feature, combines the concepts of “second-year” and “multi-year” ice ridge. Is it possible to reliably determine the age of our ice ridge? Unfortunately, only the ice core was not enough to accurately identify its age. We have information containing indirect signs of age. Each of these signs is not decisive, but together they may help clarify the issue.

First, the ice neighboring to the old ice ridge corresponded to both first-year and second-year ice. The measured thickness of neighboring level ice varied quite a lot: from 0.9 to 1.9 m, averaging 1.5 m. The texture of the ice core taken on level ice in close proximity to the ice ridge refers to second-year ice. However, the age of the ice ridge may not coincide with the age of the ice neighboring to it. Second, various researchers noted in their works the almost complete consolidation of old ice ridges (Kovacs et al., 1973, Kovacs, 1983, Høyland et al., 2008, Kharitonov and Morev, 2009, Høyland, 2008), while the incomplete consolidation inside the old ice ridge gave the authors reason to limit its age to two years (Kovacs, 1983, Høyland et al., 2008, Strub-Klein et al., 2009). In (Kharitonov and Morev, 2009), three of the four considered old ice ridges had zero porosity, and one ice ridge had a total porosity of 18% (sail - 4% and keel - 22%). The average porosity of the sail, keel, and total porosity in the second-year ice ridge according to Kharitonov (2013) was 1, 6 and 5%, respectively. L. Strub-Klein et al. (2009) give, for five second-year ice ridges, the average porosity of 4, 12, and 11% for sail, keel, and total porosity, respectively Our ice ridge has close to zero sail porosity (1%), but rather significant indicators of keel porosity (12%) and total (11%), which, guided by the above estimates, should be considered as a sign of second-year ice ridge. The relative hard ice content in our ice ridge was 79% (90% in sail, 78% in keel), and the relative thickness of the CL was 73%. At the same time, separate works (Høyland, 2008, Kharitonov, 2013), give information that on young multi-year and second-year ice ridges separate blocks in a sail can be distinguished. The sail of our old ice ridge was smoothed.

The average thickness of the ice ridge CL can be considered another indirect sign of age. In (Kharitonov and Morev, 2009), the average thickness of the CL in an ice ridge with non-zero total porosity was estimated as 2.4 m, and in three ice ridges with zero porosity it was estimated to be about 6 m. V. Kharitonov (2013) shows that the average thickness of the CL in a second-year ice ridge was 2.4 m. The average thickness of our ice ridge was 4.6 m. But if we pay attention to the distribution of CL along the drilling profile (Fig. 3), we can notice the significantly lower thickness of CL in the area of points No. 20-24, with respect to the greater part of ice ridge. If for points No. 1-19 the average value of the CL thickness is 5.22 m, then for points No. 20-24 it is only 2.23 m, which is very close to the average thickness of the CL of first-year ice ridges (2.33 m) studied in the same period. We can also see significant differences in the porosity of two fragments. The average porosity of the second fragment (33.4% for points No. 20-24) is more than 7 times greater than the average porosity of the first one (4.6% for points No. 1-19). Apparently, our ice ridge consists of a larger old fragment and a relatively small first-year fragment. In (Guzenko et al., 2019), we were able to use the empirical coefficients to correlate the average CL thickness of first-year ice ridges (H_{CL}) studied in different regions of the Kara and Laptev Seas with the sum of freezing degree-days (FDD) calculated according to the data of polar stations, corresponding to the study areas, by the following equation:

$$H_{CL}(m) = 0.074 * \sqrt{FDD} - 2.74 \quad (2)$$

Since we do not know the exact time when the CL was formed in ice ridges (as well as the exact time when ice ridges were formed), the sum of freezing degree days was calculated from the date of steady transition of the average daily air temperature through zero degrees, and the end of the calculation period corresponded to the time of study of ice ridges in a specific area. The form of the proposed dependence is based on the theoretical formula of Stefan, who showed that the thickness of the ice is proportional to the square root of the sum of freezing degree-days. The nearest operating meteorological station to the area of study of the old ice ridge is the polar station on the island of Kotelny. According to it, the sum of freezing degree-days for two winter seasons from September 7, 2013 (the day of the steady transition of the average daily air temperature through zero degrees) to May 9, 2015 (the day of the study of the old ice ridge) was 9058. If we take only winter periods, the sum of freezing degree-days for two winters (until May 9, 2015) will be 9415. Substituting in the formula (2) the average thickness of the ice ridge CL of 4.6 m, we get the corresponding value of the sum of freezing degree-days 9838. And if we take the average value of the CL thickness of 5.22 m for the obviously old fragment of the ice ridge (points No. 1-19), then the corresponding sum of freezing degree-days will be 11571. In both cases, the calculated by formula (2) sum of freezing degree-days exceeds the sum of degree-days for two winters (2013/2014 and 2014/2015) according to the weather station on Kotelny Island. This gives certain reasons to believe that our ice ridge already existed by the beginning of the fall of 2013 and, accordingly, its age is more than two years. However, you need to understand that these calculations are relative. First, the studied old ice ridge could be brought to the study area from a region with more severe temperature conditions. Second, the empirical formula (2) expresses the relationship between the sum of freezing degree-days and the average thickness of the CL of first-year ice ridges. The relationship between the thickness of the CL of old ice ridges and temperature conditions is more complex. Particularly complex is the role of summer processes to the change in the thickness of the old ice ridge CL. In (Kovacs, 1983) describes the mechanism of summer consolidation of an old ice ridge due to the drainage of meltwater from the surface and its subsequent freezing in the thickness of the ice ridge. That is, according to the author, the CL increases in the relatively warm summer period. Høyland (2008) also shows that in summer meltwater flowing down from the surface and replacing saltwater in the ice mass promotes the formation of new ice, and while meltwater is present and the keel of ice ridge maintains sufficient supply of cold for its freezing, the CL increases. This paper (Høyland, 2008) describes a consolidation model for first-year ice ridges, which the author proposes to use for old ice ridges. The model is based on Stefan's law and is a simple analytical dependence linking the thickness of the CL with the thickness of the surrounding level ice, taking into account the porosity of the ice ridge:

$$h_c^2(t) = h_{c0}^2 + \frac{h_i^2(t) - h_{i0}^2}{\eta} \qquad (3)$$

In formula (3), $h_c(t)$ и $h_i(t)$ are the thicknesses of the CL and level ice at the end of the calculation period, h_{c0} и h_{i0} are the thicknesses of the CL and level ice at the initial moment (at the previous calculation step), η is the porosity of the unconsolidated part of the ice ridge. Høyland accepted that level ice melts completely over the summer, so h_{i0} is always zero. Using the data obtained in expeditionary studies of ice ridges and level ice in this region in 2014 and 2015, we tried to estimate the dynamics of the thickness of the CL for our old ice ridge using the proposed model. We used the following points for the calculations: the average thickness over two years of first-year level ice in the region (1.1 m) and the average porosity of the unconsolidated part of the keel of ice ridges (29%) over two years. The thickness of the ice ridge CL after the first year was determined as the average value in the first-year ice ridges of this region for two years (2.3 m). According to the calculations of formula (3), it turned out that the thickness of the CL after the second year is 3.1 m, after the third year 3.7 m. Only in the sixth year under these initial conditions, the calculated value of the CL thickness reaches 5.1 m which is the closest value to the average CL thickness (5.2 m) by measurements on the old fragment (points No. 1-19) of our ice ridge. When considering the results of this model, a number of serious assumptions must be taken into account: the average thickness and age of ice surrounding the ice ridge remain constant throughout all the calculation years, and the average porosity of the unconsolidated part of the ice ridge does not change even with an annual increase in CL.

Thus, part of the parameters of our ice ridge considered above (the age of the surrounding ice, relatively high porosity of the ice ridge keel and its incomplete consolidation) is more consistent with a second-year ice ridge, and the other part of the parameters (the absence of blocks and almost complete smoothness of the sail, relatively high value of the CL thickness) are more typical for multi-year ice ridge. If we take the hypothesis that our ice ridge is a complex ice feature consisting of old and first-year fragments, we assume that according to the age of the old fraction, our ice ridge is a multi-year (probably 3-4-year-old) ice ridge.

CONCLUSIONS

The object presented here as an example of a comprehensive study is a large ice feature, the basis of which is the old ice ridge. Of course, to make more reliable conclusions about the morphometric, physical-strength and age characteristics of an object one should undertake a more detailed study of it. This applies to more detailed information about the internal structure (more drilling profiles are needed), physical properties (it is desirable to take ice cores not only in the sail, but throughout the thickness of the ice ridge and at several points, followed by a description of the texture and determination of temperature, salinity, and ice density) and strength parameters (more measurements of local ice strength at different points are required). However, even in conditions of extremely limited time and a corresponding deficit of measurements, the use of a complex approach (the simultaneous use of water drilling, total station and sonar surveys, video filming with ROV, determination of the physical and strength properties of ice) allows us to compensate for particular information gaps and get the relatively complete overall picture of the ice ridge structure.

A complex study of the old ice ridge in the East Siberian Sea in May 2015 led to the following conclusions:

A comparison of the main morphometric characteristics of the old ice ridge and the average values of first-year ice ridges studied in the same area at the same time showed that the old ice ridge had vastly superior geometric parameters. The volume and mass of the old ice ridge are 5.6 and 5.8 times greater than those of the average first-year ice ridge, respectively. Such a significant advantage of the old ice ridge is most likely due not to age (first-year ice ridges may be larger than the old ones), but to the composite nature of the ice feature. The average thickness of the CL for the entire ice feature is almost 2 times higher than the average thickness of the CL in first-year ice ridges, and the average value of CL in the old part of the ice ridge is 2.2 times greater than in first-year ice ridges. Also, the old ice ridge is characterized by almost complete smoothness (without the ability to identify separate blocks) and minimal porosity of the sail. The salinity and density of the ice composing the sail of the old ice ridge were significantly lower than in first-year ice ridges. The keel/sail ratio is on average greater for first-year ice ridges: 3.5 versus 3.1 for the old ice ridge.

The distributions of the internal structure parameters (CL thickness and porosity) over the drilling profile suggested that the ice feature studied was a composite ice ridge that experienced secondary hummocking and consisted of a larger old fragment and a relatively small first-year fragment. According to the analysis of age-related characteristics, the most likely should identify the considered ice ridge as a multi-year ice ridge which is 3-4 years old.

ACKNOWLEDGEMENTS

The authors are grateful to A.I. Shushlebin (AARI) for valuable scientific advice. Studies were carried out in the framework of the innovation activity of Rosneft Oil Company.
This study is supported by the RFBR grant 18-05-60109.

REFERENCES

Cox, G, and Richter-Menge, J (1986). "Confined compressive strength of multi-year pressure ridge sea ice samples," *Proceedings of the 5th International Offshore Mechanics and Arctic Engineering (OMAE)*, 1986, 4, 365-373.

Guzenko, RB, Mironov, YU, May, RI, Porubaev, VS, Kharitonov, VV, Khotchenkov, SV, Kornishin, KA, Efimov, YO, Tarasov, PA (2019). "Morphometry and Internal Structure of Ice Ridges in the Kara and Laptev Seas," Proceedings of the Twenty-ninth International Ocean and Polar Engineering Conference, Honolulu, Hawaii, USA, ISOPE, 647-654.

Høyland, KV, Barrault, S, Gerland, S, Goodwin, H, Nicolaus, M, Olsen, OM, Rinne, E (2008). "The consolidation in the second- and multi-year sea ice ridges, Part 1: Measurements in early winter," *19th IAHR International Symposium on Ice*, Vancouver, Canada, 1439-1449.

Høyland, KV (2008). "The consolidation in second- and multi-year sea ice ridges, Part II: Review and speculations," *19th IAHR International Symposium on Ice*, Vancouver, Canada, 1451-1457.

Johnston, m (2017). "Seasonal changes in the properties of first-year, second-year and multi-year ice," *Cold Regions Science and Technology*, 141, 36-53.

Kharitonov, VV, Morev, VA (2009). "Morphometric characteristics of multi-year ice ridges in Russian sector of Arctic," *Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions*, Luleå, Sweden, 09-121.

Kharitonov, VV (2013). "Evolution of the internal structure of ice ridge investigated at «North Pole - 38» and «North Pole - 39» drifting stations," *Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions*, Espoo, Finland, 13-048.

Kovacs, A, Weeks, W, Ackley, S, Hibler, W (1973). "Structure of a multi-year pressure ridge," *Arctic*, 26 (1), 22-31.

Kovacs, A (1983). "Characteristics of Multi-year pressure ridges," *Proceedings of the 7th Int. Conf. on Port and Ocean Engineering under Arctic Condition*, 3, 173-182.

Mironov, YU, Morev, VA, Porubaev, VS, Kharitonov, VV (2003). "Study of Geometry and Internal Structure of Ice Ridges and Stamukhi using Thermal Water Drilling," *Proc. of the 17th Int. Conference on POAC*, Trondheim, Norway, 623-634.

Richter-Menge, J, and Cox, G (1985). "Structure, salinity, and density of multi-year sea ice pressure ridge," *Proceedings of the 4th International Conference on Offshore Mechanics and Arctic Engineering (OMAE)*, Texas, USA, 194-198.

Smirnov, VN, Shushlebin, AI, Kovalev, SM, Iatskevich, AA, Shchepaniuk, SN, Efimov, YA, Kornishin, KA (2019). "Comprehensive system for determining the strength characteristics of ice in natural conditions and on samples," Patent for invention No. 2682835.

Strub-Klein, L, Barrault, S, Goodwin, H, Gerland, S (2009). "Physical properties and comparison of first- and second-year sea ice ridges," *Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions*, Luleå, Sweden, 09-117.

Sudom, D, Timco, G, Sand, B, Fransson, L (2011). "Analysis of first-year and old ice ridge characteristics," *Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions*, Montreal, Canada, 11-164.

Timco, GW, Burden, RP (1997). "An analysis of the shape of sea ice ridges," *Cold Regions Science and Technology*, 25, 65–77.