Development of a regulatory framework for supporting transport and cargo operations on fast ice in the Russian Arctic

Yuri P. Gudoshnikov[1], Nikolay V. Kubyshkin[2], Andrey A. Skutin[1], Igor V. Buzin[1], Dmitry A. Onishchenko[3]
[1] FSBI AARI, Saint Petersburg, Russia
[2] Arctic Shelf Consulting LLC, Saint Petersburg, Russia
[3] Gazprom VNIIGAZ LLC, Moscow, Russia

ABSTRACT

During the development of the Russia's Arctic zone, new hydrotechnical and other marine structures operating all year round have been built, are in operation, and are also being designed. During the ice period, the maintenance of some of them is carried out using fast ice, on which ice roads, technological passages, etc. are arranged. To ensure the safety of work carried out on the ice, it is necessary to develop regulatory and technical documents defining the procedure of ice reconnaissance, as well as requirements for the design, construction and operation of these transport facilities. The paper describes the Russian experience of using coastal fast ice for transport and cargo operations, features of ice and hydrological conditions under which the construction of ice roads on fast ice is carried out, and also gives a brief description of the existing Russian regulatory framework for performing such work. It is shown that most of the current Russian regulatory documents ensure the safety of work on fresh and brackish waters (lakes, rivers, certain parts of estuaries of Siberian rivers), but do not take into account the specific features of the fast ice developed from the seawater. To fill this gap, the specialists of the State Research Center "AARI" developed and published a methodological manual in 2020, reflecting the existing accumulated experience and best practices for providing transport and cargo operations on fast ice in various regions of the Russian Arctic. The article provides a brief description of composition of the new document.

KEY WORDS: Fast ice; Offloading on ice; Transport on ice; Russian experience; New Russian Manual

INTRODUCTION

The ice cover of seas, lakes, and rivers has always been an obstruction to navigation and the impact of ice on shores, coastal and offshore structures represents a risk to be considered in site selection and design of hydraulic engineering facilities. However, people that live in areas with freezing water bodies have long adapted to use the ice cover to reduce distances when moving and transporting goods across water bodies without watercraft.

The development of technology and the started use of rail-, wheel- and crawler-mounted heavy vehicles for transport purposes, when their loaded weight made tons and tens of tons, resulted in a need for specialized engineering support for ice crossings, which would incorporate knowledge of the hydrometeorological regime of water bodies and technical solutions for arranging roads on the ice cover. This came particularly important in the cases of long roads of several, or even tens of kilometers.

An example of engineering support for a complicate ice crossing in Russia is the 45 km-long winter railway on the ice of Lake Baikal established back in 1904. But the undoubtedly most impressive event in the history of ice crossings was and will ever remain the Leningrad "Road of Life". During the two winter seasons of its operation, 1941/42 and 1942/43, over 500,000 tons of cargo were transported along the 85-km road laid on the ice of Lake Ladoga, in addition to people evacuated from the besieged Leningrad.

Gaining experience in the organization of ice crossings was followed by a surge of publications on this topic in the 1940-s (e.g., Zubov, 1942; Ice Crossings, 1943; Kazansky, Shulman, 1946; Ivanov, Peschansky, 1949, and this list of works is far incomplete). Research on the ice load-bearing capacity, as well as organizational and technical issues related to ice road construction continued in the second half of the XX century. Research on the ice load-bearing capacity by D.F. Panfilov (1960, 1963, 1964, 1966) is well known. The method of calculating the ice load-bearing capacity was described in the fundamental work by I.S. Peschansky (1967) and is currently used in the process of educating Russian oceanologists.

The technological development gives rise to the need to carry more heavy loads across the ice, while the development of the northern territories and the associated traffic requires a longer operation period for seasonal ice crossings. To reach these goals, various methods of ice strengthening are developed: freezing, reinforcement, and the introduction of modifying additives. The works under this theme can be divided into experimental studies and descriptions of applications of various ice strengthening methods. Experimental studies are presented in the works (Peschansky et al., 1964; Nemirovsky, Romanova, 2013; Buznik et al., 2017; Cherepanin et al., 2017; Ipatov et al., 2019). The experience of applying various ice strengthening methods on the operational ice river crossings is presented in the works (Korchits et al., 1989; Tryapkin, Tryapitsyn, 2014; Sirotyuk et al., 2015; Trapeznikov, Bartholomey, 2019). Reviews of technical solutions for strengthening the ice cover are presented in the works (Bychkovsky, Guryanov, 2005; Vasiliev et al., 2013; Yakimenko, Sirotyuk, 2015).

In the second half of the XX century, with the development of a network of hydrometeorological stations in the Arctic and the establishment of research stations in Antarctica, the fast ice was often used for unloading ships and delivering cargo onshore. Despite certain similarities with the organization of ice crossings in terms of arranging transport infrastructure on the ice cover, cargo operations on fast ice have significant differences specified by the hydrological and ice conditions in the coastal zone of the seas, interoperability between the maritime and land transport directly on the ice cover, and the general plan of work organization. The experience of ice crossings exploitation was widely applied to marine operations on fast ice, in terms of determining the ice load-bearing capacity and arranging ice roads between the shore and the fast ice cargo site where the ship is unloaded. The use of fast ice for unloading ships during the ice season is described in the works (Chilingarov, 1979; Borodachev, Chilingarov, 1981; Recommendations, 1986; Arikainen, Chubakov, 1987; Kubyshkin, Gudoshnikov, 2015; Kubyshkin et al., 2018). Specific features of unloading ships on the Antarctic fast ice are reviewed in the work "The Fast Ice of East Antarctica" (1977).

Currently, when the volume of cargo transportation via the Northern Sea Route exceeded the volumes of the USSR times, the number of annual maritime operations on fast ice has also increased. Starting approximately from 2013-2015 and up to the present, unloading of vessels through fast ice is carried out by 3-7 sites of the Russian Arctic per ice season and this indicator does not display a downward trend.

Another example that confirms the relevance of the issue under consideration is the planned start of operation of the Kamennomysskoye-Sea gas field in the Ob Bay in 2025 (Gazprom, n.d.). The key object in the sea will be a special ice-resistant platform, the construction of which began in June 2020. In particular, it will house the main and auxiliary drilling modules, operational and energy complexes, and the living quarters with 120 seats.

Due to the shallow waters over the field (from 5 to 12 m), the use of icebreaking vessels is difficult, so ensuring the supply of the platform during the ice period on the ice deserves special attention. Support for the operation of the platform includes the delivery of heavy cargo, the change of personnel, ensuring industrial and environmental safety, carrying out emergency evacuation and search and rescue operations on the ice cover, if necessary, and other things. All this will probably requires the use of various types of vehicles, e.g. all-terrain vehicles on wheels, all-terrain amphibious vehicles on tracks, hovercrafts. At the same time, the relief of the ice cover in the central part of the Ob Bay is complicated by the presence of non-stationary cracks, leads, as well as ridges and hummock ice areas. These factors, as well as the high general ridging ratio, can significantly complicate the solution of the above-mentioned diverse tasks. In addition, we can expect an increase in the frequency and intensity of ice cover movements, since after the start of operation of the year-round Arctic Gates crude-oil loading terminal (Gazprom, 2016, Fig. 1), the ice cover in the northern part of Ob bay appears to be cut along into the western and eastern parts, which increases its mobility potential.

Figure 1. Ice road on the fast ice of Ob bay for servicing the Novoportovsky cargo terminal “Arctic Gate”, Cape Kamenny, 2017 (Photo by N. V. Golovin)

MATERIALS AND METHODS

In most cases of operating on fast ice, we deal with saline sea ice or with the ice of brackish water bodies (the northern part of Ob bay, the Yenisei Bay, and the eastern part of the Gulf of Finland). Fresh ice occurs in the mouth areas of Siberian rivers (e.g., the middle and southern parts of Ob bay) or when operating on the ice cover of navigable rivers (e.g., on the Yenisei). When calculating the load-bearing capacity of the ice cover at sea or in brackish water bodies, we need to account for the lower strength of saline ice as compared with fresh ice. However, the effect of reduced strength and load capacity of sea ice (due to its salinity) is often disregarded in the ice load-bearing estimate methods, since most of them are developed for river and lake crossings.

The effect of salinity is routinely included in calculations of mechanical characteristics of the ice: the maximum strength and modulus of elasticity. This is demonstrated in calculations of the ice load-bearing capacity under central loading and cylindrical bending, based on the theory of elasticity (Peschansky, 1967).

The empirical Kazansky-Shulman formula (Kazansky, Shulman, 1946), widely known and used in practice in Russia, includes salinity via a simple proportionality factor equal to 1 for fresh ice and less than 1 for sea ice (0.3 for new sea ice, 0.5 for first-year sea ice, 0.7 for estuary areas of northern rivers):

$$P = \frac{B}{N} h^2 KS,$$

where *P* is the permissible ice load, tons;

B is a coefficient equal to 100 for wheeled and 115 – for crawler-mounted vehicles;

h is the minimum ice thickness, m;

K is the temperature coefficient calculated as $K = (100+T)/100$, where *T* is the absolute average air temperature for the past 3 days;

N is the safety and crack factor ($N = 1$ corresponds to the maximum load-bearing capacity of ice without cracks);

S is the above-mentioned salinity coefficient (correction).

Throughout over a half-century history of the Kazansky-Shulman formula, no attempt has been made to represent more accurately the dependence of the salinity coefficient on the value of ice salinity (at least, we are unaware of those). The authors of this paper worked for hydrometeorological support of cargo and transport operations at various sites of Ob bay, where water salinity fluctuates from sea values (>24.8‰) on its border with the Kara Sea to almost 0‰ in its southern part; salinity coefficient was taken as 0.7 in the Sabetta area, 0.9 in the Salmanovsky berth area and 1.0 in the area of Cape Kamenny. These values were set as an expert estimate, taking into account the actual measured salinity of the fast ice at a particular site.

When planning and implementing ice engineering works on fast ice, we need to consider permanent sea level fluctuations: tidal, wind-induced surges, and also seiches in large closed water areas. These fluctuations result in through cracks that exist constantly (tidal cracks) or are formed occasionally from large sea level drop and associated ice movements. Apart from the level fluctuations, fast ice can be exposed to short-period impacts from swell waves coming from open water areas. Examples include operations on the fast ice in the straits of Franz Josef Land, when the swell coming from the open areas of the Barents Sea caused noticeable periodic wave-like fluctuations of fast ice, which was in the stage of first-year ice of medium thickness.

Another feature that distinguishes river crossings from operations on fast ice is the structure and morphology of the ice cover. Laying ice roads on fast ice, from shore to a vessel or to an offshore hydraulic structure involves crossing sections of ice cover that differ in their morphometric characteristics, ice properties, and response to the applied load. The fast ice structure differs by regions and also changes greatly between ice seasons. However, it is possible to identify the basic characteristic elements of the fast ice structure encountered in most cases of tracing and laying ice roads.

Ice foot is the safest part in terms of the load on ice. In this section, ice usually lies on the ground and if it does not reach the ground in some places, the distance between the bottom and the lower ice surface is small.

Alongshore tidal cracks separate the ice foot, which is frozen to the shore and bottom, from the main section of fast ice, which is afloat and makes vertical movements under the influence of sea level fluctuations (tidal and non-periodic). Depending on the pattern of depth changes in the coastal zone, the range of level fluctuations, the possibility of spreading swell waves under the ice, and other factors, one or more tidal cracks are formed parallel to the shore at a distance of several to hundreds of meters (sometimes up to a kilometer) from the water line. A tidal crack is often combined with an alongshore hummock ridge. The width of alongshore tidal cracks ranges from a few centimeters to several meters. During the periods of quadrature (neap) tides and in the absence of surge-induced level fluctuations, narrow tidal cracks can partially freeze and be covered with snow. During the periods of syzygial (spring) tides, such cracks “revive” and become wider; at high water, a “step” – the elevation of the seaward crack over the coastal edge – can be formed. During strong wind surges, the ice foot and the coastal beach can be flooded with water coming through the active crack nearest to the shore. In this case, the main part of fast ice, which is afloat, rises with the increase in the water level, accordingly. At the peak of the ice season, the ice foot is usually covered with a thick layer of snow; the snow thickness there is several times greater than that on the main part of the fast ice.

Areas of level ice have a large spatial extent with a steady build-up of fast ice in the absence of strong dynamic influences. Continuous level ice, from the shore to navigation depths is not often found in the places where ice infrastructure is arranged, but sometimes the conditions of ice formation and formation of fast ice favor such situations and make ice engineering works much easier. With a strong hummocking of fast ice, areas of level ice, from several tens to hundreds of meters in horizontal dimension, are found among the hummocks. Areas of level ice cover with small spatial changes in the ice thickness are most consistent with the model of a quasi-homogeneous elastic plate on a hydraulic base, for which the schemes of ice load-bearing capacity calculations are developed.

Areas of hummocky ice represent inclusions of the ice cover with irregular hummocking scattered across the area. They are characterized by a greatly uneven spatial distribution of the ice thickness and an increased snow cover in comparison with that of level ice. To determine the ice load-bearing capacity in hummocks, the thickness of the consolidated hummock layer should be taken for the ice cover thickness. The strength of the consolidated hummock layer is comparable to the strength of level ice. Due to the uneven surface of the hummocked ice and a large snow layer, the upper border of the consolidated layer can sometimes be located below the water level (submerged ice).

Hummock ridges separate heterogeneous areas of the ice cover. Also, a hummock ridge can be formed along a crack that initially diverged, then closed with the fragmentation of its edges. The same as for hummocked ice, the thickness of the consolidated layer is taken for the ice cover thickness.

Stamukhas (grounded ice hummocks) are large isolated hummocky formations with their keel resting on the seabed. A characteristic feature of stamukhas is the presence of contouring tidal cracks. Sometimes they are accompanied by radial cracks with rays diverging in various directions. Stamukhas are formed in shallow water, but this notion comes rather conventional as regards ice equipment and vehicles: the depth around the stamukha can be several meters, and it often exceeds 10 meters, so the routes of ice roads should be laid away from the stamukhas and the surrounding cracks. However, the presence of stamukhas on fast ice is a positive factor that increases the fast ice stability during offshore winds.

Hummock barrier is a large hummock ridge formed at the border between fast ice and drifting ice. In some places, the keel of this extended ice formation rests on the seabed (a stamukha-like barrier), which also leads to the formation of a tidal crack along it. Usually, the ice road infrastructure is located coastward of the main barrier. However, fast ice can be sometimes traversed by an old barrier formed at the early stages of fast ice formation, when its border was registered along the relatively small depths (5-6 meters) over a protracted period. To reach the navigation depths, ice road should be laid through such a barrier. Usually it is stamukha-like and the actual tidal cracks pass along it, so forcing the passage over them requires increased safety measures (use decking, monitor the operation of equipment and the crack condition).

The Arctic coast within the most part of the Russian sector is characterized by moderate depths and ice roads are laid from the shore to 10-15 m depth marks, where icebreakers can operate. Under such conditions, the entire water column under the ice is mixed from the surface to the bottom and the temperature is close to water freezing, while the heat influx from the water to the lower ice cover surface is negligible or zero. In deep water areas with steep shores (islands of the Franz Josef Land archipelago, Novaya Zemlya), warmer waters are present under the mixed quasi-homogeneous layer, forming a noticeable influx of heat from the water. In such conditions, when arranging ice sites and roads, the redistribution of snow over the ice surface (snowdrift formation along the sides of roads when clearing ice, etc.) modifies the heat exchange between the ice cover and the atmosphere. Under large snowdrifts, heat emission from the ice surface to the atmosphere is significantly reduced or even interrupted and the heat influx from the water begins to warm up the sea ice, provoking ice melting from below and internal melting directly in the ice column.

An important factor for operations on fast ice is its stability. In the conditions of an open roadstead, cases of fast ice break-away during strong offshore winds are common.

REGULATORY FRAMEWORK FOR CONDUCTING ICE ENGINEERING WORKS ON FAST ICE

To date, there are practically no federal and departmental instructions and guidelines in Russia that determine the procedures for exploration, design, construction and operation of infrastructure facilities on fast ice (with the exception of vessel unloading operations), while ice engineering works on fast ice are conducted, and they are regular at some facilities. This leads to the situation when operators of license areas, operating companies and subcontracting organizations select arbitrarily any of the current regulatory documents related to the ice cover of water bodies and attempt applying it to the natural and technological conditions of their object. In this case, there appears, at least, the lack of coordination between organizations that apply different ice regulations on the same object, and in the worst case, they create prerequisites for emergency situations due to the fact that ice instructions for various purposes do not provide for all the risks and threats that exist on the sea ice cover, particularly in the waters of the Northern Sea Route under the year-round navigation. The current guidelines and instructions for cargo, transport, and construction operations on ice are listed below.

“Guidelines for the design, construction, and operation of ice crossings” (ODN 218.010-98). This document is the most popular guide among organizations involved in the construction of ice sites and roads. It is intended for arranging ice crossings on public motor roads across terrestrial water bodies (rivers, lakes). It is used by the EMERCOM of Russia (State Inspectorate for Small Vessels) for the coordination and inspection of ice crossings. It includes well-developed guidelines for conducting ice engineering works, but does not cover the specifics of the hydrology of sea areas, saline ice, and does not suggest possible fleet operations in the area of ice infrastructure.

“Collection of working technological documents for the loading and unloading operations performed during unloading of vessels at no-berth sites of cargo processing via the landfast ice” (RD 31.41.21-90). The document summarizes the long-term USSR experience in unloading vessels through fast ice, examines the full range of issues: organizational, ice engineering, navigation and hydrographic, hydrometeorological support, transport, cargo, as well as labor and environmental protection. It should be noted that this collection is outdated in terms of planning, organization, and operation management.

“Recommendations for the design, construction and operation of ice berthing facilities” (RD 31.31.52-89). Currently, it is almost out of use, but it contains many helpful instructions for conducting ice engineering works, including artificial freezing of ice with sea water. It is consistent with RD 31.41.21-90 in terms of determining the ice load-bearing capacity and related characteristics.

In addition to the above listed basic guidelines, instructions for carrying out works on the ice of water bodies can be found in VSN 137-89 (2000), in the supplementary instructions of Avtodor (Russian Highways State Company) for certain types of work, in ISO 19906, in foreign manuals on ice roads (in particular, Canadian), and in various publications. In 2020, the national standard, GOST R 58948-2020, was approved and put into effect, which applies to winter seasonal public motor roads.

In 2020, the Arctic and Antarctic Research Institute (AARI) published a methodological manual on special hydrometeorological support for unloading vessels through the fast ice (Kubyshkin et al., 2020), as part of the implementation of the State Order. The manual addresses hydrometeorological issues (meteorology, hydrology and ice observations, forecasting), ice engineering aspects of the fast ice infrastructure arrangement, coordinated actions of the operator of hydrometeorological support with the fleet and coastal mechanization, labor protection for the personnel working on ice. The manual builds upon the long-term experience of working on the fast ice during Soviet times described in the Recommendations (1986) and RD 31.41.21-90, summarizes the authors' findings on fast ice operations in 2007-2019 at the sites of Arctic coast of Russia (the western coast of the Yamal Peninsula, Ob bay, Yenisei, the Novosibirskiye Islands, Franz Josef Land, etc.). This manual can be used in the development of a new guidance document or a set of rules for the arrangement of ice roads and sites for various purposes on fast ice – a special guide needed by organizations and specialists involved in the developing the Arctic coast.

CONCLUSIONS

The paper examines the Russian experience accumulated to date in providing transport and cargo operations on fast ice. It is noted that in practice, various organizations often use regulations developed for freshwater ice that do not fully take into account both the physical and mechanical properties of sea ice, as well as the specifics of fast ice as a geographical object. This situation calls for the development of a specialized document summarizing the gained experience, the practice of operations on the fast ice, and framing the unified recommendations for such operations. The new methodological manual prepared by the Federal State Budgetary Institution "AARI" and published in 2020, is the first such work in many years and it can be used in the development of special regulatory guidelines and rules to create ice infrastructure for offshore facilities situated in the zone of stable fast ice, including the designed objects for hydrocarbon development in the Ob and Taz bays. Further work in this direction is envisaged.

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