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PROMISING INVESTIGATIONS OF THE SSC AARI FOR SCIENTIFIC SUPPORT OF SHELF EXPLOITATION AND NAVIGATION IN THE RUSSIA ARCTIC

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ABSTRACT

The main concern of AARI scientific investigations from the day of its establishment was study of dynamics, distribution laws of sea ice cover in the Arctic region and of physical principles of Earth climate changes. These investigations were diversified and were oriented to several main directions or physical and geographical objects: the sea ice cover, the atmosphere, the near space, the Ocean. Transition from geographical description of phenomena and environmental objects to their physical and technical investigations allowed us to solve important applied problems, which are necessary for support of human activity in the subarctic regions and primarily for support and investigation of navigation efficiency, in parallel with fundamental scientific problems.

The AARI celebrated 75 years of its founding in 1995. All these years the Institute was engaged in fulfilment of its main scientific goal: investigation of the distribution laws of the sea ice cover and its dynamics in the Arctic region of the physical principles of the Earth climate changes. Significant applied problems were solved in parallel. Results of these studies, were important for the human activity support in the subarctic regions and primarily for the navigation support and increase of its efficiency.

Investigation in the Arctic are multidisciplinary. They are oriented to several main directions or physical and geographical objects: the sea ice cover, the atmosphere, the near space, the Ocean. Studies are carried out by highly qualified scientists, many of them are creators of schools of thoughts in chosen lines of investigations.

Transition from geographical description of phenomena and environmental objects to their physical and technical research was one of the main factors, which stimulated progress in development of Earth sciences. This research included study of a wide range of physical properties of ice and snow formations, of ice acoustics and optics, development and use of new methods and technical means of active and passive remote sensing of the ice cover and ice formations, development of environmental monitoring methods and methods of active resistance to floating ice.

All these fields of investigation provided a basis for development of currently available methods of the ice classification in naturally occurring basins, which allowed us to approach to ice cover division into zones on water areas according to prevailing ice type, ice crystalline structure and strength characteristics, to development of methods of calculation of ice loads on ships and shelf structures and of risk analysis of their exploitation in the Arctic.

The AARI fulfils at present time a wide research complex for the hydrometeorological support (HMS) of different departments and organisations. Study of the distribution laws of different sea ice cover characteristics and development on this basis of new methods of sea ice forecasts of different temporal scales together with improvement of the existing methods is traditionally the most important line of investigation (Gudkovitch et. al., 1972).

Studies of dynamic and thermodynamic processes of ice cover growth and decay, of its drift, deformation and melting are progressing too. These studies are based on vast amount of observations, which were carried out on coastal polar stations and on "North Pole" drifting stations. Nowadays, work on development of several numerical models with different description of dynamic and thermodynamic processes is completed for the Barents and Kara seas both for winter and summer periods (Appel & Gudkovitsh, 1992; Frolov, 1981).

Complex study of sea ice cover peculiarities in winter period was carried out in the context of organization of all-year-round navigation in the Kara sea. This study includes fast ice forming and its stability, distribution of flaw polynyas, distribution of cracks, leads and fractures (Mironov et. al., 1993). Succession of works on generalization of different parameters of the sea ice cover (sea ice concentration, stages of its development, hummock intensity, floe size distribution, etc.) was carried out with a help of formed databases. This work was also fulfilled for study of iceberg distribution and of their morphometric characteristics. Monograph is completed, which generalizes modern-day knowledge on the Kara sea ice cover.

Mathematical modeling of sea ice cover evolution is progressing rapidly since eighties. This line of investigation gives intensive insight into understanding of physical processes in the sea ice cover and assists organization of special field experiments. Expeditions, which were carried out on board of "Ottó Shmidt" research icebreaker, SLAR-surveys, which were carried out in the Barents and Kara seas, and the first Arctic

expedition on board of r/v "Akademik Fedorov" in the summer of 1994 are of particular interest.

Applied works receive primary attention in last years. These works are necessary for preparation of technical and economical justifications for exploitation of oil and gas fields - Stockmanovskoye and Prirazlomnoye in the Barents sea, Bovanenkovskoye on the Yamal peninsula, laying of pipelines in the Baydaratskaya Guba in the Kara sea. Special attention is paid to study of local peculiarities of the ice conditions. Principles of the environmental monitoring and of organization of special experimental works were formulated.

The following problems of HMS development offer considerable promise:

1. Development of the remote sensing methods of the ice cover and of ocean surface and development of self-contained stations.

2. Development of new and improvement of existing methods of short-, medium- and longterm ice and hydrometeorological forecasts both the stochastic and numerical ones.

3. Development of new methods of ice and hydrometeorological forecasts of special purpose for support of the navigation and shelf exploration.

5. Development of new methods of hindcasts and forecasts of possible ecological consequences of sea ice cover and ocean contamination.

6. Creation of databases and databanks of hydrological and meteorological information and of information bases of special purpose.

7. Preparation of special purpose information on hydrometeorological and ice conditions.

8. Development and use of high quality software including GIS-technologies at all stages of ice and hydrometeorological information reception, processing, analysis, forecast and storage.

9. Enhancement of HMS system taking into account specialization of the information and new technologies promotion.

The prompt support by the hydrometeorological and ice information of special purpose is possible only on condition of close cooperation and interaction of elaborators (AARI, and customers (steamship companies, firms, etc.).

The hydrometeorological support of different types of marine activity in the Arctic is one of the AARI responsibilities in accordance with Guidance on

Hydrometeorological Service of the Russian Federation and with obligations before WMO. Research process in the Institute is oriented to a large extent on resolution of this applied problem.

Work on creation of automated ice information system (ALISA) began in the seventies. The first version of this system is now operatively used. ALISA center, which is a building block of the AARI, and Arctic territorial departments of the RosHydromet (the main of them are combined with territorial navigation headquarters in Dikson and Pevek) allow users of all levels from Marine Headquarter and steamship companies till specific icebreakers and ships to obtain the ice, meteorological, hydrological, diagnostic, forecasting and reference information on all the marginal seas and the Arctic basin as a whole.

Satellites, airplanes of SLAR and visual reconnaissance, polar stations, self-contained buoys, icebreakers and vessels are used as sources of the hydrometeorological and ice information. It should be mentioned that performing of regular air reconnaissances was interrupted in the last few years because of high leasing prices of airplanes. Satellites are now the main source of obtaining of the ice information. Role of observations from vessels and of self-contained ice stations also sufficiently increases now.

The prompt ice and hydrometeorological information is presented to users as geographical maps using facsimile communication lines or using special "Kontur" format.

Further development and enhancement of the ALISA system is carried out in the following directions:

1. Subsystem of data collection : use of data of satellite remote sensing in visual, infrared and radio ranges of medium and high resolution, modification of the self-contained hydrometeorological stations installed on floating ice, islands and coasts of the Arctic seas, elaboration of helicopter SLAR-system.

2. Subsystem of data processing: automation of processes of geographical relation to coordinates and data decoding, elaboration of methods of information compensation and supplement of direct observations data by calculations, use of high quality software and the GIS- technologies, in particular.

3. Subsystem of transmission and dissemination of the information: use satellite communication lines, providing data communication between computers.

Work is underway in recent years on adaptation of the ALISA system for the hydrometeorological support of international and transit navigation along the Northern Sea Route (NSR).

Transition from geographical description of phenomena and environmental objects to their physical and technical investigations was among important factors, which had determined progress in development of Earth sciences and particularly of the polar regions.

The physical and technical investigations can be classified by convention into the following interconnected directions:

- study of snow and ice physical characteristics;
- elaboration of technical means and methods of geophysical object research;
- decoding of information on characteristics of objects under consideration.

Forming of the ice cover crystalline structure under the influence of hydrometeorological factors should be treated as problem of considerable importance of sea ice physics.

Results of generalizations (according to published data) and calculations for the main stages of ice development (from $h=10$ cm up to $h=300$ cm) and for different seasons of observation testify, that it is necessary to take into account spatial and temporal variability of the ice structure and of its physical properties for solution of a variety of scientific and applied problems of ice research among other things during preparation of Recommended Practice for Planning, Designing and Constructing of offshore structures on shelf of freezing water areas, while carrying out transport and loading-unloading operations on fast ice, for navigation in ice conditions, etc.

The offered calculation method of strength, elasticity and bearing capacity characteristics of the sea ice cover of a specified thickness (or remotely measured) using a priori known (or measured for the instant of calculation) temperature of the ice upper surface and snow cover thickness is aimed at solving of these problems. Calculated information is defined as forecast and can be either climatic or expeditious by its character. In the first case, it can be used at the stage of designing in map and reference book form. In the second case, it can be used in the form of communication (daily, for ten-day period, monthly).

This line of investigations provide a basis for elaboration of contemporary structure-genetic classification of ice of naturally occurring water areas. This

classification allows one to approach to division into zones of the ice cover on water areas according to prevailing type of the ice, their crystalline structure and strength characteristics.

Data on ice electric properties are of fundamental importance for solving of a variety of applied problems of the ice research. In the first place they are the following ones: investigations of the ice cover by remote radiophysical methods both active and passive; study of radiowave propagation in polar regions and in the system atmosphere-ice-sea water; study of the ice as dielectric material for fundamental fields of science such as molecular physics and physics of dielectrics.

Dependencies of electric parameters on frequency, temperature, physical and chemical ice properties, stage of ice development and its structure are revealed as a consequence of these investigations. Model of the sea ice as ternary anisotropic medium interacting with electromagnetic radiation was developed. Theoretical relationships of deterioration of signals in ice sheet for different wavelengths and temperatures were formulated. Taking into account polarization of sounding radiation allowed us to estimate anisotropy of the ice cover electric parameters governed by structural regularity of ice crystals growth during ice formation.

Results of these investigations have found practical utility in interpretation of radiolocation sounding and radiometric surveys data of different types of the ice cover particularly for decoding of SLAR-images obtained with a help of the "Kosmos-1500" satellite.

Theoretical and experimental research of electromagnetic wave propagation in glaciers, procedures and technology of radiolocating measurements of ice shelf and outlet glacier thickness stimulated successful development of new line of investigations-radiosounding of the sea ice and of other strongly absorbing layered media such as permafrost, peat, sands and others.

Side looking airborne radar (SLAR) stations with real or synthetic aperture apparatus hold a firm place in the last 10-15 years in broad scale study of sea ice cover conditions from the satellites. Model of such a locator of high resolution was elaborated in the AARI department of ice and ocean physics. It should be put through field tests in the nearest future.

Method of infrared (IR) radiometry is an effective remote method, which allows one to estimate thermal processes in water-snow-ice covers of polar waters areas. This

method is based on reception of inherent thermal radiation of object under consideration. Investigations of formation peculiarities of the inherent thermal radiation of the snow-ice cover of the Arctic seas in the infrared area of spectrum carried out by the AARI for solving of important applied problem of remote determination of the ice stage of development demonstrated possibility of use of aerial thermal survey data for the ice thickness determination for the ice up to 1 m.

These elaborations favoured organization of the regular aerial thermal survey of the Arctic seas.

Passive radiopolarimetry is one of the lines of development of the radiophysical methods of the sea ice cover remote sounding. This method is based on possibility of registering of the inherent radio-thermal emission of surface under consideration by highly sensitive radiometric receivers. Range of wavelengths used in the radiopolarimetry corresponds to the ultra-high frequency (UHF). Relatively weak absorption of the radiowaves of this range in the atmosphere allows one to use the radiopolarimetric methods practically irrespective of weather conditions. Spectral and polarization measurements of their radiobrightness temperature form at present time the basis of the UHF radiometric investigation methods of the sea ice cover.

It is possible to determine dielectric permeability and conductivity of the ice (electric characteristics); thermodynamic temperature, index of refraction and attenuation coefficient (physical characteristics); relative volume of liquid phase and salinity (chemical characteristics) using radiopolarimetric analysis of the inherent microwave radiation of the sea ice. Furthermore, it is possible to obtain information on character of changes of mechanical stresses in the ice cover while measuring the radiobrightness temperature of the deformed sea ice for different polarizations.

Investigations of the department of ice and ocean physics aimed at study of mechanisms of contact overcooling and active forming of shuga in local regions in water areas with complicated thermohaline structure are of particular importance for providing navigation in the Arctic regions. This line of investigations makes possible division into zones of the sea ice cover in the marginal seas with marking out the zones, where appearance of icing is highly probable, revealing of energetically active sections of "ice cushion" forming at icebreaker's hull and formulation of suggestions on icing resisting methods.

Study of methods of ice cover weakening as applied to solving of problems of ice navigation, defense of port and hydrotechnical structures, obviation of ice difficulties during exploitation of floating and stationary docks is fundamentally new line of investigation of the AARI in the last few years. One of these lines of research is connected with elaboration of passive method of influence on the ice cover by means of radiation-convection screens, which sufficiently decrease effective energy of the surface emission and gives an opportunity to decrease ice thickness growth rates and to change its mechanical characteristics. Different types of the screens with high operational characteristics and reliable in service were offered as a result of fulfilled work. These elaborations approved their efficiency in the course of prolonged experimental testing.

Applied investigation in the Arctic are performed in the AARI over several decades. Combined approach was always typical for these investigations. Extensive information on environmental conditions was a basis for theoretical and model experimental research, investigation results were subjected to tests in practice.

The first in the world ice tank has been constructed in the AARI. Several tanks are functioning at present time in the Institute. They are used for resolution of a wide range of problems.

Theoretical methods of calculation of ice resistance to ships are well-known both in Russia and abroad. Hydrodynamic model of ship's interaction with ice gained general recognition throughout the world.

The Arctic and Antarctic Research Institute gave much consideration throughout all the period of its activity to navigation security in the Russian Arctic seas. Security of the ice navigation includes, first of all, suggestions on ensuring of reasonable safety of hulls of ice class ships and icebreakers. Decrease of hull damages can be achieved in two ways: at the stage of formulation of Recommended Practice for designing of ice belt constructions and at the stage of designing of ships and icebreakers. Considerable work has been carried out in the last years in both these lines of investigations.

Concept of "ice passport" was offered and realized. The "ice passport" allows one to choose safe velocities of ship's movement depending on ice cover characteristics and navigation conditions. Such passports were elaborated on the order of steamship companies nearly for all the ships of the Russian Arctic fleet (Likhomanov et. al., 1993)

This concept is developing now. Elaboration of computer system is completed at present time. This system will allow us to obtain the ice passport in semi-automatic regime. Idea of "board ice passport" was proposed. The "board ice passport" is a software simple in use for ship's computer. Navigator can obtain offers on choice of safe movement regime with a help of this software depending on the observed ice conditions. The experimental board ice passports will be proposed to test on ships in the nearest future.

Much consideration is being given to resolution of the problem of ice loads on ships and shelf structures. One should mention among others the following investigations, which are in progress now.

It is well-known, that recalculation of the loads on structure obtained in the result of model testing is connected with appearance of errors caused by "scale effect". AARI specialists offered method of estimate of these errors. This method is based on comparison analysis of results of sets of experiments in the ice tank for the models of different scales. A variety of other original ideas was offered. These ideas should increase reliability of the experimental results.

Methods of computer stochastic modeling of the ice loads on ships and shelf structures are in progress now. These methods are based on account of stochastic character of ice interaction processes with constructions and allow us to obtain statistical characteristics of the loads determined by action of the ice (Likhomanov, 1993). It gives us an opportunity to carry out quantitative analysis of the safety of ship operation or the shelf structure in presence of the sea ice.

Algorithm was developed, which allowed us to forecast construction reliability according to different criteria of failure and given distributions of the ice load. This algorithm was tested in the framework of several contracts for calculation of the construction reliability of the ship ice belt of two different types and of ice-resisting stationary platform.

Risk forecast of ice damages will enjoy wide application in designing of the considered constructions, for estimate of unfavourable actions on environment, practice of insurance, etc.

Special attention is paid in the AARI for combined character of approach while carrying out applied research, i. e. interrelation between data collection on environmental conditions and their analysis, between theoretical and model experimental

investigations, testing of obtained results in real conditions (Busuyev and Likhomanov, 1993).

Just the fact, that all investigation carried out in the Institute are based on unique knowledge of environmental conditions in the Arctic and are realized by the most up-to-date methods in different areas of knowledge, advances many research works of the SSC AARI of the Russian Federation among those of high priority.

REFERENCES

1. Gudkovitsh, S.M., Kirillov, A.A., Kovalyov, Ye.G., Smetannikova, A.B., Spitskin, V.A., "Foundations of longterm ice forecast methods for the Arctic seas", L., Hydrometeoizdat, 1972, 348 p.
2. Appel, I.L., Gudkovitch, S.M., "Numerical modeling and forecast of ice cover evolution in the Arctic seas in the period of ice melting". St.P. Hydrometeoizdat, 1992, 144 p.
3. Frolov, I.Ye., "Numerical modeling of autumn-winter ice phenomena", Tr. AARI, 1981, v. 372, pp. 73-81.
4. Mironov, Ye.U., Spitskin, V.A., Yegorov, A.G. "Seasonal conditions in the regions of shelf exploitation in the Barents and Kara seas". Proc. of the First International Conference "Development of Russian Arctic Offshore", St. P. State Technical Univ., 1993, p. 92-93.
5. Likhomanov, V.A., Polferov, S.Yu., Stepanov, I.V., Timofeyev, O.Y., Faddeyev, O.V., "Principles for Development and Prospective Use of the Ice Passports", POAC'93 Proceedings, Vol. 1, pp. 219-226, Hamburg, 17-20 August 1993.
6. "Elaboration of combined procedure of determination of basic statistical characteristics of ice resistant stationary platform hull", Technical Report. SSC AARI of the Russian Federation. Likhomanov, V.A. editor. St.P., 1994, 109 p.
7. Busuyev, V.A., Likhomanov, V.A., "Division into zones of the Northern Sea Route by difficulty and safety of Navigation". POAC'93 Proceedings. Vol.1, pp. 393-402. Hamburg, 17-20 August, 1993.

PERSPECTIVE TYPES OF ARCTIC ICEBREAKERS AND THEIR PRINCIPAL CHARACTERISTICS

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ABSTRACT

The paper presents results of the feasibility study of the icebreaking fleet structure and technical and operational characteristics of perspective icebreakers to provide for efficient and safe functioning of the arctic marine transport system in Russia as well as to secure guaranteed icebreaker support for foreign ice ships sailing along the Northern Sea Route (NSR). Also considered was the future transit transportation and export on large ships of raw power-generating resources produced on the shelf of arctic seas. In the process of substantiation the assessment is given of the future development of cargo transportation in the Arctic. Conditions of the operation of transport fleet over perspective directions have been considered and needs in the icebreaker support studied. On the basis of the investigation of the structure of work of domestic icebreakers on the NSR, bearing in mind their additional use in non-arctic seas, the concept of the formation of fleet of linear icebreakers has been developed and a size range of perspective icebreakers proposed enabling to provide for safe cargo transportation in the Arctic and through other freezing seas surrounding Russia. Principal characteristics of the proposed types of icebreakers have been defined.

1. ROLE OF THE MARINE TRANSPORT IN NORTHERN REGIONS OF THE COUNTRY

The entrails of the North contain rich reserves of various minerals. Such resources as hydrocarbon, rare and noble metals precious minerals as well as woods determine the national economic balance of Russia. Under present day conditions the country's economy cannot be normally developed without a number of minerals concentrated in northern regions and in the arctic zone. Therefore the extractive industry in its making will inevitably expand to the North, to the shelf of arctic seas and thus define further transport development. Substantial difficulties in the

development and use in the North of the land transportation system give every reason to consider water transport as dominating here.

The Northern Sea Route serves main industrial complexes of the Arctic zone: West-Siberian oil-gas complex, Norilsk industrial center, extracting industry of the northern areas of Yakutia and Chukotski autonomous district, timber export enterprises of the Eastern Siberia and Yakutia, geological and other fixed and temporary based expeditions, organizations of different departments, populated areas etc. Subsequently it is intended to incorporate the NSR into the system of international shipping including the export of power-generating resources from the Arctic and transit through transportation.

Tasks the marine traffic faces in the Arctic were being formed in the process of the industrial exploitation of natural resources and the development of productive forces. At its point of departure the main problem was to turn the Northern Sea Route into a normally navigable water way providing for the regular communication with the Far East. Functioning of the marine transportation system during traditional (summer) periods of the arctic navigation was envisaged implying the necessity of the transition from expeditionary to regular navigation. With the increase of the scale of the industrial exploitation of mineral resources and higher significance of the latter for country's economy, as large industrial complexes were coming into being, the marine transport has been faced a qualitatively new problem to extend arctic navigation up to all the year round one and to develop material and technical base providing higher security of the delivery of cargo to points of destination within the fixed periods of time under any ice conditions. As a result of successful experimental voyages made in the 70-ies and strengthening of the material and technical base of the marine transport owing to the construction of powerful nuclear and diesel icebreakers, specialized transport ships, costal facilities etc. the system of transportation was established which all the year round ensured cargo supply of the year round ensured cargo supply of the Norilsk industrial complex. All the year round navigation on the whole western stretch of the NSR followed. Further extension of the duration of arctic navigation took place over all directions of traditional traffic where it seemed expedient and technically feasible.

2. PRESENT-DAY STATUS OF THE DOMESTIC ICEBREAKING FLEET

The development of the arctic fleet for last 50 years (Post-war period) may be divided into two stages. Each one had a program corresponding to tasks of the marine transport.

The first program aimed at turning the NSR into normally active shipping way envisaged the construction of large series of multi-purpose and specialized cargo ships with a high class of hull ice strengthening and took into account the needs of transport provision of the areas gravitating towards sea ways of the Arctic and other freezing basins. Total number of the ships built exceeded 500 units with an all in all deadweight of about 2 mln.t. Low-powered steam icebreaker fleet was gradually replaced by modern (as to that time) icebreakers with diesel-electric plants (3 units of *Kapitan Belousov* type with a power of 9.1 MW and 5 units of *Moskva* type with a power of 19.1 MW). In 1959 the first in the world nuclear icebreaker *Lenin*

(32.4 MW) was put into operation. Besides 14 port icebreakers of *Vasily Pronchichshev* type with a power of 4 MW each were built.

The second program having been realized since 1973 is associated with the task of the provision of the navigation during extended periods (up to all the year round) and the improvement of the security of arctic transportation. In the process of its implementation the Arctic Marine Transport System was set up which incorporated most powerful nuclear icebreakers of *Arktika* type (55.1 MW), shallow-draft nuclear icebreakers of *Taimyr* type (36.8 MW), diesel-electric icebreakers of *Ermak* (30.4 MW) and *Kapitan Sorokin* (18.3 MW) types with a restricted draft. Multi-purpose icebreaking ULA class transport ships of *Norilsk*, *Vitus Bering* and *Ivan Papanin* types, UL class bulkers of *Dmitry Donskoy* type, UL class tankers of *Samotlor* and *Ventspils* types, timber-pallet carriers of different types, containerships, universal ships etc. were constructed - about 200 ships all in all of a total deadweight of about 2 mln.t. Among transport ships also barge carriers of *Alexey Kossyghin* type with a diesel plant and of *Sevmorputj* type with a nuclear plant were put into operation.

The built arctic fleet enabled to solve historical task on the organization of all the year round navigation in the western section of the NSR with a steady mode of sailing. The problem of all the year round navigation in main freezing ports of non-arctic bassins has been solved even earlier, in the 60-ies.

Table 1
Composition of the fleet of linear Russian icebreakers as of 1995

Name of icebreaker	Year of construction	Installed capacity power, MW	Icebreaking capability, m	Registry
Nuclear icebreakers				
<i>Arktika</i>	1974	55.1	2.3	MSC
<i>Sibirj</i>	1977	55.1	2.3	MSC
<i>Rossia</i>	1985	55.1	2.5	MSC
<i>Sovyetskiy Soyuz</i>	1989	55.1	2.5	MSC
<i>Yamal</i>	1992	55.1	2.5	MSC
<i>Taimyr</i>	1989	36.8	2.0	MSC
<i>Vaigach</i>	1990	36.8	2.0	MSC
Total		349.1		
Diesel-electric icebreakers				
<i>Ermak</i>	1974	30.4	1.8	FESCO
<i>Admiral Makarov</i>	1975	30.4	1.8	FESCO
<i>Krasin</i>	1976	30.4	1.8	FESCO
<i>Kapitan Sorokin</i>	1977	18.3	1.4	MSC
<i>Kapitan Nikolaev</i>	1978	18.3	1.4	MSC
<i>Kapitan Dranitzyn</i>	1980	18.3	1.4	MSC
<i>Kapitan Khlebnikov</i>	1981	18.3	1.4	FESCO
<i>Murmansk</i>	1988	19.1	1.5	FESCO
<i>Vladivostok</i>	1989	19.1	1.5	FESCO
Total		202.6		
In all		551.7		

After the disintegration of the Soviet Union and division of fleet the material and technical base of the Russian Sea transport turned out to be unbalanced and incapable of fully realizing its potential. Need of the new revival of the merchant fleet of Russia became obvious.

At the moment the linear icebreaker fleet includes 16 arctic icebreakers, 7 units are equipped with nuclear power plants (NPP) and 9 - with diesel-electric plants (DEP). Composition, dates of construction and ownership of linear icebreakers are presented in table 1. In addition to ships indicated in the table, at the shipyard Baltiysky the fitting-out of the nuclear icebreaker *Ural of Arktika* type but with the improved shape of forebody, is being completed. Besides, this icebreaker is adapted for cruise polar voyages with 100 passengers aboard.

As one can see from the table, the Russian merchant marine is comparatively young - all arctic ships except icebreakers of *Moskva* type have been built in 1974-1992. However by 2000-2005 all diesel-electric and some nuclear icebreakers will reach the age of 25-30 years, becoming obsolescent and subject to putting out of service. Taking into consideration this fact, to provide for the already traditional cargo transportation in the Arctic, at this stage the Program of the revival of Russian fleet envisages the reinforcement of the arctic fleet by icebreakers and icebreaking cargo ships, in the first place for the replacement of old written off equipment. The emergence in the future of non-traditional cargo transportation in the Arctic will require the construction of new types of icebreakers complying with the solution new problems [1].

3. ASSESSMENT OF THE FUTURE DEVELOPMENT OF CARGO TRANSPORTATION IN THE ARCTIC

Goods traffic through northern seas of the country along with the qualitative and quantitative composition of transport ships as well as environmental (ice) conditions are main factors defining the size and structure of the icebreaking fleet.

During the entire post-war period the economic exploration of mineral resources of the North was carried out intensively and always on a larger scale. Goods traffic increased accordingly having reached in 1987-1988 its maximum. Subsequently under the influence of the reconstruction processes and the corresponding reduction of commercial production and investments into its development, decrease of foreign trade exchange, reflux of the population from northern areas and other peculiar characteristics of the new policy the goods traffic everywhere dropped, in some cases twice and more [2].

At present the process of structural reorganization is not yet finished, a number of basic provisions for the assessment of the future do not manifest clearly enough. Stabilization of the situation and subsequent growth of the production may be expected after 1995-1996. The restoration of the level of production and its development, especially in northern areas, require enormous efforts on the organizational and technical improvement and large expenses. Proceeding from these considerations the anticipated volumes of transportations for the future may reach the level of 1987-1988 beyond 2000, probably by 2010. By this time, only

due to the obsolescence of ships, complete replacement of the icebreaking fleet will be required.

Main goods traffic provided by the marine transport in the Arctic basin is carried out over the traditional directions mentioned earlier. It is intended in the future to incorporate the Northern Sea Route into the system of international shipping. One should expect the emergence of non-traditional large-scale freight traffic associated with the export of hydrocarbons from the deposits of the Barents and Kara seas

Western-Siberian oil and gas complex represents one of the most promising regions of the economic exploration of the North. The North of the Western Siberia is a principal source of the increase of gas production for next 40-50 years. The system of gigantic deposits (Urengoiskoye, Medvezhye, Yamburgskoye) includes also the fields of Yamal. Among the latter, Bovanenkovskoye, Kharasaveiskoye and Kruzensternskoye contain about 6.5 bln.m³ of natural gas. Of practical interest are oil and gas deposits on the shelf of the south-western part of the Kara Sea. According to "Sevmorgeologia" the predicted oil resources here amount to approximately 15 mlrd.t and gas - about 19 bln.m³. Especially worth mentioning are the largest local Structures - Rusanovskaya and Leningradskaya situated at accessible depths near the mouth of river Kharasavey. In the south-eastern part of the Yamal peninsular the export by sea through the Ob Gulf of oil from Novy Port seems promising. Transportation of gas condensate from Yamal will be also required.

Works on the exploration of shelf of the south-western part of the Kara Sea are being continued. Alternative of the oil and gas production on shelf of this part of the Kara Sea and the transportation of hydrocarbons will be more accurately defined later on and the production proper will apparently start after 2015.

Development of the transport facilities of the south-western part of the Kara Sea is closely associated with the operations in the south-eastern part of the Barents Sea. Now these operations are directed towards the delivery of cargo of geological survey expeditions in the northern regions of the Timano-Pechorskaya oil and gas province. Potential resources of hydrocarbons on the shelf (Prirazlomnoye oil field), on the coast and in inland areas are estimated here as exceeding 5 mlrd.t in oil equivalent.

Practically completed is the preparation of documents for a number of large-scale projects costing tens mlrd. of US dollars. There are such projects which envisage not only bringing in cargo for exploration of deposits, accommodation and equipment, but also export of hydrocarbons by sea. At present it is difficult to foresee the scale of the exploration of this region by 2010 and to evaluate the perspectives of the construction of appropriate marine transport and technological systems (TTS), but such possibility should not be disregarded.

After 1987-1988 the freight traffic through freezing routes of non-arctic seas was also everywhere reduced. However the transportation volumes bound for Russian ports of the North-West will reach the 1988 level apparently in shorter periods than arctic and far-eastern traffic. The conception of the development of Russian ports envisages the construction in the Gulf of Finland and on the White Sea of new transshipment systems and the increase of the capacity of existing ones in order to re-orientate the goods traffic passing now through the ports of Baltic states. Anticipated increase of the traffic by 2010 in comparison with 2000 will be here 20-30%

4. SCHEME OF THE USE OF THE RUSSIAN ICEBREAKING FLEET

Scheme of the use of linear icebreakers offers the scope of their operation during different seasons on routes of various basins. This enables ensuring their maximum capacity and accordingly reducing their number. At the same time the icebreaking capability of icebreakers, their dimensions and other parameters are mainly determined proceeding from the working conditions in the Arctic Work in freezing non-arctic seas is considered as additional one. Such universalization permits not only to curtail the quantitative but also to reduce the number of types of promising icebreakers.

4.1. Work of icebreakers on the Northern Sea Route

Extended period. Cargo transportation through the western part of the Russian Arctic during winter is carried out over two principal directions - towards the Yenisei river and the Yamal peninsula. Besides, within an extended period the limits of which are fixed from November to May, one-time carriages are carried out to Novaya Zemlya, coast of the Pechora Sea as well as to Amderma, Dickson Island and Franz Josef Land.

Principal direction of winter traffic is towards Dudinka. The Dudinka TTS of all the year round mode of operation came into being in the 70-ies with a purpose of providing for continuous export of metal products from the Norilsk Mining and Iron-Steel Plant and steady moving in of basic cargo, structural materials, equipment and consumer goods. Works on the export of timber from Igarka terminate in November.

In February-May the winter-spring operations are carried out on the delivery of cargo to the western coast of the Yamal peninsula. Unloading is made onto the fast ice near the cape Kharasavey, mouth of the Mordyakha river and in other places (for the supply of geological survey expeditions).

The icebreaker support system directed towards Yenisei due to restricted depths on the river section of the route has two (river and sea) sub-systems. The first one involves the assistance by shallow-draft icebreakers of *Taimyr* type. From the Yenisei Gulf to the ice edge of the Barents Sea transport ships are supported by icebreakers of *Arktika* type. In the case of two icebreakers of *Taimyr* type working on the route under ice conditions accessible for these icebreakers on the sea section there exists the possibility of their supporting ships from Dudinka to the ice edge without the transfer to *Arktika* type icebreakers. This approach is fairly efficient because it eliminates the loss of time for the rendezvous of icebreakers or permits to shift a rendezvous place depending on the situation.

The system of icebreaker support in the Yamal direction of transportation in the majority of cases is combined with the Dudinka system.

Besides the servicing of ships along their routes, icebreakers are required in Igarka for manoeuvring works in port and to convoy ships as far as Dudinka; in Dudinka - for manoeuvring; on western coast of the Yamal - for the fast ice mooring of ships to be unloaded, letting them out of the fast ice and for greater safety near a place of unloading. For operations in Igarka one of port icebreakers of *Mudyug* type is used, while in Dudinka and on the Yamal linear icebreakers of *Taimyr* or *Kapitan Sorokin* type are employed.

Traditional period. This period of navigation in the western area of the Russian Arctic usually begins in May by a voyage of supply vessels to the Franz Josef Land and the Sedov archipelago under assistance of an icebreaker.

Each year in May a nuclear icebreaker of *Arktika* type leaves Murmansk bound for the eastern part of the Arctic along the NSR to provide for the convoy of ships there.

Mass convoying of ships to Igarka for the export of timber begins in the second half of June and follows the breaking through of a channel in the fast ice of the Yenisei Gulf along which the movement of ships assisted by an icebreaker is carried out.

Main obstacle while moving from the Barents to the Kara Sea is the ice massif of Novaya Zemlya (see fig.1). As a rule, independent (without icebreaker) navigation in the south-western part of the Kara Sea, starts in the third ten-day period of July. By this time the Yenisei Gulf also becomes free of ice.

As the massif of Novaya Zemlya disintegrates, linear icebreakers move eastwards to convoy ships through ice massives of Severnaya Zemlya and Taimyr to points of the Laptev and East Siberian Seas. First ships leave the Dickson Island area usually at the end of June following through the slightly disintegrated ice of the fast ice of the Nordensheld archipelago and arrive in Tiksi in the first ten-day period of July. Ships proceeding further eastwards approach Pevek in the third ten-day period of July.

The icebreaker support in the Vilkitsky strait and at the approaches to it is usually provided during the entire navigation.

One of the shallow-draft icebreakers of *Kapitan Sorokin* type works during the whole summer on the section Khatanga-Tiksi being sometimes called for the convoying of ships through the Dmitry Laptev strait or the massif of Yana.

As a rule, one-two icebreakers during the whole period of navigation accompany supply vessels ensuring their safety in almost inaccessible areas.

Total number of icebreakers engaged during summer navigation in the western part of the Arctic may be 8-9 bearing in mind the anticipated volumes and directions of transportation.

Last transport ships pass through the Vilkitsky strait from the east at the end of October. Traditional operations in the western part of the Arctic continue in November-December only over the Yenisei direction.

Operations in the eastern area of the Arctic usually start in the first ten-day period of June. First ships arrive in Pevek in the second half of June, to the Schmidt cape - in the third ten-day period of June, to Kolyma - in the first ten-day period of July, in Tiksi - in the third ten-day period of July. Operations in the eastern area finish in Tiksi and on Kolyfya in the middle of October, in Pevek - at the end of October.

Total demand in linear icebreakers over the eastern area sections varies within 6-8 units including icebreakers of the FESCO and MSC.

4.2. The use of icebreakers in freezing non-arctic seas

Baltic Sea. Icebreaker support over St.Petersburg-Vyborg direction by linear icebreakers is required from the beginning of January to the end of April. At the beginning of winter navigation the operations are carried out by local port icebreakers, later on icebreakers of *Kapitan Sorokin* type MSC, becoming involved

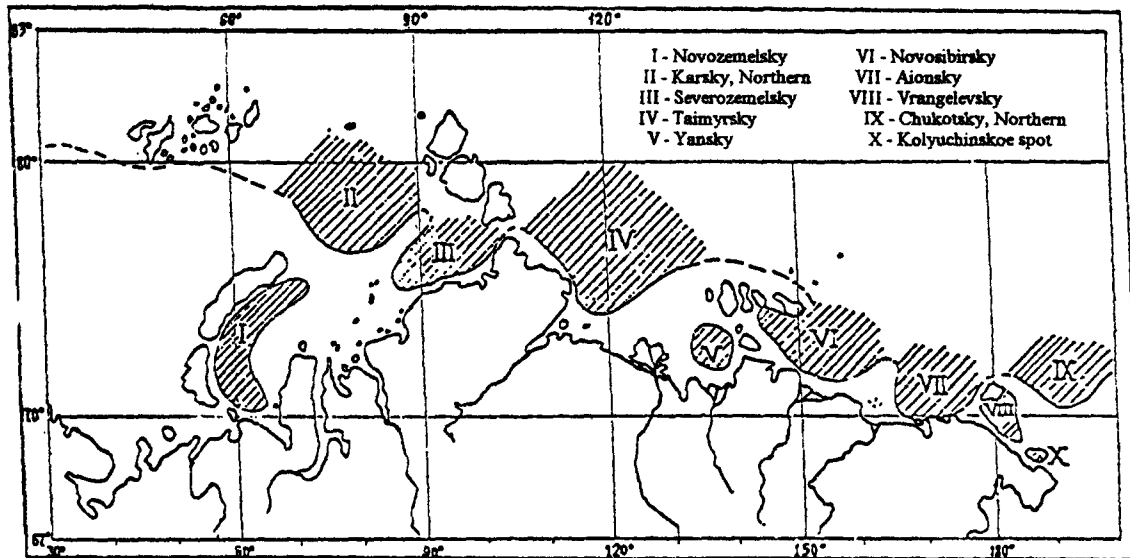


Fig. 1. Location of main ice massifs in summer (after P.A.Gordienko)

in the convoying. For convoying in the Gulf of Finland one-two linear icebreakers were usually used.

White Sea. Since the third ten-day period of December until the first ten-day period of May the sailing of ships here is possible only under the support of icebreakers. Over the water area of the port of Arkhangel'sk and the shallow regions the convoying is carried out by local port icebreakers. In open sea areas under the heaviest ice conditions the services of linear icebreakers are applied to.

Barents Sea. Operations in the Barents Sea usually begin in December and are related to the support of ships of the Yenisei and, later, of Yamal directions of transportation. The work of icebreakers here is of a transit character; there are no icebreakers assigned to this region. In separate cases the icebreaker convoying is provided around Novaya Zemlya from the North. The convoying on this section stops at the end of June - beginning of July.

Apart from the transit traffic mentioned, in the Barents Sea during the winter-spring period the operations are carried out related to the delivery of cargo to points of the western coast of the Novaya Zemlya and Pechora Sea. In May one of linear icebreakers while returning from the Baltic Sea calls at Ice-fiord on Spitzbergen, breaks the fast ice and for some time remains there to ensure safety of the first ships.

Within the Franz Josef Land archipelago in the majority of cases the supply vessels operate under assistance of linear icebreakers.

Far-Eastern basin. Sailing of ships towards large freezing ports of the Far East (Magadan, Vanino, De-Kastri) is carried out in all the year round mode thanks to the icebreaker support. Convoying by icebreakers is periodically needed for the maintenance of shipping in January-April at the approaches of the port of Korsakov. Ports of Beringovskiy, Anadyr, Egvekinot and Providence work in seasonal mode, but at the beginning of navigation (May-June) and during the period of its completion (November-December) sailing of cargo ships is assured by linear icebreakers.

Convoying of ships during winter navigation in the northern part of the Sea of Okhotsk (approaches to the port of Magadan) is usually headed by icebreakers of *Ermak* type the auxiliary service being provided by icebreakers of *Moskva* and *Kapitan Sorokin* types. Required number of icebreakers at the volume of traffic planned for 2010 in the period of the maximum growth of ice (February-April) is two-three units.

Sailing in winter towards the port of De-Kastri situated on the shallow gulf of Chikhachev is supported by port icebreakers and to the port of Vanino from January to March - by one linear icebreaker.

The above scheme of the use of icebreakers taking into account anticipated volumes and directions of traditional cargo traffic by the estimated period of time will require the availability in Russia of 14-16 linear icebreakers. To provide for new perspective (non-traditional) transportation of cargo in the Arctic the increase of the number icebreakers will be needed.

5 TYPE SIZE SERIES OF ICEBREAKERS FOR THE ARCTIC AND FREEZING SEAS

The above considerations about the anticipated development of cargo flows in the Arctic and the scheme of the use of fleet in the Arctic basin and in freezing seas surrounding Russia allows tracing a type size series of perspective domestic icebreakers. The replenishment of the icebreaking fleet is meant here both in the nearest future envisaged by the Program of the revival of the Russian merchant fleet and in a more distant future taking into account the exploration of raw power-generating resources of the North and the organization of transit transportation along the Northern Sea Route including icebreaker servicing of foreign ships.

As it is known, instead of linear icebreakers of *Moskva* type and port icebreakers of *Vassily Pronchishchev* type (taking part in summer arctic operations as auxiliary vessels). Which are being put out of service at present the Program of the revival of fleet provides for the construction up to 2000 of icebreakers of two type sizes diesel-electric icebreakers of LK-25 type with a shaft power of about 24 MW and icebreakers of LK-7 type with a power accordingly of 7 MW [1, 3]. Feasibility study of these icebreakers and principal specifications to them were made earlier by CNIIMF, technical designs developed by AO "Iceberg" [4] and also by other foreign shipbuilding companies on the basis of competition. Demand for such types of diesel-electric icebreakers is confirmed by the results of investigations performed. Required number of each series of icebreakers is still to be more accurately specified.

For the realization of future large-scale freight movement in the Arctic, in contrast to traditional transportation principally new types of arctic transport vessels and accordingly icebreakers should be developed these ships being capable to ensure reliable, economically efficient and safe shipping in the Arctic including all the year round operation.

For the export of power-generating raw material from arctic regions it is necessary to construct large icebreaking crude oil carriers, gas-carriers for LNG and tankers for gas condensate. These ships should meet specific operational and technical requirements based on working conditions in the Arctic (low ambient air temperature heavy ice conditions, shallowness of the arctic coastal waters, transshipment operations without mooring etc.) and from the point of view of economic efficiency these ships should be big-tonnage ones.

Development of transit transportation over the shortest high-latitude sections of the NSR will require the construction of competitive large ice containerships with a capacity of up to 3000 TEU.

As the comparative technical and economical assessments made earlier at CNIIMF have shown, all the year round use in the Arctic of icebreaking transport ships of active navigation without icebreakers is not advisable [5]. Preferable is the traditional procedure of ships' convoying by icebreakers. Proceeding from that the use in the Arctic of perspective large-tonnage ships will require the construction of corresponding super-powerful icebreakers-leaders capable of providing for reliable, regular and safe all the year round sailing along the NSR including high-latitude sections [6].

As the experience and research works have shown, multi-purpose route icebreakers of a new generation adapted for operation in the shallow areas of the Arctic [7] are preferable to form a basis of the arctic icebreaker fleet.

Bearing in mind the requirements for the restriction of principal dimensions and in the first place of icebreaker draft at the same time providing for practically unlimited endurance, mobility and accordingly high reliability of arctic operations, the advisability of the construction of powerful arctic icebreakers with nuclear power plants has been proved. Besides, icebreakers with a power of 20-25 MW intended for operation in freezing non-arctic seas (Baltic, of Okhotsk etc.) should have powerplants working on the organic fuel. As to the economic efficiency, it was shown that the rational power boundary of the use of the nuclear energy on icebreakers is within 35-40 MW [8, 9].

Consequently the advisability of the following type size series of perspective icebreakers has been substantiated:

- icebreaker-leaders of LK-110N type having an icebreaking capability of 3.5 m, draft on the design waterline 13 m and minimum working draft 11 m, intended for the secure conveying of ships over traditional directions of traffic in the Arctic during the winter-spring period and also for the leading of perspective big-tonnage ships designed for all the year round export of raw materials produced on the shelf of arctic seas and the guaranteed through transit cargo transportation between Western Europe and Far East;
- linear double-draft route icebreakers of LK-60N type with an icebreaking capability of up to 3 m, designed draft 11 m and minimum operating draft 9 m intended for leading the ships' convoys over traditional sections of the NSR during traditional periods of arctic navigation and also for escorting ships under complicated ice conditions in coastal arctic areas including mouths of siberian rivers; these icebreakers should replace icebreakers of *Arktika* type operating at present;
- linear sea icebreakers of LK-25 type having an icebreaking capability of about 2 m, design draft 8.5 m intended for the escorting of ships and the leading of convoys through freezing seas and as auxiliary ships within complex convoys on the NSR as well as for independent escorting over shallow stretches during summer arctic navigation;
- auxiliary icebreakers of LK-7 type with an icebreaking capability of about 1 m, design draft 6 m intended for the escorting of ships through freezing non-arctic seas near large ports and over their water areas as well as in shallow areas of arctic seas in the summer period.

In a more distant future beyond 2015 one may expect the emergence of the demand for nuclear shallow-draft icebreakers of LK-35N type for the Arctic. The question is not only of the construction of new generation *Taimyr* class icebreakers in view of the wear and putting the first ones out of operation but also of the servicing of new perspective (as to the production of hydrocarbons) shelf areas in the south-eastern part of the Barents Sea and south-western part of the Kara Sea.

While making the feasibility study of principal dimensions of icebreakers for the Arctic, not only the guarantee of escorting perspective large-tonnage ships along deep-water sections of the NSR, but also the necessity of their interchangeability in the restricted depth areas was taken into account. Minimum unballasted working

draft of powerful icebreakers of each type size was chosen in view of the possibility of their use in heaviest ice conditions on routes with the support of less powerful icebreakers. This will allow to increase the security of the escorting of ships in the Arctic perspective of ice conditions. The efficiency of perspective arctic transport and engineering system will to a considerable extent depend on the maintenance of stability of shipping in a given mode of operation.

6. TECHNICAL AND OPERATIONAL CHARACTERISTICS OF ICEBREAKERS OF PERSPECTIVE TYPES

Expected characteristics of icebreakers of the suggested type size series (LK-110N, LK-60N, LK-25 and LK-7) obtained from the results of design studies conducted by AO "Iceberg" [4] on the basis of the technical and operating requirements of CNIMF are given in table 2.

Table 2

Principal elements of the perspective types of icebreakers for the Arctic

Characteristics	LK-110N	LK-60N	LK-25	LK-7
Length, m:				
overall	206.0	177.0	139.6	92.0
on design waterline	193.6	164.0	129.6	85.8
Breadth, m:				
overall	40	35	30	23
on design waterline	38*	33	28	22
Depth, m	20.3	18.0	13.2	9.8
Draft, m:				
designed	13.0	11.0	8.5	6.0
moulded	11.0	9.0	8.5	6.0
Design displacement, t	55600	36500	19500	6050
Type of propulsion plant	NPP	NPP	DPP	DPP
Power, kW:				
PP	130000	74000	29300	8500
on shafts	110000	63000	24000	7100
Number of propellers	3	3	3	2
Propeller thrust, t	950	680**	320**	92
Speed in clean water, kn	24.0	22.0	19.2	17.0
Icebreaking capability, m	3.5	2.9	2.0	1.2
Fuel endurance (main engines working at full power), days	Unlimited	Unlimited	35	25
Crew number	115	95	45	28

Notes:

- * Taking account of the escorting of perspective big-tonnage ships it is advisable to investigate icebreaker alternatives with a breadth increased up to 40-42 m.
- ** Versions with a centre ducted propeller.

Universal duty and multi-purpose use of icebreakers of new replenishment predetermine the application of conventional but improved form of hull lines enabling to provide for substantial (up to 50%) gain of the power retaining the efficiency of operation under any ice conditions as well as acceptable seaworthiness during the navigation through clean water [10, 11, 12].

To ensure high ice qualities including manoeuvrability in ice on perspective icebreakers, new progressive driving propulsion systems, lubrication systems, thrusters and other means to increase the icebreaking capability including the use of the steel clad with the outer stainless coating for the underwater hull plating.

It is obvious however that by the moment of the construction the renewal of the existing designs of future icebreakers will be needed. They should use latest achievements of the world icebreaker-building as far as propulsion machinery, architecture and lay-out, hull structure and technology of construction are concerned.

At present recommendations are formulated on the rational composition of the reviving Russian icebreaker fleet and main technical and operating characteristics of perspective icebreakers evaluated. It should be noted however that in connection with the lasting in stability of the economic situation in Russia and the unreliability in forecasting the development of arctic cargo traffic, the above suggestions and recommendations on the structure of the domestic icebreaker fleet as well as on required parameters of different types of icebreakers will need later on more accurate definition

REFERENCES

- 1 Цой Л.Г., Максutow Д.Д., Зимин А.Д. Флот Арктики и его будущее. - Судостроение, N 11-12, 1993
- 2 Стоянов И.А., Плаксий В.Я. Исходные данные и методика расчета потребности в линейных ледоколах Союзморниипроект, рукопись, М., 1994.
- 3 Иерусалимский А.В., Лившиц С.Г., Цой Л.Г. Обоснование основных параметров и проектная проработка перспективного дизель-электрического ледокола мощностью 25 МВт Третья Международная выставка и симпозиум по судостроению, судоходству и разработке шельфа НЕВА 93, Сборник тезисов, СПб, 1993
- 4 Макеев А.Н., Старшинов В.А. ЦКБ "Айсберг" и развитие арктического флота Судостроение N 11-12, 1993
- 5 Tsoy L.G. Methodology of the Determination of the Parameters of Large Ships Designed for Independent Navigation in Ice-Covered Waters and of Those Supported by Icebreakers The Proceedings of the Second International Offshore and Polar Engineering Conference, Vol II San-Francisco, USA, 1992.
- 6 Demianchenko V., Kovalenko V., Shershnev V., Nuclear-Powered Icebreakers of Murmansk Shipping Company Soviet Shipping? N 2, 1991
- 7 Tsoy L.G. Feasibility Study of a Nuclear Icebreaker of *Arktika* Class of New Generation 5-th International Conference on Ships and Marine Structures in Cold Regions ICETECH 94 Calgary, Canada 1994

8. Цой Л.Г. О рациональной области применения ядерных энергетических установок на ледоколах Сб. научн трудов ЦНИИМФ. Архитектурно-конструктивный тип, мореходные и ледовые качества транспортных судов СПб, 1992.

9 Коваленко В К , Лившиц С.Г. Ледоколы мощностью 24 МВт с атомной и дизель-электрической энергетическими установками. Сравнение технических и экономических показателей Международная конференция по судостроению, посвященная 100-летию ЦНИИ им акад А Н.Крылова, СПб, 1994.

10. Цой Л.Г., Глебоко Ю В. Влияние формы носовых обводов ледоколов на ходкость на тихой воде и волнении Сб научн.трудов ЦНИИМФ. Архитектурно-конструктивный тип, мореходные и ледовые качества транспортных судов СПб, 1992

11 Ierusalimsky A , Tsoy L The Efficiency of Using Non-traditional Hull Lines for Icebreakers 5th International Conference on Ships and Marine Structures in Cold Regions ICETECH'94 Calgary, Canada, 1994

12 Tsoy L On the Improvement of Traditional Form of the Hull Lines of Icebreakers and Icebreaking Transport Ships 12-th International Symposium on Ice IAHN 94, Trondheim, Norway, 1994

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MAIN TYPICAL FEATURES IN THE DISTRIBUTION OF ICE COVER CHARACTERISTICS AND THEIR INFLUENCE ON ICEBREAKER MOTION IN THE ARCTIC BASIN IN SUMMERTIME (FROM DATA OF HIGH-LATITUDINAL CRUISES)

ABSTRACT

The paper presents the results of studies of ice conditions of navigation during cruises of Russian nuclear icebreakers to the North Pole. Observations included determination of the characteristics of ice zones directly on the icebreaker motion route. Simultaneously with ice observations some operating indicators were recorded - mean motion velocity in an ice zone, times for penetrating it, motion time by ramming, etc.

Experience of hydrometeorological support to high-latitude voyages and transit cruises along the NSR has shown that one of the most important ice characteristics of navigation is the type of the orientation of discontinuities of ice cover relative to the general motion course of icebreaker. Five main types were identified.

Probabilistic estimates of the length of the navigation route, typical distribution features and variability in main ice cover characteristics and operating indicators of icebreaker motion were obtained for each type.

INTRODUCTION

An intensive increase in shipping along the Northern Sea Route has been observed in recent years. Modern icebreaking and transportation fleet, knowledge of natural conditions allowed a substantial extension of the navigation period along the NSR.

Simultaneously, there is an active search for perspective non-traditional routes for transit navigation in the Arctic region.

In connection with these facts, a lot of attention is paid to studies of ice conditions of navigation in high latitudes of the Arctic, including the near-pole regions. The number of marine operations that are carried out in the central Arctic Ocean increases from year to year.

Thus, for the period of 1991-1994 icebreakers reached the North Pole 14 times during scientific and tourist cruises.

Some data on the distribution of ice cover characteristics collected in these voyages are published (Eicken and Haces, 1991; St. John et al., 1991; Tunik, 1993; Brigham, 1995).

The paper presents the generalized results of investigating ice conditions of navigation during cruises of the Russian nuclear icebreakers of the "Arktika" type to the North Pole.

1. Description of initial data

Special observations were carried out by the AARI specialists on board an icebreaker during six cruises in 1991-1993 (Table 1).

Table 1. Dates and routes of cruises

Year	Month	Icebreaker	Main route points
1991	August	"Sovet. Soyuz"	Murmansk port-FJL-NP-De-Long Islands-Provideniya port
1992	July	"Sovet. Soyuz"	Murmansk port-NP-FJL-Murmansk port
1992	August	"Sovet. Soyuz"	Provideniya port-De-Long Islands-NP-FJL-Murmansk port
1993	July	"Yamal"	Murmansk port-NP-FJL-Murmansk port
1993	August	"Yamal"	Murmansk port-FJL-NP-Severnaya Zemlya Islands-Provideniya port
1993	August	"Yamal"	Provideniya port-De-Long Islands-NP-FJL-Murmansk port

Note FJL - Franz-Josef-Land archipelago
NP - North Pole

Observations were of a visual character and included determination of a standard set of the characteristics of ice zones directly on the icebreaker motion route in the area whose width exceeded 6-fold and length 3-fold the width and length of the icebreaker's hull, respectively.

Ice observations included determination of concentration and age categories: thickness, amount of hummocking, degree of decay, prevailing ice forms; presence and intensity of pressures. Simultaneously with ice observations some operating indicators were recorded - mean motion velocity in the ice zone, operating characteristics of ramming, etc. Observations were performed on the basis of common methods according to the "Instruction for shipborne ice observations" using terminology and measurement scales of characteristics adopted in Russia (Instruction, 1975). The length of the route covered by observations was about 3000 miles.

Experience of hydrometeorological support to high-latitude voyages and transit cruises along the NSR allowed Ye.I.Makarov and C.V.Frolov to find that one of the most important ice characteristics of navigation is the type of the orientation of discontinuities in ice cover relative to the general motion course of icebreaker (Brovin and Frolov, 1995). Let us note that discontinuities include fractures, cracks and leads in the ice cover.

Five main types were revealed.

Type A - a zone of "oriented" discontinuities: the prevailing orientation of the system of discontinuities and the general icebreaker's course coincide or differ not more than by 30°;

Type B - a zone of "non-oriented" discontinuities: the orientation degree of discontinuities is small or the prevailing orientation of discontinuities differs from the general motion course of icebreaker more than by 30°;

Type C - a zone of increased fracturing of ice cover: navigation is, as a rule, in the oriented zone with prevailing broken forms of ice cover (amount of ice floes is less than 5 arbitrary units);

Type D - a zone of the absence of discontinuities; icebreaker motion is in compact ice (concentration 10/10) with prevailing ice floes;

Type E - a zone of decreased concentration of ice cover: pronounced discontinuities are absent, icebreaker motion is in the ice which is equally distributed over the area, its concentration is 8/10 and less.

This subdivision into types serves as a basis for delineating ice zones during special observations from icebreaker.

2. Main typical features in the distribution of ice cover characteristics on the icebreaker's motion route in the Arctic Basin

A vast set of full-scale data obtained allows estimating changes in ice conditions during the period July-August and consideration of the typical distribution features of main ice cover characteristics and operating indicators of icebreaker motion on two segments of the high-latitude route: FJL archipelago - North Pole and North Pole - De-Long Islands. The sailing routes of icebreakers on the first segment were located in a sector restricted by 30° and 60°E for the first segment and 140-160°E for the second segment. The southern boundary of the sectors is the edge of old ice whose position corresponds, on average, to 81-82°N for the first segment and 79-80°N for the second segment.

In July on the segment FJL - NP navigation is mostly in the zone of "oriented" discontinuities (type A) - 43% of the total length of the route and in the zone of increased fracturing (type C) - 36%. There are basically no zones with decreased concentration and the total length of zones with the absence of discontinuities (type D) is 6% (Table 2).

In August, in connection with the process of desintegration of br'ccia fields, the length of the navigation route in the zone of "oriented" discontinuities (type B) increases by a factor of 2. The length of the navigation route in the zone of increased fracturing in July and August is basically equal

Naturally, these ratios can vary in different years, thus, in July they are more stable with regard to interannual variations than in August (see Table 2).

Table 2. A relative length of the navigation route in zones with a different type of orientation of discontinuities (in % of the total length of the segment)

segment, month	Type A	Type B	Type C	Type D	Type E
FJL-NP, July	$\frac{43}{32-57}$	$\frac{15}{11-17}$	$\frac{36}{30-42}$	$\frac{6}{2-9}$	-
FJL-NP, August	$\frac{27}{16-44}$	$\frac{30}{10-68}$	$\frac{34}{16-51}$	$\frac{1}{0-5}$	$\frac{8}{0-32}$
NP-De-Long Islands, August	$\frac{33}{28-32}$	$\frac{35}{27-50}$	$\frac{24}{15-41}$	$\frac{2}{1-3}$	$\frac{6}{0-10}$

Note: numerator - mean relative route length,
denominator - range of changes in different years.

The differences in the study characteristics on the segments FJL-NP and NP-De-Long Islands are less significant in August. However, on the segment FJL-NP navigation is mostly in zones of the type B and C - 64%, and on the segment NP-De-Long Islands - in zones of the type A and B - 68%.

It is typical that motion in zones with absent discontinuities (type D) in August is 1-2% on average of the total length of the navigation route, and in zones with decreased concentration (type E) - 6-8%.

Obviously, general processes of ice cover melting and decay in summertime govern the differences in the distribution of concentration on the navigation route in July and August. On the segment FJL-NP a relative length of the route in the ice of 9.5-10/10 in concentration is 72% in July and 44% in August (Fig. 1), and in ice with concentration of 8.5/10 and less - 6% and 17%, respectively.

The distribution of concentration on the segment NP-De-Long Islands differs from a corresponding distribution on the segment FJL-NP in the shift toward smaller concentration values. Thus, the length of the route in ice of 9.5-10/10 on the segment NP-De-Long Islands is 25% and in ice less than 7/10 in concentration - it is 4 times longer than on the segment FJL-NP (see Fig. 1).

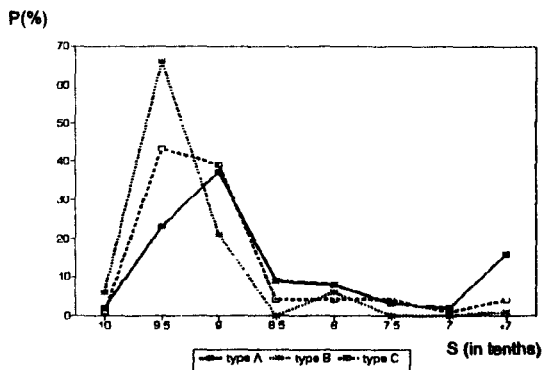


Fig. 1. Relative length of the navigation route in ice of different concentration on the segments of the high-latitude route

- 1 - segment FJL-NP, July,
- 2 - segment FJL-NP, August,
- 3 - segment NP - De-Long Islands, August.

The distribution of concentration on the navigation route in zones with different types of the orientation of discontinuities also has some special features. Naturally, the zone of the absence of discontinuities is

the least favourable, and the zone of decreased concentration - the most favourable for icebreaker motion. However, the probability of using these zones when navigating in the Arctic Basin in summertime is small (see Table 1). That is why, the distribution of concentration in zones of A, B and C types is most interesting.

In July on the segment FJL-NP the most favourable zone for navigation (by the distribution of concentration) is the zone of increased fracturing of ice cover (type C). The length of the route in ice of 9/10 in concentration and less is 50% in these zones (Fig. 2a).

In August the distribution of concentration on the navigation route in zones A and C becomes actually identical on the indicated route segment.

It should be noted that the effect of the processes of ice cover decay in summer is less in the zones of "non-oriented" discontinuities (type B). For this zone type the length of the route in ice with concentration of 9.5/10 is maximum being 94% in July and 80% in August (Fig. 2a, 2b).

The distribution of concentration in typical zones on the segment NP - De-Long Islands differs from a similar distribution on the segment FJL - NP by a 31%, 17% and 23% increase in the length of the route in ice of less than 9/10 for types A, B and C, respectively. Maximum differences are observed for zones of "non-oriented" discontinuities (type B). The length of the route in ice of 9.5/10 in concentration on the segment NP - De-Long Islands is 65% less than on the segment FJL - NP (Fig. 2b, 2c).

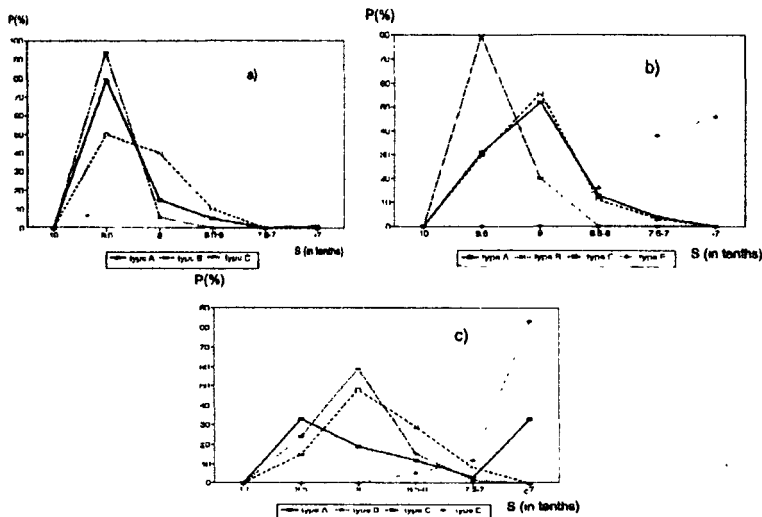


Fig. 2. Distribution of concentration on the navigation route in zones of different orientation of discontinuities:

- a) segment FJL-NP, July,
- b) segment FJL-NP, August,
- c) segment NP - De-Long Islands, August.

A selective character of icebreaker motion, i.e. a maximum use of the segments with easier navigation conditions (with smaller concentration, reduced ice thickness background, smaller amount of hummocking, etc.) influences the ice thickness distribution (Buzaryev and Fedyaev, 1981) Figs. 3 and 4 present thickness distribution of ice which is directly overcome by icebreaker when travelling in the Arctic Basin. It should be noted that during observations the thickness of level ice was recorded (outside hummocked ice).

The character of ice thickness distribution in zones of different orientation of discontinuities coincides on the whole (Fig. 3). Therefore, let us restrict ourselves to considering generalized data on the navigation route length in ice of different thickness (age) on the delineated segments (Fig. 4).

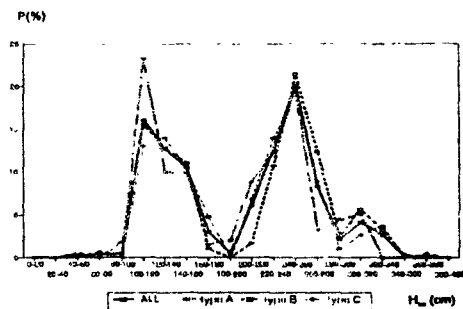


Fig. 3. Ice thickness distribution on the navigation route of icebreaker in zones with a different orientation type of discontinuities in August 1993 on the segment FJL-NP.

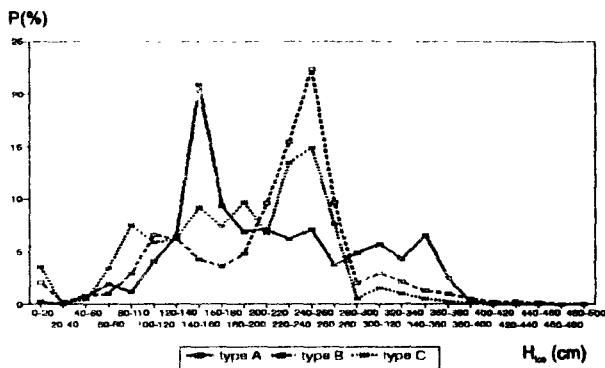


Fig. 4. Ice thickness distribution during icebreaker navigation on the segments of the high-latitude route

- a) segment FJL-NP, July.
- b) segment FJL-NP, August.
- c) segment NP - De-Long Islands, August.

Comparison of data presented for the route segments shows significant differences between them. On the segment FJL-NP in July much of the route is in ice 120-180 cm thick (37%), and in August on the segment FJL-NP and NP-De-Long Islands - 180-280 cm (62% and 52%, respectively).

In view of conventional thickness boundaries of ice of main age gradations, one can determine the length of the route in ice of different age categories (Table 3).

A reverse ratio of the amount of first-year and second-year ice on the segment FJL-NP in July and August is attributed to intensive melt out of first-year ice during summertime. An increased amount of first-year ice on the segment NP-De-Long Islands is governed by an export character of the drift of first-year ice from the East-Siberian and Chukchi Seas to the Arctic Basin.

Typical features of the distribution of hummocked ice on icebreaker motion route are also related to a selective character of icebreaker motion. Thus, the length of the navigation route in hummocked ice of more than 3 arbitrary units in summer is about 2% (Fig. 5).

Table 3. A relative length of the route in ice of different age categories (in % of the total length of the route in ice)

Segment, month	First-year $H_1 < 180$ cm	Second-year $H_1 = 180-280$ cm	Multiyear $H_1 > 280$ cm
FJL-NP, July	52	24	24
FJL-NP, August	28	62	10
NP-De-Long Islands, August	44	52	4

The character of the distribution of the amount of hummocking on the study segments in August is basically identical. The differences between July and August reach more significant values. The length of the route in relatively level hummocked ice up to 1 arbitrary unit in July exceeds a similar indicator in August by 7 times. A shift in the distribution toward greater values of the amount of hummocking in August is governed by the process of melting of more level first-year ice in summertime (see Fig. 4).

The length of the route in hummocked ice of more than 2 arbitrary units which is unfavourable for icebreaker motion has the largest occurrence frequency in August in the zone of "non-oriented" discontinuities (type B) - 62-84%, in July - in the zone of increased fracturing (type C) - 40% (Fig. 6).

Pressures in ice cover is a factor that significantly influences the icebreaker's velocity. Strong pressures frequently make icebreaker move by ramming, sometimes resulting in a complete halt of motion.

According to data of special observations in July on the segment FJL-NP pressures of 0.5-1 arbitrary unit in intensity have the largest occurrence frequency - 53% (Table 4).

In August the intensity of pressures significantly decreases, which is related to a decrease in concentration of ice cover on the navigation route of icebreaker. A relative length of the route in the absence of pressures in August on the segment FJL-NP is 72%, on the segment NP-De-Long Islands - 90%. The occurrence frequency of strong pressures (intensity of 1.5-2 arbitrary units) is five times less in August than in July (see Table 4). Very strong pressures of 2.5-3 arbitrary units in intensity were not recorded in the Arctic Basin in summertime by special observations.

The distribution of pressures in the zones with a different orientation type of discontinuities corresponds on the whole to the general distribution of the characteristics under study on the route segments (Table 5).

However, it can be stated that the distribution of pressures is more favourable for navigation in the zone of "non-oriented" discontinuities (type B) on the segment FJL-NP in July and on the segment NP-De-Long Islands in August. The largest occurrence frequency of the absence of pressures on the segment FJL-NP in August is observed for navigation in the zone of increased fracturing (type C) - 75% (see Table 5).

Table 4. Distribution of pressures in ice cover on the segments of the high-latitude route (in % of the total length of the segment)

Segment, month	Intensity of pressures (arbitrary units)		
	0	0.5-1	1.5-2
FJL-NP, July	38	53	9
FJL-NP, August	72	26	2
NP-De-Long Islands, August	90	10	0

Table 5. Distribution of pressures in ice cover in zones with a different orientation type of discontinuities (in % of the total length of the segment)

Zone type	Segment FJL-NP, July			Segment FJL-NP, August			Segment NP-De-Long Islands, August		
	Intensity of pressures (arbitrary units)								
	0	0.5-1	1.5-2	0	0.5-1	1.5-2	0	0.5-1	1.5-2
A	40	52	8	72	25	3	87	13	-
B	37	63	0	63	36	1	91	9	-
C	34	53	13	75	23	2	87	13	-

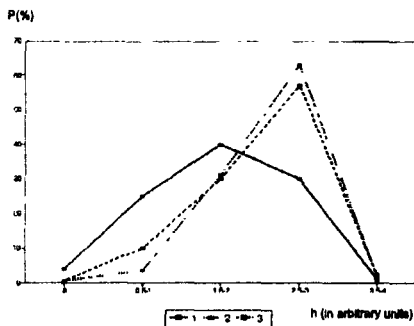


Fig. 5. Distribution of the amount of hummocking on the navigation route of icebreaker on the segments of the high-latitude route
 a) segment FJL-NP, July,
 b) segment FJL-NP, August,
 c) segment NP - De-Long Islands, August.

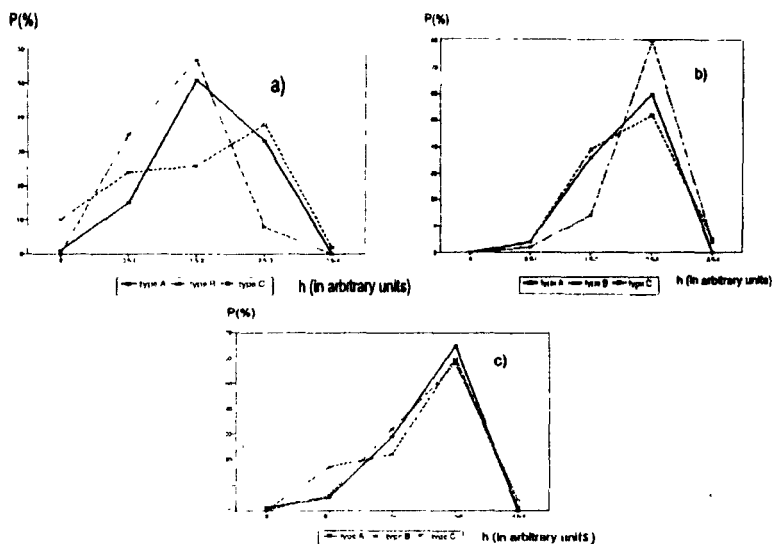


Fig. 6. Distribution of the amount of hummocking in zones with a different orientation type of discontinuities:
 a) segment FJL -NP, July,
 b) segment FJL -NP, August,
 c) segment NP - De-Long Islands August

3. Main typical features in the distribution of some operating characteristics of icebreaker motion in the Arctic Basin in summertime

To address the questions of using high-latitude routes in the interests of economy, knowledge on the distribution of main ice cover characteristics on the navigation route in this region is necessary, but this is not sufficient. It is important to investigate the influence of ice conditions on operating indicators of icebreaker motion - times, motion velocity, power plant operation mode, motion character (continuous, by ramming, etc.).

The operating motion velocity of icebreaker is an integral characteristics of the system of ice-ship interaction reflecting the effectiveness of using ships of different classes on the route (Gordiyenko et al., 1967).

Operation of Russian nuclear icebreakers of the "Arktika" type in tourist cruises showed that icebreakers of this class are capable to navigate with an average velocity of 8-9 knots in July on the segment FJL-NP, in August - 10 and 12 knots on the segments FJL-NP and NP-De-Long Islands, respectively.

Comparison of the distributions of the route length by velocity ranges allows determining zones where navigation is most effective. Thus, in July, most favourable for navigation are zones of "oriented" discontinuities (type A) and zones of increased ice cover fracturing (type C) - a relative length of the route with a mean velocity more than 10 knots in these zones is 35% and 39%, respectively.

The motion with a velocity of 5 knots is of unstable character - the probability of halts, moving by ramming is large. The length of the navigation route with such a velocity for the indicated zones in July is 17% (Fig. 7a).

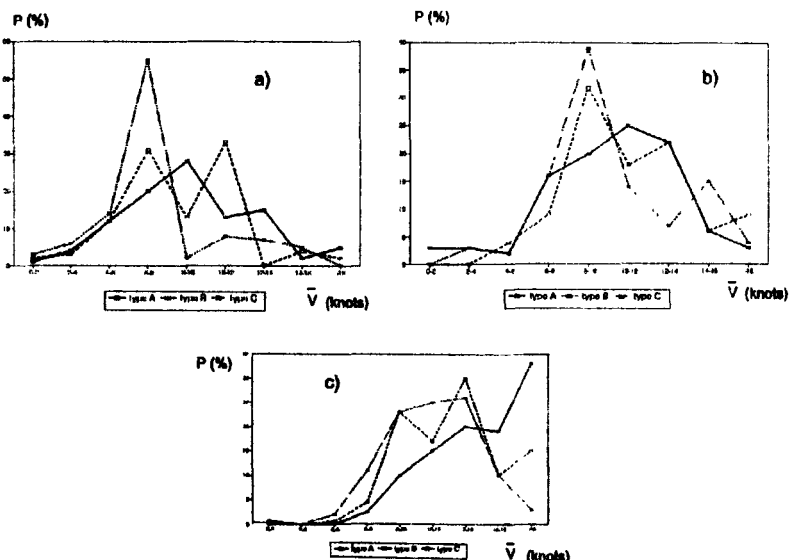


Fig. 7. Distribution of the relative length of the route by velocity ranges in zones with a different orientation of discontinuities
 a) segment FJL-NP, July,
 b) segment FJL-NP, August,
 c) segment NP - De-Long Islands, August.

Zones of the types A and C are also most favourable for navigation on the indicated segment in August (Fig. 7b). The length of the navigation route with a velocity more than 10 knots in these zones increases up to 55-56%. However, motion with a velocity less than 5 knots in the zone of increased fracturing (type C) is 4% of the segment length, thus, half as large as compared with a similar navigation indicator in the zone of "oriented" discontinuities (type A).

On the segment NP - De-Long Islands the most favourable navigation zone is the zone of "oriented" discontinuities (type A). The length of the route with an average velocity more than 16 knots is 33% of the total segment length. Icebreaker develops such a velocity when travelling in large fractures and leads whose width exceeds the width of icebreaker's hull. Let us note that a relative length of the navigation route with such a large velocity on the segment NP-De-Long Islands corresponds to the length of the route in the ice with less than 7/10 in concentration (see Fig. 2c).

The probability of moving by ramming is another important indicator of navigation difficulty.

The probability of moving by ramming is maximum when navigating in the zone of the absence of discontinuities (type D) (Table 6). However, the length of the navigation route in zones of this type in summertime is small (see Table 2). In July, when navigating in zones of other types, the largest probability of moving by ramming is characteristic of the motion in the zone of "oriented" discontinuities. This is related to the need for overcoming compressed junctions of ice floes, heavy ice isthmus between fractures and cracks. In August motion by ramming in the Arctic Basin is of a single character (see Table 6).

Table 6. A relative number of ramblings in zones with a different orientation of discontinuities (number of ramblings per 100 miles of the route)

segment, month	Zone type			
	A	B	C	D
FJL-NP, July	18.5	9.4	8.2	360.0
FJL-NP, August	1.2	5.2	0.3	0
NP-De-Long Islands, August	0	0.3	0.4	11.1

CONCLUSION

This work is in fact a first attempt to describe ice navigation conditions in the Arctic Basin based on vast full-scale data. The determination of typical features in the distribution of main ice characteristics and operating indicators allowed us to find that among zones with different orientation types of discontinuities in the ice cover relative to the general course of icebreaker motion, zones of increased fracturing and "oriented" discontinuities most favourable for navigation.

The differences in navigation conditions in typical zones are more significant in July than in August. It is probable that the indicated differences will be maximum in the winter-spring period.

Modern remote-sensing means of ice cover studies (satellites, aircraft radars) allow determining a spatial location of favourable navigation zones which in combination with knowledge of navigation conditions in them is necessary for choosing an optimal motion variant and estimating the scales of difficulties of the planned cruises to the Arctic basin.

The database of ice navigation conditions which includes data of special observations obtained during 11 high-latitude cruises and methods for processing these data allow us to solve the following objectives in the near future:

- to study seasonal changes in ice conditions of navigation on separate segments of high-latitude routes and in typical zones;
- to study interannual variability in the distribution of main ice characteristics on the navigation route in the Arctic Basin in different seasons;
- to determine typical features in the distribution of ice characteristics and operating indicators in summertime on the segments of the high-latitude route located along 0° E (Fram Strait - North Pole), 100° E (Severnaya Zemlya Islands - North Pole), 180° E (Wrangel Island - North Pole);
- to compare data of special observations with data obtained from other sources.

The author proposes cooperation to investigators and institutions interested in the problems of shipping in the Arctic Basin and will gratefully accept comments and additions.

In conclusion, the author gratefully acknowledges assistance of Mr. A.G. Gorshkovsky and Mr. A.A. Smirnov, masters of icebreakers, of the Administration of the Murmansk Shipping Company in the person of Mr. N.I. Khvoshinsky and Mr. Yu.F. Glushko in providing the possibility for observations and of Mr. I.Ye. Makarov (AARI) in the organization of observations and creative help.

REFERENCES

- Brigham L.W. (1995): Icebreaker Transit Analysis for a Voyage Across the Arctic Ocean. Proceeding, International Conference on Northern Sea Route Program, Tokyo 1-6.
- Brovin A., Frolov S. (1995): Analysis of ice-operating and ice-navigation indicators of navigation conditions applicable for the organization and planning of shipping along the NSR INSRP Working Paper 1.5.5, 1995, section 2.
- Buzuyev A.Ya., Fedyakov V.Ye. (1981): Variability in ice conditions on the navigation route of ships. Moscow, Meteorology and Hydrology, No. 2, pp.69-76.
- Eicken H., Haces (1991): Sea-Ice Observation, ARK VIII/3 cruise of R/V POLARSTERN into the Arctic Ocean, August-October 1991. Report Alfred Wegener Institut fur Polar-und Meeresforschung, Bremerhaven, Germany.
- Gordiyenko P.A., Buzuyev A.Ya., Sergeev G.N. (1967): Studies of sea ice cover as a shipping medium. Leningrad, Problems of the arctic and the Antarctic, iss. 27, pp.93-104.
- Instruction (1975): Instruction for shipborne ice observations. Leningrad, Archives of the AARI, 67 p., (Prepared by Churkina N.A.).
- St.John J., R.Sheinberg, R.Rish, G.Liljestrom (1991): Icebreaker ODEN Trafficability Data. Report, USCG, Washington, D.C.
- Tunik A. (1993): Trafficability in the Arctic Ocean in summer: experience gained from a North Pole voyage. Proceeding, NEVA'93, Seminar on ARCTIC TRANSPORTATION, St.Petersburg, Russia, 14-17 September

ICE PASSPORT OF A NEW GENERATION

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In the 1950s the Department for Ship Performance in Ice has suggested a concept and then developed in detail the methods for preparing ice passports for ships. This is a document containing reference data on the technical capabilities of a specific ship and recommendations for choosing safe and effective ship navigation modes under specific ice conditions. Ice passports were developed for 16 types of ships of different ice categories of the Sea Register of Russia as ordered by the Shipping Companies. Below, the description of an ice passport of a new generation is presented. It includes software for the onboard computer showing permissible and dangerous parameters of ship motion both in a self-contained voyage and in a convoy. The board ice passport takes into account the hull wear, shaft power, a wide set of parameters of ice situation: ice thickness, water and air temperature, water salinity, degree of destruction, degree of fracturing, ice concentration. The software has reference capabilities with regard to the ice situation along the NSR.

The preparation of the information sets of the passport is based on the concept of safe navigation in the ice and is carried out by means of the developed software for calculating ice performance and ice strength of a ship.

The ice passport - a document containing data on the main ice capabilities of a ship, as well as on the resulting curve of safe (permissible) velocities, has been developed for more than 20 years for ships of the Russian Fleet by the Department for Ship Performance in Ice of the AARI [1]. A traditional ice passport in the form of a document can cause some difficulties to be quickly used by navigators. The equipment of ships and icebreakers by personal computers allows the formation of the ice passport on a qualitatively new level. This level has to provide navigators with information on safe and dangerous motion modes within a possible range of ice conditions and navigation ways (self-contained or escorted by icebreaker), as compared with the previous passports which contained motion parameters for a restricted range of the ice situation parameters. Thus, to meet these requirements resulted in creating software for two levels:

1 Software for preparing and calculating the curves of the ice passport that are used by a specialist developing an ice passport. The results of the work: information sets that are input to software of the next level

2. Board Ice passport - software for the computer on the Master's bridge showing a range of recommended motion modes under ice conditions observed at a selected way of navigation.

The software of the first level presents a package of independent software which can be divided into two groups: calculations of ice performance and calculations of ice strength.

Software for calculating ice performance allows the following automated operations: calculation of the propulsion characteristics of the propeller, calculation of ship resistance in open water, calculation of ice resistance for different ice conditions, formation of the curves of permissible velocities in different ice conditions. The software package for calculating the ice strength allows determining ice loads within the hydrodynamic model of the ship impact on the ice, determine the load corresponding to the fibre yield and ultimate load for ship multispan beam of an arbitrary or standard cross-section with attached flange [2,3,4,5]. For calculating more sophisticated structures of the ice belt, the system ANSYS 5.0 is used. Both software groups are connected with respect to information through the computer database on ice-strengthened ships and icebreakers. This allows a data input on new ships, review and correction of data on main particulars, ice belt geometry, ice belt grillage structure, theoretical drawing of the hull, propeller characteristics, removal of records for separate ships if necessary, display of the lines-drawing projection, an automated creation of the initial data file for most of the calculations of ice performance and ice strength.

Let us consider the first software group in more detail. The software for calculating the propeller characteristics allows calculating the propeller propulsion of a prescribed geometry of one of the twelve types (series) taking into account the effect of the ship's hull and prescribed range of shaft power. The output software data: the curves of the shaft moment and curves of the propeller thrust depending on the shaft power and ship velocity (Fig. 1). The calculation uses a method of approximated polynomials of dimensionless moment and thrust curves according to the data of serial tests of propellers. The software for calculating resistance in open water uses a traditional Schtrumpf's method and when there is a necessary set of initial data plots the curve of the dependency of open water resistance on the ship velocity. Calculation of ice resistance is performed using the original methods of the AARI and allows forecasting ice resistance in ice cake, small floe and compact ice [6]. Calculation of resistance in ice cake can be performed with the following variable parameters of ice and ice situation: ice thickness, mean floe length, ice concentration, degree of ice compression, ice density, friction coefficient between the ship's board and the ice and the width of the channel. Calculation of the resistance in small floe can be performed at a varying ice thickness or the mean floe length. The

software allows calculating the ship resistance in compact ice parametrically from the ice thickness, ice density or strength. The calculation results are in all cases the curves of the ship ice resistance depending on the velocity at a constant chosen parameter of the ice situation (Fig. 2). The software for calculating the curves of permissible velocities allows right away the construction of the curves in co-ordinates H - ice thickness and V - ship velocity which show the capabilities of the ship propulsion complex when moving in the ice situation prescribed by a definite set of characteristics.

On the basis of software described above, the ice passports of the M/V "Mekhanik Yartsev" [7] and partly of the research-expedition vessel the "Akademik Fedorov" were prepared. A vast volume of information resulting from the use of the first level software by a qualified specialist, is difficult for perception by navigators in the ice situation both during a self-contained voyage and in the convoy. The software of the second level - the board ice passport - allows using all information that is contained in the ice passport and its quick transformation into the form suitable for operational understanding by a navigator. The board ice passport presents the software the work with which begins by entering a three-variant menu: reference ship data, a self-contained voyage, navigation in the channel behind icebreaker. For selecting the last two branches a small number of standard parameters of the ice situation should be prescribed: a safe velocity at which no hull damages occur and a dangerous velocity whose excess results in a sharp increase in the volume of ice damages of the hull structures of the ice belt. For selecting the branch of travelling in a convoy, in addition, a safe distance to an icebreaker or the stern of the ship moving in front at its sudden halt and manoeuvre "Forward - Stop" are given.

The trial of the board ice passport was made in the expedition of the "Akademik Fedorov" in summer of 1994. The expedition has shown that in addition to reference ship information which contains the main results of the first-level software, it is desirable to introduce into the ice passport a reference block on mean statistical parameters of the ice situation in the navigation regions obtained from multiyear observations. When ships navigate in the convoy following an icebreaker it makes sense to arrange the ice passport of the convoy on an operational basis which will automatically indicate for the Master of an icebreaker an ultimate velocity of the convoy, safe distance in the convoy, maximum draft of ships in the convoy, etc. All these characteristics are determined on the basis of ships limiting the convoy

It is necessary to mention that all information that is presented by the board ice passport should be displayed on the screen in the form clear to navigators of medium qualification. Automated recording of output information is possible which

will increase the responsibility of navigators in the case of large ice damages and allow a more objective settlement of disputes between navigators and ship owners in the case there are large losses from marine transport operations in the ice.

On the whole, the ice passport of a new generation will allow a more optimal way for controlling a ship or a convoy of ships in the ice and will open new possibilities for increasing the cost-effectiveness of such transport operations.

REFERENCES

1. Likhomanov V.A., Polferov S.Yu., Stepanov I.V., Timofeyev O.Y., Faddeyev O.V. Principles for Development and Perspective Use of the Ice Passports. POAC'93. Proceedings. Vol.1, pp.219-226, Hamburg, 17-20 August 1993.
2. Popov Yu. N., Faddeyev O.V., Kheisin D.Ye., Yakovlev A.A. Strength of ships navigating in ice. L.: Sudostroyeniye, 1967, 224 p.
3. Kurdyumov V.A., Kheisin D.Ye. A hydrodynamic model of the impact of a solid body on the ice. Applied mechanics, p.XII, No. 10, pp.103-109, Kiev, 1976.
4. Ryvlin A.Ya., Kheisin D.Ye. Trials of ships in ice. L.: Sudostroyeniye, 1980, 208 p.
5. Beneson A.M., Kurdyumov V.A. Calculation of ultimate equilibrium of bar structures taking into account a shear. Applied mechanics, vol. XX, N0.12, Kiev: Nauk.dumka, 1984, pp.90-94.
6. Kurdyumov V.A. The use of the method of ultimate loads for designing ice forces. Vol. of papers of the Soviet-Finnish Workshop on ice strength of ships. L.: Sudostroyeniye, 1988, pp.41-50.
7. Kashtelyan V.I., Poznyak I.I., Ryvlin A.Ya. Ice resistance to ship motion. L.: Sudostroyeniye, 1968, 238 p.
8. The ice passport for the ship of the type "Mekhanik Yartsev". The AARI's archives. Supervised by V.A. Likhomanov. Prepared by O.Ya. Timofeyev, O.V. Faddeyev. St. Petersburg, 1993, 67 p.

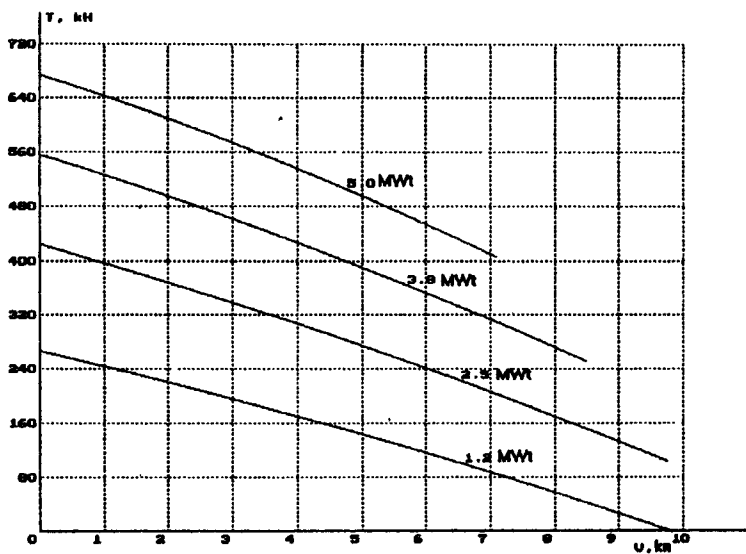


Fig. 1. Curves of the propeller propulsion depending on the velocity and power.

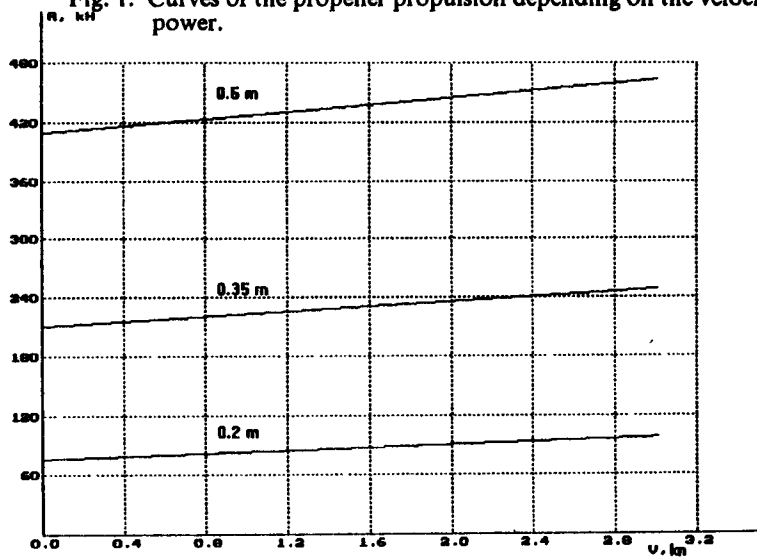


Fig. 2. Curves of ice resistance depending on the velocity and ice thickness.

The investigation of ice damages and increasing of demands to the ice strength of Arctic vessels.

Introduction.

The exploitation of vessels in the Arctic seas is traditionally accompanied with increased level of damages to the structures interacting with ice. After the powerful icebreakers of "Arktika" type were commissioned in the last 70-th., velocities of vessels leading in ice were increased. At the same time a change to extended and year-around navigation in the Arctic began. As a result, the level of damages has trended to the double or triple increase. This led to the necessity of improving the methodology for regulation the ice strength of polar-class vessels. The general approach to constructing the improved methodology is outlined in [1]. The presented below investigations analyses the following topics more precisely:

- Possible diminishing of damages' level through increasing the level of safety of ice enforcement structures
- Determination of allowed level of ice damages within the regular term of vessel exploitation.
- Taking into account the laws of damages formation in regulation of the concepts and criterion of dangerous conditions

1. The general description of the ice damages.

The basic type of damages of polar-class vessels is the change of initial geometrical form of constructions. This occurs as a consequence of plastic deforming under the action of ice forces. These damages, which are named the ice damages henceforth, are the object of the executed below analysis. As a data base regarding the ice damages we use the information collected under the order of Krylov Institution by N. Barabanov, V. Babtzev, V. Lutzenko and G. Shemenduk, the specialists of the vessel structure department of Far East Polytechnical Institute (DVPI) in the 80-th. The information is related to the ice damages to the vessels and icebreakers, which were exploited under the heaviest ice conditions in the East region of the Arctic. The following data is considered as the most important. The basic part of damages is accounted for by the old vessels (the types of 'Pioner', 'Povenetz', 'Sibirles', 'Amguema' etc.), the exploitation term of which had covered 15-20 years by the moment of the change to extended navigation. These vessels, excepting 'Amguema', satisfy to the category L2, L1 of the modern Rules of Shipping Register and are not destined for exploitation under the hard conditions of the Arctic extended navigation. That is why the damages are of numerous character. There are significant areas of goffering of external plating in all the levels which interact with ice (bottom, board). The dents are of significant length (within 2 - 10 spacing).

The level of damages to the 'Amguema' vessel, which have higher level of strength, were characterised by some positive trends: decreasing of areas of goffering of external plating and diminishing of the dents length up to 2-6 spacing.

In the last 70-th the commissioning the new vessels (type 'Samotlor' UL, CA-15 ULA, 'Vitus Bering' ULA) started. The new vessels generally satisfied to the requirements of the Rules [2-4] to the ice strength of vessels of the highest ice class. The new vessels showed to a greater extent the trends peculiar to 'Amguema'. The dents length was in average within 2-6 spacing and within 2-4 spacing for the ice level of ULA-class vessels. The external plating of ULA-vessels ice level can be characterised by less significant damages and less areas of goffering. The basic part of damages to the set of frames represents the local dents in the frames, deformed between board stringers. There is no facts of involving the basic part of overlap into the plastic deformation registered. The increase in strength of the vessels have led to the change of damages character from numerous and global (long dents and gofferings) to separate local one (local dents) [fig 1], but haven't decided the problem of damages completely.

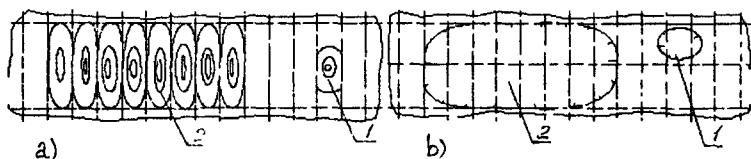


Fig. 1. Allowed (local) and not allowed (global) ice damages:

- a - external plating
 - 1 - allowed, 2 - not allowed (goffering)
- b - the set of frames
 - 1 - allowed (local caving in)
 - 2 - not allowed (global caving in)

On the grounds of outlined above, it's possible to state that arise of some damages under the conditions of extended Arctic navigation should be considered as normal practice of exploitation. The numerous damages of ice enforcement constructions are to the necessary excepting [fig 1]. The quantitative measure for allowed number of ice damages can be determined on the grounds of statistic analysis of data regarding level of damages.

2. The statistic analysis of data regarding level of damages.

The data regarding the probability of damage to hull structure members within the normal term of vessel exploitation is of interest for the statistic analysis. The initial information cannot provide for the mentioned data. However, the represented data regarding the level of damages to the old vessel allows to obtain the needed information by supplementary indirect estimating. On the grounds of analysis of the dock statement, V Lutzenko defined the average annual velocity of replacement the outside plating (V_c) with the respect to the old vessels of 4 types ('Amguema', 'Belomorles', 'Pioner', 'Poventz'). The average area of plating replacement for the normal term of one vessel exploitation is determined

$$F_c = V_c \cdot T_n$$

The value of F_c includes the change of plating due to the ice damages, when residual caving of plating exceed the allowed ones (F_c ice) and as a result of deterioration (F_c w). The indirect estimation determines the following:

$$F_{c_{\text{ice}}} = Z_4 F_c, \quad Z_4 \approx 0.7$$

In order to estimate the probability of replacement of external plating due to the ice damages, the value of hull surface area F_{ice} , which carries the ice loads should be set into the correspondence with the value of F_c ice. This value can be defined by excepting the areas, where no damages has been registered, from the submerged hull area. The procedure is executed with using the histograms of plating and frame damages with the respect to the old vessels [Fig 2]:

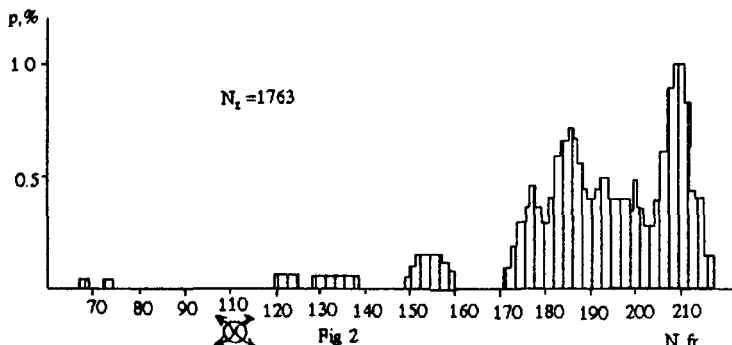


Fig. 2. The distribution of relating frequencies of damages to the set of frame of "Pioner" type vessels.

On the grounds of these histograms, designed by V. Babtzev it's possible to determine

$$F_{ice} = Z_2 F_{uv}, \quad Z_2 \approx 0.6$$

The presented correlation allows to determine the measure of probability of replacement of outside plating due to the ice damages within the normative term of exploitation of the old vessels:

$$K_c = \frac{F_{ice}}{F_{ice}} = \frac{T_n \cdot Z_4 \cdot V_c}{Z_2 \cdot F_{uv}}$$

As the calculations showed, the value K_c is quite stable among the taken into consideration types of vessels ($K_c=0.1-0.15$). The value K_c can be characterised by the value average for the named types of vessels

$$\bar{K}_c \approx 0.125$$

V. Babtzev collected the following information regarding the damage level of set of frames for the old vessels (type 'Amguema', 'Belomorskles', 'Pioner', 'Povenetz', 'Sibirles', $i=1.5$ is the index of vessel type).

- The number of tested vessels (N_{ci})
- The mean term of vessel exploitation (T_i)
- The total number of frame damages to set of frame (N_{fi})

- The mean area of one dent (F_{fi})

On the basis of outlined above it's possible to determine the measure of probability of damages to set of frames due to the ice damages within the normative term of exploitation of the old vessels

$$K_{fi} = \frac{T_H}{T_1} \frac{F_{fi} N_{fi}}{Z_2 F_{wr} N_{e1}}$$

As the calculations showed, the values of K_{fi} are characterised by more significant fluctuation ($K_{fi}=0.15-0.4$) in comparison with the value of K_c . This stems from the fact that the strength level of ice enforcement set of frames is prone to wider fluctuations in comparison with plating. That is why the value of \bar{K}_f should be considered as an objective characteristic of the damage level with the respect to the set of frames:

$$\bar{K}_f = \frac{\sum K_{fi} N_{e1}}{\sum N_{e1}} \quad \bar{K}_f = 0.25$$

3. The laws of the ice loads distribution.

The obtained average statistical data can be used for determining the distribution law for the ice loads if the approach to the treatment the ice loads is specified. The approach, usually being used in the tasks regarding damages, connected with taking into consideration the remained plastic deformations of construction as a result of acting upon the construction of the most significant load. This allows to use the principle of the single loading. As an alternative it's possible to consider the damages as a result of accumulation of remained plastic deformation in the process of repeated loading. However, in this case the process of obtaining the final result is far more difficult.

Let consider that there are m arranged corresponding the increase loads, acting upon the construction among other force influences. Each of these loads generates the arise of the plastic deformations by the single loading.

$$\{Q_n\} = Q_1, Q_2 \dots Q_m, \quad Q_1 \geq Q_p, Q_n \leq Q_{n+1}, n=1, \dots, m.$$

where Q_p is the load which generates the arise of the first plastic deformations. The principle of the single loading is available while the following conditions are executed

$$w\Sigma \approx w_m \quad (1)$$

where $w\Sigma = w(\{Q_n\})$ is the total remained caving in of the construction under the action of the aggregate of loads $\{Q_n\}$;

$w_m = w(Q_m)$ is remained caving in of the construction under the action of the maximal load $\{Q_m\}$.

However, taking into consideration the level of accuracy of the initial data, it's possible to allow the 'soft' satisfying to the condition (1):

$$w\Sigma \leq \gamma w_m, \quad \gamma = 1.5 \sim 2 \quad (2)$$

Because of peculiarities of taken into consideration structures in the brackets of the classical theory of adaptability, [5] it's possible to suggest that there is no accumulation occurs in the constructions of ice enforcement. That means that the condition (2) is granted to be executed. However, the approaches based on taking into account the relaxation of remained stresses and change of the construction geometry demonstrate the possibility of significant accumulating of remained cavings under the definite conditions of loading

The special analysis, executed with the respect to the polar-class vessels with taking into account the named approaches [6] allowed to determine the following

- The arise of remained cavings which can be registered in structures of ice enforcement under the single loading takes place under the loads more than ultimate loads Q_{ult} , determined in the brackets of the theory of ultimate loading
- There is no accumulation occurs in the beam constructions under the multiple action of the loads less than ultimate ones ($Q_m \leq Q_{ult}$) In this case the moderate accumulation of the remained cavings in the plates of external plating is possible. The top margin of this can be estimated by the following values

$$w_m^{ult} = w(Q_m / Q_m \leq Q_{ult}) \approx (0.3 \div 0.5) t$$

$$w_z^{ult} = w(Q_n, Q_m \leq Q_{ult}) \approx (0.5 \div 0.8) t$$

where t is the thickness of the external plating

It's important to notice that these values are significantly less than the values of the remained cavings in the plates which arise as a result of the ice damages [fig 3]

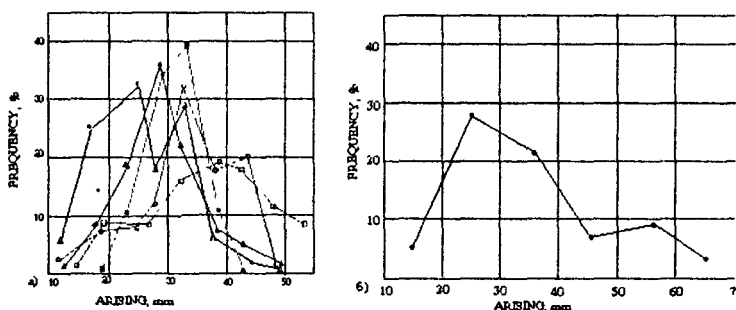


Fig 3 The distribution of relating frequencies of arising of remained caving
 a)- on the old vessels
 ○ - "Amguerna", △ - "Pioner", ▲ - "Povenetz", □ - "Belomorskles"
 ■ - "Siburles"
 b) - on the vessels of CA-15 type

$$wd \approx (2-3)t$$

On the grounds of the outlines it's possible to conclude that the remained cavings, registered as damages, are the result of action of the loads which exceed the marginal ones

Let's consider $P1(Q)$ as the long-term probability of a single exceeding of the exploitation load with the respect to Q . Then in accordance with the outlined above and the experience in the exploitation of the old vessels follows

$$P1(Q_{ult}) = \bar{K}_{r=0.25} \quad (3)$$

The obtained equation allows to estimate the possibility of the accumulation factor in the area $Q > Q_{ult}$. The action of the loads $\{Q_n\}$, $Q_m > Q_{ult}$ upon any construction element can be considered as independent events. The probability of exceeding the marginal load is:

$$P_n(Q_{ult}) = P_1^n(Q_{ult}) \ll 1, \quad n \gg 1 \quad (4)$$

The equation (4) shows that in spite of significant level of damages for the old vessels the probability ($n=100-10000$, see [6]) of the multiple action of loads $Q > Q_{ult}$ upon the construction elements is insignificant. That's why it's possible to neglect the possibility of accumulating the remained cavings in this area and suggest that the principle of the single loading is valid. So, it's possible to set the correspondence between replacement of external plating due to the ice damages and the single action of the load which is more than Q_c and leads to the arise of remained cavings, not allowed by the present norms of construction defectation [7]. So, the equation (5) is in accordance with (3):

$$P_1(Q_c) = \bar{K}_c = 0.125 \quad (5)$$

Let's consider $P(Q)$ as the distribution function of the load Q by the single loading. According to the accepted approach [8] the function can be satisfactory approximated by Weibull law:

$$P(Q) = \exp[-(Q/a)^\alpha] \quad (6)$$

where α, a are unknown parameters.

If a construction is subject to the M loadings within its term of exploitation then the following equation is valid for the asymptotic area ($M \rightarrow \infty$):

$$P_1(Q) = M \cdot P(Q) \quad (7)$$

The joint decision of (3), (5), (6), (7) leads to the following expression for the probability of exceeding the ice load:

$$P_1(Q) = M \exp[-(\ln M - \ln \bar{K}_f) \left(\frac{Q}{Q_{ult}}\right)^\alpha] \quad (8)$$

$$\text{where } \alpha = \frac{\ln \varphi}{\ln \beta_Q}, \quad \varphi = \frac{\ln M - \ln \bar{K}_c}{\ln M - \ln \bar{K}_f}, \quad \beta_Q = \frac{Q_c}{Q_{ult}}$$

The corresponding decisions and software are obtained for determining Q_c and Q_{ult} for the specific structures. Without paying close attention to these decisions it's necessary to notice that taking into account the non-linear geometric factors and the interaction between deformed area of the structure and surrounding unloaded areas is necessary in decisions for Q_c . It's possible to consider $\beta_Q \approx 2$ in the brackets of the present analysis which is oriented to the average values. So, the number of loadings M is the only undetermined parameter in the equation (8). As the calculations show, the function $P_1(Q)$ is in insignificant dependence of the named parameter in the real band of the parameters changing $M=100-10000$. The value of the parameter can approximately be considered as $M=1000$.

The final view of the function is represented in fig. 4.

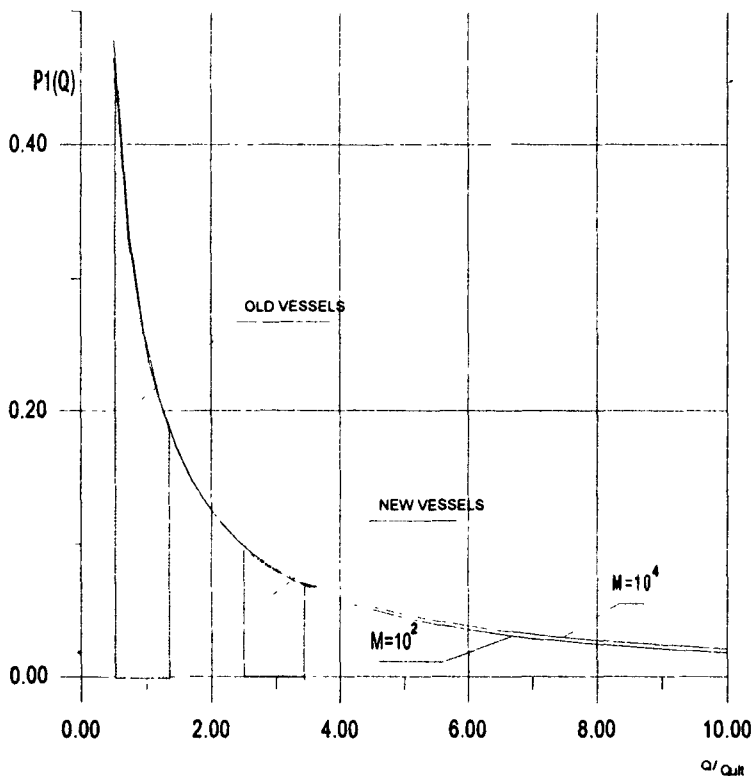


Fig. 4. The distribution of the long-term probability of single exceeding the load Q
 Q_{ult} is the average level of ultimate strength of the old vessels

Though the function has been obtained on the grounds of the data regarding the level of damages to the old vessels it's possible to say that it is peculiar to the conditions of the extended Arctic navigation. It can be extended to the vessels of all categories because of the following reasons

- At the moment of the data collection the polar fleet consisted 88 percent of the L1 and L2 category vessels. The possibilities of changing the contents of the fleet in dependence of the ice conditions were quite limited. Practically all the vessels were almost under the same ice conditions, even more peculiar to the highest ice categories.
- About 80% of all the damages was obtained during the navigation in icebreaker's trace when the difference in the regimes of ice motion is levelled for the vessels of different categories.

4. The normative level of damages and the strength criterion for the vessels of ice navigation.

Ultimate strength of the vessels of ULA type recommended itself satisfactory under the condition of extended navigation

$$Q_{ult}^M \approx 3Q_{ult}^0$$

The long-term probability of arising in their constructions the registered damages is

$$P_1(Q_{ult}^M) \approx 0.07 = \delta \quad (9)$$

That is why the level of damages δ (7% of the total number of constructional elements) is suggested to be considered as the standard for the introduced above conception of allowed separate damages. As it stems from fig. 4, the attempts of diminishing this level up to complete excluding of damages are connected with significant overloading the hull and practically are not executable. The new vessels of ULA category have a correspondence between the level of damages δ , the practice of exploitation under conditions of extended navigation and ultimate strength of their ice level. The introduction of exact quantitative regulation of allowed conditions of polar navigation is necessary so that the vessels of other categories achieve the level δ . It's necessary to underline that the achievement of the normative level of damages will be granted under the condition of change to projecting the ice enforcement constructions by ultimate strength criterion. That stems from the fact that the stable reserve of ultimate strength of all the structure members is the guarantee for excluding the numerous damages.

The possibilities of rational material distribution among the constructive elements with the aim of reducing the volume of repair of hulls of the ice navigation vessels can be realised on the grounds of analysis of ice enforcement structures working at the stage of deep plastic deforming with taking into account the geometrical non-linearity.

5. The general method of statistical analysis of data regarding ice damages.

In conclusion we outline the method of statistical analysis of data regarding ice damages which generalises the procedure of constructing the function of long-term probability $P_1(Q)$ (8) offered in 3rd unit. Let's consider that each ice category (i) consists of m_i types of vessels ($\mu=1, \dots, m_i$ - is the index of type) and each type μ includes n_μ vessels ($v=1, \dots, n_\mu$ - is the index of vessel). The vectors of strength characteristics and level of damages are defined for every vessel for all 12 areas of ice enforcement:

- l_h - the index of area,
- l - regarding the length of hull (bow($l=1$), middle ($l=2$), stern($l=3$));
- h - regarding the perimeter of cross section (ice level ($h=1$), transitional level ($h=2$), bildge level ($h=3$), bottom level ($h=4$)),

$$(B_{lhj}^{\mu v}) = (Q_{ult\ lh}^v, Q_{c\ lh}^v, K_{f\ lh}^v, K_{c\ lh}^v), \quad j=1 \dots 4$$

Executing the procedures of averaging we change from the vectors of specific vessel to the vectors of types and then to the whole ice category

$$B_{lhj}^\mu = \frac{1}{n_\mu} \sum_{v=1}^{n_\mu} B_{lhj}^{\mu v}, \quad B_{lhj}^i = \frac{1}{m_i} \sum_{\mu=1}^{m_i} B_{lhj}^\mu$$

The functions of long-term probability for all the areas of ice enforcement of i-numbered category $P_1(Q)$ can be constructed by values of vector elements (B_{lhj}^i) on the basis of (8)

Let's consider that criterion of ultimate strength is used as a basis for regulating the strength of the ice enforcement constructions. This allows to consider that designing ice loads, regulated by the present normative act ($Q_{d\text{lh}}^{(Q)}$) are linearly connected with ultimate loads $Q_{ult\text{lh}}^i$ (through reserve coefficient). Let's introduce the values of normative level of damages $K_{N\text{lh}}^i$ for all the areas. Then the condition for determining the designing loads ($Q_{d\text{lh}}^{(Q)}$), corrected on the grounds of the data regarding level of damages, can be expressed as follows:

$$P_1(Q_{d\text{lh}}^{(Q)}) = K_{N\text{lh}}^i \quad (10)$$

Deciding this equation with the respect to ($Q_{d\text{lh}}^{(Q)}$), it's possible to obtain the following correlation for correcting designing ice loads:

$$Q_{d\text{lh}}^{(Q)} = Q_{d\text{lh}}^i \psi_{\text{lh}}^i (\{B_{\text{lh}}^i\}, K_{N\text{lh}}^i) \quad (11)$$

where $\psi_{\text{lh}}^i = \left(\frac{\ln(M_{\text{lh}}^i / K_{N\text{lh}}^i)}{\ln(M_{\text{lh}}^i / K_{f\text{lh}}^i)} \right)^{A_{\text{lh}}^i}$, $A_{\text{lh}}^i = \frac{\ln(Q_{c\text{lh}}^i / Q_{ult\text{lh}}^i)}{\ln\left(\frac{\ln(M_{\text{lh}}^i / K_{c\text{lh}}^i)}{\ln(M_{\text{lh}}^i / K_{f\text{lh}}^i)}\right)}$

In practical use of the equation (11) it's worth considering the value of $K_{N\text{lh}}^i$ form (10) as equal for all the areas:

$$K_{N\text{lh}}^i = K_{N11}^i$$

This is because the level of damages of the bow area of the ice level is the most stable and as a rule satisfactory one. Also because the methods for determining the ice loads are more elaborated for this area. So $\psi_{\text{lh}}^i = 1$, whereas the equation (11) gives the value of designing ice loads for all the areas of ice enforcement as the parts of the designing load acting upon the bow area of the ice level. That is why the matrix (ψ_{lh}^i) should be considered as a coefficient matrix for designing ice loads which grants the distribution of strength reserves of the ice enforcement area according to smoothing their levels of damages.

Conclusions.

The represented investigations allowed

- To justify the concept of separate allowed ice damages;
- To determine the concepts and criterion of the dangerous conditions for the ice enforcement constructions;
- To define the distribution law of the ice loads on the grounds of the data regarding the level of damages;
- To regulate the normative level for the level of damages for the ice navigation vessels;
- To elaborate the general method of statistical analysis of ice damages and correcting the designing ice loads on the grounds of statistical data regarding the damages of the Arctic fleet

It's worth using the obtained results for increasing the demands of The Rules of classification societies to the ice strength of vessels. It can be also used for designing of prospective vessels of ice navigation and icebreakers.

References.

- 1 Appolonov E.M, Nesterov A B, Timofeyev O Y. Ice strength in connection with classification of ships and icebreakers - ISC-proceeding, St Petersburg 1994
- 2-4. The Shipping Register of the USSR The Rules for classification and shipbuilding - Leningrad, 'Transport', 1981, 1985, 1990
5. Koyter V T. The general theorems of the theory of expansible-plastic conditions Moscow 1961
6. Belenky L M The design of vessel constructions at the plastic stage Leningrad, 'Sudostroenie' 1988
- 7 The complex system of technical service and repair of vessels The methodology of the sea vessel hull defectation Moscow, 'Mortechinformreklama' 1988
8. Boitzov G.V Knoring S D The strength and efficiency of hull constructions Leningrad, 'Sudostroenie' 1972

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The Way of Reglamentation for Allowable Ice Condition for Navigating in Ice in the Frame of Demands to the Arctic Class of Arctic Ships.

The existing international practice of the demands of the classification societies suggests the availability ice condition corresponding an ice class index. In the Russian national Rules such description had superiority a qualitative character. It could be explained by multiforming of ice conditions in Russian Arctic which makes difficult to include in Rules the quantitative estimations.

There is a new project of revision of the Rules of Russian Sea Shipping Register (RR) to the ice strengthening of ships and icebreakers [1], including of a new way of quantitative description of navigation conditions for ships along Northern Sea Route (NSR)

It was used by this way development the hydrodynamical model of ship hull-ice impact [2] which is usual for Russian practice and the described in [3,4] methods for the ultimate strength of ice belt structures estimation and for the determination of safe speeds of ships moving in ice

The way methodological ground is determined the using in the project principals of ice classification:

- the main characteristic of an ice category (class) is a base regime which is a function of the ship motion dangerous speed depending on the level ice thickness. The dangerous speed is a speed above which it is possible an appearance of limited ice damages.
- in the frame of one ice category for the ships of different displacements and hull shapes is used the adequate safe navigating ice conditions.

For the standard base creating of way of reglamentation of motion regimes was done a statistical analysis of data about ice cover parameters and ice strength parameters. The analysis was done under assumption that the main environmental factors are a geographical region, a season and a relative difficulty of a year

The geographical region under consideration are five seas of Russian Arctic Barents Sea, Kara Sea, Laptev Sea, East-Siberian Sea and Chukcha Sea Every mentioned sea was divided on two areas Northern and Southern areas. So, there are ten areas There are two season types: winter-spring (November - May) and summer-autumn (June - October) The ice classification was done on the ground of ice age, which correlates with ice thickness

1 young gray ice	10 - 15 cm,
2 young gray-white ice	15 - 30 cm;
3 thin first year ice	30 - 70 cm,
4 medium first year ice	70 - 120 cm,
5 thick first year ice	120 - 150 cm,
6 second - year ice	150 - 300 cm,
7 multi - year ice	more 300 cm

The statistical data (for example [5,6]) was used for the histogram of ice thickness development for chosen areas and seasons, which were approximated by Weibul low The example of such histogram is shown on the Fig 1.

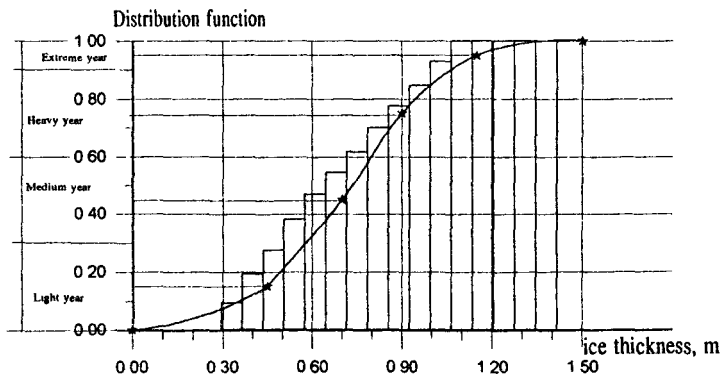


Fig.1 Histogram and distribution function for ice thickness on the North Barents sea on winter.

It was used usual for Russian practice fare bull year difficulty: light, medium (normal), heavy (with average repetition of each - one time per 3 years) and extreme year (with average repetition - one time per 10 years; for example - the autumn-winter navigation of 1983 in East sector of Russian Arctic). So, in the middle for ten years ship exploration there are three light years, three medium, three heavy ones and one extreme year

In corresponding with it the probabilities of the thickness distribution function were divided on three regions

- 0 - 0.3 - light year
- 0.3 - 0.6 - medium year
- 0.6 - 0.9 - heavy year
- 0.9 - 1.0 - extreme year

The design ice thicknesses were determined as corresponding to the middle probabilities values for mentioned regions of the distribution function: light year - 0.15, medium year - 0.45, heavy year - 0.75, extreme year - 0.95 (see Fig.1). The ice thickness calculated such way are in the Table 1.

The same procedure was applied for the ice strength parameters. The main factors in this case are an air temperature and an water salinity. On the ground of data about depending these parameters ([7-11]) were generated the empirical functions which allow to connect the ice strength parameters with ice temperature and salinity, and ice temperature and ice salinity with air temperature and water salinity. Using this function and taking into account statistical information about the air temperature and the water salinity in the Russian Arctic seas the values of prognosed parameter of ice strength were calculated in the form analogical Table 1.

But for the solving of the problem of the reglamentation of the allowable ice conditions in the frame of RR Rules it is necessary to give this data in more simple form. The carried out analysis shown that the satisfied way of ice strength parameters could be based on the early used approach [1, 4, 12] which used the function connecting ice strength parameters and ice thickness. The physical aspect of such approach is real increasing ice strength parameter and ice thickness with ice age increasing. The positive correlation between ice thickness and ice strength parameters gives the possibility to assume the next analytical function which allows to calculate the ice strength parameters depending on ice thickness (Fig 2)

$$\begin{aligned} \sigma_b &= k_n \sigma_b^0(h), \\ a_c &= k_s a_c^0(h), \end{aligned} \quad (1)$$

where $k_s = 0.8$ - for the summer - autumn season

$k_n = 1.2$ - for the winter - spring season

$$\sigma_b^0(h) = 0.34 h^{0.8} \quad \text{by } h \leq 2.5 \text{ m}$$

$$\sigma_b^0(h) = 0.54 h^{0.3} \quad \text{by } h > 2.5 \text{ m}$$

$$a_c^0(h) = 132 h^{1.1} \quad \text{by } h \leq 2.5 \text{ m}$$

$$a_c^0(h) = 330 h^{0.3} \quad \text{by } h > 2.5 \text{ m}$$

σ_b - the bending ice strength (MPa),

a_c - the crushing ice parameters in the technical unit system [11],

h - ice thickness, m

The methodology of the new revision of RR Rules [1] is based on the uniform for every ice category the base motion regimes corresponding to the ice loads determining the ice belt structures ultimate strength (so called, the dangerous motion regime which leads to the beginning of appearance of large plastic deformations of the ice belt structures) By the

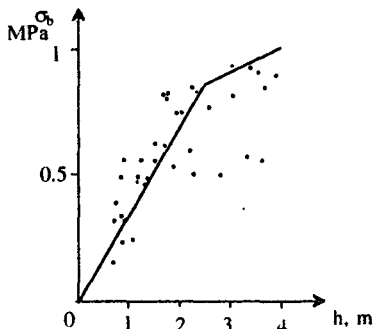


Fig.2 The interdependence of the ice bending limit stresses and the ice thickness for NSR-seas on winter.

• - the result of statistical analysis;
 — - function (1).

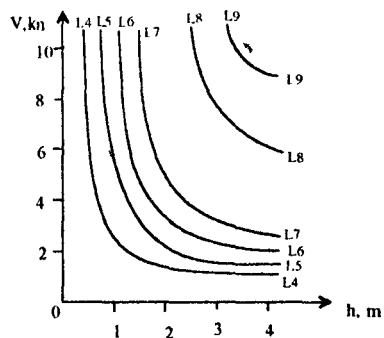


Fig.3 The characterised view of the allowable

speed regimes curves;

h - the level ice thickness;

V - motion speed;

L4 - L9 - ice strengthening categories corresponding the project of new revision of RR Register [1].

— - concentrated ice;

- - in ice of low concentration.

navigation conditions regulation it is necessary used the allowable motion regimes in average corresponding to the beginning of the ice belt structures plastic deformation. The load level for them could be calculates

$$P_{al} = \frac{P_{ult}}{k_n} \quad (2)$$

where P_{ult} - ultimate load [1, 3],

$k_n \approx 1.8$ - standard safe coefficient.

The way of generating of the permissible motion regimes curves (Fig 3) uses the methodology [4] which is based on the hydrodynamical model of ship - ice impact and the models of ice over destruction by bending and by crushing. The ice belt structure strength is

characterized by the demands to the ultimate strength [1] for the choosed ice category taking into account (2) The ice cover strength is characterized by the (1)

It is necessary to determine some standard speed values for the solving of the problem of allowable operation because in connection with methodology the load level on the structure depends on the motion speed in ice. With the methodological point of view it is worth to take two speed values

u_o - operational speed is a low boundary of the operational speeds range by which is possible a normal navigation in ice,

u_m - minimal speed is a upper boundary of the speeds range by which is no a stable motion of a ship in ice

By the transit navigating the values of standard speed are determined from the assumption that a ship must have some inertia storage to cross the ice isthmus. In this case could be taken $u_o=6$ kn, $u_m= 5$ kn

By the navigating in a channel behind icebreaker the main factors are the course stability and her control ability than $u_o = 3$ kn, $u_m = 2$ kn. The data of the Table 1 on the base of the allowable motion regimes (like Fig 1) could be calculated the allowable motion speeds u_{al} for every considerable region, season and year difficulty. Depending on the u_{al} value could be confirmed the deduction about the exploration permission:

$u_{al} > u_o$ - exploration permitted

$u_{al} < u_m$ - exploration prohibited

$u_m \leq u_{al} \leq u_o$ - the decision about exploration possibilities depends on concrete ice condition and is under ship - owner competention. The results are in the Table 2

Besides Table 2 results on the early design stages it is interesting the information about allowable motion regimes (main ice thickness and motion speeds) depending on not only season and region but on such parameters as ice concentration and hummock degree. For these aims are calculated

- the thickness of flow ice of difference hummock degree in which the ship operation is permitted with two characterized speeds: about 4 - 5 knots and 8 - 10 knots,
- the permissible navigating speed in heavy hummocked ice (characterized for every ice category) of difference ice concentration;
- the permissible thickness of ice cake for the non arctic categories ships by the motion speeds 3.5 and 8 knots

For the calculation there were used the next model The taking into account the hummock influence was done on the ground of the approach of AARI using for the passport development problem [8, 9] This approach allows for the every value of hummock degree to use the coefficient of recalculation for the hummocked ice thickness to the equivalent level ice thickness

For the quantitative estimation of the ice concentration influence was developed the special model based on approach that with ice concentration increasing the ship maneuver possibilities are getting low by the motion between separate floes As the calculational analysis shown by the ice concentration 4 ball and low ship can avoid the direct ice impacts in the bow region and impact only by intermediate area between bow and middle regions (intermediate are, Fig 4,a).

By the ice concentration 7 ball or up the ship must by motion crush and remove the floes (Fig 4.b) In this case the ice loads have actions on the regions near bow stem In the region 4-7 ball it is realized the intermediate ice navigation condition

The typical hull merchant ship shapes lead to design load which are realized. by impact in the bow region - for thick ice and relative low speeds, by the tendency impact in the intermediate region - for the relative thin ice and higher motion speeds. It is reason why for arctic ice categories L4 - L7 by the navigating in the relative thick ice (1 + 2 m) of low ice concentration could be possible to increase the allowable motion speed The upper arctic ice categories L8, L9 have not this effect because their permissible regime curve move to the area of bigger ice thickness which could be met as multiyear ice fields

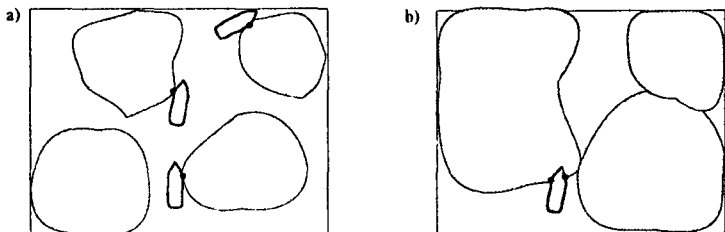


Fig.4 The ways of ship - ice interaction by sailing in ice low (a) and big (b) concentration.
 • - the position of the hull - ice interaction zone center.

As for as non arctic ice categories ships L1 - L3 concerned for them the taking into account the ice concentration influence don't lead to the existent changing of allowable speed

because such ships have not the intermediate region of ice belt corresponded intermediate hull area and the hull shape is designed usually for the enough performance on the smooth water

For the non arctic ice category ships the main ice motion regime is sailing in ice cake This factor is took into account as an assumption that than large a ship than the maneuver ability less and a ship have to have a contact with larger floes It leads to

$$\frac{R^2}{\Delta} = \text{const} \quad (3)$$

where R - floe radius

Δ - ship displacement

The outlined method of the quantitative description of the allowable ice condition supplies an objective information for the ship ice class choosing even on the early ship design stages Given corresponding data on ice condition it can be described the allowable condition of navigating in other Arctic seas It is possible in principal the reglamentation by the same way for the allowable condition for ice classes of the other classification societies

References

- 1 Appolonov E.M., Nesterov A.B., Timofeev O.Y., Ice strength in connection with classification of ships and icebreakers Thesis of international conference dedicated to 100-anniversary of CRI by name A.N. Krylov, S-Pb, 1994
- 2 Kurdumov V.A., Kheisin D.E., Hydrodynamical model of ship hull - ice impact Applied mechanics, 1976 v XII, N10
- 3 Appolonov E.M. The ice belt structures development on the ultimate strength criteria "Shipbuilding", N2, 1992
- 4 Appolonov E.M., Nesterov A.B. The refined method for the design speeds determination for ice going ships - The notes of CRI by A.N. Krylov, v 514, I. 1991
- 5 Romano, I.P. The ice cover of arctic basin AARI, L. 1991
- 6 Atlas of Arctic Edited by A.F. Treshnikov MD of Geodesy and Mapgraphics by SSSR, M., 1985

- 7 Ryvlin A Y The method of the bending ice cover strength prediction - The problems of Arctic and Antarctic, v 45, 1974
- 8 Gavrilov V P, Lebedev G A, Fedorov V I, Cherepanov N V The season changeability of physics - mechanics sea ice properties - The notes of AARI, v 421, 1991
- 9 VSN 41 88 The development of iceresistant stationary platforms Minneftprom, SSSR, M 1998
- 10 SNiP 2 06 04-82 Loads and actions on the hydrotechnical structures (waves, ice and from vessels), M, 1983
- 11 Kheisin D E, Likhomanov V A, Kurdumov V A The determination of the specific energy of destroying and contact pressure by the impact a solid body and ice The notes AARI, v 526 The physics methods of research's of ice and snow, L, 1975
- 12 Lavrov V V The sea ice classification on strength - The notes of AARI, v 331, L, Hydrometeoizdat, 1976
- 13 AARI - Ice passport of the m/s "Dmitry Donskoy", L, 1979
- 14 AARI - Ice passport of the m/s "Norilsk", L, 1984

Table 1

The statistical analysis result for the designing ice thickness determination depending geographical region, season and year difficulty

N	Geographical region	Winter - spring				Summer - autumn			
		Year difficulty				Year difficulty			
		L	M	H	E	L	M	H	E
1	Barens sea North	0.45	0.7	0.9	1.17	0.23	0.35	0.45	0.59
2	Barens sea South	0.32	0.55	0.72	1.1	-	-	-	-
3	Kara sea North	0.75	1.25	1.75	2.35	0.38	0.63	0.88	1.18
4	Kara sea South	0.45	1	1.7	2.2	0.23	0.5	0.85	1.1
5	Laptev sea North	1	1.9	2.8	4	0.5	0.95	1.4	2
6	Laptev sea South	0.65	1.5	2.25	3.7	0.33	0.75	1.15	1.85
7	East-Siberian sea North	1	1.7	2.4	3.2	0.5	0.85	1.2	1.6
8	East-Siberian sea South	0.6	1.34	1.9	2.95	0.3	0.67	0.95	1.5
9	Chukcha sea North	0.85	1.5	2.5	3.75	0.43	0.75	1.25	1.88
10	Chukcha sea South	0.5	1.18	2	3.45	0.25	0.6	1	1.73

Year difficulty sign

L - light

M - medium the average repetition - one time per 3 years

H - heavy

E - extreme - the average repetition one time per 10 years

Table 2

The allowable operational regions for the arctic ice categories ships

Ice category	Navigating way	Winter - spring navigation					Summer - autumn navigation				
		1	2	3	4	5	1	2	3	4	5
		EHML	EHML	EHML	EHML	EHML	EHML	EHML	EHML	EHML	EHML
L4	TR	----+	- - - -	- - - -	- - - -	- - - -	++++	- - + +	- - - +	- - - +	- - + +
	EX	- * + +	- - - +	- - - -	- - - -	- - - *	++++	* + + +	- - + +	- * + +	- * + +
L5	TR	- - + +	- - - +	- - - -	- - - -	- - - -	++++	- + + +	- - + +	- - + +	- - + +
	EX	* + + +	- - * +	- - - +	- - - +	- - * +	++++	* + + +	* + + +	* + + +	* + + +
L6	TR	* + + +	- - - +	- - - +	- - - +	- - + +	++++	++++	- + + +	- + + +	- + + +
	EX	++++	* + + +	- * + +	- * + +	- * + +	++++	++++	++++	++++	++++
L7	TR	++++	- - + +	- - - +	- - - +	- - + +	++++	++++	++++	++++	++++
	EX	++++	++++	* + + +	* + + +	* + + +	++++	++++	++++	++++	++++
L8	TR	++++	++++	- * + +	* + + +	* + + +	++++	++++	++++	++++	++++
	EX	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++
L9	TR	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++
	EX	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++

1 - Barenz sea

2 - Kara sea

3 - Laptev sea

4 - East-Siberian sea

5 - Chukche sea

TR - transit ice navigation

EX - escorted by icebreaker

+ - navigating is permitted

- - navigating is not permitted

* - as up shipwener

E - extreme navigation (average repetition one time per 10 years)

H, M, L - heavy, middle, light navigation (average repetition one time per 3 years).

P.S There is next approximate equivalence between ice categories of new revision RR Rules and present Rules - 1990 L4 - L1, L5 - UL, L7 - ULA.

Methods of Ice Strength Standardization for Large Tonnage Ice Breaking Transport Vessels

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Abstract

In order to safely and economically transport Yamal hydrocarbons to markets, Amoco has proposed a marine export system that will include an offshore terminal, offshore and onshore pipelines, tankers, and icebreakers. Use of large, newbuilt icebreaking tankers is being considered. Conceptual designs for such vessels have recently been developed, and design reviews have been carried out. Because similar vessels do not currently exist, and because the current rules of the Russian Register of Shipping are not directly applicable to the proposed vessels, a study on the required ice strengthening design using Russian approaches has been carried out. Principles of ice strength standardization for large tonnage icebreaking transport ships on the basis of Russian approach are presented in this paper. Two methods are discussed. The first is a method for extrapolation on existing rules to large tonnage icebreaking vessels. And the second is an approach based on calculation of ice loads, given environmental conditions and a set of operational modes as input.

Introduction

Several trafficability and economics studies [1] have helped Amoco to select the following sizes of tankers for concept design work: a 110,000 cubic meter capacity LPG Carrier and a 120,000 dwt crude oil tanker. These large vessels are

designed for independent navigation is the western Kara and SE Barents Seas, although all options of assisted and unassisted navigation are still open at this stage of the project, as noted in [1]. The concept design of these tankers was carried out according to Western methods used by Kvaerner Masa Yards, and checks were made with a special DNV class. However, no prototype of these types of icebreaking tankers or their class exists today. In view of this, it was decided to develop a suitable Russian approach, to be able to draw from the extensive Russian operating experience in the Arctic, and to compare with the Western approach used for concept design. This paper outlines the methods of the Russian approach. The methods will also have applications to other large cargo or tanker projects for the Russian Arctic, including vessels that are designed for independent navigation in complicated ice conditions (i.e., icebreaking transport vessels. Two methods for ice strength standardization for these large transport vessels are suggested.

The first method is based on extrapolation of existing design procedures and of operational experience of vessels used in active ice navigation and icebreakers. This experience is generalized in the Rules of Russian Register of Shipping. We developed the needed levels (standards) of ice strength for a certain category of ice strengthenings by an extrapolation of regulations given in the Rules of Russian Register.

The second method is based on calculations for a given, restricted region of operations when the modes of ship operation are given. The calculations are carried out using a Russian approach. Essentially, a reverse problem is solved in

this approach.

Mathematical formulation, derivation of the method and the logic, and programming of the software was done for both methods. A model of ship/hull interaction was developed and optimized. This was used to provide solutions for both methods.

1. Ice strength standardization based on extrapolation of existing Rules of Russian Register

Ice Strength and design Strength are two important technical terms used in the Russian approach. Design strength is measured by calculating the ice load resulting in the limit of permissible deformations or stresses. This term has the normal meaning, as would immediately be perceived by any engineer. Ice strength represents the operational ability of ship hull for operations in ice infested waters to withstand impacts against ice of certain strength and thickness, under permissible deformations or stresses. Basically, ice strength represents a descriptions of the design strength in terms of operational or environmental parameters. The hull is not allowed to deform beyond the utmost permissible conditions set in the Rules. One of the most important ice strength parameter is the safe speed of the ship, V_s which is used in the Rules of Russian Register as a standard of ship hull ice strength sharakteristic. The speed V_s controls the ice strengthening of the hull. As a result; the hull strength is adequate for all ice thicknesses, when the vessel moves at speeds equal to or less than the safe speed (V_s). This is because V_s corresponds to impact conditions

against a thick ice sheet not subject to failure by bending. Thus, the use of the concept of safe speed V_s implies that we are considering an extreme situation in which the ice does not fail by bending.

The variations of V_s for Arctic transport vessels of various dimensions and ice strengthening categories were originally estimated during the derivation of the Russian Register Rules of 1981. Analyses were carried out at the time for vessels with a displacement (Δ) varying between 2,000 and 25,000 tonnes. The results showed that the safe speed decreases with an increase of the vessel displacement [2], for the same ice class. The functions $V_s(\Delta)$ that had been obtained during this exercise were extrapolated to larger vessel displacements of up to 60,000 tonnes. Based on this approach, the first set of standards for ice strengthening of hull structures of Arctic transport vessel were formulated. This approach to ice strength standardization is employed in the Rules of 1985 and 1990 which have been successfully used for designing of modern Russian transport vessels for navigation in the Arctic.

The decrease of the ship's speed V_s with the increase ship displacement can be explained by the following arguments:

- The relative ship power capability P/Δ (P - ship power output) decreases with an increase in the displacement, for the same ice category.

- A decrease in the relative ship power capability leads to a decrease in the ship speed for both solid and broken ice cases resulting in a decrease of the ice impact speed.

- The experience gained during the design and operations of

tens of ships in the Russian Arctic helped develop the relationship between the relative ship power and strength of the hull structures. An increase in the relative power for a ship of certain hull strength could lead to a higher level of damage probability and to a decrease in ship loading capacity.

The fundamental relationship between the hull strength of a ship and its displacement is represented by the decreasing safe speed. This fact has been recognized by many experts involved in the classification and design of ice going vessels [3].

The following suggested approach to ice strength standardization for large tonnage icebreaking transport vessels, is based on simple principles formulated in the Rules of the Russian Register. The method is based on the combination of the design strength and the ice strength for ship structures that comply with the Register's regulations. Some parameters or coefficients are defined for this purpose.

$$p^*(\Delta) = p_d / (c^{\sqrt{\Delta}} F_p)$$

$$q^*(\Delta) = q_d / (v^{\sqrt{\Delta}} F_q)$$

$$b^*(\Delta) = b_d / (f^{\sqrt{\Delta}} F_b)$$

where p_d , q_d , b_d are parameters of design strength for plates and beams of the ice belt structures representing the maximum (design) contact pressure, the maximum linear intensity of the load, and the maximum height (depth) of the contact zone [2]; Δ is the ship displacement; and F_p , F_q , F_b are functions of hull

form, and are called shape functions. These are not non-dimensional, and the full expressions can be found in [2]. The coefficients p^* , b^* , q^* do not depend on specific ship particulars and they define the ice strength of the ship in an inevident way [2]. These coefficients are ice strength parameters and they represent the ice going abilities of the ship from structural point of view. Parameters of ice strength and design strength are related in the above expression through the shape functions and displacement.

Parameters p_d , q_d , b_d are obtained by means of calculation of design strength of plates or beams for structures of existing or proposed ships. This is a way to take into account the design and operational experience for ships of various ice categories.

Following steps are to be taken in obtaining the results for the ice strengthening for ice breaking transport vessels of large tonnage:

1. The values of coefficients p^* , b^* , q^* for icebreakers of various categories and for a broad range of displacement of ULA-category transport vessels (up to 120,000 t) are to be estimated, and diagrams of $p^*(\Delta)$, $b^*(\Delta)$ and $q^*(\Delta)$ are to be plotted. It is possible to do this by extrapolating the Rules of Russian Register beyond their original range of validity.

2. Assuming that the coefficients (p^* , b^* , q^*) are fixed for a given displacement (Δ) and for certain parameters of the hull form (F_p , F_q , F_b), it is then necessary to recalculate the design strength parameters (p_d , b_d , q_d) for each case.

3. On the basis of correlations which describe model of ship hull/ice interaction for a given design strength (p_d , b_d ,

q_d) in the area of ship bow, the safe speed of ship motion can be determined for vessels of various displacements and ice strengthening categories.

4. Safe speed values obtained as above using extrapolation of Russian Register Rules must be defined more precisely using a successive approximation converging method, since coefficients p^* , b^* , q^* implicitly depend on safe speed. This process results in a set of safe speed curves $V_s(\Delta)$ for different categories of icebreakers and icebreaking transport vessels.

Some results based on the method described above are shown in Fig.1 to 5. Values for ice strength coefficients and design strength parameters are shown for some icebreakers and transport vessels designed for independent navigation. There are following notations of the shape functions in the Figures 1 to 5: $v = F_p$; $u = F_b$.

The following values of shape functions have been assumed: $F_p = 0.5$, $F_b = 0.5$, $F_q = 0.25$ for the LL4-icebreakers and ULA-transport vessels: $F_p = 0.61$, $F_b = 0.69$, $F_q = 0.38$ for icebreakers and icebreaking transport vessels of higher categories. In the first case, these values correspond to the direct (first) impact, in the second case, they correspond to the reflected impact for vessels having a hull form similar to that of the "Sevmorput". Conception employed in Russian Register Rules is the reason of such approach. A direct impact mode is a design one for ice going transport vessels and for LL4-category icebreakers [4]. A reflected impact mode is a design one for icebreakers of higher category [5].

The design strength parameters q_d , b_d (Fig.3 and 4) for ULA

category vessels correspond to the coefficients q^* which are defined by the diagram $q^*(\Delta)$ in Figure 1. For vessels of higher category, parameters q_d and b_d are defined in accordance to the following two concepts:

1. The value of $q^*(\Delta)$ when ship power output is minimum for the Russian Register ice category is $q_{min}^*(ICE\ CATEGORY) = \text{constant}$ ($q_{min}^* = p_{min}^* b_{min}^*$). This is applicable to icebreaker concept.

2. The given coefficients q^* are defined by extrapolating the form of existing curves for $q^*(\Delta)$ applicable for the icebreaking transport vessel concepts.

Results shown in Figure 3 show that it is very problematic to design framing for the sides of the ship with suitable forms of sections for a constant level of ice strength for large tonnage vessels ($\Delta = 100,000-120,000$ t) even for LL3-category.¹

It is reasonable to decrease the coefficient p^* for larger displacements. As a result, design pressure values for icebreaking transport vessels will be somewhat less than those that correspond to the icebreaker concept or $p^*(ICE\ CATEGORY) = \text{constant}$ (see Figure 2). This approach ensures better correlation of design load intensity for ice belt framing and plating. For the same reasons, the values of the dynamic strength parameters a_p for large displacement ships are increased (see Figure 5). This increase is a result of

1) Experience of ice strengthening design is a confirmation of it. The level of design loads (14-15 MH/m) is so high that it is very problematic to get acceptable dimensions of ice belt framing.

approximate (conditional) description of a ship/ice interaction problem by hydrodynamic model of a rigid object impacting against ice [6] .²

In Figure 5, plotting the variation of the safe speed for the bow area for various categories, permits us to draw a line $V_b(\Delta)$. This line determines the design speed of an icebreaker during an impact (ramming) against the edge of an ice field. Points can be found on this line that would correspond to minimum design speed $V_s^{(min)}$ for each category of icebreakers. The least possible displacement of an icebreaker of certain category corresponds to each of these points. This also means that an icebreaker of certain category can not have a displacement smaller than what is indicated.

The design speed values for LL4 category icebreakers correspond to intersection points of the safe speed curve $V_s(\Delta)$ for ULA category vessels with the curve $V_b(\Delta)$ representing the lower bound displacement. This means that the displacement of ULA - transport vessel can not be less than 4,500-5,000 t. In principle ULA - vessels and LL4 - icebreakers may be put into the same category.

A similar idea can be used to plot the safe speed curves for icebreaking transport vessels of higher ice strengthening categories. The regulations that define the category of ice strengthening (main machinery output, strength of structures,

² A hydrodynamic model of a rigid object impacting against ice was derived from measurements taken from drop ball tests. The drop ball model test helped to define a correlation between contact pressures, ice characteristics, mass of the object and speed of its motion in the direction of the impact [6].

etc.) conclude that, for small tonnage ships, these curves represent the design strength standards for icebreakers. However, with current need for larger vessels for oil and gas transportation in the Russian Arctic seas, with this method, there exists a possibility to economically design safe and efficient icebreaking transport vessels.

The ice strength standardization method suggested in this paper provides a basis for putting together a single classification system for icebreakers and icebreaking transport vessels.

2. Basing of ice strength category required for an icebreaking transport vessel by vessel specific calculations

We will now consider the second method mentioned in the introduction. A necessity may spring up in the practice of designing ships to work out ice strengthening structures that would correspond not to an existing category of Russian Register but to a specific set of design operational modes during navigation in ice. Such an approach would enable one to take into account special operational features for the vessel, and to determine the required level of ship hull ice strengthening on that basis.

Design operational modes are determined with values of the following parameters: design thickness of ice field or ice floe mass and corresponding permissible ship speed; design values that characterize strength of ice (flexural strength of the ice field, dynamic strength of ice in crushing). In addition, design

operational modes may be determined by vessel's ability to move in solid or broken ice of various concentrations, by her ability to move in a channel behind icebreakers, if navigation with the aid of icebreakers is intended. Maneuvering in ice and impacts against the edge of ice fields in the process of astern motion are to be considered as well.

Regime that corresponds to independent operation in hummocked ice zones (ramming mode) may be taken as a design scenario for icebreaking transport vessels (impact against ice which would not be destroyed due to bending).

Design values of strength of ice are fixed on the basis of analysis of design and operational experience of ice going vessels and icebreakers. This information is summarized in the Rules of Russian Register of Shipping.

Usual (normal) modes of ship hull interaction with ice and extreme ones are possible in the process of ship operations. When this interaction is usual, the ship-master has full control of ship motions in ice. Ship motion parameters (speed, course) are chosen in accordance with the actual situation; taking into consideration the strength of hull structures. Extreme modes in ship navigation occur as a rule as a result of ship-master's errors when ice conditions are extremely difficult. Ship-master would then lose control of ship motion. It may happen primarily in multi-year pack ice, grounded hummocks, etc. In such cases, ice is too thick to fail by bending, and crushing of ice takes place, very likely on ship sides. Compression of the ship with multi-year pack ice, ship collision with a bit of continental ice are taken as extreme situations too. Phenomenon which may be

a result of extreme loads on hull structures occurs only once during vessel's life time.

According to Russian practice different design approaches are used with respect to vessels for ice navigation and to icebreakers.

Icebreaker hull structures located in the area of ice belt are to withstand damages even in extreme exploitation modes. This is the **damage-proof structures** conception.

The hull of any transport vessel engaged in active ice navigation may be exposed to impact loads due to collision with large ice formations. Situation of high intensity compression with ice is possible too. A requirement to design a ship structure which would be **damage-proof** in any possible situation leads to substantial increase in weight and to worse operational characteristics of the vessel. Therefore an **acceptable damage conception** is applied to the design of transport vessel structures.

Corresponding level of design loads for transport vessels and for icebreakers is fixed in the Rules of Russian Register on the basis of generalization of long term experience of vessels for navigation in ice. This includes design and operational experience and analyses of damages.

Choice of required category of ice strengthening is based on results of direct ice load calculations for the totality of design operational modes. Methods and software have been developed that enable us to solve this problem. Correlations of theoretical model of ship hull interaction with ice which is used in Russian practice served as a basis for these methods and

software. Pressure in the area of contact with ice is determined using hydrodynamic model of a rigid body impact against ice [6].

Results for a large tonnage vessel intended for independent navigation in the Kara Sea are presented in Figure 6. This vessel has the displacement of about 120,000 t and the length of about 266 m.

Special research permitted to choose a set of operational modes according to which requirements of ice strengthening category are to be formulated for these vessels. The following modes were considered in the calculations:

1. First (direct) and second (reflected) impact against an indestructible ice floe at the speed of 6 knots (extreme modes).

2. Ship bow impact against an edge of an ice floe of maximum possible thickness for ramming mode at the speed 15 knots (maximum thickness of hummocked ice in the area of operations is about 2.3 m; maximum thickness of rafted ice is assumed to be about 2.8 m).

3. Ship stern impact against edge of ice floe 1.6 m thick due to ship astern motion at the speed of 7.5 knots.

4. Ship impact against a floating floe with mass of 600-1000 t in the process of maneuvering or of turning motion with speed of 6-10 knots (turning radius (1.8 to 4.0) length of the ship; angle of heel 1-6°; drift angle does not exceed 15°).

5. Ship stern impact against ice floe edge (ice field) in the process of maneuvering or of turning motion at the speed of 6-10 knots and ice thickness of 1.2-1.7 m.

6. Lateral compression of the ship with ice 1.4 m thick.

Design values of ice thickness were assumed on the basis of

special analysis of possible ice conditions in the intended operational area of the vessel. Design characteristics of strength of ice are based on Russian experience of designing and exploitation of vessels for ice navigation and icebreakers. Results of experiments in which these characteristics were estimated have been taken into account.

Design speed for extreme modes is taken as that for POLAR-20 DNV ice category. Acceptable damage criterion for these extreme modes is recommended, since the probability of such design situation is extremely small: there are neither thick multi-year ice nor icebergs in the proposed exploitation area; waters depth on ship routes in that area is more than 25 m, and therefore the probability for a ship to encounter a grounded hummock is very small too.

It is reasonable to take ice loads that correspond to these modes as ultimate ones. Design ice loads³ may be evaluated as

$$p_d = p_u/n_p; q_d = q_u/n_f,$$

where p_d and p_u are design and ultimate pressure for outer plating; q_d and q_u are design and ultimate linear load intensity for ordinary framing; n_p and n_f are ultimate strength safety coefficients for ice belt plating (n_p) and framing (n_f).

The values of n_p and n_f on the basis of ultimate strength

3) Situation that corresponds to appearance of two plastic hinges is assumed to be a design one for outer plating in the Rules of Russian Register. Fibre yielding is assumed as design situation for framing.

analysis applied to ice belt plating and framing of ice going vessels are: $n_p \cong 1.4$; $n_f = 1.8-2.2$ [6].

The method presented above enable to base the required ice strengthening category as well as the length of ice strengthening areas along the ship hull.

Comparison of the results of the second method which are given in Figure 6, and results of Russian Rules extrapolation (see Figures 1-5) reveals that ice strength of bow area hull structure of vessel for independent navigation in Kara Sea is to be at the level of regulation for ULA-category vessels.

Conclusion

Principles of ice strength standardization for large tonnage icebreaking transport ships on the basis of Russian approach are presented in this paper. Two methods are discussed. The first is a method for extrapolation of existing rules to large tonnage icebreaking vessels. And the second is an approach based on calculation of ice loads, given environmental conditions and a set of operational modes as input.

References

1. Bhat S.U., Jurmaa K., Tsoy L.G., Trjaskin V., Brovin A.I., McRae R.K. and Blanchet D., 1995. "Arctic Tanker Trafficability Studies for Yamal". Proceedings, Second International Conference on Development of the Russian Arctic, St.Petersburg, Russia, Sept.18-22.

2. Курдюмов В.А., Тряскин В.Н., Хейсин Д.Е. Определение ледовой нагрузки и оценка ледовой прочности корпусов транспортных судов. - Труды ЛКИ, Ледопроходимость и ледовая прочность морских судов, 1979, с.3-12.
3. Edelman G. Updating of the Finnish-Swedich ice class Rules. VTT- Symp., 1984, N 52, p.231-245.
4. Тряскин В.Н. Исследование работы бортовых конструкций транспортных судов ледового плавания. Диссертация на соискание ученой степени кандидата технических наук, Ленинград, 1979.
5. Курдюмов В.А. Определение нагрузок на конструкции ледового пояса ледокола при ударе о лед. Диссертация на соискание ученой степени кандидата технических наук, Ленинград, 1975.
6. Бененсон А.М., Курдюмов В.А. Предельная прочность бортовых перекрытий судов ледового плавания.- Судостроение, N 6, 1984, с.5-8.
7. Курдюмов В.А., Хейсин Д.Е. Гидродинамическая модель удара твердого тела о лед. Прикладная механика, Т.ХII, N 10, с.103-109.

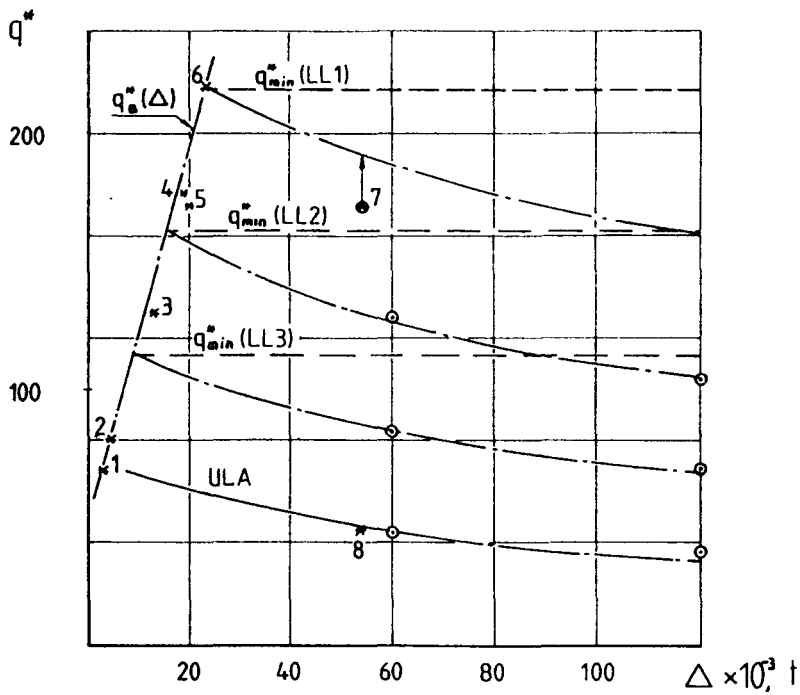


Figure 1

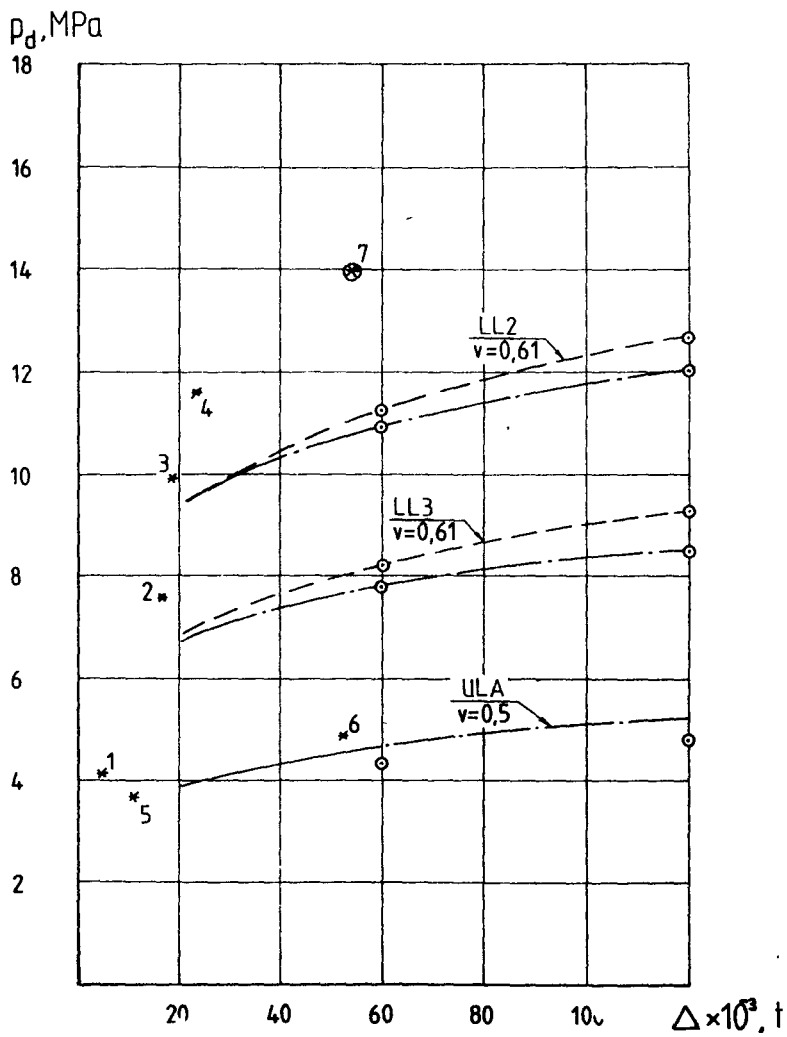


Figure 2

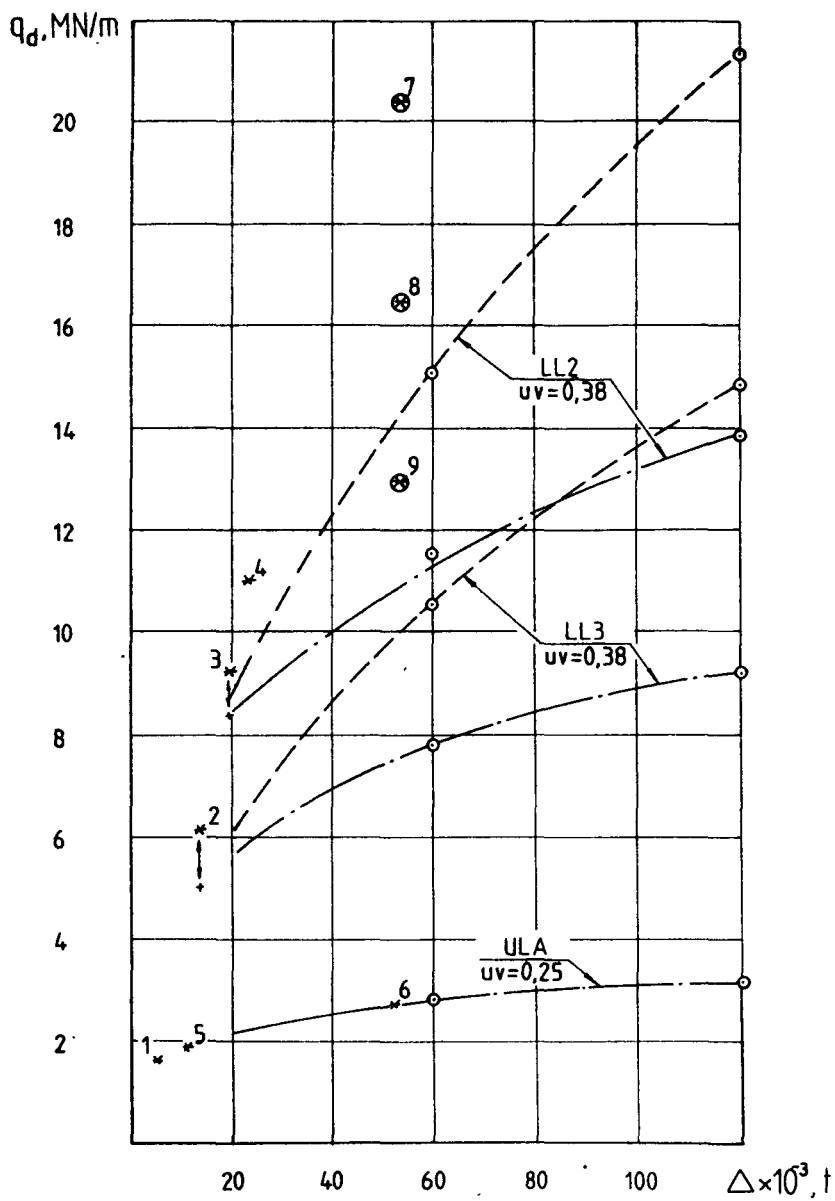


Figure 3

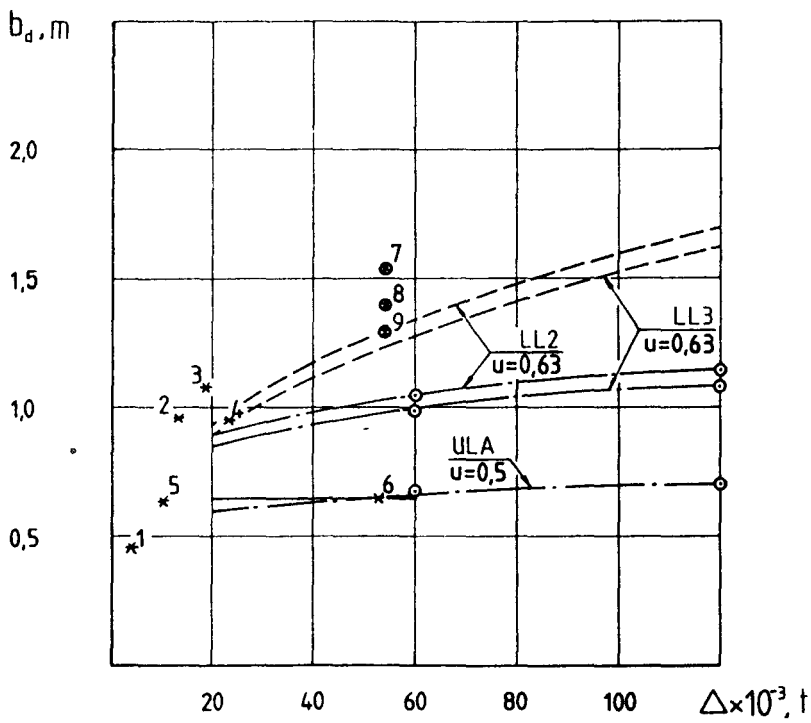


Figure 4

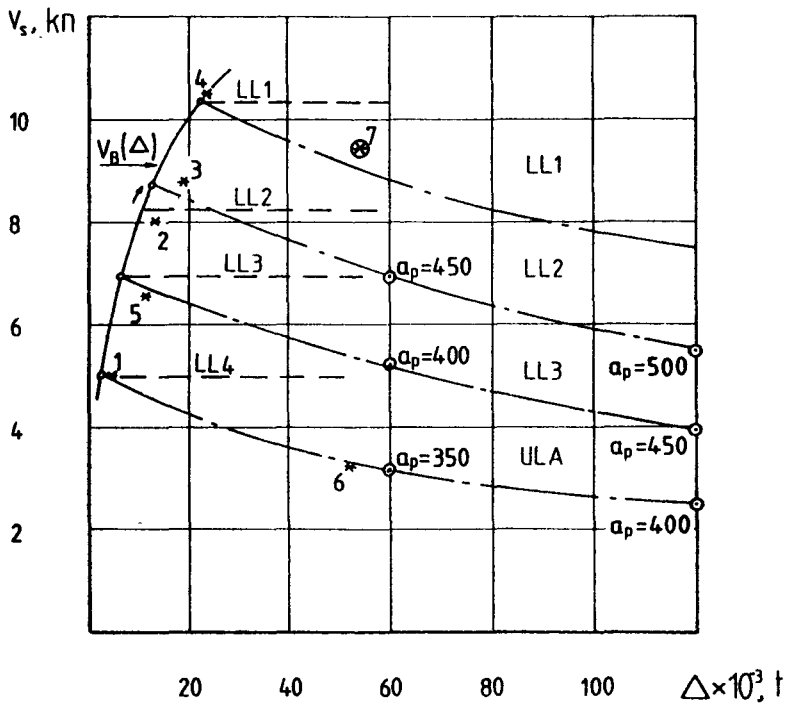


Figure 5

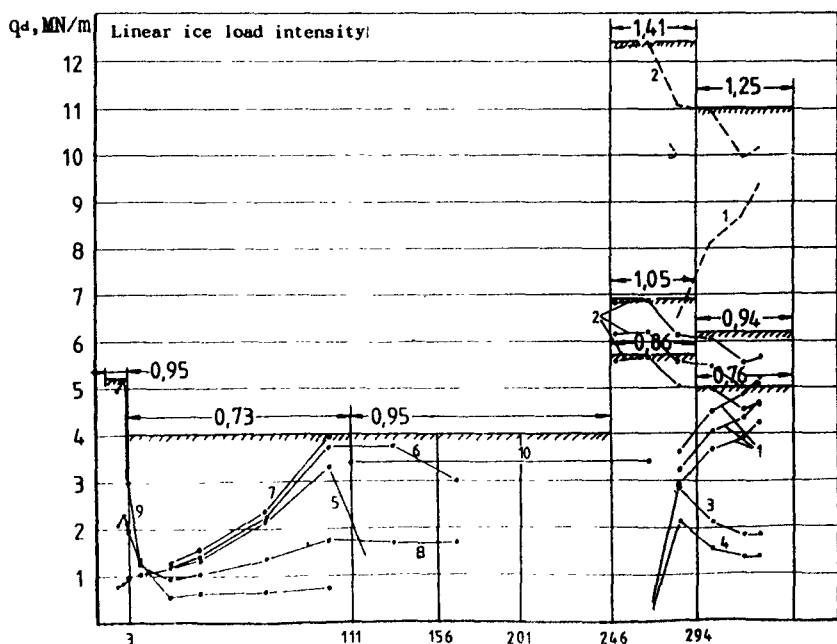
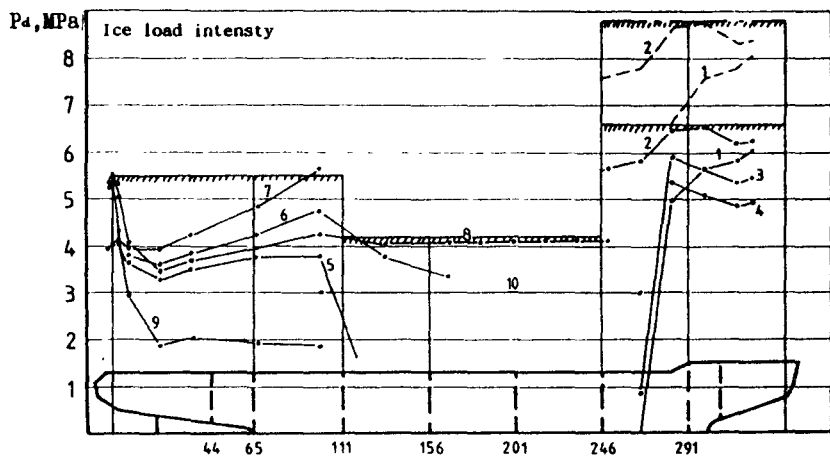


Figure 6

Names of the Figures.

Figure 1. Framing ice strength parameters calculation results for icebreakers and for ULA-category transport vessels

- * - according to the Russian Register Rules for the following types of icebreakers and vessels: 1-"V.Prontchistchev"; 2-"Cap.Bielousov"; 3-"Moscow"; 4-"Lenin"; 5-"Ermak"; 6-"Arctica"; 7-a design with power output of 110 MWt; 8-"Sevmorput".
- (- -) - at minimal for a certain class power at propeller shafts;
- (—) - according to the Rules regulations for ULA-vessels;
- (-.-) - extrapolation results
- o - evaluations for vessels of 60 and 120 th.t displacement.

Figure 2. Design contact pressure for ice belt bow structures of icebreaker and of transport vessels.

- * - according to the Russian Register Rules for icebreakers: 1-"Cap.Bielousov"; 2-"Moscow"; 3-"Lenin"; 4-"Arctica"; for icebreaking transport vessels: 5-"Anguema"; 6-"Sevmorput".
- - according to results of design exploration for an icebreaker with power output of 110 MWt (7).
- o - evaluations for vessels of 60 and 120 th.t displacement.
- (—) - according to the Rules regulations for ULA-vessels;
- (- -) - icebreaker conception at minimal power output;
- (-.-) - icebreaking transport vessels conception (extrapolation).

Figure 3. Design linear intensity of ice load for ice belt bow structures of icebreakers and of icebreaking transport vessels.

- * - according to the Russian Register Rules:
- for the following icebreaker types: 1 - "Cap.Bielousov"; 2 - "Moscow"; 3 - "Lenin"; 4 - "Arctica";
- for icebreaking transport vessels: 5-"Anguema"; 6-"Sevmorput";
- - for an icebreaker design with power output of 110 MWt: design speed of the second impact 12 knots - 7; 10 knots - 8; 9 knots - 9 (actually assumed in the design);
- + - actual data according to structures calculations results.
 - o -evaluations for vessels of 60 and 120 th.t displacement.
- (---)-according to the Rules regulations for ULA-vessels;
- (- -)-icebreaker conception at minimal power output;
- (-.-.)-icebreaking transport vessels conception (extrapolation).

Figure 4. Design contact area height for ice belt bow structures of icebreakers and for icebreaking transport vessels.

- * - according to the Russian Register Rules:
- for the following icebreaker types: 1 - "Cap.Bielousov"; 2- "Moscow"; 3 - "Lenin"; 4 - "Arctica";
- for icebreaking transport vessels: 5-"Anguema";6 -"Sevmorput";
- - for an icebreaker design with power output of 110 MWt: design speed of the second impact 12 knots-7; 10 knots-8; 9 knots - 9 (actually assumed in the design);
- o -evaluations for vessels of 60 and 120 th.t displacement.
- (---)-according to the Rules regulations for ULA - vessels;
- (- -)-icebreaker conception at minimal power output;
- (-.-.)-icebreaking transport vessels conception (extrapolation).

Figure 5. Design safe speed for icebreakers and for icebreaking transport vessels.

- * - according to Russian method for the following icebreaker :
 - 1-"Cap.Bielousov"; 2-"Moscow"; 3-"Lenin"; 4-"Arctica";
 - 7 - design with power output of 110 MWt;
- for icebreaking transport vessels: 5-"Anguema"; 6-"Sevmorput";
- (- -)-at minimal for a certain class power at propeller shafts and a constant value of ice strength standard;
 - o -evaluations for vessels of 60 and 120 th.t displacement;
- (—) -according to the Rules regulations for ULA - vessels;
- (-.-.)-extrapolation.

Figure 6. On the definition of ice strengthening areas length:

- 1 - direct (first) impact against an ice floe that would not be destroyed due to bending, $V_0 = 6$ kn;
 - 2 - reflected (second) impact against an ice floe that would not be destroyed due to bending, $V_0 = 6$ kn;
 - 3 - impact against an ice floe edge while overcoming an ice isthmus $V = 15$ kn., $H = 2,8$ m ;
 - 4 - impact against an ice floe edge while overcoming an ice isthmus $V = 15$ kn., $H = 2,3$ m ;
 - 5 - direct impact against an ice floe edge in astern motion $V = 7,5$ kn., $H = 1,6$ m ;
 - 6 - reflected (second) impact against an ice floe edge in astern motion $V = 7,5$ kn., $H = 1,6$ m ;
 - 7 - stern impact against an ice floe edge while manoeuvring $V = 6$ kn., $H = 1,7$ m ;
 - 8 - impact against a floating floe with weight of 600 t while manoeuvring or turning motion $V = 10$ kn. ;
 - 9 - leaning on an ice floe edge that would not be destroyed due to bending, while the ship is moving astern, $V = 2$ kn;
 - 10 - compression in ice with thickness $H = 1,4$ m.
- (- - -) - ultimate load (extreme navigation mode);
 (—) - design loads curve;
- +1,25+, etc.-design height of ice load distribution, $b_d = q_d / p_d$, (ml).

THE MODEL EXPERIMENTAL INVESTIGATION OF ICE ACTION ON THE OFFSHORE PLATFORM "PECHORA"

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ABSTRACT

The platform "Pechora" is being designed by Design Bureau "Rubin" for exploitation in the Pechora Sea on Priraslomnoye field. Results of the model experimental study of ice/structure interaction are presented. The main goal of the study was evaluation of total ice loads on the platform. A great deal of attention was paid to estimation of "scale effect" errors. Such an estimation was made on the base of models of various scales tests results analysis.

1. Introduction

During 1994 the Department of Ship Performance in Ice of the Arctic and Antarctic Research Institute studied the processes of ice interaction with structures of the ice resistant platform "Pechora". The platform is being designed by the Design Bureau "Rubin" which has requested to perform this study and it is to be used in the Pechora Sea on Prirazlomnoye field. The scheme of the platform is presented in Fig. 1. This article briefly describes the methods for the experimental investigation of the ice action on the "Pechora" platform and presents main results obtained in the course of model experiments.

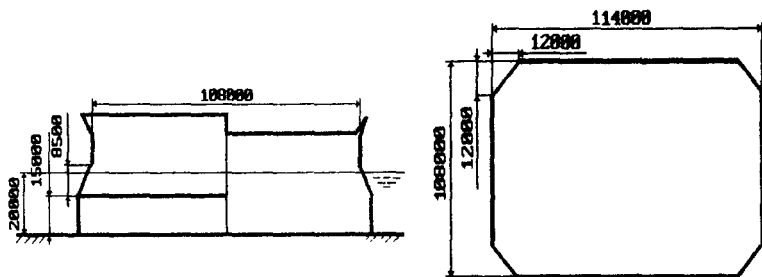


Fig. 1. The scheme of the ice-resistant platform "Pechora"

2. Experimental facility and investigation methodology

As it is known, one of the most considerable difficulty in experimental estimating of ice loads on offshore structures by means of small models is governed by an impossibility to provide ratios for ice parameters following from the similarity theory. In particular, the ratios between the compressive strength, flexural strength, and the modules of the elasticity of modelled ice can not be equivalent to the same ones in natural conditions. That is why, the direct rescaling of the experimental results with regard to nature leads to the occurrence of errors which attributed to the "scale effect". The suggested approach is based on series of tests with models of various geometric scales and intercomparison of rescaling results.

Since, as a rule, the scale effect is the stronger the smaller the geometrical scale of the model, the experimental study of the ice action on the "Pechora" platform aimed at a maximum increase in the scale of the model. As the "Pechora" is a structure with a wide front interacting with the ice, in order to achieve a larger scale of the models we refused from a geometrical modelling of the platform as a whole (the model of the scale 1:50 would have the dimensions 2.16 x 2.04 m). It was decided to determine ice loads per unit length; it allowed to increase the vertical scale of the model leaving the width of the model of acceptable value for testing in the ice tank. The models were made of steel plates strengthened by vertical and horizontal frames presenting part of the platform board on a corresponding scale. In total, 4 models were produced; their parameters are given in Table 1.

Table 1
Geometrical characteristics of the models

Designation of the model	1	1A	2	3
Scale	1:50	1:50	1:75	1:100
Width, mm	1400	700	1000	1000
Height, mm	720	720	540	360
Height of the underwater vertical part, mm	300	300	225	150
Height of the inclined part in the ice belt area, mm	170	170	128	85
Angle of slope of the inclined part of the ice belt area to the horizon, deg.	70.6	70.6	70.6	70.6
Distance from the bottom of the model to the waterline level (draught), mm	400	400	300	200

The tests were performed in the main ice tank of the Arctic and Antarctic Research Institute. The model was mounted on a standard carriage which can move on rails located on the tank sides along the tank operating length. The electric drive of the carriage was supplied additionally with a hydraulic drive. This allowed to provide a constant small velocity of the model towing through the ice field; the towing velocity could vary in a wide range by means of the throttle valve. Vertical and horizontal ice forces acting on the model were measured.

In order to take into account the features of the processes near the sides of the structure, the experiments were made in two variants. In the first variant, the model moved through a undamaged ice field. In the second one, there were made longitudinal slits in front of the model from its sides; thus, the model interacted with the strip whose width was equal to the width of the structure front. This case corresponded to the processes of ice interaction with a platform with an infinite front and it allowed to find accurate values of the loads per unit length. The difference between the forces measured during the first experimental variant and the second yielded a quantitative estimate of the addition to the total ice load caused by the side effects.

A great deal of attention was given to studying the processes of hummocking at model motion in the ice. The heights of the underwater and above-water parts of the ridge formed in front of the model were estimated. The vertical and horizontal loads both in the presence of the ice ridge and in the case when before the experiment the ridge in front of the model was removed and a straight edge of the ice field was provided.

To take into account the effect of the angle at which ice approaches the platform loads, the model was set up at an angle of 0° (the model front is perpendicular to the velocity vector), 15° , and 30° to the motion direction.

In total, more than 160 tests were conducted which differed in the size of the tested models, ice thickness, motion velocities, angles of model setting, the presence or absence of hummocks in front of the models, motion in undamaged ice field or in the field with longitudinal slits. During the experiments photo- and video surveys were made.

The thickness of modelled ice changed from 16 mm to 51 mm, which corresponds to natural ice from 0.8 m to 2.55 m thick at a geometrical scale of 1:50. In the course of the experiment in addition to vertical and horizontal components of the force acting on the model, the thickness dynamic friction coefficient, flexural strength, and normal

elasticity modulus of modelled ice were measured. The flexural strength was estimated by means of loading of two-support beams cut throughout the whole of the ice cover thickness 70-90 mm wide and 200-350 mm long.

To determine the normal elasticity modulus of modelled ice, strips 550-600 mm wide were cut from undamaged ice cover extending from one side of the tank to the other. Strips were loaded over the whole of their breadth by stepwise growing vertical force with a step of 10 N up to the destruction of the strips. At each load value the deflections at the point of the force application were measured.

3. Experimental results

The tests confirmed the validity of technical decisions that have been made during the preparation of the experiment and the suitability of the experimental facility for ice loads determining. A qualitative picture of ice deformation and destruction, hummocking in front of the model coincided with that observed under full-scale conditions.

For a quantitative analysis the experimentally obtained ice loads were transformed according to the following formulas:

$$C_h = F_h^m \lambda / (R_f^m b^m) \quad (1)$$

$$C_v = F_v^m \lambda / (R_f^m b^m) \quad (2)$$

$$S_h = F_h^m \lambda / R_f^m \quad (3)$$

$$S_v = F_v^m \lambda / R_f^m \quad (4)$$

where b^m is the width of the model, m; R_f^m is the flexural ice strength in the experiment, MPa; λ is the geometrical scale of the model; F_h^m , F_v^m are the horizontal and vertical components of the ice load on the model, MN; C_h , C_v are the values which were called the coefficients of the horizontal and vertical loads per unit length, m; S_h , S_v are the values which were called the coefficients of the horizontal and vertical total loads, m².

The formulas (1) and (2) were only applied for the experiments in which the model moved in the ice field with slits.

The introduction of the force coefficients in accordance with the formulas (1) - (4) allows writing the expression for the ice load acting on one side of the full-scale platform in the form

$$F_h = C_h b R_f + 2D_h R_f \quad (5)$$

$$F_i = C_i b R_f + 2 D_i R_f \quad (6)$$

where F_h , F_v are the horizontal and vertical ice loads on one side of the platform, MN; b is the width of the platform front, m; R_f is the flexural ice strength, MPa; D_h , D_v are the coefficients of additional horizontal and vertical loads governed by the side effect, m².

The coefficient D_h is equal to half the difference between S_h , determined from measuring the forces when the model moved in the field without the slits and the same value when it moved in the field with slits; the coefficient of the additional vertical force D_v was determined likewise.

In the general case, all coefficients C_h , C_v , S_h , S_v , D_h , D_v , are functions of the ice thickness, the ice relative motion velocity, the angle between the structure front and motion direction, the scale of the model at whose testing these coefficients were obtained, and a number of other factors.

For further applications we calculated the values of the above-mentioned coefficients from the results of all tests with the models of different scales. The statistical analysis of these data allowed to make the following conclusions:

- the tests of the models 1 and 1A having equal scales but different widths justified the use of the suggested method for estimating the side effects and, respectively, the applicability of the formulas (5) and (6);

- the variance in the experimental data obtained during the tests of the smallest model (model 3, scale 1:100), especially in thicker ice, is so significant that it is not reasonable to use these results for further processing;

- in the experimental data the dependence of the ice load on the velocity in the studied range of velocities and parameters of the experiment was not found (at a multi-factor analysis the confidence level of the parameter governing the dependence on ice thickness differed by 3 orders of magnitude from the same value for the velocity);

- the relation of ice loads to the thickness of the acting ice is well approximated by a power function of the type ah_d^b .

Tables 2 and 3 present the values of the parameters of some of these approximation dependencies.

According to the results of testing a model of the scale of 1:50, the following regression formulas were obtained for the coefficients of the additional horizontal and vertical forces:

$$D_h = 0.333 h_d^{3.36} \quad (7)$$

$$D_1 = 0.017h_d^{1.97} \quad (8)$$

It is important to note that the regression formulas in Table 2 and 3 and (7), (8) cannot be of a universal character. They were obtained as a result of processing data of measurements conducted for a structure of specific geometry and in the considered range of the parameters.

For illustration, Fig.2 shows experimental points and the regression dependencies approximating them for the coefficients of the horizontal C_h and vertical C_v loads per unit length for the case when the normal to the model front coincides with the motion direction (line 1 of Table 2).

The coefficients of the total horizontal forces (test points and regression dependencies) are depicted in Fig.3. The upper diagram corresponds to the motion through the ice field without the slits, the lower - with the slits.

For three ice thicknesses (1.0 m, 1.5 m, and 2.0 m) the calculated coefficients of the forces are given in Table 4.

The analysis of data in Table 4 allows to make the following conclusions:

- hummocking in front of the platform model increases, on the average, the horizontal force by 17% and the vertical force by 57%; this fact can be used for recalculating the loads obtained for ice interaction with the structure without taking into account hummocking;

- with regard to the platform "Pechora" according to the model experimental data taking into account the width restriction ("side effect") gives an increase in the load of about 1%; hence, for determining the forces acting on the structure one can use the values of loads per unit length multiplying them by the front width;

- the experiment on small models gives underestimated values of the coefficients of forces, i.e. error on the dangerous side; since the coefficients obtained from testing the models of various scales considerably differ, it is recommended prior to perform additional studies to use relative values for practical calculations rather than rescale the values of forces directly by the formulas (5) and (6).

Table 2
Values of the parameters of the regression dependencies
for the coefficients of load per unit length

No	Scale of the model	Angle between the normal to the model front and the motion direction	Additional conditions of interaction with ice	Values of the parameters a and b of the regression dependencies in ah_h^b			
				C_h, m		C_v, m	
				a	b	a	b
1	1:50	0		0.212	1.16	0.047	1.08
2	1:50	15		0.155	0.82	0.045	0.81
3	1:50	30		0.164	1.83	0.040	1.39
4	1:50	0	prior to the test the ice ridge in front of the model was removed	0.199	1.03	0.046	0.26
5	1:50	0	a developed hummock in front of the model	0.223	1.03	0.046	1.39
6	1:75	0		0.151	1.47	0.044	0.84

Table 3
Values of the parameters of the regression dependencies for the coefficients of total forces (the model front is perpendicular to the motion direction)

No	Scale of the model	The presence or absence of the longitudinal slits	Values of the parameters a and b of the regression dependencies in ah_h^b			
			S_h, m^2		S_v, m^2	
			a	b	a	b
1	1:50	without the slits	0.361	1.86	0.099	1.45
2	1:50	with the slits	0.295	1.16	0.067	1.08
3	1:75	without the slits	0.125	2.73	0.020	3.39
4	1:75	with the slits	0.151	1.47	0.044	0.839

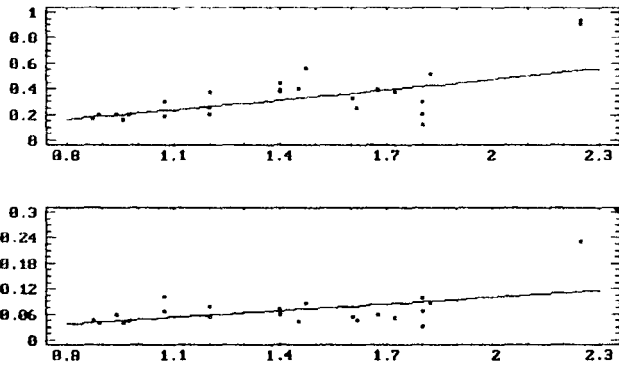


Fig. 2. Experimental points and regression dependencies for the coefficients of the horizontal C_h , m (top) and the vertical C_v , m (bottom) loads per unit length; the x-axis shows ice thickness in m. The model front is perpendicular to the motion velocity vector; model 1 (scale 1:50).

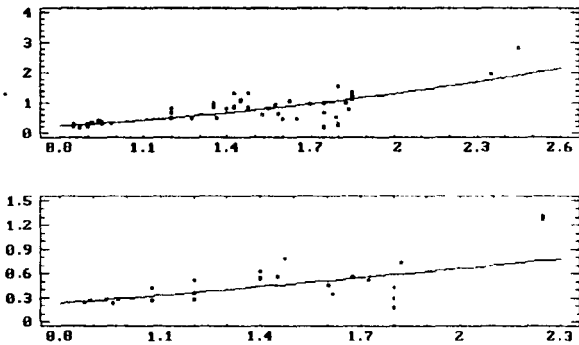


Fig. 3. Experimental points and regression dependencies for the coefficients of the horizontal total force S_h , m^2 at the motion of model 1 (scale 1:50) through the ice field without the longitudinal slits (top) and with the slits (bottom); the x-axis shows the ice thickness, m.

Table 4
The values of the coefficients of forces

No	The formula used	The coefficient value					
		of the horizontal force			of the vertical force		
		ice thickness, m					
		1.0	1.5	2.0	1.0	1.5	2.0
1	Line 1 of Table 2	0.212	0.339	0.474	0.047	0.073	0.100
2	Line 2 of Table 2	0.154	0.215	0.273	0.045	0.062	0.078
3	Line 3 of Table 2	0.163	0.343	0.580	0.040	0.071	0.106
4	Line 4 of Table 2	0.198	0.301	0.405	0.046	0.052	0.056
5	Line 5 of Table 2	0.224	0.354	0.490	0.046	0.081	0.121
6	Line 6 of Table 2	0.151	0.273	0.417	0.044	0.061	0.078
7	Line 1 of Table 3	0.360	0.776	1.309	0.099	0.179	0.273
8	Line 2 of Table 3	0.296	0.475	0.664	0.066	0.102	0.104
9	Line 3 of Table 3	0.125	0.378	0.831	0.020	0.079	0.209
10	Line 4 of Table 3	0.151	0.273	0.417	0.044	0.061	0.078
11	Formula (7) and (8)	0.032	0.146	0.323	0.017	0.039	0.067

Interaction of Ice Cover with Hydrotechnic Structures of Various Types

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Abstract

The experimental results on investigations of interaction between structures and ice sheet in case of its first twitch are presented in the paper. The following cases of piles arrangement were considered:

- in one row perpendicular to the ice sheet moving;
- in several rows parallel to the ice sheet moving.

There was taken into consideration in the experiments, that before beginning of ice pushing every pile was surrounded with solid ice sheet, but there wasn't the adfreeze bond of ice to pile. The experiments were carried out with equivalent materials and in experimental ice basin.

Nomenclature

C - cohesive strength of ice;	m - shape factor;
d - pile diameter;	n - number of piles in group;
E - elastic modulus of ice;	q - variation coefficient of R_c ;
F - total ice load;	R_c - uniaxial unconfined compressive strength;
F_1 - ice force on a single pile;	σ_y - normal stress;
F_{hh} - ice force on a separate pile;	ϵ - strain rate;
h - ice thickness;	φ - angle of inner friction;
k - aspect ratio d / h ;	τ - shear strength of ice;
l - space between piles;	μ - Poisson's ratio of ice.

Key words: Ice force. piles group, ice-structure interaction

Introduction

Ice pressure is taken into account as a main horizontal force in making design of multilegged type structures for construction in aquatory, which may be covered with ice. However, in comparison with a separate pile - ice sheet interaction, system of piles - ice sheet interaction has same peculiarities. As a rule the ice pressure on a single rigid pile is considered as a maximum one. The experiments made by several researchers (Kato and Sodhi, 1983; Misikos, 1986) show reducing of averaged ice pressure on a pile, and consequently on the whole structure, that can occur as a result of interinfluence effect. It is recorded, that this effect appears under certain geometrical arrangement of the piles and the direction the ice sheet movement (Evers and Wessels, 1986; Kawasaki et al., 1987; Saeki et al., 1978; Timko, 1986). In the experiments mentioned the drifting ice sheet pressure on a structure was investigated.

The results of the investigation experiments of multilegged type structure and ice sheet interaction in case of its twitching are reported. There were under consideration two cases of the piles arrangement:

- in one row perpendicular to the ice sheet moving;
- in several rows parallel to the ice sheet moving.

The experiments were carried out with equivalent material and in the experimental ice basin with saline model ice .

Model tests

a) Tests conditions.

There were accepted two main schemes of piles arrangement:

- 1) in one row perpendicular to ice cover moving direction, number of piles $n = 2$ and 3 ;
- 2) in one row, $n = 2$ and 3 , and in two rows, $n = 4$ and 6 , parallel to ice displacement direction.

In these experiments it was taken into account, that before ice twitch begins every pile is surrounded by solid ice sheet and there is no freezing together piles and ice sheet surfaces.

According to modeling criteria there was accepted, that the

ice sheet failure occurred by crushing while interacting with piles. So, calculations were carried out on possibility of ice buckling failures using formulas (Sodhi, 1978; Wang, 1979).

The calculations have shown there is no really ice sheet buckling failure for schemes accepted in the model tests ($d/h < 5$; $n < 3$).

b) Tests with equivalent material (EM).

Testing set consisted from three parts:

- carriage with EM;
- massive cast-iron plate, pile models were arranged at the plate;
- loading unit with dynamometer.

The pressure on models was generated by carriage moving with velocity $V = 1 - 5$ mm/s. Equivalent material consisted from sand, wax, technical oil and gum crumb, and had following characteristics:

$h = 26 - 30$ mm; $R_c = 0.17 - 0.2$ MPa; $\phi = 19 - 23^\circ$;

$C = 0.05 - 0.07$ MPa. Model diameter $d = 30$ and 60 mm.

While testing in all cases ice failure occurred by crushing. The results of the tests for first scheme are presented in Fig.1.

c) Arctic and Antarctic institute tests in ice basin.

The tests were carried out with saline model ice and had following characteristics:

$h = 26 - 36$ mm; $R_c = 30 - 38$ KPa;

The pressure on the model was generated by model displacement in ice field. Displacement velocity $V = 0.06 - 0.1$ m/s; model diameter $d = 23$; 40 ; 60 mm.

In most tests the ice sheet failure occurred by crushing while interacting with piles, but in some cases buckling failure occurred when there were small spaces between piles, and it might be explained by low values of model ice elastic modulus.

The tests on ice basin have shown qualitative similarity with analogous tests results on the testing set with equivalent material, and supplement the data of investigation.

Ice-load on the front row of piles during the first displacement

During the first displacement of the surrounding ice-sheet the highest ice-load values occur on all the piles in a row si-

multaneously. An averaged load on a pile as compared to that a separate pile may decrease due to piles interinfluence and ice heterogeneity.

The total ice-loading on a support including a pile group may be presented as a sum of load values per pile according to formula (Afanasyev, 1989):

$$F = k_1 \cdot n \cdot F_1, \quad (1)$$

where k_1 - reducing coefficient of load reduction due to ice-cover heterogeneity, it may be defined by formula [10]:

$$k_1 = \frac{1 + \alpha q n^{-0.5}}{1 + \alpha q}, \quad (2)$$

where α - the number of standard deviations of ice strength.

The results of physical analysis have shown that the pile interspace at which the piles function as separate mustn't be less than the cross-section of the crushed ice volume $a \cdot h$. If the piles arranged at a closer distance, the interinfluence effect causes loading decrease. Experiments have shown that the destruction zone caused by ice-sheet crushing against a pile may be expressed by this dependence: $b = d + 2a \cdot h$ (Fig. 2). Coefficient value a may be determined from the condition:

$$n \cdot F_{bh} \cdot k_1 = F_L, \quad (3)$$

where

$$F_{bh} = m \cdot k_b \cdot R_c \cdot d \cdot n - \text{ice-load on a separate pile [15]}, \quad (4)$$

F_L - ice-load required for the crushing of ice-sheet before the structure on section L (Fig.2); k_b - aspect ratio (Afanasyev, 1973; Assur, 1972; Bercha and Brown, 1985).

The formula expresses the beginning of pile interinfluence. We decode formula (3) taking (4) into account

$$m \cdot n \cdot k_b \cdot R_c \cdot h \cdot d \cdot k_1 = n \left(d + 2a \frac{n-1}{n} h \right) h \cdot R_c \cdot k_{b1} \cdot k_1, \quad (5)$$

or

$$m \cdot k_b = \left(1 + 2a \frac{h}{d} \frac{n-1}{n} \right) k_{b1}, \quad (6)$$

The analysis of equation (6) shows that the condition of equality is fulfilled for $d / h = 1 \div 5$ when $a = 1.0 \div 2.0$. Thus the piles will function as separate ones at a range $l_0 > 2 h$. When $l_0 = 0$, the averaged ice-pressure on a single pile will be:

$$F_1 = \frac{m k_b d n R_c h k_1}{n} = m k_b R_c h d k_1, \quad (7)$$

here $k_b = f(dn/h)$.

Linear interpolation between (4) and (7) may be used for evaluating ice-load on a pile when $0 < l < 2 a h$.

The results of experiments corroborate the dependences obtained (Fig. 1). The graph in Fig. 1 shows how the ice-load on a pile depends on piles interspace.

The ice-load may depend on number of piles n . Analysis of Fig.3 allows us to make a conclusion that n influences on $\ell(H_1)$ and thus on ice strength $R_c(\ell)$. The space between piles influences on ice strength as well (Fig.4). Usually it is ignored.

Interaction of a succession of piles and the solid ice-sheet during the twitch

This section deals with the problems, which are common for the interaction of multilegged structures located in estuaries, straits and other aquatories and twitching solid ice-sheet. Here the ice-cover twitch in question is the one which is largely stimulated by the stream and is strictly directed along the stream. Therefore structures are designed with due regard for a particular ice-movement direction.

In solving this problem it is assumed that by the time of actual twitch each pile has been encircled by the ice-sheet and both pile and ice surfafaces haven't been frozen together. To analyse the piles system - ice-cover interaction a number of tests on equivalent material have been conducted wherein a paraffin mixture with different additions was used as working media. There've also been some experiments on saline ice in an ice-model basin.

A one-row pile system

The experiments have shown that if the pile interspace is

large enough (more than critical) the ice-cover load on each pile and the type of destruction are in fact the same and correspond to the ice - separate pile interaction.

If the piles interspace is less than critical, there occurs a dislocation of ice-model between the piles (Fig.5). In this case the dislocations in question is due to breach of continuous ice cover when the ice has been cut by the foremost pile. The critical pile interspace depends on the pile diameter, thickness of ice and its solidity.

The initial scheme is an infinite plate with circular cuts on its surface. The facets of the cuts are exposed to the pressure by solid cylindrical bodies. As it's been shown by both theory and practice, further development of deformities in the material is characterized by the formation of plasticity zones and cracks accordingly. Crack-formation is not only restricted by the pressure zone but spreads out over the axial diametrical plane which is perpendicular to the plate movement and the force.

This fact allows to regard the problem at the stage of crack formation as the one of the pile model influence on the semi-infinite plate. On this problem there exists a considerable amount of both the theoretical and experimental data [4, 6, 11, 14, 19].

The ice-pressure on the front pile should be calculated according to formula (5). As to the pressure on the other piles it must be estimated with due regard for the pile interspace (Afanas'yev, 1990). During ice-shift between the piles forces on the rear pile are (Fig.5):

$$F_k = 2 F_b + F_c \quad , \quad (8)$$

where F_c - contact force along a sector width with an angle 2ψ , F_b - contact force along a sector width with an angle $\pi/2 - \psi$ expressed by (Timoshenko and Godier, 1970):

$$F_c = \frac{2 F_k}{\pi} (\psi + \sin 2\psi) \quad , \quad (9)$$

$$F_b = \frac{F_k}{\pi} (\pi/2 - \psi - \frac{1}{2} \sin 2\psi) \quad . \quad (10)$$

F_c value must be balanced by resistance to displacement of ice volume along the width of sector 2ψ :

$$F_c = 2 T_c h , \quad (11)$$

$$\text{where } T_c = C L_1 + \text{tg } \varphi \int_0^{L_1} \delta_y dL_1 ; \quad (12)$$

δ_y - normal stress along the shear plane:

$$\delta_y = \frac{2F_k \text{Sin}^2 \beta \text{Cos } \beta}{R} . \quad (13)$$

In formula (13)

$$\beta = \psi - \text{arctg} \frac{\text{Sin } \psi}{2m_1 - \text{Cos } \psi} ; \quad m_1 = \frac{L_0}{d} ;$$

$$R = \frac{d \text{Sin } \psi}{2 \cdot \text{Sin } \beta} .$$

Angle ψ (rendering the width of cut off ice volume) to be calculated may be estimated from the condition: force F_k on a pile is minimal while cutting. For easier calculations there has been drawn a graph (Fig.5), based on formulas (8) - (13), where undimension value ξ , which depends on angle φ and m_1 , noted. Thus while cutting ice load is expressed by the formula:

$$F_k = \xi \cdot h \cdot r \cdot c . \quad (14)$$

The whole loading on a pile as pile-group will be equal

$$F_s = F_{bh} + k_1 \sum_{k=1}^{n-1} F_k . \quad (15)$$

To calculate it is to take lesser loading from (1) and (15).

Two-row pile system

There are different types of interaction between multi-row pile support systems and ice at nearly stage of drifting. Experiments have shown that a multilegged structure may interact with ice-cover as a single massive support when the piles are arranged in rows and between rows, the pile interspace being close enough.

The compression caused by the first displacement is followed by the destruction of ice-cover before front piles. The interac-

tion of ice-cover and external lateral surfaces of piles causes a partial "cut-off" along the plarves of the former. There also occurs a "tearing off" of ice extreme pile interspace in adjacent rows. The inner space between piles may be filled with what ice remains undestroyed (Fig. 6). The actual ice-loading values are also presented in this scheme. At a larger interspace piles will interact with ice-cover as separate ones.

The dependences obtained previously allow to calculate the ice-loads on a multi-row system of piles.

Summary

Many problems of the ice - structure system can only be solved using different methods of physical modelling. The most widespread method is investigation in ice-model basins.

However certain cases of the system interaction can be investigated preliminarily on relatively simple devices using composite materials which possess certain given ice properties. It's in this way that investigations have been carried out for multi-pile structures - solid ice-cover interaction while first displacement.

Primarily the experiments were carried out on a testing set with a composite material, the latter consisted of a paraffin mixture with different additions. Another series of experiments was carried out in ice-model basin.

The results of preliminary experiments allow to draw the following conclusions:

- the pile interspace can influence for a particular type of ice-destruction and ice-load value;
- when the pile interspace and space between rows of piles are small, monolithic ice volume can be retained between the piles after the ice sheet displacement. In this case the structure stiffness increases whereas ice-load values can decrease.

The experiments in an ice-model basin have corroborated the results of preliminary investigations. It has also been shown that during ice-displacement all the piles of a structure are in fact exposed to extreme force simultaneously. Thus the global ice-load on a piles system caused by ice-displacement is considerably greater than the one caused by drifting ice-cover.

REFERENCES

1. Afanasyev V.P. 1973. Ice Pressure on Vertical Structures. National Research Council of Canada, Technical Trans., 1708.
2. Afanasyev V.P. 1989. The Forces on Front Row of Piles from Ice Sheet Displacement. Proc. Conf. on Problem Hydrotechnical Structures, "Energoatomizdat", pp. 199-201 (in Russia).
3. Afanasyev V.P. 1990. Ice Forces on Multipiled Structures. J. Transportnoe Stroitelstvo, No 5, pp. 28-29.
4. Assur A. 1972. Structures in Ice Infested Waters. Proc. IAHR Ice Symp. Vol. 1, Leningrad, pp. 93-97.
5. Bercha F.G. and Brown T.G. 1985. Scale Effect in Structure Interactions, Proc. Int. OMAE Symp., Vol. 2, Dallas, pp. 310-314.
6. Croasdale K.R. 1989. Ice Forces Current Practices. The Northern Engineer, Vol. 21, No 3, pp. 22-40.
7. Evers K.I. and Wessels E. 1986. Model Test Study of Level Ice Forces on Cylindrical Multilegged Structures. Proc. Polartech-86, Vol. 3, pp. 251-275.
8. Kato K. and Sodhi D.S. 1983. Ice Action on Two Cylindrical Structures. Proc. OTC, Vol. 1, pp. 159-166.
9. Kawasaki T. et al. 1987. Study of Ice Forces for Offshore Structures. Mitsubishi Bul. No 174, pp. 1-26.
10. Kopaigorodsky E.M., Uporov A.V. and Vardanjan S.S. 1984. Horizontal Loads on a System of Columns Induced by Sea Ice Fields. Proc. Conf. on Problem Hydrotechnical Structures, "Energoatomizdat", pp. 189-192 (in Russia).
11. Korzhavin K.N. 1971. Action of ice on Engineering Structures. CRREL Draft Translation, No 260.
12. Mizikos J.P. 1986. Ice Design of Multi-legged Structures. Proc. Polartech-86, ESPOO, Vol. 2, pp. 735-748.
13. Saeki H., Ono I., Ozaki A., Abe Sh. 1978. Estimation of Sea Ice Forces on Pile Structures. Proc. IAHR Ice Symp., Vol. 1, pp. 465-478.
14. Schwarz J., Hirayama K., Wu H.C. 1974. Effect of Ice Thickness of Ice Forces. Proc. OTC, pp. 145-156.
15. SNIP 2.06.04-86 Construction Standards and Rules Loads Exerted on Hydraulic Structures by Waves, Ice and Ships.

16. Sodhi D.S. 1979, Buckling Analysis of Wedgeshaped floating Ice Sheets. Proc. POAC-79, Trondheim, V.1, pp. 797-810.
17. Timko G.M. 1986. Ice Forces on Multi-Legged Structures. Proc. IAHR ice symposium-86. Iowa, City, V. 2, pp. 321-337.
18. Timoshenko S.P., and Goodier S.N. 1970. Theory of Elasticity. McGraw-Hill.
19. Tunik A.L. 1988. Design Ice Forces on Offshore Installations. Proc. OMAE-88, Heeuston, Texas, pp. 159-163.
20. Wang Y.S. 1978. Buckling of a Half Ice Sheet Against a Cylinder, J. of the Eng. Mech. Div., EMS, pp. 1131-1145.

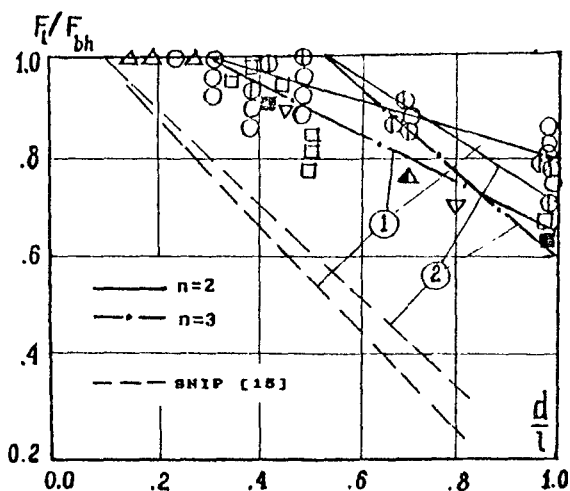


Fig.1. Influence of space between piles on normalized ice load.

① ② - according to method presented for $d/h = 1$ and 2 .

Tests with EM: ○; ⊙ - $d/h = 1.0$ and 2.5 ($n = 2$).

Tests in ice basin: ▽ - $d/h = 1.4$ ($n = 2$);

△; ▲ - $d/h = 0.9$ and 1.4 ($n = 3$).

Saeki et al. tests[13]: □; ■ - $d/h = 1$ and 2 ($n = 3$).

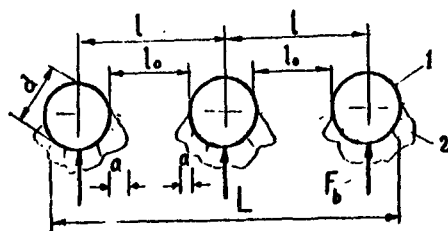


Fig.2. Calculation scheme for determining of ice load on piles.

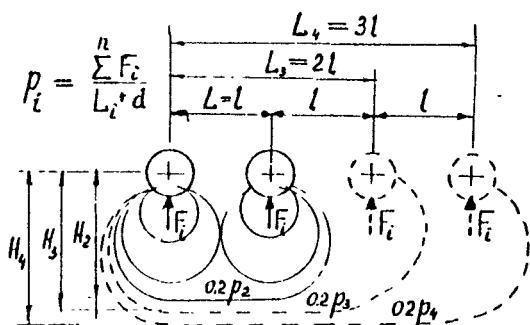


Fig.3. Influence of pile quantity on $\dot{\epsilon}$ (strain ratio).

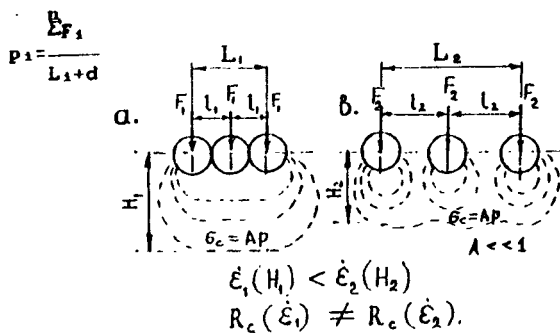


Fig.4. Influence of pile space on $\dot{\epsilon}$.

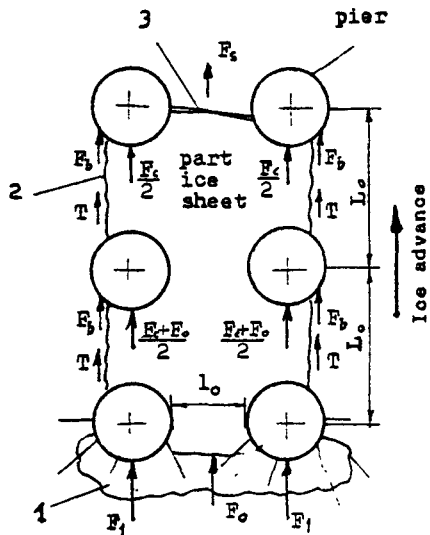


Fig. 5. Interaction scheme of ice sheet and piles in two rows.

- 1 - crushed ice zone;
- 2 - shear plane;
- 3 - cracks of the gap;
- 4 - monolithic ice massif.

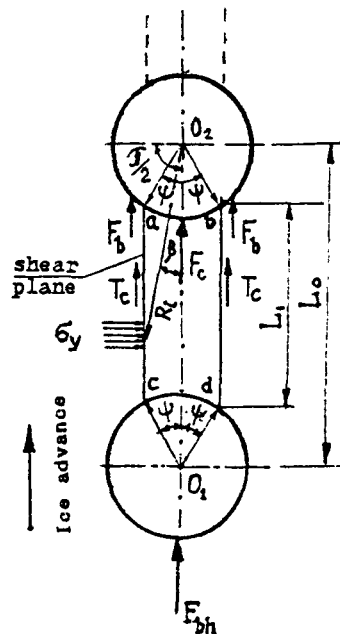


Fig. 6. Calculation scheme for determining of ice load on piles in one row:

INTERNAL STRUCTURE OF ICE PRESSURE RIDGES IN THE SEA OF OKHOTSK

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The most serious problem when designing offshore oil and gas producing structures is that of hummock impact on such structures. Design parameters are selected based on the results of field studies aimed at obtaining morphology and strength characteristics for ice features.

Several models for hummocks exist, however, the model consisting of sail, consolidated part and keel (partially consolidated part) is more frequently used in the engineering practice over the last years.

The difficulty in applying the assumed model is attributed to the lack of reliable data on porosity of ice in a hummock and thickness of a consolidated part of a hummock.

Porosity is defined as a ratio of pore volume (voids between ice fragments) to total volume of a hummock. All the available porosity values "are based on qualitative evaluation of visual observations and subjective logical conclusions". In this connection, hummock porosity estimated by several authors, varies in a wide range: from 70-50% (N.N.Zubov) to 20% (A.A.Kirillov) for sails and from 70-50% (N.N.Zubov) to 20 % (A.V.Bushuev, N.A.Volkov, V.S.Loschilov) for keels (1).

The problem of distinguishing consolidated part of a hummock is relatively new and poorly investigated. The most investigated hummocks are those in the Beaufort Sea, thickness of consolidated part of hummocks being in the range of 2.4 to 5.0 m (2, 3).

Sakhalin Oil and Gas Institute (SakhalinNIPImorneft) has been involved for several years in studies of hummocks and grounded hummocks (stamukhas) in the Sea of Okhotsk. These studies apply thermal drilling and are aimed at obtaining data on geometry and internal structure of ice features. The quoted method for studies was also approved in other regions.

Ice features investigated in the Sea of Okhotsk comprise hummocks and stamukhas on fast-ice edge in three regions: Odoptu oil and gas field, Sakhalin Bay and Northern Bay.

Bore holes on ice features were located essentially along longitudinal and lateral profiles. Records of drilling practices were kept, relative ice strength was determined, encountered voids and alternation of layers of various densities were registered during drilling. Special attention was paid to defining thickness of consolidated parts of hummocks.

Drilling showed that hummocks and stamukhas are composed of ice fragments, which are characterized by various configurations and thicknesses and are laid with various degrees of compaction. Basically, the layers of the following

fractions were distinguished: 1 - small ice cake and shuga, 2 - large voids, 3 - ice fragments with small voids, 4 - poorly consolidated (loose) ice, 5 - consolidated ice. For the most part, ice features were composed of loose and compact ice layers.

Data obtained during drilling of each well were used to determine porosity and thickness of consolidated layers.

Water-filled voids and shuge were considered as pores, while compact and loose ice as solid part in order to estimate porosity. Consolidated part included first compact ice block below water level without large voids. Ice portion above consolidated part was considered as sail and below consolidated part as keel.

In general, hummocks in the Sea of Okhotsk consist of three parts. Upper part is above consolidated ice and is essentially represented by young ice; average porosity being 26-43 %. Consolidated part is basically composed of blocks of fast ice and rafted ice with a thickness from 0.5 to 8.5 m. Average porosity of consolidated part is 2.9 m for Odoptu, 4.1 m for Sakhalin Bay and 1.4 m for Northern Bay. Lower part is composed of blocks and fragments of young and first-year ice, which are not interfrozen; average porosity being 15-28%. Figs.1 and 2 give porosity distribution for sails and keels of hummocks. Fig.3 gives thickness distribution for a consolidated part of hummock.

Total porosity for hummocks and stamukhas in the Sea of Okhotsk in the regions under consideration varies from 5 to 24%.

The studies resulted in obtaining the relation of a consolidated part of a hummock to the total porosity of a hummock (Fig.4). The analysis of such relationship suggests that thickness of a consolidated part decreases with the increase of total porosity of a hummock. Hummocks with porosity in excess of 35% may lack consolidated part. However, thickness of compact rafted ice may reach 5.5 m. These are tentative suggestions, which need further substantiation by field studies.

The above-mentioned results suggest the necessity for careful investigation of morphology of hummocks and rafted ice for reliable selecting a hummock or a hummocking ridge (depending on the direction of impact) to be used in design, based on up-to-date technical means and assistance of companies having such means at their disposal.

Summarized experience gained in the studies and presented in this paper suggests that minimum series of observations should be at least 5 years prior to the beginning of the actual designing of facilities for each specific oil and gas field.

REFERENCES:

1. Grischenko V.D. "Morphometric characteristics for hummock ridges in the Arctic basin"- AANII Proc., 1988, 401, pp 46-55.
2. Vaudrey K.D. Characterization of offshore and Coastal Ice conditions. Design for Ice forces, State of practice report. "ASCE", New York, 1983, 3-16.
3. Mc Gonigal D., Wright B.D. First-year pressure ridges in the Beaufort sea. Proc."Intermaritec", 1982, 82, 444 - 459.

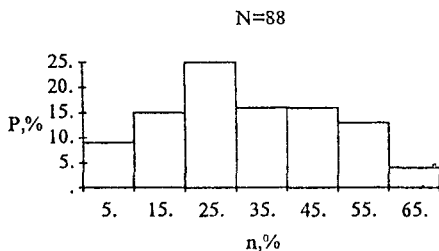


Fig. 1 Porosity distribution for hummock sails.

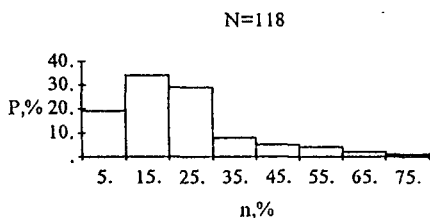


Fig. 2 Porosity distribution for hummock keels.

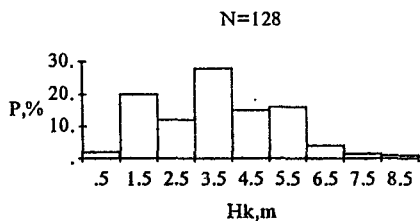


Fig. 3 Thickness distribution for consolidated parts of hummock.

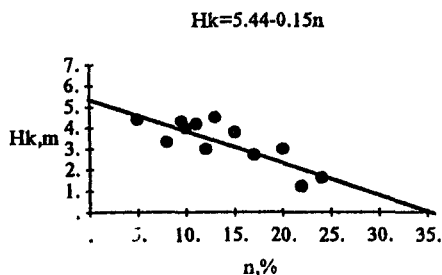


Fig. 4 Consolidated part thickness vs. hummock porosity.

LONG-TERM PROBABILITY DISTRIBUTIONS OF ICE LOADS ON A TERMINAL FOR ARCTIC OFFSHORE

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ABSTRACT

Surface oil terminals as a part of the Arctic submarine transport system are considered. Results of the study of ice action on the terminals of two types (conic and with cylindrical pier) are presented. The study includes both theoretical and model experimental investigations. Stochastic character of maximum ice loads values caused by random environmental conditions variation is taken into account. It provides an opportunity to evaluate design ice loads on an offshore structure by direct making allow for a safety factor.

1. Introduction

The conception of a submarine transport system was formulated as a solution of the problem of all-the-year-round supply of settlements at the Russian coast of the Arctic Ocean with oil products. In accordance with this conception cargo delivery is carried out by submarine tankers which get unloaded at a number of coastal reloading complexes - underwater and/or surface oil terminals.

Ice action is an important factor that influences on choice of the architectural type and design features of the surface terminal for the Arctic shelf. That is why study of ice resistance ability of various terminal types was developed at the Arctic and Antarctic Research Institute according to a contract with the "Malahit" Design Bureau. The main goal of this work was determination of the design ice loads. Brief description of the study results is presented in this paper.

The terminals of two types were considered. One of them (Variant 1) has the shape of a truncated cone; its broader base is laying on the seabed or on a special foundation. The main shape characteristics of this type of the terminal are as follows.

Variant 1 a:

diameter of the lower base D , m 37.1;
diameter of the upper base d , m 10.0;
diameter at the waterline b , m 20.0;
height (distance between the upper and the lower bases) H , m 22.0;
height of the submerged part (distance from the bottom up to the waterline) T , m 15.0;

angle of slope (to the vertical) β , deg. 35.5.

Variant 1 b:

diameter of the lower base D , m 57.1;

diameter at the waterline b , m 40.0;

height of the submerged part (distance from the bottom up to the waterline) T , m 15.0;

angle of slope (to the vertical) β , deg. 35.5

The second type of the terminal (Variant 2) has an upper superstructure which is mounted on a cylindrical pier; its diameter is equal to 25 m. Only these pier interacts with the ice directly.

Approach developed by us for solution of this problem is rather universal and may be used for estimation of the ice loads on the terminals which are installed in various regions. At this stage numerical results were obtained for the region of the Petshorskaya Guba.

2. Principles of the suggested approach

Determination of the ice loads on offshore structures is the aim of a large body of researches and publications on this subject are quite voluminous. However, it is unlikely to expect complete solution of this problem in the nearest future because of objective complexity of the ice/structure interaction processes.

Our approach is based on the following main principles.

At first, stochastic character of seasonal and inter-annual variability of environmental and especially ice conditions generates a need of consideration of the design (maximum) ice loads in the context of the probability theory. Ice loads probability distribution laws for a calculation period (for example for expected period of exploitation) should appear as investigation results. It allows a designer to obtain the loads of a given probability of exceeding. This probability is fixed in accordance with requirements of construction reliability. We used stochastic simulation method for these distribution laws determination; the stochastic simulation, in its turn, was based on deterministic solution of the ice loads assessment problem.

The second principle is to the effect that the deterministic relationships for the loads are founded on comparison of experimental and theoretical studies results; the theoretical study includes use of semi-empirical formulas and finite element numerical solution of the problem.

Thirdly, models of various scales are tested for estimation experiment errors caused by "scale effect". Differences of loads which are calculated for the full-scale construction from tests with models of different scales characterise the value of this error.

3. Theoretical studies

The semi-empirical formulas from the Regulations (see Reference) and numerical finite element procedure developed in co-operation with A.Ye.Babskiy (Technical University of St.Petersburg, Russia) were used for theoretical solution of the problem.

The numerical procedure of a first step approximation for ice loads on the conic terminal evaluation was based on the following assumptions.

1. The ice was considered to be isotropic material with piece-wise linear relationship between stress and strains:

$$\sigma = \begin{cases} E\varepsilon, & \text{for } \sigma < \sigma_T \\ E_1, & \text{for } \sigma \geq \sigma_T \end{cases}$$

where σ, ε are the stress and the strain in the ice; σ_T is the yield limit of the ice; E is the modulus of elasticity (small strains interval); E_1 is so called tangential modulus (large strains interval); $E_1 \ll E$.

2. The following relationships were implemented for the ice and the terminal surface contact zone:

$$\begin{aligned} \delta \geq 0, \sigma_n \leq 0, \sigma_t &= 0; \\ \sigma_n &= 0 \text{ for } \delta > 0; \\ \sigma_n < 0 \text{ for } \delta &= 0, \end{aligned}$$

where δ is a gap between the ice and the cone; σ_n is normal to the terminal surface stresses; σ_t is tangential to the terminal surface stresses.

3. Action of buoyancy force on the ice sheet from water was simulated by springs. Reaction of these springs was assumed to be proportional to vertical displacement of ice cover points.

4. Step-by-step loading method was used for solution of the physically non-linear problem.

5. Principle of motion inversion was employed i.e. it was supposed that the construction moved through the ice; the terminal was assumed to be secured from all displacements with the exception of the horizontal one.

Calculations using this model with taking into account one-way ties without friction and plastic ice model for the Variant 1 (conic) terminal showed us that the interaction took place along relatively small spot in the region of the axis of symmetry near the lower ice sheet edge (the spot was about one third of the maximum contact area corresponding to complete envelopment of the cone by the ice along its perimeter). Tensile stress zones were observed in the upper part of the ice sheet and zone of compression in its lower part. This stress distribution is inconsistent with behaviour that is observed in real conditions and in experiments in which ice bending goes on in the reverse direction.

It may be explained by impossibility in the framework of the used computer system to simulate brittle fracture and geometrically non-linear problem if shape of boundary surfaces changes for each step of loading and the increasing load is applied to the deformed ice cover. Considerable increase of the displacements should result from the global ice fracture practically without force increase. However, the plastic model that was realised in the computer program gives smooth relationships between the displacement and load. That is why it is impossible to give reliable estimation of the maximum forces under this approach.

In connection with the ideas mentioned above the problem solution was obtained as the second approximation which was based on the following principles.

1. The ice fractures in the immediate region of the cone in a brittle way. Thin brash-like layer appears in the result of this process. This layer transmits uniformly the load from the cone along all the contact surface.

2. Total pressure on the cone at the first step is determined by means of linear problem solution for a unit load uniformly distributed over the cone contact surface. Von Mises stresses σ_m in elements are calculated as follows.

$$\sigma_m = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2},$$

where $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses.

Because of the linear problem is solved and the load is the unit one, at the first step it is possible to formulate the following relationship for load p calculation $p = I \times R_f / \sigma_m^{\max}$, where p is load that corresponds to appearance of crack propagation zones; R_f - bending strength of the ice; σ_m^{\max} is maximum Von Mises stress. This load is used at the second step of the calculation. The second step algorithm is as follows.

1. The maximum stresses and the elements where stresses are in the range $[0.95\sigma_m^{\max}, \sigma_m^{\max}]$, are determined. All these elements are assumed to be destroyed.

2. Initial data for the next task are prepared: exclusion of the destroyed elements is achieved by decreasing of strain modules in these elements by 50 times.

3. The linear problem is solved with new characteristics.

4. The stresses are analysed and searching for the new destroyed elements is developed.

5. If such elements are not found than the load is increased by 10%.

6. If ice cover rigid fragments appear than the load is assumed to be of maximum value.

Beginning of the ice fracture in accordance with the described algorithm of calculations goes on with crack formation. Two types of cracks are formed: the radial crack propagating along the axis of symmetry and the circumferential one. This result is in a good agreement with observations in real conditions. Calculated deformed surface of the ice cover is presented in Fig.1 as an example of interaction with the conic terminal analysis (the state preceding the cracks formation is shown).

The similar calculations were carried out for the case of cylindrical construction. It should be mentioned that in this case there is no fracture of the ice sheet by bending and influence of buoyancy forces is very small.

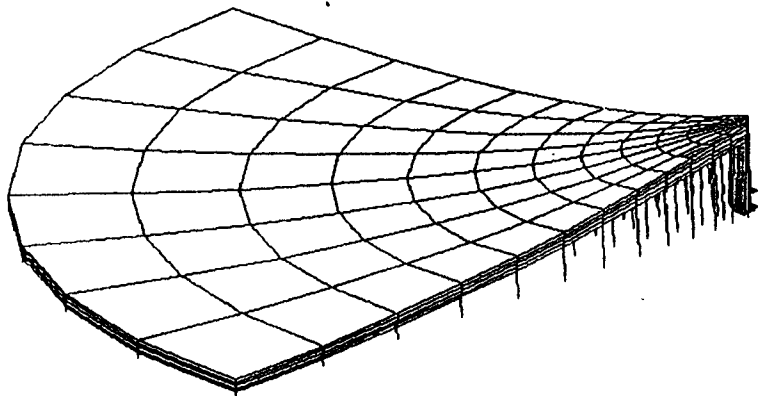


Figure 1. Calculated deformed surface of the ice cover under interaction with the conic terminal.

4. Model experiments

Impossibility of providing exact similarity of processes in real conditions and in modelling causes appearance of errors which are in general connected with the "scale effect" evidence. As it is impossible to estimate good enough magnitude of these errors we carried out a set of experiments with models of various scales for determination of "scale effect" influence for estimation of ice loads on the conic terminal. Three models were made: the M1 model (scale 1:75), the M2 model (scale 1:100), and M3 model (scale 1:125). Their sizes are given in the Table.

Table
Geometric characteristics of the full-scale terminal and the models.

Characteristic	Full-Scale (sizes in meters)	Models (sizes in millimetres)		
		M1	M2	M3
Diameter of the lower base	37.1	495	371	279
Diameter of the upper base	10.0	133	100	80
Diameter at the waterline	20.0	267	200	160
Total height of the conic part	19.0	253	190	152
Height of the above water part	7.0	93	70	56

The experiments were carried out in main ice tank of the Arctic and Antarctic Research Institute. Models were mounted under standard carriage. The carriage can move on rails located on the tank boards along the tank working length. A stopper was installed on a rail and the carriage was connected with it through a hydrocylinder. Hydrocylinder oil supply rate was varied by means of a set of diaphragms with holes of various diameters. The models were fixed under the carriage with a help of L-looking measuring beam. Signals from tensometers that were pasted on this beam were registered on a band of a recorder. Method of model fastening and placing of the tensometers were chosen in such a way that measured strains of L-beam elements were proportional to values of vertical and horizontal components of force acting on the model.

The experiments were processed in the following succession. Ice of required thickness was frozen in the tank and the model was mounted. The hydrocylinder rod was push out at maximum length (0.5 m). The stopper fixed and oil started to feed the hydrocylinder. During the rod pulling in the carriage moved translationally together with

the model with a low constant speed. Speed value depended on the diaphragm hole diameter. Because of not only the geometric scale influence on ice loads but also the temporal scale influence were of practical interest, the tests were carried out over a wide range of interaction velocities. The modelled ice thickness was varied from 14 mm up to 26 mm that corresponded to the thickness of the real ice from 1.0 m up to 3.3 m. The ice thickness, coefficient of dynamic friction, and bending ice strength were measured during the experiments in addition to the vertical and horizontal components of the acting force. The bending strength was estimated by floating ice consoles loading.

Photographing and video recording were made during the experiments as well.

5. Comparison of the loads determined theoretically and experimentally.

Calculation of the loads on the conic terminal with the diameter of 20 m at the waterline (Variant 1a) and on the terminal with the cylindrical pier 25 m in the diameter (Variant 2) were carried out using the semi-empirical formulas (see Reference) and with a help of the above mentioned procedure based on the finite element method for a set of initial parameters values:

ice thickness h_d , m: 0.5; 1.0; 2.0; 3.0;

ice compressive strength R_c , MPa: 0.25; 0.50; 1.00;

ice bending strength R_f , MPa: 0.25; 0.50.

Calculation results are presented in Fig.2 and Fig.3. As illustrated in these Figures the semi-empirical formulas give greater forces than the finite element method practically for all thickness and ice strength values.

The horizontal F_x and vertical F_y forces were transformed into dimensionless form (variables K_x and K_y respectively) for comparison of theoretical and experimental data:

$$K_x = F_x / (R_f h_d^2) ;$$

$$K_y = F_y / (R_f h_d^2) .$$

The dimensionless total force was calculated as follows

$$K = \sqrt{K_x^2 + K_y^2} .$$

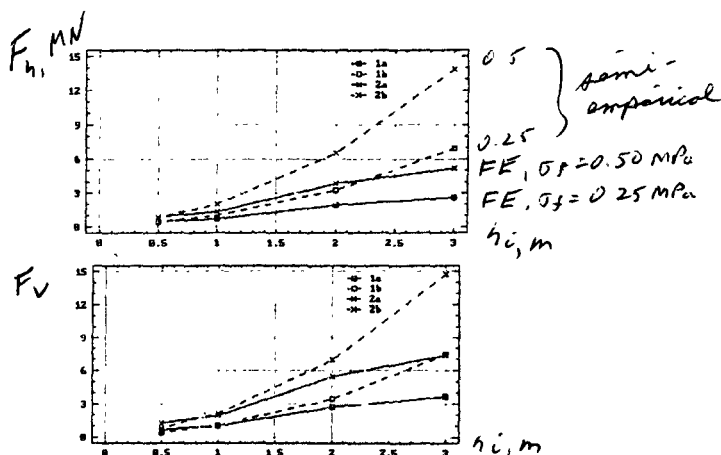


Figure 2. Horizontal (top) and vertical (bottom) loads on the conic terminal with 20 m diameter at the waterline, x-axis- ice thickness in meters, y-axis- force in MN.

1a, 2a - the finite element method; ice strength R_i is equal to 0.25 and 0.50 MPa respectively;

1b, 2b - the semi-empirical formula; ice strength R_i is equal to 0.25 and 0.50 MPa respectively.

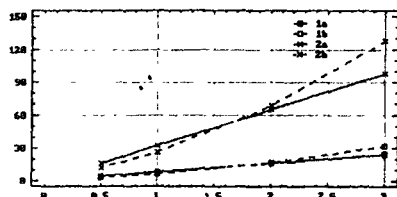


Figure 3. Horizontal load on the terminal with the cylindrical pier 25 m in diameter. x-axis- ice thickness in meters, y-axis- force in MN.

1a, 2a - the finite element method; ice strength R_i is equal to 0.25 and 0.50 MPa respectively;

1b, 2b - the semi-empirical formula; ice strength R_i is equal to 0.25 and 0.50 MPa respectively.

Experimental smoothed plots of the dimensionless horizontal and vertical forces versus full-scale ice thickness and velocity are given as an example in Fig.4 and Fig.5. Actual three scales models tests data are marked out as squares.

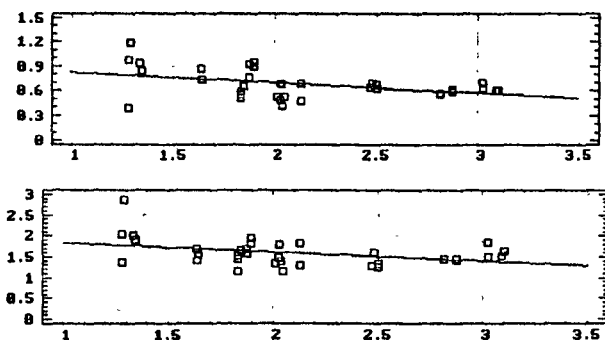


Figure 4. Experimental plot: dimensionless horizontal K_x (top) and vertical K_y (bottom) forces versus full-scale ice thickness (thickness varies along the x-axis in meters).

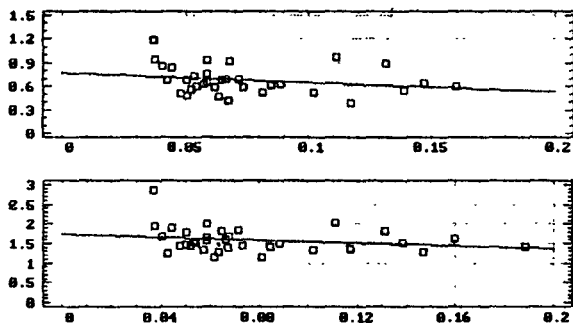


Figure 5. Experimental plot: dimensionless horizontal K_x (top) and vertical K_y (bottom) forces versus full-scale ice drift velocity (the velocity varies along the x-axis in m/sec)

For further applications regression formulas for the dimensionless horizontal, vertical, and total forces in dependence on ice thickness and ice drift velocity were deduced from each of three scales models tests measurements separately. Analysis of obtained results allowed us to make the following conclusions.

1. Values of the dimensionless forces obtained during the experiments with the models of different scales varied in some cases by a factor of three and more.
2. The experiment allows to obtain correct qualitative relationship for parameters under consideration.

7. At present the fulfilled set of tests does not allow us to carry out justified extrapolation though it gives an opportunity to estimate value of the scale effect (see Fig.6).

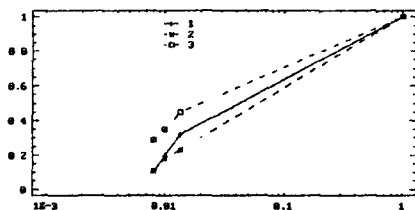


Figure 6. Estimation of the scale effect value. Logarithm of the model scale varies along the x-axis; ratio of total dimensionless force K , determined during model experiments, to the same variable obtained using the semi-empirical formulas varies along the y-axis.

Note: actual values at each of the curves correspond to the left three points; straight line between the third and the fourth (extremely right) points is an extrapolation.

6. Evaluation of the ice loads probability distributions on the base of stochastic simulation

In order to estimate statistic characteristics of the ice loads on the terminal we used computer stochastic simulation method, algorithm of which may be schematically represented as follows.

Step 1. Information on ice conditions in a region of planned terminal installation is processed statistically. Probability distribution laws and regression equations are determined for all those parameters of the ice cover which determine the ice loads value.

Step 2. Process of the construction exploitation is simulated on a computer. Specific ice conditions are simulated by means of pseudorandom number generators according to the laws revealed during the first step. The ice loads are calculated for each variant of the ice conditions with a help of the deterministic procedure. The semi-empirical formulas (see References) were used because they gave error on the safe side in comparison with the finite elements method.

Step 3. Samples obtained as a result of the second step is processed statistically. It gives final estimation of the long-term ice loads probability distributions.

Statistic analysis of data of multiyear observations at the Khodovarykha and Varandey polar stations allowed us to make a conclusion that the maximum ice thickness distributions in this region were good fitted by the normal distribution law and found out the parameters of these laws. April was taken as calculation (the heaviest) month because values of products $R_d h_d$ and $R_d h_d^2$ reached their maximum just in this month. Values of the ice loads on the cylindrical pier and on the conic terminal are proportional to these products according to the semi-empirical formulas.

Histograms of the distributions of the annual maximum ice loads on the conic terminals and on the cylindrical piers are given in Fig.7 and Fig.8. Normal probability densities are also shown in these Figures. Knowledge of parameters of these distribution laws allows us to obtain values of the design external forces if probability of exceeding is specified. For example, the annual maximum horizontal load on the conic terminal (Variant 1a) equals 5.26 MN for the probability of exceeding 10^{-6} . Probability of the event that the real maximum load will be greater than this value during 25 years of exploitation is equal to $1-(1-10^{-6})^{25}=2.5 \times 10^{-5}$.

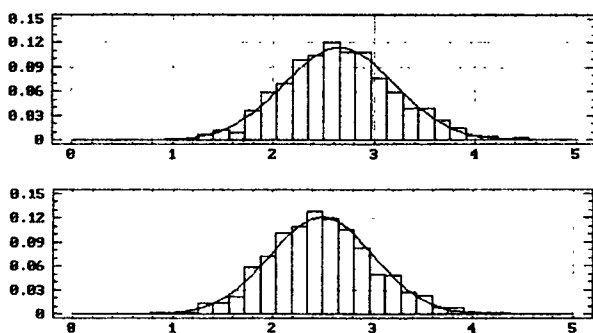


Figure 7. Histograms and there normal probability densities approximations for the horizontal (top) and vertical (bottom) loads on the conic terminal 20 m in diameter at the waterline due to ice drift.

x-axis - force, MN; y-axis - frequency (probability).

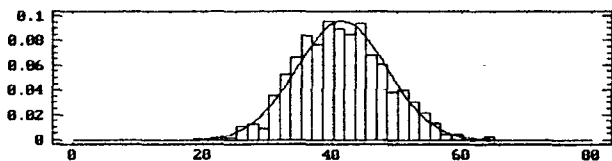


Figure 8. Histogram and its normal probability density approximation for horizontal loads on the terminal with the cylindrical pier 25 m in diameter due to ice drift.
 x-axis - force, MN; y-axis - frequency (probability).

Reference.

VSN 41.88. Design of ice-resistant stationary platforms. Minnefteprom of the USSR, M. 1988. 136 p. (in Russian).

RELIABILITY ESTIMATE OF ICE BELT CONSTRUCTION OF ICE CLASS SHIP AND ICE-RESISTING STRUCTURES

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Introduction.

Probability of un failing work of structure according to chosen criterion of failure for specified period of time is understood in proposed report as a term safety. Notion safety with reference to ship construction or structures, which resist to ice action, has not been actively used in technical calculations. The main reasons of this circumstance were the following: variety of strength criteria of the construction failure and insufficient knowledge of ice load statistical parameters. The main amount of repair works on ice class ships and icebreakers falls on hull maintenance. Reduction of this amount of the hull construction repair will increase profitableness of sea transport operations. On the other hand, decrease of damage level is obtained at the expense of reduction of ship's velocity in presence of ice and this deceleration adversely affects on the profitableness of the transport operations. Quest of ranges of the optimal velocities of transport ships in high latitudes and in freezing non-Arctic seas causes problem of calculation of ice damages of the ice belt construction. Exploitation of oil and gas deposits on the Russian Arctic shelf with a help of stationary and floating technique necessitates estimate of ecological and economic investigations of different possible accidents and calculation of appearance probability of these accidents in ice conditions. Damages and failures of the hull constructions causing oil spills are the most dangerous type of the accidents. The problem of forecasting of the ice belt construction reliability appears again for making of optimal designing decisions and for determination of justified insurance payment during exploitation of the shelf technique. Method of the safety estimate of the ship ice belt and structures elaborated in AARI is brought to notice in this report. This method is illustrated by several examples.

Reliability Estimate Method.

The applied procedure of the safety estimate supposes fulfilment of a sequence of steps, which are independent and labour consuming. This work is carried out in the following order:

1. Collection and processing of information on the ice conditions in supposed regions of navigation or mounting of the shelf structures. Processing of this information is a method of obtaining of probabilistic distribution laws of ice cover characteristics, which determine ice loads. Two models of loading and their modification are used in subsequent investigations: model of ice sheet action on inclined board taking into account interaction of ice crack edges (Kurdyumov, 1987)

and hydrodynamic model of ice sheet impact on solid body (Kurdyumov and Kheisin, 1976). The following ice cover characteristics are included in direct or indirect way in these models: ice thickness, bearing strength of ice, bending strength of ice, dynamic ice strength, ice floe probability, probability of small floes and ice cake, drift velocities of medium floes, drift velocities of small floes and ice cake, ice density. Distribution laws of these characteristics should be determined. All these variables are considered to be random. Some ice characteristics in hydrological data are given in a form of interval of values, therefore in these cases these variables are supposed to be uniformly distributed in a given interval, and it increases variation of desired results. The ice strength characteristics in absence of reliable data were calculated as functions of water salinity and air temperature. The ice floe drift velocity is calculated as a function of wind speed, which is uniformly distributed in the indicated interval of values.

2. Simulation of ice load parameters is carried out using the results of the first stage for the purpose of determination of the probabilistic distribution laws of these parameters. It is necessary for that purpose to have reliable models of ice loading of metal structures. The two above mentioned approved models were used in Russian practice to the present day. These models were also used in the submitted calculations. Number of the load parameters can vary from 1 up to n , where n is a finite value.

3. Construction of surface of strength state using the load parameters as coordinates. The surface of state is an ensemble of points matching to such a combination of the ice load parameters, when the construction failure happens. Choice of the strength criterion of the failure is a separate problem. Two such criteria are used in world shipbuilding practice for the ice belt constructions: criterion of fibre yield and ultimate strength criterion. Use of the first criterion in designing causes additional increase of weight of the ice belt on the one hand and on the other hand analysis of damages of the ice belt structures brings out vast regions of material transformation in plastic state. The ultimate strength criterion has received wide acceptance due to simplicity of its application and its accounting for plastic features of material. But rigid-plastic or ideal elastic-plastic diagram of material deformation used in the theory of limit equilibrium describes the real stress-strain diagram of up-to-date compression not thoroughly enough, because these compression have very small yield area or do not have it at all. The main troubles during exploitation of the shelf structure can be connected with the ice belt failure and loss of its impenetrability. This problem necessitates the safety estimate according to additional criterion - the structure failure criterion. Investigations reveal, that damages of ice belt continuity are also common for ships operating in presence of ice (Alekseyev, 1987). The deformation criterion of steel failure can be chosen for

simplicity, but it is necessary to take into account accumulation of the damages during exploitation and stress relaxation in the construction at a later time.

4. Data collected during the previous stages allow us to calculate probability of the construction failure according to the chosen criterion for a wanted period of time. This period equals one year for action of the ice load, because one year is a cycle of ice condition variations.

5. Calculation of the construction failure probability for the assumed time interval of the exploitation and of the construction safety for this period.

The above mentioned stages were used for the reliability estimate of outside plating of the ship ice belt of the ice class ship, of sheet panels of the ice belt of the ice-resisting stationary platform and of the ice belt grillage of this platform.

Reliability of the Ice Belt Plating of the Ice Class Ships.

Calculation of the outside plating safety were fulfilled for the ship of the "Pavlin Vinogradov" type, the UL ice class, LBP=122 m, BWL=18.7 m, D=11260 t, DW=7000 t. It was supposed, that the ship operated in the south-eastern region of the Kara Sea in winter period and in the north of the Chukcki Sea in summer period. It is exploited just after construction, so hull wear is not taken into account. Thickness of the outer plating of the ice belt equals 20 and 15 mm, frame-spacing equals 360 and 350 mm, yield strength of material - 560 and 300 Mpa, respectively. The first values are given for bow region, the second ones - for the region between the bow and cylindrical mounting. The estimate was determined for three values of ship velocity. Ice load simulation was carried out for one constructive waterline. Two load parameters are significant for analysis of plate stress state: ice compression p and height of load distribution b . Formulation of the distribution laws of the ice load parameters (two first steps of this method) was carried out with a help of universal Γ - distribution. Examples of these calculation are given in Figures 1-4 for the third theoretical cross-section for different ship velocities in presence of ice. The second step - determination of curves of plate state in the co-ordinates p and b , was fulfilled for two conventional failure criteria: the fibre yield and the ultimate strength. Probability of the plate failure Q is then calculated using the following algorithm:

$$Q = \sum_{i=1}^n Q_i$$

where Q_i are partial cumulative probabilities

$$Q_i = P(p > p_i) P(b_i < b < b_{i+1}) = P(p > p_i) [P(b > b_i) - P(b > b_{i+1})] \quad i=1, \dots, n-1$$

$$Q_n = P(p > p_n) P(b > b_n)$$

$P(p > p_i)$ is probability of the event, that the compression p_i will exceed $P(b > b_i)$ value. Ensemble (p_i, b_i) is a discrete grid on the curve of construction state $p(b)$. The plate reliability is calculated as follows

$$R = 1 - Q.$$

Values of R are calculated for all the hull sections being analysed along hull length. Calculation results are presented in Figures 5 and 6. They show a greater expected probability of damages in the Chukchi Sea in comparison to the Kara Sea and also significant dependence of the safety on the exploitation velocity.

Reliability of the Ice Belt Panel of the Stationary Platform.

The platform was mounted in the Pechora bay. Analysis of ice conditions and simulation of the load parameters p and b was carried out for every month separately. Simulation results are presented in Figures 7 and 8. The ice loads were calculated for two cases of loading: crawling of continuous ice sheet against the ice belt and impact of a floe on the structure. Model of the structure impact on ice was modified for the second case in the assumption of structure immobility and its infinite mass. All the monthly samplings for p generated using determined approximating laws were collected in equal portions in one sampling. Sampling for b was generated by analogy using calculated correlation dependencies. Histograms for p and b in a year course were also approximated by the Γ -distribution law. (See Figures 9 and 10). The reliability R was calculated in a year course using curves $p(b)$ of the fibre yield and the plate ultimate strength. The R_m reliability for m -year period of exploitation is determined as follows: $R_m = R^m$. This relation is justified, if construction wear is excluded, because this factor exerts significant influence on the structure member strength. Calculation was fulfilled for the period of exploitation being equal to 50 years.

Reliability of the Ice Belt Grillage of the Stationary Ice-Resisting Platform.

Five parameters of the load were determined generally for the ice belt grillage: two co-ordinates of load centre across grillage area, height and width of ice load distribution, the ice pressure. Surface of state has therefore five dimensions. It is advantageous to separate safety analysis according to cases of loading in order to decrease amount of calculations: the ice sheet compression and the ice floe impact. The surface of state becomes three-dimensional in the first case: location of the load centre along height, height of the load distribution and the ice compression. The surface of state is constructed with a help of a set of calculations using the finite element method (See Figure 11) with elements having shape of shells and beams. These elements work in elastic and plastic domains. Real stress-strain diagram of grillage material is used.

Future Trends of this Method.

Comparison with actual data on the technical means failure is correctness criterion of all theoretical safety forecasts. Computer database is generated in AARI for that purpose. This database will include data on hull ice damages of the ice class ships and icebreakers. Data array of this base contains three types of information:

1. Data on damaged surface for head ship of a series, i.e. geometric and constructive topology of outside plating plan.

2. Data on damages obtained by processing of statements of dock and diver inspections of ships. The damages are separated into two groups: cumulated and non-recurrent. The cumulated damages increase in the course of ship exploitation (dents, gofers, plastic deformation of stems, etc.). The non-recurrent damages appear during the single ice load action (holes, vast plastic deformation of the grillages). Geographic co-ordinates and date can be obtained for the majority of these cases. It is necessary to know region of navigation for analysis of reasons of the cumulated damages.

3. Data on conditions of damage sustaining - regions and periods of navigation for the cumulated damages and geographical co-ordinates and date of damage sustaining for the non-recurrent damages.

The damages are subdivided into 12 types. Each of these types is described by one numerical parameter. Regions of the damages are determined by co-ordinates of arbitrary quadrangle angles in co-ordinate system of the outside plating plan.

Subsequent data processing will allow us to adjust the safety estimate method.

Other line of development of these investigations is creation of method of determination of optimal level of the construction safety. Development of reliable numerical schemes is necessary for estimate of cost of construction failure consequences leading to environment pollution, cargo damages, removing of ship or construction from service. The estimate of cost of the damage consequences will allow us to complete this work for two important applications:

1. Combined method of justified determination of insurance payment for insurance of the ice class ships, Arctic shelf structures and cargoes transported in ice conditions.

2. Creation of normative base for designing of metal constructions, which are under influence of ice with optimal level of norms.

REFERENCES.

1. Kurdyumov, V.A. "On loads appearing under ship compression in ice". Tr. of LSI. Problems of hulls, L. 1987.
2. Kurdyumov, V.A., Kheisin, D.Ye. "Hydrodynamic model of solid body impact on ice". "Applied mechanics", 1976, v. 12, N 10, pp. 106-108.
3. Ryvlin, A.Ya., Kheisin, D.Ye. "Ship testing in ice conditions". L. Sudostroyeniye", 1980.
4. Alekseyev, V.I. "Analysis of hull damage sets caused by ice loads". Vladivostok, 1987. FEEMS named after G.I. Nevelskoy.

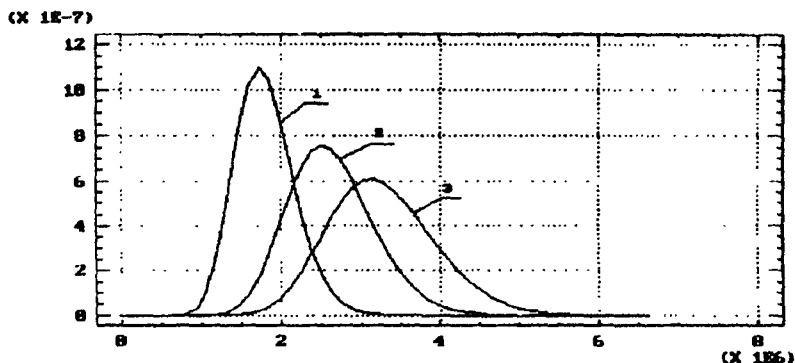


Figure 1. Distribution of the ice pressure p (Pa) on the third theoretical cross-section (the south-western part of the Kara Sea, winter). Rate of contact with ice: 1-3 knots, 2-6 knots, 3-9 knots.

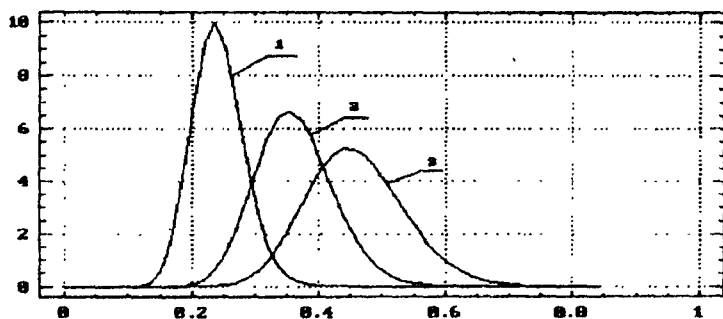


Figure 2. Distribution of the load height h (m) on the third theoretical cross-section (the south-western part of the Kara Sea, winter). Rate of contact with ice: 1-3 knots, 2-6 knots, 3-9 knots.

(X 1E-7)

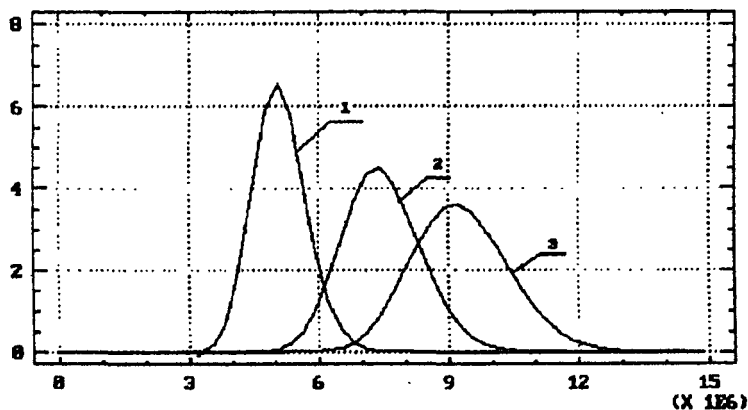


Figure 3. Distribution of the ice pressure p (Pa) on the third theoretical cross-section (the northern part of the Chukchi Sea, summer). Rate of contact with ice: 1-3 knots, 2-6 knots, 3-9 knots.

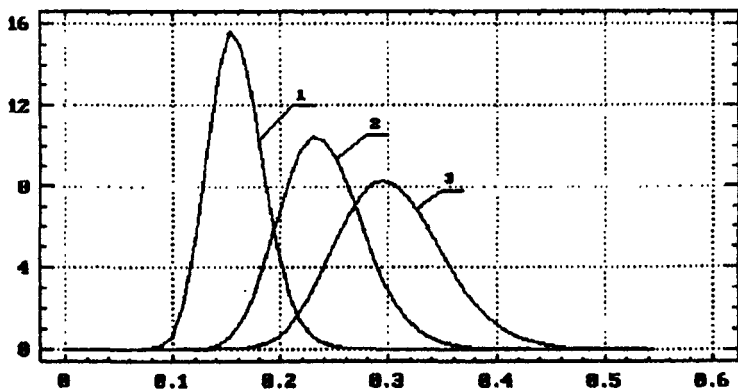


Figure 4. Distribution of the load height b (m) on the third theoretical cross-section (the northern part of the Chukchi Sea, summer). Rate of contact with ice: 1-3 knots, 2-6 knots, 3-9 knots.

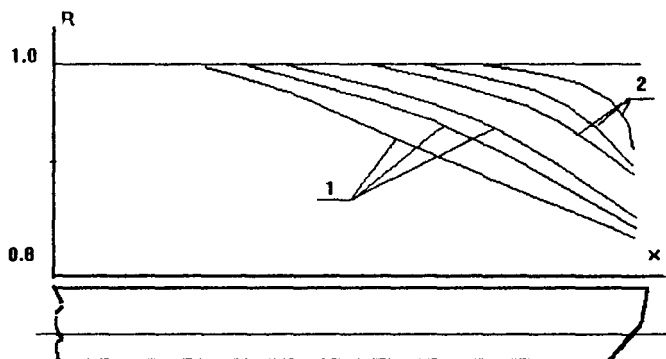


Figure 5. Reliability of the ice belt plating of the ship "Pavlin Vinogradov" in the south-western part of the Kara Sea in winter according to the fibre yield criterion (curves 1) and to the ultimate strength criterion (curves 2), x- plate location in reference to ship length. Curves correspond to different ship velocities.

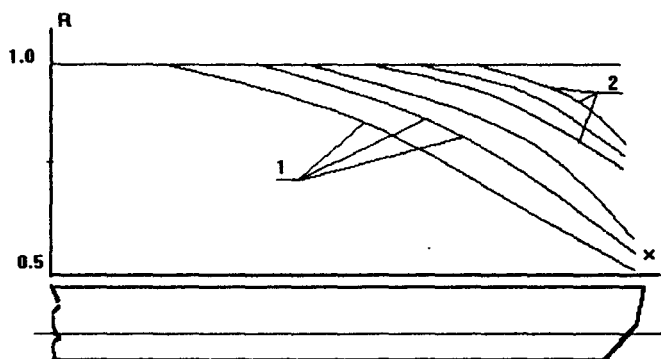


Figure 6. Reliability of the ice belt plating in the northern part of the Chukchi Sea according to the fibre yield criterion (curves 1) and to the ultimate strength criterion (curves 2), x- plate location in reference to ship length. Curves correspond to different ship velocities.

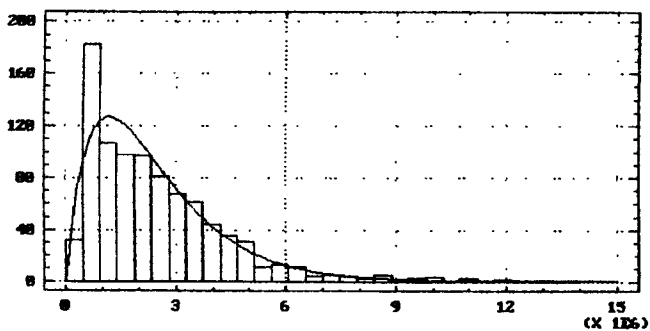


Figure 7. Simulated histogram of the ice pressure for one of the months and its approximation by the Γ -distribution law.

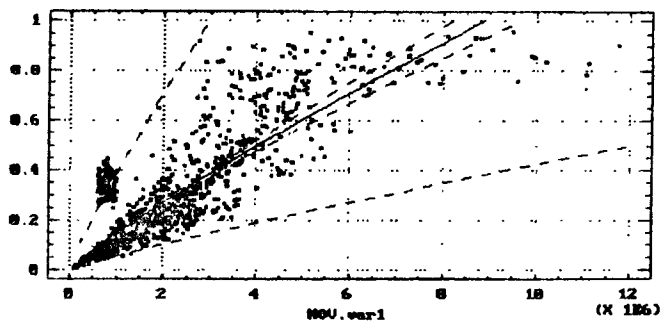


Figure 8. Field of the simulated values of p and b and correlation curve between these values.

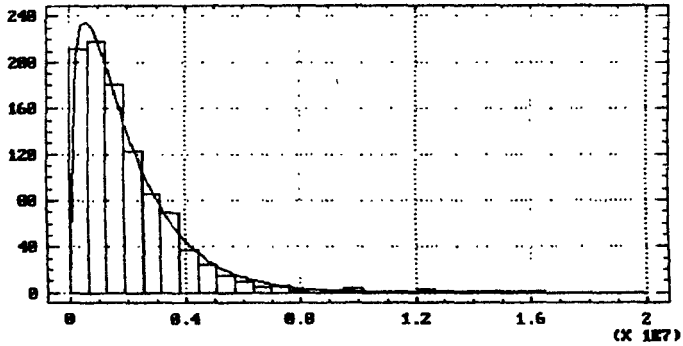


Figure 9. Histogram of annual sampling for p and its approximation by the Γ -distribution law.

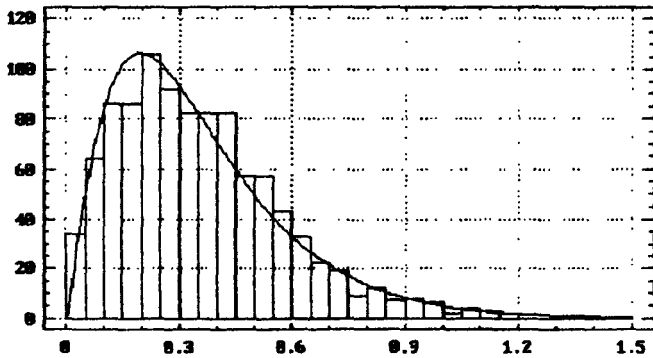


Figure 10. Histogram of annual sampling for b and its approximation by the Γ -distribution law.

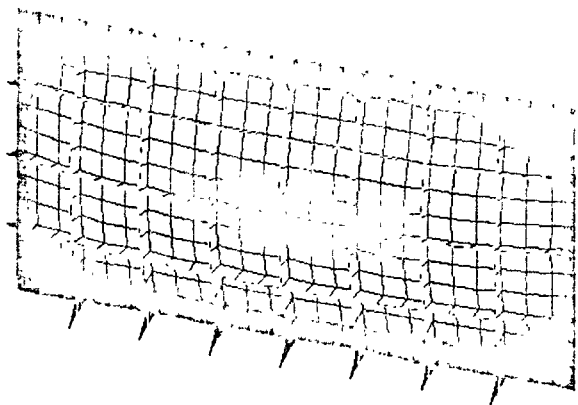


Figure 11. Stress states of the ice belt grillage under the ice load exerted by ice sheet.

INLETS, ENTRANCES AND ICE Per Bruun, Hilton Head Island, SC, USA

INTRODUCTION

Navigation and ice conditions in the Arctic are interrelated. This is the reason for the large icebreaker fleet stationed here in MURMANSK.

Through the years numerous tests on ice-breaking procedure, using a variety of vessels built and fitted for ice-breaking, have been undertaken. Proceedings from 12 POAC conferences since 1971 have about 90 papers on the subject referring almost entirely to open sea conditions, including breaking through ice ridges and pilings of various origin.

A ship's voyage has a starting and an ending point, where its commodity is unloaded/loaded at a quay or at a terminal. Such harbour facilities are almost always located in areas protected from heavy wave action that is in a bay, lagoon, fjord, behind an island or reef, or in a river mouth. While in some instances protection against waves also means protection against ice, in others, and perhaps in most cases, wave protection schemes could result in increased problems with ice, as ice masses contrary to water masses in currents and waves stick together forming pile-ups, ridges, jams, etc. While any kind of hindrance to wave action will destroy, reflect, refract or diffract waves, ice is more tough in its interaction process with a structure. Ice is neither destroyed or visibly reflected. Ice "refraction" or "diffraction" is a very local affair (Bruun, 1983). Certain similarities, however, exist in the interaction between currents and waves versus ice. Waves and currents propagating in the same direction flatten waves and spread the ice. Opposing currents increase the steepness of waves and opposing ice movements, e.g. due to winds and/or currents, may cause ice ridges or ice jams. For people working with ice problems this is all very elementary. They instinctively try to avoid any kind of possibility for concentration and packing of ice. In doing so they try to stop or to slow down the movements of ice towards the area they want to protect against ice and wave action. Therefore, they look for shores which are as little as possible ice-infested.

Site selection for harbours is usually dictated by protective criteria against wave, current and sediment transport conditions. Land-dictated criteria, however, may sometimes override, wholly or in part, such natural maritime considerations. This could finally result in severe maintenance problems, thereby in a poor economy for the project as a whole (Bruun, 1990, Vol. 2).

Considerations to ice is usually based on experiences on local conditions. It was e.g. observed that ice-jamming was less pronounced in certain areas and consequently it was concluded that these areas were best suited for fixed installations. In most cases this was probably correct, but in others it was overlooked that a structure placed in ice by its mere presence changed natural conditions and thereby would increase dangers of ice-packing. And if ice has first moved in and perhaps has grounded, it may be very difficult to get it out again, voluntarily or by force.

The following may sound elementary, but practical experiences have proven that it may sometimes be important to return to or remind on important basic aspects. Certain general principles on protection against ice are outlined briefly in the following.

MAN-MADE STRUCTURES IN ICE

A harbour installation must not "catch" or "trap" ice. Where ice has first formed it may stay put or it may move under the influence of winds and/or currents. If the ice hits a substantial hindrance it may be stopped or it may also bypass and continue its movement. In the case of the former, a reservoir of a proper size is needed. When the reservoir is filled the ice may continue its movement which may generate new problems "downstream". The similarity to littoral drift conditions, therefore, is striking (Bruun, 1990, Vol. 2). A reservoir of proper capacity and geometry is essential. In this respect the similarity with littoral drift conditions is obvious. In littoral drift technology we talk about the "predominant drift". Its counterpart in ice technology is "the predominant ice drift", recognizing that the drift may come from either side. The standard technical solution to the littoral drift problem is breakwaters or jetties which shall protect against wave action and stop the littoral material drift. Their ability to do that depends upon their length and configuration. They are usually built perpendicular to the shoreline thereby increasing their capacity as reservoir structures. Their outer section may be curved downdrift to generate an outer harbour and guide the material transport past the entrance whether this is sand or ice (Bruun, 1990, Vol. 2). For site selection, therefore, the two criteria: (1) ample reservoir capacity and (2) bypassing - are mandatory. For example, according to American experience the sand trap to be installed on the updrift side of a littoral drift barrier shall have a minimum capacity of 1/12 of the annual drift by sand from the updrift side.

The two criteria for sand and ice may, however, oppose each other. Reservoir capacity means a large updrift bay area, e.g. generated by a headland (Fig. 1). Bypassing by natural forces requires a stream-lined shore geometry without any hindrance to free movement.

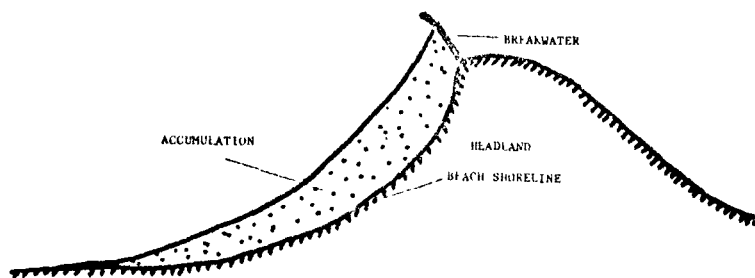


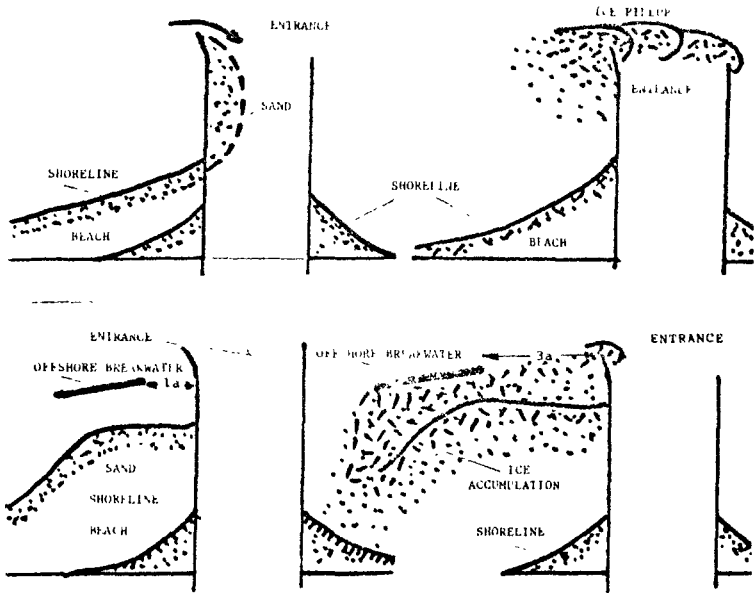
Fig. 1. Reservoir for sand or ice at headland.

Ultimately the reservoir may be filled with sand or by drifting ice which then finally has to bypass - or it has to be bypassed to avoid blocking of an entrance. Bypassing of sand passed an entrance is a normal feature on littoral drift shores. Bypassing of ice is sometimes practiced by "ice-sluices" at hydraulic power plants built under arctic conditions, e.g. in Iceland, Alaska, Canada, Norway and Russia. But quantities of ice are very modest and it is not possible to use the same technique on open sea shores. Ice may anyhow bypass by natural action due to currents, sometimes assisted by wave action. The principal question then becomes the site selection in relation to quantities and carrying capacities and how to use these without introducing adverse effects. If such effects occur the problem is how to minimize them or eliminate them entirely.

Harbours on arctic shores are always located in fjords, in river entrances or in estuaries. As such they are facing a condition which may experience ice-flows from either direction, particularly caused by tidal currents.

Large reservoirs can only be generated by natural headlands. Headlands usually mean concentrations of currents. In either case concentrated drifts by sand and ice may result and the problem is how to get the material passed the headland and its structures in the most painless way, after the reservoir capacity has been exhausted.

In this respect sand and ice demonstrate behavioral similarities as well as differences making a direct transfer of technologies difficult or impossible. Fig. 2 shows behavior as well behavioral differences of sand and ice action at a harbour or inlet entrance to a bay, lagoon or basin. It is assumed, based on numerous practical experiences, that some sand or ice enters between the jetties. In this respect the detailed pattern of sand and ice movements differ - and so do the technical measures against the sand or the ice, as it may be seen from Figs. 2. Note e.g. that an updrift offshore breakwater must be placed further away from the entrance than the littoral drift breakwater to produce benefits on ice in the entrance area.



Figs. 2. Accumulation of sand/ice at a jetty protected entrance and on the updrift side by a shore parallel offshore breakwater.

Fig. 3 shows a rather narrow entrance to a harbour, like NOME, ALASKA (Sackinger et al, 1983). Such entrance will relatively easily be clogged by sand or ice. Wave action will concentrate in the middle of the entrance due to diffraction. Ice will rather cling to the side. In either case shallow water berms as seen in Fig. 3 will by refraction or in the case of ice by "a similarity to refraction" improve conditions for wave as well as ice action in the entrance channel

As mentioned above most harbour installations in arctic waters are placed in protected areas like fjords, bays, lagoons and river mouths. Obviously, if the choice of shores framing an entrance is free, facilities should be placed on the leeside, where wave and ice action are least (Fig 4). Analyses of sea ice drift in coastal zones, therefore, are important (e.g. Smith, 1989)

If one is faced with placement of a harbour or a terminal on the open coast, the existence of islands, reefs, shoals or canyons may be taken advantage of as indicated in Fig 5

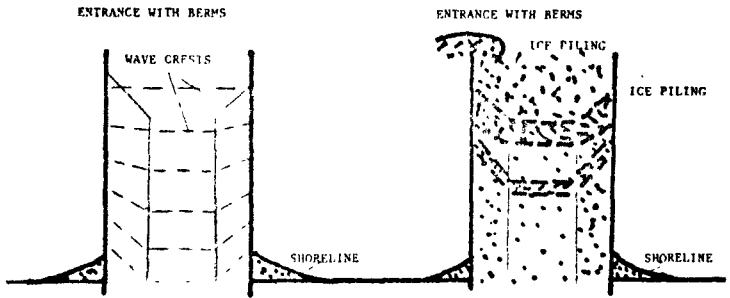


Fig. 3 Wave and Ice-absorbing berms in an entrance

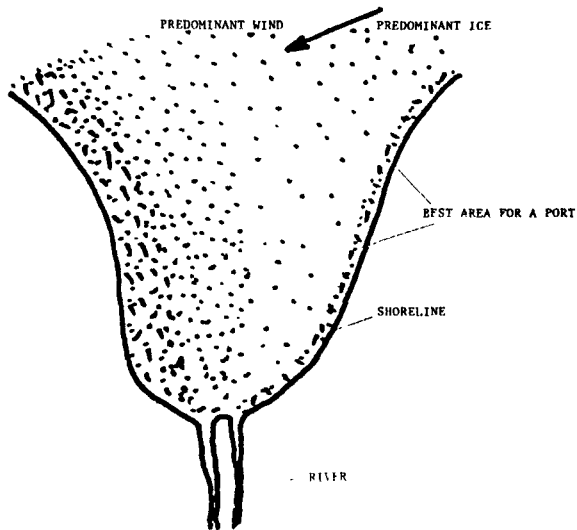


Fig. 4 Location of harbour-facility . . . relation to predominant winds and/or predominant ice movement in an estuary or fjord.

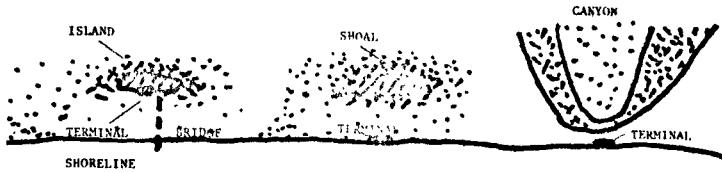


Fig. 5. Island, reef, shoal or canyon as wave or ice protective structures.

As river ice during the spring and early summer continues to flow towards the entrance for a longer period of time, great care should be demonstrated in selecting the proper site on the shore. As shown in Fig. 6, a flood channel is preferable for an ebb channel carrying more ice.

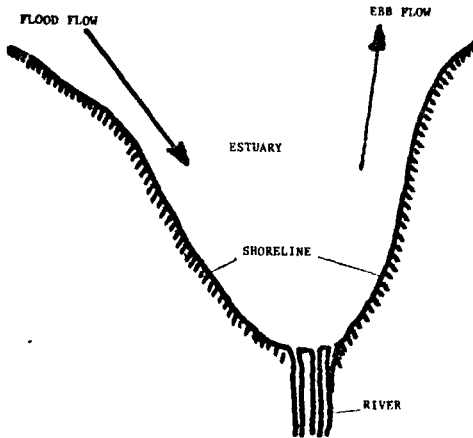


Fig. 6. Location of facility is best in a flood channel.

DISCUSSION

It seem obvious that some definite similarities exist between the behavior of littoral drifts and ice drifts versus structures and that similar measures against these drifts are possible. The difference in behavior is caused by:

- (a) Sand travels mainly along the bottom, while ice floats in water or in ice.
- (b) Water is high viscous, ice, and in particular broken ice, has a highly variable "viscosity" much lower than sand-filled water.
- (c) While sand may or will settle down, ice keeps floating in water or in ice masses. Sand, therefore, is easier to catch and handle than ice in all its varieties. Measures against the adverse effects of the two materials and their modes of drift, therefore, differ quantitatively, but not much qualitatively.

Perhaps the days are close when during certain circumstances at entrances it may be practical to dredge ice ridges and barriers by hydraulic equipment, including cutterheads, and transfer the mass discharging it, where nuisance will become minimum or not existing.

REFERENCES

- Bruun, P., 1983, "Ice Behavior at a Free End Obstruction Comparison with Wave and Sediment Conditions", Proc. POAC-83, Helsinki, Vol. 1, pp. 350-369.
- Bruun, P., 1990, "Port Engineering, IV," Vol. 2, The Gulf Publishing Company, Houston, TX, USA.
- Sackinger, Wm., Bruun, P. and Widdis, J., 1983, "Wave and Ice Design Criteria for a Terminal at Nome, Alaska", Proc. POAC-83, Helsinki, pp. 563-590.
- Smith, Piper, A., 1989, "Analyses of Sea Ice Drift in a Coastal Ice Zone", Proc. POAC-89, Luleå, Sweden, pp. 168-172.

FORECASTING OF ICE CONDITIONS IN THE PECHORA SEA WITH A DIFFERENT PERIOD IN ADVANCE FOR SUPPORTING ENGINEERING ACTIVITIES AND SHIPPING

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ABSTRACT

Five groups of ice conditions are identified taking into account their seasonal changes. On this basis a method for long-range forecasting of the distribution of the ice edge position and the boundaries of close ice has been developed. On the basis of a mathematical model of the ice cover evolution in spring-summer a method for short-range forecasting of the distribution of ice and zones of ice pressures has been evolved. It is shown that the use of probabilistic and numerical methods provides a possibility for setting up a flexible system for providing prognostic ice information with different periods in advance for sea operations.

INTRODUCTION

The increase in the activities on the shelf of the Pechora Sea requires addressing new objectives necessary for planning and operational management of non-standard sea operations.

At the stages of early drilling and construction of off-shore structures it is suggested to use floating drilling platforms and auxiliary vessels that do not have an ice class. This will require knowledge of the dates of clearing from ice and of ice formation over the water area, the duration of the ice-free period, boundaries of the distribution of close and very open ice and, respectively, forecasting of ice conditions from 1-3 days to 3-4 months in advance.

At the stage of the exploitation of the structures, forecasting of such dangerous ice phenomena as pressures, ice rubble, icing, extreme shifts of the ice edge and icebergs will be primarily required.

LONG-RANGE FORECASTING METHOD

Ice conditions in the Pechora Sea are distinguished by significant interannual and seasonal changes in the ice cover distribution (G.K. Zubakin, 1987; Ye.U. Mironov et al., 1993). That is why, different groups (types) of seasonal changes in ice conditions are used as a basis for long-range ice forecasting.

The groups (types) of ice conditions were identified by analyzing monthly changes in the ice area, the occurrence frequency of the ice edge position in the grid points with a spatial scale of 25 km.

A number of years from 1934 to 1994 was considered. Two time periods were analyzed: the period of ice growth (December-April) and the period of melting (May-August). As a result, five groups were identified. The first group includes the years with large (1.2σ) positive anomalies in the ice cover extent, the fifth group - with large negative anomalies (V.A. Spichkin, 1990). The second and the fourth groups include the years with enhanced and decreased background of the ice cover extent, respectively (from 0.4 to 1.2σ). The third group includes the years with a mean background of the development of ice processes (0.4σ). The analysis of changes in the ice cover extent both during the ice growth and melting periods for the whole of the series under consideration has revealed their range and mean values for each group for each month. Fig. 1 presents a change in mean ice cover extent by groups during the year. From the ice cover extent values for December-January one can actually identify the group to which the given year belongs, and hence, forecast the ice cover extent values for February-April. From the values of the ice cover extent for April, the group of the development of ice conditions in spring-summer can be estimated.

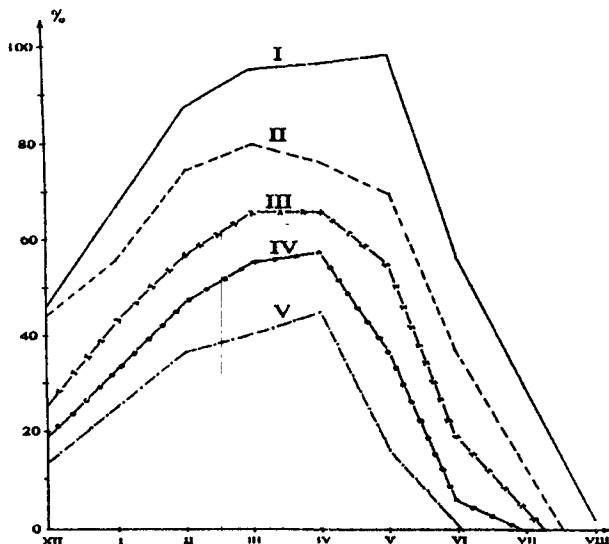


Fig.1 Changes in mean ice cover extent by groups during the year for the southeastern Barents Sea.

Typical positions of the ice edge and boundaries of close ice corresponding to each of the groups identified by the values of ice cover extent were identified. Thus, along with the forecast of ice cover extent variations for February-April which is

prepared at the end of January and for May-July which is prepared at the end of April, simultaneously, the ice edge position for each of these months is being forecasted.

A number of predictors were obtained allowing updating the ice cover extent forecast by the end of February and respectively, the ice edge position for the period of its growth and by the end of May for the period of melting.

These predictors include:

- a sum of air temperatures at the polar station Maly Karmakuly for October-February for the period of ice growth, as well as a sum of air temperatures for March-May for the period of melting,
- water temperature in the layer of 0-50 m at the section N-9 west of the Svyatoy Nos cape,
- occurrence frequency of the direction of air flows and their intensity in the region of the Kolguyev Island both for the period of ice growth and ice melting.

The use of actual knowledge of the ice cover extent and predictors found allows developing a multilevel scheme for forecasting ice conditions taking into account their seasonal changes 1-3 months in advance.

SHORT-RANGE NUMERICAL FORECASTING METHOD

During the spring-summer period which covers the time interval from the onset of snow melting to the onset of ice formation the numerical method of ice forecasting is used for issuing a forecast for ice conditions from 1 to 7 days in advance. It is based on a mathematical model of the ice cover evolution as affected by the dynamic and thermal factors which has been specially developed for the purposes of ice forecasting. The adaptation of the model for the other seas of the Russian shelf allowed creating similar methods for the Barents, Kara, Laptev, East-Siberian and Chukchi Seas.

The model allows calculating the following characteristics of sea ice:

- drift rate;
- ice cover concentration;
- thickness;
- position of the drifting ice edge;
- zone of pressures.

A spatial interval of the model is equal to 25 km, the calculation of changes in the ice edge position is made with an accuracy of 5 km.

A detailed description of the model is presented in the monograph of Appel and Gudkovich (1992) and in the paper of Aksenov Ye.O., Gudkovich Z.M., Panfilov A.A., Pozdnyshev S.P., Speransky D.A "Methods for operational numerical forecasting of ice conditions for the Russian Arctic Seas" presented at the conference.

The following types of hydrometeorological information are needed to develop a forecast:

- initial distribution of concentration and thickness (or age gradations) of ice cover;
- a forecast for the surface atmospheric pressure field;
- mean multiyear values of incoming total short-wave radiation and air temperature;
- mean multiyear actual velocities of surface or calculated for typical pressure situations currents.

For operational application of the model in prognostic mode, software was developed for automated input, preparation of initial information, as well as presentation of the calculation results in the form of the traditional chart of the distribution of zones of different concentration of ice cover. The preparation of the forecast up to 7 days in advance takes 3-4 hours.

Figs 2-4 present an example of forecasting the redistribution of ice in the Pechora Sea.

Fig.2 presents the actual distribution of sea ice which is a result of combining satellite information over this region for the period May 8-10, 1995. Fig.3 presents the forecast for May 16, 1994 and Fig.4 - the actual distribution of concentration obtained by combining satellite information for the period May 14-17, 1994.

Changes in the ice cover concentration between these dates are related to the effect of the winds of eastern and south-eastern directions on the ice cover, as well as to the onset of melting.

The eastern component of air flows resulted in the formation of a strip of open water along the western coast of Novaya Zemlya (along the eastern coast the polynya disappeared). The export of ice through the Kara Gate strait increased. This ice formed an ice tongue up to 9/10 in concentration extended westward and making difficult the approaches to the strait. To the west and north-west of the Kolguyev Island an extensive zone of open water continued to develop. The outer edge of the drifting ice in the Pechora Sea also shifted to the west and mean concentration of ice cover as affected by the processes of diffusion and melting was slightly reduced.



Fig. 2 Actual total ice concentration, 9 May 1994.



Fig. 3 Total ice concentration calculated for 16 May 1994.

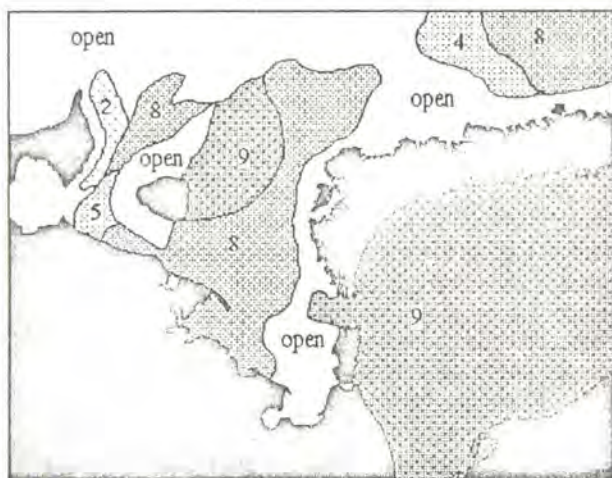


Fig. 4 Actual total ice concentration, 16 May 1994.

In our opinion the prognostic distribution of the ice cover reflects the main features of changes that have taken place. The differences present are connected both with errors when collecting and combining the actual information and computational errors.

CONCLUSIONS

The use of statistical methods allows forecasting ice conditions according to the following scheme:

At the end of January - for the period February-April, at the end of February - for the period May-July, at the end of May - for the period June-July.

Thus, the distribution of ice cover (ice edge position, close ice boundary) is forecasted with a 10-day interval and 1-3 months in advance.

The use of the numerical method allows forecasting of the ice drift rate and direction, distribution of ice cover, position of the pressure zones during the period May-July from 1 to 7 days in advance. It is also planned to develop a numerical forecasting method for wintertime in the very near future.

A combination of using the probabilistic methods and thermodynamic models gives a possibility for arranging a flexible system for providing prognostic ice information with different periods in advance for sea operations over the Pechora Sea area.

R/V "Akademik Fedorov" Expedition along the Northern Sea Route during Summer 1994: Ice conditions, Ship Performance in Ice, and Ice Loads on the Ship Hull.

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Timofeyev, O.Ya.	Arctic and Antarctic Research Institute	Russia

1. Introduction.

Russian-Swedish Arctic Expedition "Ecology of tundra-94" was executed on board of the research expeditionary vessel "Akademik Fedorov". The Arctic and Antarctic Research Institute is ship's owner. This expedition was executed in the period 30 May-13 September, 1994 in accordance with general agreement between the Swedish Secretariat of Polar Research and Russian Academy of Sciences and Ministry of Environment Protection and Natural Resources of the Russian Federation. The "JV INTAARI" joint-stock company was appointed as official operator of the expedition.

Aim of the expedition was combined research of flora and fauna and of contamination level of Arctic coast and islands in 18 points beginning from the Kola Peninsula and finishing in the Kolyutchinskaya Guba on the Chukchi Peninsula. Oceanographic and ice observations were carried out in addition to the main ecological ones. Measurements of ice loads were fulfilled with a help of board tensometric station.

The expedition consisted of three stages with rotation of scientists in Khatanga on 4-5 July and Tiksi on August, 8.

2. Ship's Characteristics and Research Programme.

The scientific expeditionary vessel "Akademik Fedorov" is flagship of the Russian Antarctic research fleet. It was built by the "Rauma-Repola" company (Finland) in 1987. Ship's main characteristics are the following:

Length	145. m
Width	23.5 m
Draught	8.5 m
Nominal Capacity of Propeller Electro-Engine	12 MWt
Speed in open water	16 knots
Displacement	16000 t
Crew	90 persons
Scientific Staff	160 persons
Ice Class of Russian Register	ULA

The ship was equipped during construction by the board tensometric station elaborated by VTT (Finland) for measurement of ice loads on ship's hull. The tensometric station works uninterruptedly retrieving information of each channel with 100Hz frequency. The total number of channels 32. Two channels are connected with pressure sensors, five channels are for stress measurements in outside plating and the other twenty-five channels measure reaction of framing beams on the ice load action. The sensors are located in two zones of the hull: in the ship's bow of starboard

between the cross-sections 150-159 and in the middle area between the cross-sections 87-93 (See Figures 1).

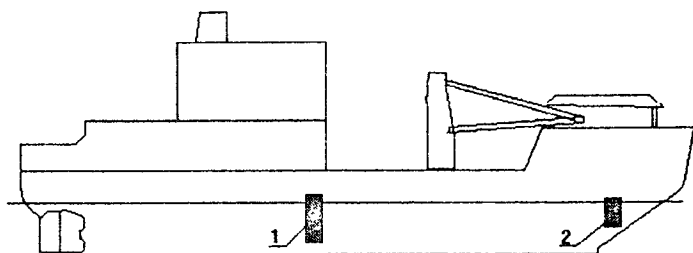


Fig. 1. Sensors areas of the hull: 1- middle area, 2- bow area.

The following investigation were included in the expedition programme:

1) Combined ice condition observations along the expedition route including observations from board of the ship obtaining data for determination of ice cover statistical parameters, ice condition observations from board of aeroplane or helicopter, satellite data.

2) Initial information was obtained for analysis of ship's ice passage capability in the Arctic in summer.

3) Data collection on the ice loads measured with a help of the board tensometric station apart with ice condition and ice cover parameters observations and record of ship's speed with a help of the GPS satellite system.

3. General Description of Ice Conditions along the Navigation Route.

The expedition route is shown on the fig. 2.

The first stage of the expedition was carried out at the section from the Kola Peninsula till the Khatanga Bay region. The observations in the first point at the Kola Peninsula started on July, 10. Ice free zone was observed according to obtained satellite information in the Barents Sea up to the Kolguev Island, further very open floating ice was observed (concentration 10-30 %) in the Pechora Sea up to the Yugorski Shar. Fast ice in the Yugorski Shar was fractured, large polynya was observed near the Amerdema coast. The ship sailed in this polynya and then after surmounting narrow ice isthmus (ice concentration 90-100%, width 18 n.m.) it entered polynya along the Yamal coast. "Akademik Fedorov" reached without assistance region of the Bely Island, where it met the "Taimyr" atomic icebreaker, "Akademik Fedorov" was piloted by the "Taimyr" atomic icebreaker during 23-29 June at first along polynya up to the Dickson Island and then along channel in fast ice of thick first-year ice (120-150 cm) carrying out scientific observations. After the caravan got out of the fast ice between the meridians 107° and 111°, it sailed at first along flaw polynya and then along narrow flaw zone (ice concentration 50-80%) up to the point 8 in the Peter Islands region. The "Taimyr" atomic icebreaker ended piloting on June, 30 because of finishing of leasing and sailed to the west. "Akademik Fedorov" during 2-4 July moved to the south and south-east to the point, where the rotation of scientists of the first and second stages was fulfilled. The mean speed along this section up to the latitude 75°35' N was equal to 5 knots in medium first-year ice (ice concentration 90-100%, melting stage - 2-3 arbitrary units, amount of hummocking 2-3 arbitrary units, ice thickness 50-70 cm). Further the ship moved in

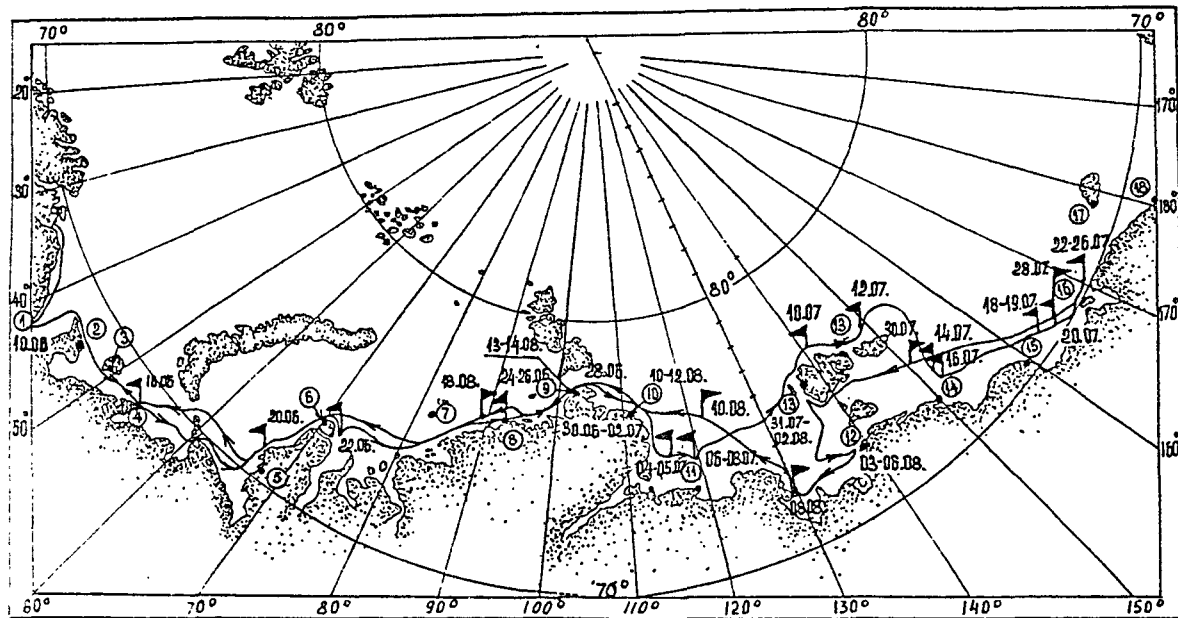


Fig. 2. The "Akademic Fedorov" route during "Tundra Ecology-94". Signs: \blacktriangleright - vessel position, $\textcircled{6}$ - number of point of ecology observations.

almost impassable very close thick first-year ice (ice concentration 90-100%, amount of hummocking - 3 arbitrary units, in places even 4; melting stage -2 arbitrary units) working by impacts.

Further navigation route in the eastern direction was chosen taking in to account obtained satellite information approved on 4-5 July by air reconnaissance carried out with a help of SLAR-station. "Akademik Fedorov" moved in the zone of thick first-year ice (concentration 80-90%) up to the meridian 122°. It entered flaw polynya on July, 9. This flaw polynya spread to the east. Then the ship sailed to the north-east doubling the Kotelny and Faddeyevskiy Islands up to the meridian 144°30'E. The ship met ice isthmus of thick first-year ice (concentration 90-100%, amount of hummocking 2-3, melting stage 2-3 arbitrary units) while reaching the meridian 147°. This isthmus was forced, and the ship entered polynya to the north of the New Siberia Island on July, 11, then it continued its movement up to the meridian 151°30'.

The most severe section of the navigation in the East Siberian Sea began after leaving this polynya. The Ayonsky ice massif forcing continued till Pevek. It should be mentioned, that transport ships in this period of the year can surmount this region only piloted by atomic icebreakers of the "Arktika" type. There was no experience of self-contained navigation of the SA-15 type ships. "Akademik Fedorov" fits into this class of ships. The ship moved to the east up to the meridian 155° in open and close floating ice with the concentration from 50 till 80% and then to the south keeping close to the 20 m depth isoline. Separate fractures and zones of very open floating ice were formed as a result of action of the eastern winds in ice massif of thick first-year ice (concentration 90%) in the region between 75° and 74° N. They were formed between floes and at leeward side of grounded hummocks. It allowed "Akademik Fedorov" to sail predominantly in open floating ice piloted by the helicopter up to the latitude 73°50' N on July, 13. Sample of helicopter reconnaissance result is shown on the fig. 3.

Later on, unfavourable northern and north-eastern winds (3-7 m/sec) were observed. These winds closed all the leads and fractures, and the ship continued its movement in the ice massif of thick first-year ice (concentration 90-100%) with predominance of big floes with the amount of hummocking 1-2 arbitrary units and ice compacting 1-2 arbitrary units. The ship's velocity was equal to 1-3 knots on 13-14 July up to the latitude 72°30' N, at some intervals it decreased up to 0.1-0.4 knots. The ship lay in drift for the next two days waiting for improvement of the ice conditions. The expedition staff carried out observations in the Indigirka river-month.

Further navigation of "Akademik Fedorov" to the east to the Ayon island (168°) on 16-20 July happened in ice massif of thick first-year ice (concentration 90-100%, amount of hummocking - 2-3 arbitrary units, melting stage - 3 arbitrary units) using somenarrow elongated fractures and zones of the ice concentration being equal to 90%. These zones were revealed with a help of the helicopter. Strip of thick first-year ice (concentration 100%, amount of hummocking - 4-5 arbitrary units, very polluted and practically impermeable even for atomic icebreaker was located to the north off the Ayon Island between 168° and 170°. The ship sailed in the region to the north off this zone in thick first-year ice (concentration 90-100%, amount of hummocking 3 and in some places 3-4 arbitrary units). Separate ice floes occurred in this region, which were parts of fractured fast ice with the amount of hummocking 5 arbitrary units. The ship's velocity in this region was equal to 2-4 knots on average, but the ship remained immobile during 12 hours at night and in the morning of July, 21. "Akademik Fedorov" lay to drift on the beam of the Shelagski Cape in the point with the coordinates 70°14' N, 170°21.7'E. Further movement to the east in the region of the Kolyetshinskaya Guba would have require 10-12 days. This delay

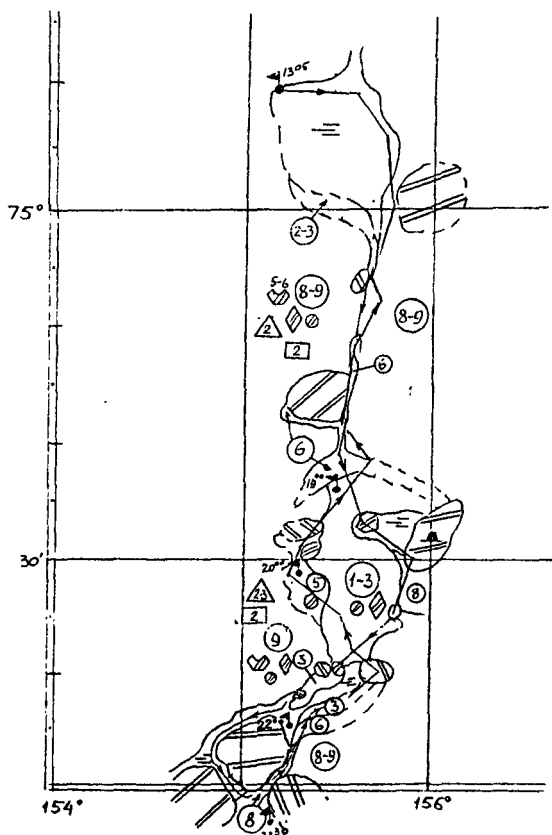


Fig. 3. Helicopter ice reconnaissance data of 12 July 1994. Map symbols:
 (8-9) - ice concentration [1 unity: 10% of area], \triangle - ice hummocking [1 unity:
 20% of area], \square - ice fracturing, \diamond - big floes of first-year ice (0.5-2 km)
 \diamond - medium floes (0.2-0.5 km), \odot - ice cake, \blacktriangle - grounded hummock,
 — - ice free zone, \rightarrow - helicopter flight route, \blacktriangleright - position of the
 "Akademik Fedorov"

would have made impossible fulfilment of expedition schedule. It was decided, therefore, to stop further movement to the east and to carry out the observations in the remaining two points on the Wrangel Island and in the Kolyutshinskaya Guba with a help of the helicopter.

The southern winds, which were observed on 23-26 July in the region of the ship's drift, had velocities 2-15 m/sec. They caused polynya formation and intensive ice drift to the north. The ship moved, therefore, during its return journey in this polynya and then in ice massif of thick first-year ice (concentration 90-100%, amount of hummocking 3-4 arbitrary units) up to 165° E. Ice compacting was observed in the massif on July, 27 caused by the eastern winds. The ship's speed in this period was equal to 2-3 knots, and in places it was equal to 0.7-0.8 knots. While moving further, "Akademik Fedorov" met massif of thick first-year ice (concentration 80-90%, amount of hummocking -2 and melting stage -4 arbitrary units), which was easy for passage. It was in the region between 165° and 150° E. The fast ice fracturing in the region to the south off the New Siberian Islands and the Sannikov strait happened on July, 29. The ship moved, therefore, in ice massif of vast and relatively level floes of thick first-year ice (concentration 90-100%, amount of hummocking 1-2 and 2 and melting stage -3 arbitrary units) from 150° meridian up to the Kotelny Island. Prevailing ice thickness was equal to 60-100 cm. The ship after finishing its work on the Kotelny island in accordance with the obtained satellite information reached ice free zone on August, 2 after it had passed 20 miles through ice massif of thick first-year ice (concentration 90-100%). Doubling the ice massif it turned to the south-east up to the latitude 72°50' N. In this point it turned to the east. Ice massif of thick first-year ice easy for passage was met at this last section of the route. It consisted of thick first-year ice, medium and small floes prevailed. The ice concentration was equal to 90%, and the melting stage -4-5 arbitrary units.

The ship sailed on 5-8 August along the coast in ice free zone to Tiksi and in the reverse direction. "Akademik Fedorov" departed from Tiksi on August, 8 with the third group of the expedition staff. It began its movement with composite course to the north-west in the ice free zone up to the ice edge reaching the point 76°N, 122°30'E. The ship reached the Taimyr Peninsula on August, 10 having moved to the west in very open and open floating ice. It crossed also several ice isthmuses of close floating ice (concentration 80-90%, width 15-25 n.m.). Further movement to the Vilkitski Strait began on August, 12 after finish of the expeditionary work. This sailing took place in very open floating ice up to the meridian 107°. Satellite images revealed, that fast ice in the Vilkitski Strait and further to the west up to exit from the Matisen Strait (95°) had fractured on August, 11. The ship moved along this section of its route forcing vast floes of the fractured fast ice of thick first-year ice (concentration 100%, amount of hummocking 1-2, in places 2-3 arbitrary units). The ice compacting (intensity 1-2 arbitrary units) appeared on August, 14 caused by the unfavourable western winds with speed 5-11 m/sec. The ship's mean speed was equal to 3 knots. After leaving the compacting zone it increased up to 6 knots. The "Taimyr" atomic icebreaker overhauled the ship at the meridian 96°40' E. The ship was piloted along the northern part of the Matisen Strait along polynya, which had been formed by the northern winds. This polynya was revealed during the helicopter air reconnaissance. "Akademik Fedorov" moved without assistance in the region to the west off 95°E up to the ice edge (76°26' N, 90°28.6' E). This movement took place in ice massif of thick first-year ice with the concentration 90 and 90-100%, the amount of hummocking -3 and the melting stage -3 arbitrary units. It reached ice free zone on August, 17 and finished its ice navigation.

4. The Ice Passage Capability and the Ice Loads.

It is common knowledge, that the ice cover of the Arctic seas can be divided into two main types: drift ice and immobile ice (fast ice). The drift ice can also be divided into several main types of ice formations. Ice massifs are the largest of these formations (Gudkovitch et al., 1972). The ice massifs are temporally and spatially stable accumulations of the drift ice with the thickness exceeding 30 cm. The ice concentration in the massif exceeds 70%. The ice massifs are significant obstacle for ship's navigation for all the ship's classes. Special difficulties appear by surmounting of the so-called kernel of the massif (ice thickness exceeds 120 cm, ice concentration exceeds 70%).

It is advantageous to carry out analysis of the ice passage capability of "Akademik Fedorov" for the navigation along the most severe, limiting sections. These sections along the Northern Sea Route were the following: fast ice region of the north-eastern part of the Kara Sea and the Taimyr and Ayon ice massifs.

Samplings were made and distributions of some main ice cover characteristics (the ice thickness and the amount of hummocking) were constructed for estimate of the ice passage capability with a help of formed database of the ice conditions of this navigation. Distribution of operational indexes (the mean ship's speed) was also determined for sections in the fast ice, ice massif periphery (part of the massif with the exception of its kernel) and in its kernel. It is known, that ship's movement in ice is selective by its character. This character reveals itself in maximum use of sections with more easy ice conditions (with a lesser concentration, decreased background of the ice thickness, amount of hummocking, etc.). This selective character exerts influence on the ice cover characteristics distribution along the navigation route (Buzuyev and Fedyakov, 1981).

The ship's navigation in the fast ice region was carried out along the channel, which had been previously formed. Information obtained during detailed instrumental air reconnaissance determined breaking the channel by the "Yamal" atomic icebreaker without maximum use of ice inclusions with the decreased background of the ice thickness and amount of hummocking. Relative extent of the navigation in the ice with its thickness up to 120 cm was equal to 93% (See Figure 4).

The fast ice thickness distribution is bimodal by its character. Navigation in ice with the thickness being equal to 30-80 cm (37%) took place mainly along the section - the western fast ice edge - the Nordensheld Archipelago. Navigation in ice with the thickness 80-120 cm (56%) took place mainly along the section - the Nordensheld Archipelago - 102°E.

The ice thickness in the Vilkitski Strait along the navigation route was in the range 120-200 cm (7%).

Ship's navigation in the fast ice happened mainly in relatively level ice (amount of hummocking - 1 arbitrary unit; 70% of total section length; See Figure 5). Navigation in ice with the amount of hummocking exceeding 2.5 arbitrary units, i.e. hummock square exceeds 50% of total area, does not exceed 17% of the route in the fast ice.

The mean operational velocity of "Akademik Fedorov" during its piloting by the "Taimyr" atomic icebreaker was equal to 9.2 knots in the fast ice along broken earlier channel and it varied in the limits 5-12 knots (See Figure 6).

The ship's navigation in the drift ice of the Taimyr ice massif took place in peripheral regions of the massif. The ice thickness in this region varied in the range between 10 and 180 cm. The main part of the route, however, was in ice with the thickness less, than 120 cm, - 95%, just as it was for the fast ice. Relative extent of the route in ice with the thickness less, than 30 cm, contributed 16% (See Figure 4).

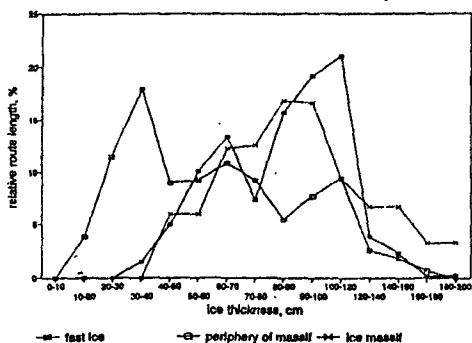


Fig. 4. Ice thickness distributions along the vessel route.

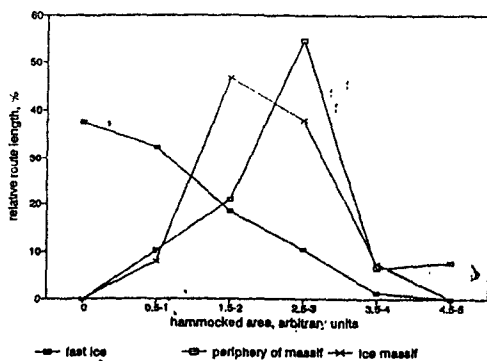


Fig. 5. Hummocked area distributions along the vessel route.

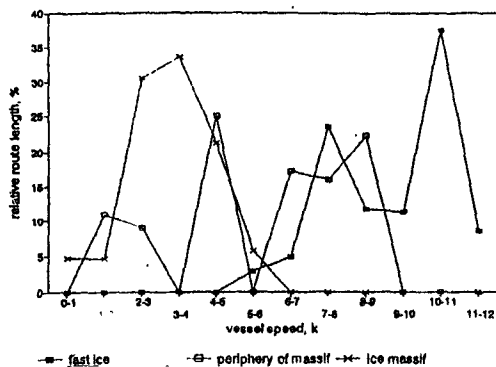


Fig. 6. Vessel speed distributions.

The ice thickness distribution in the kernel of the Ayon ice massif differs from that of the Taimyr massif periphery by its shift to greater values of the thickness (See Figure 4). There was no ice with thickness less, than 40 cm, along the navigation route in the massif kernel according to our observations. Relative extent of the route in ice thicker, than 120 cm, is 15% greater, than for the periphery.

The amount of hummocking distributions for the periphery and kernel of the ice massif also differ significantly.

The navigation in the Taimyr ice massif periphery took place along the eastern coast of the Taimyr Peninsula. This region is characterised by increased ice cover dynamics. Significant part of the route took place in ice with the amount of hummocking exceeding 2.5 arbitrary units (69%, See Figure 5). It should be mentioned, that 8% of the total route in the peripheral region was in the ice with the amount of hummocking 4.5-5 arbitrary units.

The amount of hummocking distribution in the massif kernel was more uniform (See Figure 5). Amount of hummocking values of 1.5-2 arbitrary units have maximum recurrence (47%) just in this region.

It is obvious, that differences of the ice cover characteristics distribution in the ice massif periphery and kernel determine differences in the mean velocity distributions in these ice formations.

The ship velocity distribution for the massif periphery is complicated by its character (See Figure 6). It varied between 1 and 10 knots having mean value 5.7 knots.

The navigation in the massif kernel is characterised by a more stable velocity, its mean value being equal to 3.3 knots. The ship's velocity for the most part of the route in the massif kernel (64%) varied between 2 and 4 knots (See Figure 6).

It is typical, that the ship's velocity was less, than 2 knots, for 10% of total route extent for the considered ice formations. Movement with such velocity is most commonly carried out by attacks.

Data were chosen for illustration of ice condition and hull section influence on ice load values. This data were obtained by means of the pressure sensors, and they are the most informative ones. The sensors were located as follows: in the bow section near the cross-section 158 (approximately 10 m to the stern from fore perpendicular); in the middlebody near the cross-section 88 (practically at the midship). Ice pressure distribution laws of long duration just as for the ice passage capability analysis were estimated separately for three variants of movement: in the fast ice during the icebreaker piloting; self-contained movement in the ice massif periphery and in the massif kernel. Points illustrating results of measurement processing and curves smoothing these results are given in Figure 7. The ice pressure varies along the x-axis (MPa); frequency (i.e. number of observations with this pressure value divided by the total number of observations) varies along the y-axis. The measurements were carried out in discrete mode with frequency of sensor tests 100 Hz. Each plot is a result of sampling processing, and each sampling contains several millions observations. Smoothing was fulfilled by exponential function.

As it can be seen from Figure 7, the maximum pressure values were observed in the bow section for all the types of movement. This result is in a good agreement with popular opinion. It is also quite reasonable, that the ice pressure is higher for heavier ice conditions. Attention should be drawn to the fact, that the ice pressure in the middlebody increases more significantly for the movement in the ice massif in comparison with the piloting in the fast ice, than for the bow section.

It is obviously, that the maximum ice loads are of particular interest for practical purposes. The maximum measured pressure values are given in Table 1. Account must be taken of actual maximum dependency on ship movement duration in the ice conditions under consideration. Data on the distribution laws of long duration

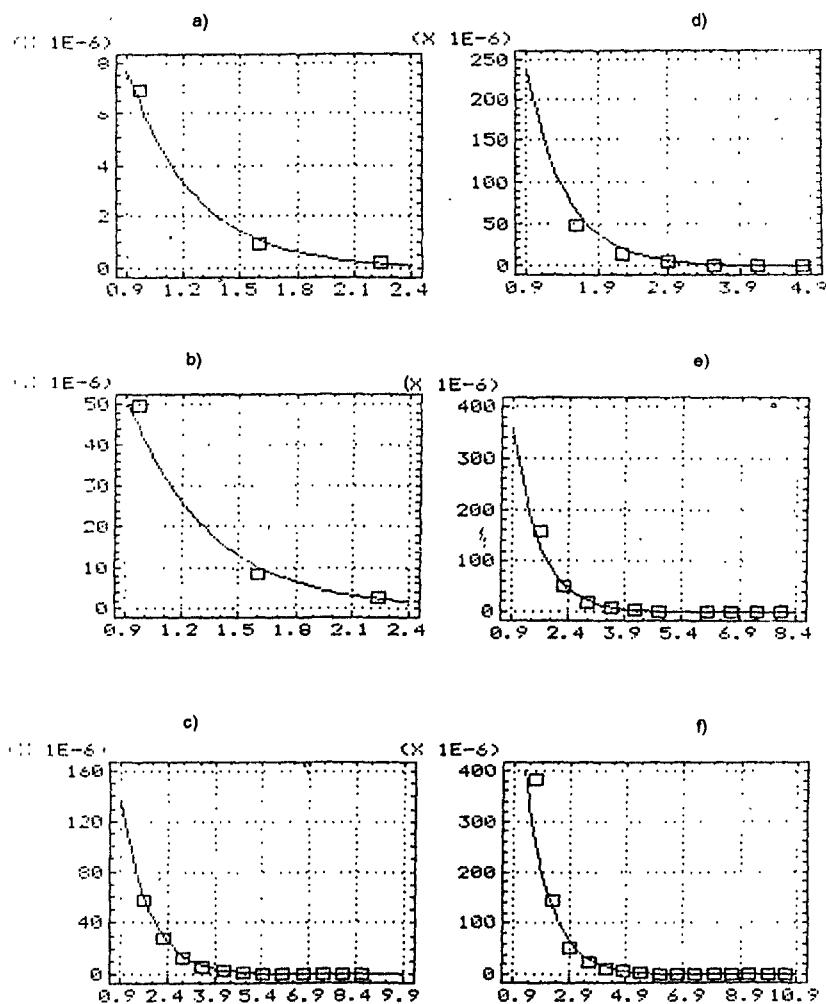


Fig.7. Ice pressure frequency histograms:

a, b, c - pressure on the plating in the vessel middle region;

d, e, f - pressure on the plating in the vessel bow region;

a, d - movement in a channel through fast ice;

e - movement through periphery of the ice massif;

c, f - movement through the ice massif;

Ice pressure, MPa is along the x-axes; frequency is along the y-axes.

for load probabilities contain much more information. Approximations of distribution densities of the ice pressure are given in Figure 7.

Table
The Maximum Measured Values of the Ice Pressure, MPa.

Conditions of movement	Bow section	Middlebody
In fast ice piloted by icebreaker	4.80	2.24
Self-contained in ice massif periphery	8.00	2.24
Self-contained in ice massif kernel	10.56	8.64

5. Conclusions.

Fulfilled analysis of data, which were collected in the course of the expedition in the summer of 1994 on the ice passage capability of "Akademik Fedorov" and on the ice loads on its hull, allows us to make the following conclusions.

1. Piloting of the ship of the "Akademik Fedorov" type in the fast ice with the ice thickness along the route up to 120 cm and the amount of hummocking up to 2 arbitrary units along the broken earlier channel is realised with the mean velocity 9 knots.

2. The self-contained ship's movement in the periphery of the ice massif with the ice concentration up to 90%, the prevailing ice thickness up to 120 cm, the amount of hummocking 2.5-3 arbitrary units, the melting stage 2 arbitrary units is realised with the mean velocity 6 knots.

3. The ship's movement in the ice massif kernel for the case of ice concentration increase up to 90-100% and increase of amount of the ice with the thickness exceeding 120 cm is unstable by its character. The mean ship's velocity equals 3 knots.

4. Ship of this class in self-contained navigation moves about 10% of route extent by attacks.

5. The estimates of the ice passage capability obtained during this expedition correspond to summer period (period of ice melting).

6. The probability densities of the ice pressures on ship's hull of long duration are well approximated by the exponential function with the exception of small values of this characteristics (up to 1-1.3 MPa).

7. Presence of clearly pronounced relation between the ice loads the ice conditions and the hull section was approved. Qualitative estimate of this relationship was obtained for the self-contained navigation and for the icebreaker piloting for different ice conditions.

8. Dock inspection of the ship's hull fulfilled after the expedition indicated, that strength of ice belt constructions is sufficient for "Akademik Fedorov" navigation in the Arctic, because plastic deformations of plating and framing in this regions were practically negligible.

References.

1. Gudkovitch, S.M., Kirillov, A.A., Kovalyov, Ye.G., Smetannikova, A.V., Spitchkin, V.A. " Method foundations of long-term ice forecasts for the Arctic seas". 1972, Leningrad, Hydrometeoizdat, 348 p.
2. Buzuev, A.Ya., Fedjakov, V.E., "Variability of ice conditions along navigation route", 1981, Moscow, Meteorology and Hydrology, N 2, pp. 69-76.
3. Gordienko, P.A., Buzuyev, A.E., Sergeev, G.N. "Study of sea ice cover as navigation environment", 1967, Leningrad, Problems of the Arctic and Antarctic, v.27, pp. 93-104.

**PREDICTION OF ICE LOADS
ON A WIDE ICE-RESISTANT STRUCTURE**

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ABSTRACT

At many typical situations the structure-ice cover interaction begins through local ice crushing resulting finally in the formation of sectors due to ice bending. The sector formation mode under floating ice cover edge bending is observed for a wide range of failure processes and properties of ice at ice cover break-off near by obstacle (for large size of obstacle $d/h > 10$). This interaction process (and the observed loads) can be theoretically considered by the only approximate way - with a help of subdivision of the whole process on to a few characteristic scales of consideration.

The results of sensitivity analysis of ice load acting on an ice-resistant structure to the contact failure mechanism are presented. Numerical calculations were performed by three-dimensional boundary element modelling of some characteristic failure process sequences of ice cover deformation and failure near by a structure. Geometric and force parameters of interaction processes are determined on the basis of conjugate numerical solution for some sequence of scales, which are typical for sector fracture of ice cover edge.

INTRODUCTION

An interaction of ice resistant structure with floating ice cover causes a number of special problems related to the ice failure processes. The main failure processes include local crushing of ice near the structure, ice cover bending failure, formation of ice pile-up against the structure or ice ridges during ice interaction. The main

parameters affecting these processes are ice thickness, movement velocity of ice field, ice mechanical properties, friction between structure and ice etc.

In typical situations all these failure modes interact, thus the general situation is multi-scaled. As result it could be analysed as a series of interconnected sub-problems corresponding to the appropriate scales.

The approach of Goldstein and Osipenko, 1983, chosen for the study of multi-scale deformation and failure of ice cover at interaction with ice-resistant structure, interprets the general failure process as a combination of a various sub-processes of different scales of geometric and force parameters.

The report is connected with investigation of floating ice cover failure under interaction with wide structure (the ratio of characteristic size d of structure to ice thickness h is greater than 30 - the region of parameters, which is very difficult for the study).

To simplify the general problem let us assume that an ice cover is a piece-wise isotropic plate (on a hydraulic foundation) and it's deformation is linearly elastic. This is convenient at the case of comparatively high strain rate, when the time of the individual acts of ice cover failure is much smaller than the relaxation time for corresponding scale of interaction. The further simplification is ensured by the assumption of quasi-static deformation of an ice cover.

Even at the assumptions and the simplifications involved the closed analytical solution for many problems of practical interest is often impossible; therefore the numerical methods of solid mechanics (especially 3D boundary element software, developed at the IPM/RAS) are used. These methods give the possibility to analyse specific ice failure modes depending on various geometric and force factors by relatively chip way (see, for example, Danilenko and Rogachko, 1991).

GENERAL DESCRIPTION

At many typical situations the structure-ice cover interaction begins through local crushing of ice resulting finally in the formation of sectors due to the bending of ice. The sector formation mode under floating ice cover edge bending is observed for a wide range of failure processes and properties of ice at ice cover break-off near by obstacle (for sufficient size of obstacle $d/h > 10$).

A natural explanation of the sector formation is the buckling of floating ice field. The line load q required to cause the buckling of a half-infinite beam on an elastic foundation can be calculated with the equation (Heteny, 1946):

$$q = \sqrt{h^3 \frac{\rho g E}{12(1-\nu^2)}} \quad (1)$$

where h is ice thickness, E -elastic modulus, ρ -water density, ν -Poisson ratio. The depth of the sector separated from the ice field can be approximated by calculating the half wave length l of buckling failure:

$$l = \pi \left[\frac{Eh^3}{12(1-\nu^2)\rho g} \right]^{1/4} \quad (2)$$

But the measured at field conditions or during ice basic tests load values are typically lower and sector depth is smaller than obtained with equations (1)-(2).

The ice cover is obviously modelled in ice engineering problems by ice plate, located in the x - y plane (Fig. 1) on elastic foundation (see, for example, Saveliev, 1963). The bending (vertical) P and compressive (horizontal) N loads act on the straight-linear plate edge. Then the ice cover deformation under action of engineering structure is similar to the behaviour of corresponding beam (of the unit width, infinite length along y -axis, loaded on a free edge). The differential equation for the deflection f (along vertical axis z) is

$$EI \frac{d^4 f}{dz^4} = -P \frac{d^2 f}{dz^2} - Rf \quad (3)$$

where I is the corresponding moment of inertia, R is the coefficient of elastic foundation rigidity for floating ice (about 10 kN/m^2 for fresh water).

Taking into account the corresponding boundary conditions one can write the formula for the bending radius r of a floating ice plate:

$$r = \frac{\pi}{4} \left[\frac{(25P^2 + 196EIR)^{1/2} - 5P}{28EI} \right]^{-1/2} \quad (4)$$

Unfortunately the straight-linear configuration of contact plate edge is observed only at the early stage of interaction. It is more complex - as result of local ice edge crushing, sector fracture of ice cover edge, etc., and the corresponding beam approach is not correct.

One can see that for various loads P (smaller than ice compression strength) the difference between corresponding bending radius of ice cover (for ice thickness about 1.25 m) doesn't exceed 1.0 m, that is 4% of the bending radius. This constancy of the geometry of bending determines (in the frame of failure mode) the analogies of mechanisms and geometry of failure. In particular, one can consider the geometric parameters of sectors being nearly constant and at the case quasistatic loading, closing to the bending radius.

Let us mention that - according to numerous field observations, at the ice thickness near by 1 m or greater the region of contact failure, preceding the individual sector formation, is of a small (near by ice thickness) size - relatively the sector length. Thus the contact failure processes (flaking, crushing) occur in general on the ice edge lodges, formed on the preceding stages of break-off (it is the result of the fact that the effective contact ice strength is much greater of uni-axial compressive strength). The forming sector geometry is strongly characteristic - it was observed in the field conditions by Kashtelian et al. (1968), that the ratio of the sector length to the sector width is near by 4:6 (at the case of ice thickness about 1 m) with the typical angle of lodge sharpening between sectors about 120° .

As a result of these processes, the ice cover edge geometry is very complex and the interaction process (and the observed loads) can be theoretically considered by the only approximate way - with the help of subdivision of the whole process on a few characteristic scales of consideration

THE EXTERNAL SCALE

It is the scale of the elongated ice field interaction with a wide structure. At this scale the floating ice field is considered as a linear-elastic plate on a hydraulic foundation, loaded by large-scale forces (wind, flow, etc.) and by averaged contact loads - from an ice-resistant structure. The stress state of floating ice field at this scale determines the corresponding boundary conditions for smaller scale. One can point out two different cases - freezing and non-freezing contact between ice cover and structure. The first one is connected with the initial stage of sector formation mode in the freezing ice cover. In particular, the initial sectors are formed under transversal loading at the region of contact failure; at the rest part of contact the coupling is observed.

The corresponding model task represents loading of half-space by uniform compression at the plane of ice cover (with value near by compressive strength of ice) and in the transversal direction on a plane with length, determined by values of limit tractions under tension (or compression) at the region of possible sector formation. The rest part of contact edge is clamped (displacements are absent).

If the contact freezing is absent (normally the situations corresponding to the steady state of sector formation), the external scale problem is modelled by a plane contact task for elastic loading of half-space (punch problem). But numerical methods strongly extends the region of possible parameters.

In turn, after solution of the external and intermediate problems the total load on an engineering structure is calculated by corresponding summation of separate sector parts, determined in the frame of intermediate problems along the contact edge of an ice cover.

THE INNER SCALE

The inner scale of the problem under consideration is connected with processes of contact ice failure on the contact edge of an ice field. They are strongly dependent upon the specific geometry of the contact edge of an ice cover, which often is not flat but has more complex form (for example, convex one). Moreover, there are the planes of direct contact between structure and un-failed parts (ledges) of an ice cover; and the other ones where loads are transferred over products of ice, failed at the previous

stages of interaction (e.g., as a result of sector break-up of an ice cover near by structure surface).

More specific approach to the study of local contact processes reported by Kujala et al., 1993, Danilenko and Goldstein, 1994.

In the present report the local traction presentation is performed in general, taking into account friction and failure processes on the contact edge of an ice cover. In particular, the ratio P/N of horizontal and vertical load components on the contact edge of an ice cover is from 0 to 3.1 for declination angle of the ice resistant structure surface 60° , and from 0 to 12 for 90° .

THE INTERMEDIATE SCALE OF A SEPARATE SECTOR

This scale, connected with sector failure of the contact edge of an ice cover, is determined by the size of a separate sector (Fig. 1). The ice thickness for all problem under consideration is equal to 1.25 m; the bending radius is about 18 m. As a result of a stress state symmetry relatively to the vertical planes, going through the centre of contact place and through the centre of sector, the transversal size of the main element is equal to the bending radius r . The longitudinal size is equal to $2r$. The test calculation data for rectangular ice cover element (wide beam), demonstrate the satisfaction of these sizes. The element is clamped far from contact edge. The loads on side edges are determined by the conditions of concordance with neighbouring sectors.

There are sector hollows along contact edge of element, which represents part of a circle with radius $2r$ (or an ellipse with big axis $2r$). The ratio of sizes (transversal and longitudinal) of a sector hollow is equal about 2. The size of a contact place is estimated by comparison of the conditions for failure initiation on sector contour and for failure on contact place (or for initial stage of ledge break-off). This size is a part of the element width under constant ratio of transversal and longitudinal sizes of a sector hollow. The loads on this place models contact loading during contact failure of ice. They are determined as horizontal P and vertical N loads from the inner problem.

The calculated stresses σ_{yy} for plate without sector hollow under uniform contact loads ($P = 0$, $N = 1$) and ($P = 10$, $N = 1$) demonstrate maximal tension location at the distance about 17 m (the bending radius) from the loaded edge. These data show that defined geometric and load parameters are adequate for the problem under

consideration. According to theoretical analysis, the horizontal loading lowers the maximal bending stresses, but don't effects it's location.

The example of σ_{yy} and σ_{xx} stresses (the declination angle 70° , the longitudinal load $P = 5$, the transversal load $N = 1$) at the bottom surface is presented in Fig. 2 and 3.

3. On the basis of these results one can suggest the self-reproducing mechanism of ice cover edge failure under steady sector formation regime.

Let us estimate tension fracture initiation according to the criterion of maximal tension stresses at the case of sharp contact ledge (short contact edge with $l \sim 2$ m), when the stresses σ_{yy} near by contact ledge produce ledge break-off, and the next failure process locates on more longer contact place. Then (Fig. 3) the maximal tension stress is σ_{xx} , and failure initiates along the axis of symmetry of a sector hollow if the longitudinal load P is not very big (depending on the geometric parameters of the problem under consideration). A crack initiates at the bottom surface and propagates inwards an ice cover. Reaching the region of tensile stresses σ_{yy} on the bottom surface, this crack turns along x -axis and forms new sector. Thus the new sectors determine new contour of ice cover edge, close to initial one.

The analysis of the data demonstrates a possibility of such self-reproducing schemes at the case of the big longitudinal (horizontal) load P .

There are local failure sources at the locations of stress concentration on the top surface of an ice cover. They don't propagate into magistral cracks, but can lead to the break-off the formed sector on 2-3 parts. This process does not effect the total loading on the ice-resistant structure, but can change the kinematics of failure products.

The calculated data demonstrate the dependence of contact failure parameters upon boundary conditions of external loading and contact interaction (the output data of the external and inner problems).

ACKNOWLEDGEMENTS

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REFERENCES

Danilenko, V.I., and Goldstein, R.V., 1994, "Study of the Ice Cover Fracture by Boundary Element Methods", Proceedings of the 13th International Conference on Offshore Mechanics and Arctic Engineering, the CIS Arctic Development Workshop, February 27-March 3, 1994, Houston, USA.

Danilenko, V.I., and Rogachko, S.I., 1990, "Numerical and Experimental Investigation of Plane Ice Fields Interaction", Mechanics of Solids, N.6, pp.186-190 (in Russian).

Goldstein, R.V., and Osipenko, N.M., 1983, "Some Aspects of Fracture Mechanics of Ice Cover", Proceedings of the 7th International Conference on Port and Ocean Engineering, 1983, Helsinki, Vol.3, pp.132-143.

Hetenyi, M., 1946, "Beams on an Elastic Foundation", The University of Michigan Press, 255p.

Kashtelian, V.I., Poznyak, I.I., and Ryvlin, A.Ya., 1969, "Ice Resistance to Ship Motion", Shipbuilding Publ., Leningrad, 238p. (in Russian).

Kujala, P., Goldstein, R.V., Osipenko, N.M., Danilenko, V.I., 1993, "A Ship in Compressive Ice. Analysis of the Failure Process", 1993/M-165, 1993, Helsinki University of Technology, Otaniemi, Finland.

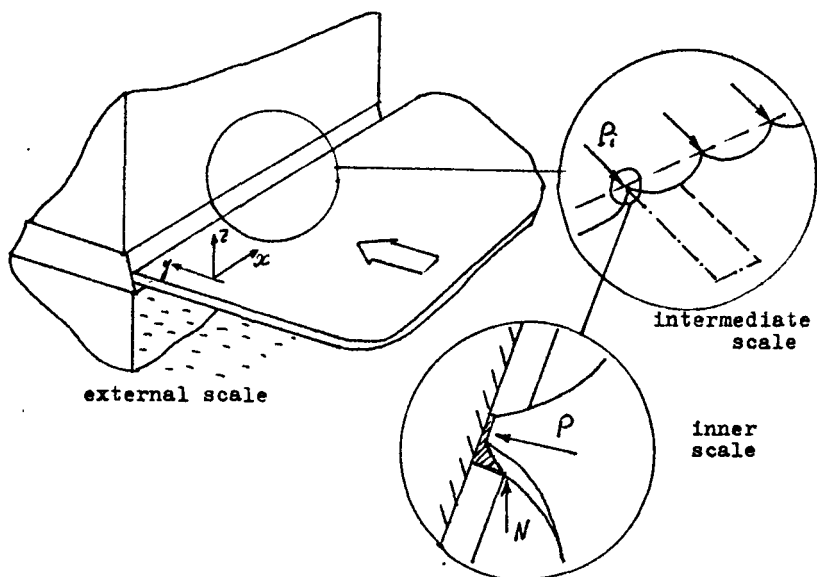


Fig. 1. The scheme of scale subdivision

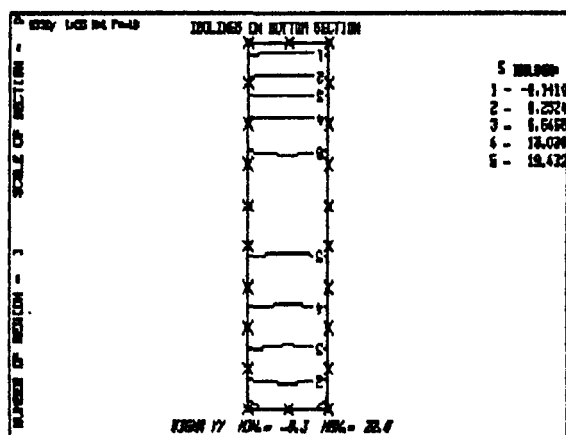


Fig. 2. The rectangular ice plate on a hydraulic foundation:
 $N=1$; $P=10$

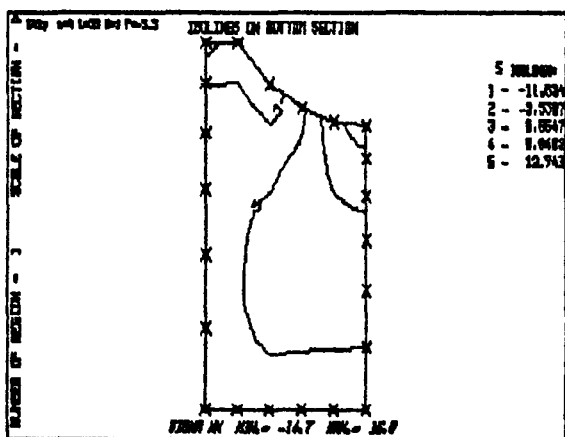
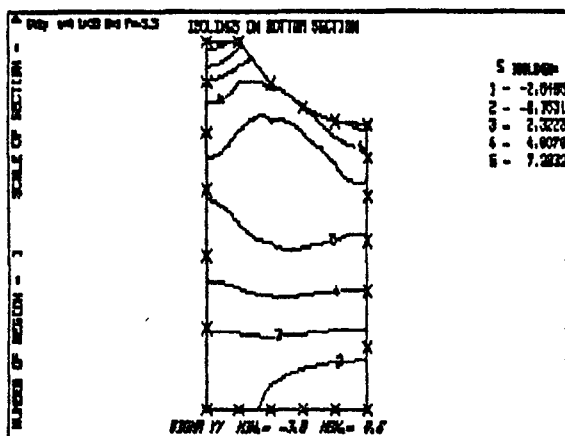


Fig. 3. The stresses σ_{yy} and σ_{xx} on the bottom surface: $N=1$; $P=5.3$

FREE VIBRATIONS OF AN ELASTIC ICE COVER WITH CRACKS, CHANNELS AND ICE RIDGES

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ABSTRACT

The paper is devoted to study of the self oscillations and edge waves in a nonhomogeneous ice cover. Ridges and cracks are considered as nonhomogeneities. Edge waves propagating along the ridge or crack represent the new type of waves on the fluid surface. They have no analogs in the case of the fluid with free surface. The energy of the edge waves is localized in the vicinity of the nonhomogeneity. The edge waves have exponential decay in the direction transverse to the nonhomogeneity.

1. INTRODUCTION

Among the characteristic types of nonhomogeneities of the ice field structure, one can mention ridges, cracks and channels. These nonhomogeneities have the strong influence on the ice cover dynamics and transfer processes in the system atmosphere-ice cover-ocean.

In particular, ridges and cracks can change the feature of the wave motions in the system fluid-ice cover. It is known that in ice covered seas flexural-gravitational waves can occur [1-3]. These waves can be induced, e.g., by the swelling waves incident from the open water or wind action along the ice cover surface. Features of the flexural-gravitational wave propagation depend on ice cover properties. This differs the flexural-gravitational waves from surface waves in a fluid with the free boundary.

The paper is devoted to study of the self oscillations and edge waves in a nonhomogeneous ice cover [4-7]. Ridges and cracks are considered as nonhomogeneities. Edge waves propagating along the ridge or crack represent the new type of waves on the fluid surface. They have no analogs in the case of the fluid with free surface. The energy of

the edge waves is localized in the vicinity of the nonhomogeneity. The edge waves have exponential decay in the direction transverse to the nonhomogeneity.

2. BASIC EQUATIONS

Linearized equations of potential motions with small amplitudes for a fluid layer with finite depth H can be written as follows

$$\left(\Delta\varphi + \frac{\partial^2}{\partial z^2}\right)\varphi = 0, \quad \eta > z > -H; \quad (1)$$

$$\frac{\partial\eta}{\partial t} = \frac{\partial\varphi}{\partial z}, \quad z = \eta; \quad (2)$$

$$\frac{\partial\varphi}{\partial t} + g\eta + \frac{p - p_0}{\rho} = 0, \quad (3)$$

$$\frac{\partial\varphi}{\partial z} = 0, \quad z = -H;$$

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right), \quad \Delta = \nabla^2,$$

where φ is the potential of the velocity, η is the height of the free fluid surface measured from the horizontal equilibrium position, x and y are the horizontal coordinates, z is the vertical coordinate, t is the time, p is the pressure in the fluid, and p_0 is the atmospheric pressure.

We will consider the ice cover using the above-mentioned model of a thin elastic plate. Such an approach yields [4]

$$p - p_0 = \frac{Eh^3}{12(1 - \nu^2)} \Delta^2 \eta, \quad (4)$$

where E , ν , and h are the Young modulus, Poisson ratio, and ice thickness, respectively.

Functions $\varphi(x, y, z, t)$, $p(x, y, z, t)$, and $\eta(x, y, z, t)$ in equations (1)–(4) are unknown, and the external pressure $p_0(x, y, t)$ is specified. To separate a unique solution of the problem, we should subject equations (1)–(4) to initial and boundary conditions.

When studying various problems, it may be of fundamental importance to consider solutions written in terms of the elementary waves that satisfy equations (1)–(4)

$$\varphi = Ae^{i\mathbf{kx} + \omega t} \cosh k(z + H),$$

$$\eta = -i\omega^{-1} Ake^{i\mathbf{kx} + \omega t} \sinh kH,$$

$$\mathbf{x} = (x, y), \quad \mathbf{k} = (k_x, k_y), \quad k = |\mathbf{k}|,$$

where ω and k are related by the dispersion equation

$$\omega^2 = \left(g + \frac{Eh^3}{12\rho(1-\nu^2)} k^4 \right) k \tanh kH. \quad (5)$$

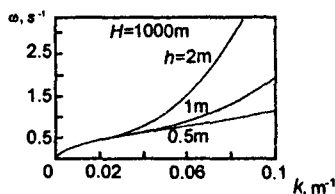


Figure 1. Dispersion curves for waves in fluid under an elastic ice cover.

Figure 1 shows the dependence $\omega = \omega(k)$ for various h at $H = 1000\text{m}$, $E = 3 \cdot 10^9 \text{N}\cdot\text{m}^{-2}$, $\nu = 0.33$, and $\rho = 1000 \text{kg}\cdot\text{m}^{-3}$ [5].

let us consider the problem on the existence of the real roots k_x of (1.5) at various frequencies ω . The dispersion curve given in Fig.1 shows that the each ray $0 < \omega < \infty$ is separated on two parts $l_1 = (0, \omega(k_y))$ and $l_2 = (\omega(k_y), \infty)$ at the fixed wave number $k_y = k$. The real roots k_x are absent in the region l_1 . Two real roots $\pm k_x$ exist in the region l_2 . The roots correspond to the monochromatic waves with the wave vector $\mathbf{k} = (\pm k_x, k_y)$. The segments l_1 at the different values of k_y fill the region below the dispersion curve $\omega(k_y)$. The below rays l_2 fill the region above the dispersion curve. It will be shown later on that the edge waves exist in the region placed below the dispersion curve. These edge waves propagate along the ice cover nonhomogeneity lying along the y -axis.

3. CONTACT - BOUNDARY CONDITIONS

In what follows, we will study bending and torsion vibrations of the ridge. Characteristic spatial scales of the vibrations significantly exceed sizes of the ridge cross section. We will model the ridge by a thin elastic rod. We assume that elastic properties of the ridge are only determined by the region where ice pieces have frozen together. At the same time, considering inertial properties of the ridge, we should take into account the entire volume of the ridge, including water between ice pieces [4].

We will study vibrations in the fluid-ice cover-ridge system with characteristic horizontal scales considerably exceeding the characteristic scale of the ridge cross-section by the vertical plane. Under these conditions, the ridge can be considered as a pointwise nonhomogeneity at $x=0$ in cross sections where vertical planes $y = \text{const}$ intersect the elastic plate under consideration.

The equation of bending vibrations of a ridge can be written as follows [5]

$$M_b \frac{\partial^2 \eta_0}{\partial t^2} + C_b \frac{\partial^4 \eta_0}{\partial y^4} - F^+ - F^- = 0, \quad (6)$$

$$C_b = E_b I_x.$$

Here, η_0 is the displacement of the ridge in the vertical direction; M_b is the whole mass of the ridge per unit length in the direction of the y -axis, including water between ice pieces; E_b is the Young modulus of the ridge; I_x is the moment of inertia of the cross-section in the frozen part of the ridge with respect to the horizontal axis that passes through the center of mass of the cross-section; and F^+ and F^- are the forces that act on the ridge from the deformed ice cover. The equation for torsion vibrations of the ridge can be written as [5]

$$C_t \frac{\partial^2 \phi}{\partial y^2} - I \frac{\partial^2 \phi}{\partial t^2} - M^+ + M^- = 0 \quad (7)$$

Here, ϕ is the rotation angle of the cross section of the ridge with respect to the equilibrium position, C_t is the torsion rigidity of the frozen part of the ridge, I is the moment of inertia for the total cross section of the ridge with respect to the gravity center of the frozen part, and M^\pm are the torsion moments applied to the ridge from the deformed ice cover.

In the regions where hummocks are joined to the plate, we should determine cutting forces F^\pm and bending moments M^\pm that act on the edges of the plate for $x \rightarrow \pm 0$. Forces and moments that act on the ridge from the plate are equal to $-F^+ - F^-$ and $-M^+ + M^-$, respectively [4]

$$F^\pm = \mp \frac{Eh^3}{12(1-\nu^2)} \lim_{x \rightarrow \pm 0} \frac{\partial}{\partial x} \left(\frac{\partial^2}{\partial x^2} + \nu' \frac{\partial^2}{\partial y^2} \right) \eta, \quad \nu' = 2 - \nu \quad (8)$$

$$M^\pm = - \frac{Eh^3}{12(1-\nu^2)} \lim_{x \rightarrow \pm 0} \left(\frac{\partial^2}{\partial x^2} + \nu \frac{\partial^2}{\partial y^2} \right) \eta$$

We assume that, in the regions where ridges are joined to the plate, displacements should meet the continuity condition,

$$\lim_{x \rightarrow \pm 0} \eta = \eta_0, \quad x = 0. \quad (9)$$

Furthermore, we assume that the moments applied to the edges of the plate satisfy the relation for elastic deformations,

$$M^\pm = \pm \alpha \lim_{x \rightarrow \pm 0} \left(\frac{\partial \eta}{\partial x} + \phi_0 \right). \quad (10)$$

Under these conditions, the moment applied to the edge of the plate is proportional to the variation in the angle between the middle line of the plate in the direction of the

x -axis and the axis that is rigidly connected with the ridge and coincides with the vertical direction in the undisturbed state.

For $M_b = C_b = C_T = I = \alpha = 0$ we can derive the contact-boundary condition for a symmetric wave that propagates along a fault with noninteracting edges [4],

$$M^\pm = F^\pm = 0. \quad (11)$$

Equations (6),(7) and (9),(10) we represent the contact-boundary conditions near the hummock ridge, and equations (11) will be named as contact-boundary conditions on the edge of the crack.

4. EDGE WAVES

Suppose that a fluid layer beneath an ice cover has an infinite depth. Let us introduce dimensionless variables, which will be denoted by symbols with primes (below we will omit these),

$$(x, y, z) = l(x', y', z'), \quad t = \omega^{-1}t', \\ l = (D/g)^{1/4}, \quad \eta = a\eta', \quad \varphi = a\omega l\varphi'.$$

Here, ω^{-1} and l are the temporal and spatial scales, respectively, and a is the wave amplitude.

We assume that, in dimensionless variables, the dependence of η on t and y is described by a factor $\exp i\theta$, where $\theta = \mu y + t$.

The nontrivial solution of (1)–(3) limited within the entire region of motion for $\gamma^2 < \gamma_0^2$ is given by [4]

$$\varphi = \frac{e^{i\theta}}{2\pi i} \int_{-\infty}^{\infty} \frac{P_3(k)}{\kappa(\gamma, \lambda)} e^{ikx + \lambda z} dk, \quad (12)$$

$$\eta = \frac{e^{i\theta}}{2\pi i} \int_{-\infty}^{\infty} \frac{P_3(k)}{\kappa(\gamma, \lambda)} e^{ikx} dk, \quad (13)$$

$$\kappa(\gamma, \lambda) = \gamma^2 - \lambda(1 + \lambda^4), \quad \gamma_0^2 = \frac{\omega^2 l}{g}$$

$$\lambda = \sqrt{\mu^2 + k^2}, \quad \gamma_0^2(\mu) = \mu(1 + \mu^4),$$

where $P_3(k) = d_0 + d_1 k + d_2 k^2 + d_3 k^3$ is the third-order polynomial with arbitrary constants d_i , which can be determined from contact-boundary conditions. Using residues in the upper and lower half-planes of the complex variable k to calculate integrals, we find

$$\eta = \sum_{l=0}^3 d_l \left[r_l(-k_0, \lambda_0) e^{\pm i k_0 x} + r_l(\pm k_1, \lambda_1) e^{\pm i k_1 x} + r_l(\mp k_1^*, \lambda_1^*) e^{\mp i k_1^* x} + \dots \right] e^{i\theta},$$

$$J_l^\pm = (\pm i)^l \frac{i\gamma^2}{\pi} \int_{\mu}^{\infty} \frac{n^l \sqrt{n^2 - \mu^2} e^{\mp nx}}{\gamma^4 + (n^2 - \mu^2) [1 + (n^2 - \mu^2)^2]} dn, \quad (14)$$

$$r_l(x, y) = -x^{l-1} \frac{y^2}{1 + 5y^4}.$$

The sign + corresponds to the region $x > 0$, and the sign - corresponds to the region $x < 0$.

Substituting (14) into contact-boundary conditions, we derive a set of homogeneous linear algebraic equations for d_l . As can be easily seen, the number of constants d_l in the solution (14) coincides with the number of contact-boundary conditions. The existence of nontrivial solutions to the set for d_l requires the determinant of the corresponding set to be equal to zero.

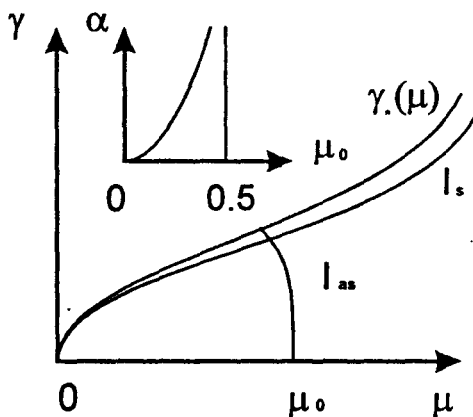


Figure 2. Typical dispersion curves for symmetric and antisymmetric free vibrations of a hummock ridge.

When considering symmetric or antisymmetric waves, we should set in (14) $d_1 = d_3 = 0$ or $d_0 = d_2 = 0$, respectively. Substituting (14) into (6)-(10), we derive sets of homogeneous linear algebraic equations of the second order for $d_{0,2}$ and $d_{1,3}$. Let us employ Δ_s and Δ_{as} to designate the determinants of the sets for symmetric and antisymmetric waves, respectively. The condition of existence of nontrivial solutions is reduced to determining real solutions to the equations

$$\Delta_s(\gamma, \mu) = 0, \quad (15)$$

$$\Delta_{as}(\gamma, \mu) = 0. \quad (16)$$

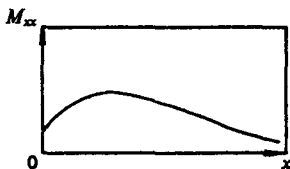


Figure 3. Typical dependence of the bending moment M_{xx} on the coordinate x for an edge of ice weakly fastened to a hummock. The coordinate x is defined as the distance between the hummock ridge and the point of observation.

Equations (15) and (16) provide dispersion relations between frequency of the edge wave and the corresponding wave number in the direction of the y -axis.

5. RESULTS OF NUMERICAL SIMULATIONS

We investigated the existence of solutions to (15) and (16) using numerical methods by scanning functions $\Delta_s(\gamma, \mu)$ and $\Delta_{ss}(\gamma, \mu)$ in the plane of γ and μ for $0 < \gamma < \gamma_*$. In so doing, we varied parameters D_b , D_t , m_b , m_t , and α of hummocks in accordance with an actual physical situation.

We considered an ice plate with parameters [5]

$$E \approx 10^9 \text{ N} \cdot \text{m}^{-2}, \quad \nu = 0.34, \quad h = 1 \text{ m}.$$

We assumed that the hummock is characterized by the following parameters [4]:

$$E_b \leq 10^9 \text{ N} \cdot \text{m}^{-2}, \quad E_t \leq 10^9 \text{ N} \cdot \text{m}^{-2}, \quad h_r = 1 - 5 \text{ m}.$$

Here h_r is the height of above-water part of ice ridge.

Formulas (2.1)-(2.5) yield the following estimates,

$$\begin{aligned} D_b &\leq 10^2, & D_t &\leq 10^2, \\ m_b &= 0.1 - 0.5, & m_t &\approx 10^{-2}. \end{aligned}$$

We performed calculations for $\gamma = 0 - 10$ and $0 \leq \alpha < 100$. Large α correspond to rigid fixation of the edge of the ice cover to the hummock. For $\alpha = 0$, the ice edge may freely rotate at the point of contact with the hummock. Curve l_6 in Fig. 4 displays a typical dispersion curve for symmetric waves near the crack or near the ridge.

Calculations show that symmetric waves may exist for small α and $\alpha = 0$. The corresponding typical distribution of the bending moment M_{xx} is shown in Fig. 3. As can be seen from the figure, M_{xx} reaches its maximum at a certain distance from the hummock at the point O_m . The influence of waves with sufficiently large amplitudes may result in destruction of the ice cover at this point, which forms a new hummock ridge under compression of ices. New hummock ridges will be parallel to the previously produced ridge that passes through the point $x = 0$. This mechanism accounts for the existence of parallel hummock ridges in sea ices.

Calculations show that antisymmetric edge waves exist only near the ice ridge. Figure 2 displays typical dispersion curves for antisymmetric waves. This dispersion curves have the beginning point $\mu_0(\alpha)$ on the axis μ . The dependence $\mu_0(\alpha)$ is performed on the Fig. 2. Point $\mu_0(\alpha)$ in Fig. 2 corresponds to the stationary solution of the problem with the frequency $\gamma = 0$. In the steady state, the elastic plate compensates the stress in the hummock, which is characterized by a nonzero angle of torsion around the inertia axis. Antisymmetric edge waves have anomalous dispersion. The corresponding group and phase velocities have opposite directions.

6. CONCLUSION

In the paper the properties of the edge waves, being the new type of waves in the system ice cover-fluid propagating along cracks or ridges were studied. The energy of the edge waves is localized near by the crack or ridge and this is their main feature. Hence, the lengthy cracks or ridges represent waveguides for the edge waves.

Edge waves can be excited in various processes at the ridge formation when the ice floe edges are overlayed forming tooth-shaped rafting [1], at the interaction of surging waves with cracks and ridges, at the wind action on ridges. One can wait that the spectrum of the flexural-gravitational oscillations of the sea ice cover is influenced by the edge waves [7].

A crack represents the limiting form of a channel in the ice cover when the channel width tends to zero. Contact-boundary conditions on the crack and channel edges are the same. In case of a channel a countable set of eigen oscillations localized near by the channel can exist as opposed to the case of a crack in the ice cover. One can wait that the presence of the eigen oscillations in the channel can influence the dependence of the wave resistance of a ship on the speed of its motion in the channel.

The typical dependence of the wave resistance coefficient of a ship on the speed of its motion in the channel with rigid walls and section of a finite area is given in Fig. 4. [8]. The wave resistance and wave action on the channel faces significantly increase when the ship speed tends the critical one, V_1 . At further growth of the speed up to the value V_2 the wave resistance continues to increase, however, slowly compared to the case when $V < V_1$. It was observed formation of a bulkwave and progressive ship floating up relative to its static position at $V_1 < V < V_2$. After transition of the critical speed V_2 , the bulkwave and ship floating up disappear. The wave resistance has minimum at a certain speed V_3 .

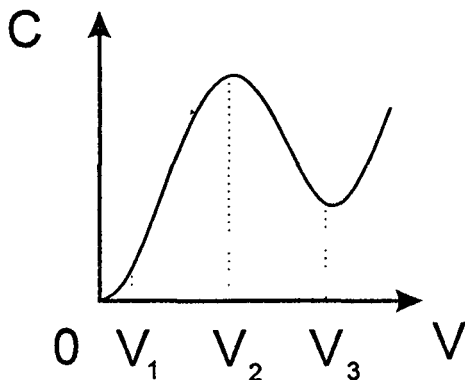


Figure 4. Typical dependence of the wave resistance coefficient of the ship of its motions in the channel .

The effect described above is connected with the resonant excitation of the eigen oscillations in the channels by the moving ship. The speed V_2 is close to the one of the first mode of the eigen oscillations. One can wait that similar features take place at the ship motion in a channel in the ice cover. In that case the critical speed V_2 will be connected with the edge waves in the system fluid-ice cover with channel respectively. Maximum of the wave resistance will take place at a certain critical speed. At the same speed the channel faces fracture by the waves propagating from the ship will be more intensive. These effects need to be studied both theoretically and experimentally.

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References

- [1] N.Zubov. Arctic ice (English translation). San Diego, California: U.S. Navy Electronic Laboratory, San Diego.
- [2] V.A.Squire, J.P.Dugan, P.Wadhams, P.J.Rottier, A.K.Liu. Of ocean waves and sea ice. *Annu. Rev. Fluid Mech.* 1995. 27:115-68.
- [3] A.V.Marchenko, A.Yu.Semenov. Edge waves in a shallow fluid beneath a fractured elastic plate *Fluid Dynamics*, Vol. 29, No. 4, 1994.

- [4] A.V.Marchenko, A.Yu.Semenov. Computetional of definite integrals in the Wiener-Hopf method by residue series summation. *Comp. Maths. Math. Phys.*, Vol. 35, No. 3, 1995.
- [5] R.V.Goldstein, A.V.Marchenko, A.Yu.Semenov. Edge waves in the fluid beneath an elastic plate with a crack. *Proc. RAS.*, Vol.339, No. 3, 1994.
- [6] A.V.Marchenko. Free vibrations of hummock ridge in an elastic ice cover floating on the surface of a deep water. *Fluid Dynamics*, Vol. 30, No.3, 1995.
- [7] L.D.Landau and E.M.Lifshitz. *Theory of elasticity*. Reading, Mass.: Addison- Wesley, 1965 (in Russian).
- [8] V.V.Bogorodsky and V.P.Gavrilo. *Ice: Physical Properties and Modern Methods of Glaciology*. Leningrad: Gidrometeoizdat, 1980 (in Russian).
- [9] Ia.I.Voitkunsky. *Resistance to ship motion*. Leningrad.: Sudostroenie,1988 (in Russian)

BEARING CAPACITY OR PENETRATION OF (RADIALLY) CRACKED ICE SHEETS

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Abstract: Some recent results concerning the mechanics of crack closure in a plate are discussed as well as several applications. The fundamental solution required is that for an elastic Kirchhoff-Poisson plate containing through-the-thickness or (part-through) surface cracks under closure. The cases considered include a single crack, a collinear system of cracks, and a radial system of a large number of cracks. Asymptotic solutions, remarkably accurate even for rather short cracks, are derived for cases in which the ratio of the crack length to its depth is large. Asymptotic expressions are obtained for distributions of the crack surface interaction force and moment, the contact strip width, and the contact stresses. For the radial crack system under a central lateral force, the crack growth stability and the limiting crack zone size are determined as well. For the single crack, it is shown that the crack surface interaction in-plane force and bending moment can be derived directly from the initial force and moment distribution acting in the intact plate on the prospective crack line. The same result is valid for a collinear system of cracks; this collinear system may include alternating open and closed crack segments. As is shown, the width of the contact strip decreases as the crack length increases; the limiting contact force and moment distribution may be determined by considering an edge-cracked strip with zero stress intensity factor. The asymptotic stress distribution obtained is unique and universal for any slowly curving crack or crack system under closure.

INTRODUCTION

One of the major difficulties in the analysis of either the bearing capacity or penetration of an ice sheet (Dempsey and Zhao, 1993; Sodhi, 1995a) is the treatment of the circumferential and radial cracking that occurs. The deformation of the wedge sectors, which are generated by the radial cracks at a load that is significantly below the breakthrough load, produces a wedging action (Sodhi, 1995b) that closes the radial crack faces on the compressive side of the plate. To date, the coupled plane-bending interaction of the radial crack faces has been ignored (Slepyan, 1990; Li and Bazant, 1994). Historically, the difficulties introduced by such crack closure phenomena have long been recognized (Jones and Swedlow, 1975; Heming,

1980; Hellan, 1984); however, a framework for the application of fracture mechanics to cracked plates subjected to closure does not yet exist.

The objective of this paper is to provide such a framework. With this in mind, the fluid support is but an unnecessary complication. The crux of the analysis presented in this paper is a rigorous specification of the closure parameters. The 'inner' or 'local' elasticity contact deformations in the vicinity of each crack closure region must be kinematically compatible with the 'outer' or 'global' plane-bending plate deformations. The formulation of the inner problem required that wide-ranging stress-intensity-factor and crack-opening-displacement expressions be provided for the edge-cracked strip subjected to

both an axial force and a moment. While the energy balance may be deduced from either local or global considerations, the derivation of the local energy-release-rate expression proved to be non-traditional. The analytical solution noted above facilitated not only the verification of the final local expression but also an analytical expression for the energy-release-rate from the assumed pseudo-axisymmetric array of radial cracks.

SINGLE CRACK CLOSURE

The single crack closure problem for a part-through surface crack in an elastic plate under bending can be formulated via the surface crack line spring model of Rice and Levy (1972). Their problem reduced to two coupled integral equations that was solved numerically for the case of semi-elliptical part-through crack. Rice and Levy (1972) also discussed various important simplifications. The coupled, plane-bending problem in the 'many' radial cracks formulation (via a pseudo-axisymmetric formulation) was considered by Hellan (1984) for a through-the-thickness crack in a finite elastic plate subjected to a central lateral force. Hellan's formulation presumed line contact at the compressive edge each radial crack face. Under the same assumption, a plate under bending containing a single crack and subjected to a uniform bending moment was recently considered by Young and Sun (1992, 1993); closed form solutions were presented.

These four papers are closely related to the topic considered by many concerning through-the-thickness crack problems for a plate under bending (they include a representative literature survey). In the papers by the authors (Dempsey et al., 1995; Slepyan et al., 1995), an asymptotic description of the mechanics of crack closure is constructed upon the foundation laid by Rice and Levy (1972), Hellan (1984), and Young and Sun (1992, 1993). For cases in which the ratio of the crack length to its depth is large enough, it is shown that the crack surface interaction in-plane force and bending moment can be derived based on the assumption of line contact at the compressive crack face. The contact area may be also considered as a uniform contact strip. At the same time, the contact stress distribution can be found based on the asymptotic nonuniform distribution of the contact strip width, and it is expressed as the product of the thickness averaged closure stress and a function of a normalized plate thickness coordinate

FORMULATION

Consider a cracked infinite elastic plate (Fig. 1a). The plate may be subjected to in-plane and trans-

verse forces as well as bending moments of general distribution. The loading is assumed to induce internal in-plane force and moments distributions that vary slowly (compared to the crack depth) in the intact plate on the prospective crack path. Further, there are no shear stresses in the crack plane. The crack is assumed to be either through-the-thickness or part-through; the latter surface crack being formed by the contact interaction of the through-the-thickness crack surfaces. Closure causes a zero stress intensity factor, except at the through-the-thickness crack tips. Nevertheless, almost throughout, the considerations are valid for a surface crack with a nonzero stress intensity factor.

Let the coordinates x_1, x_2 ($x_2 = 0$ on the crack) for the single crack problem, and the coordinates r, θ for the many radial cracks problem be placed in the plate middle plane, and x_3 be the transverse coordinate. The three-dimensional fields in the vicinity of the crack tips (in the x_1, x_2 , or r, x_3 - plane) are neglected. The title problem is comprised of three sub-problems. The first problem is a plane problem (x_1, x_3 or r, x_3 - plane) for an elastic layer containing a through-the-thickness crack (Fig. 1b) with a contact force, $S(x_1)$ or $S(r)$. This force is assumed to be applied in the middle plane ($x_3 = 0$). The second problem is a bending problem for a Kirchhoff-Poisson plate containing the same crack (Fig. 1c) with a contact-induced bending moment, $M(x_1)(M(r))$. The third problem is considered as a plane contact problem for an elastic layer containing a part-through surface crack (Fig. 1d) with a normal stress distribution, $\sigma(x_1, x_3)$ (in the axisymmetrical problem, it is $\sigma(r, x_3)$), acting on the continuation of the crack line, $-h \leq x_3 \leq h - a$.

THE CONTACT PROBLEM

In the closure region, the global planar and bending deformations of the thin plate are well described by the usual assumptions (for example, planes remain plane and perpendicular to the neutral axis). However, 'close' to the crack surface interaction area, the deformations can only be described by an 'inner' or 'local' elasticity solution. The stress distribution of the local problem differs from that for the global problem by a self-equilibrated stress field; the latter causes an additional crack opening displacement such that 'far enough' from each crack the actual physical extent of contact can be deduced by prescribing kinematic compatibility. The plane contact problem (Fig. 1d) describing the conditions in the closure region, similar to the paper by Rice and Levy (1972), relies heavily on the solution for an edge-cracked strip in plane strain subjected to an axial force S and moment M per unit thickness

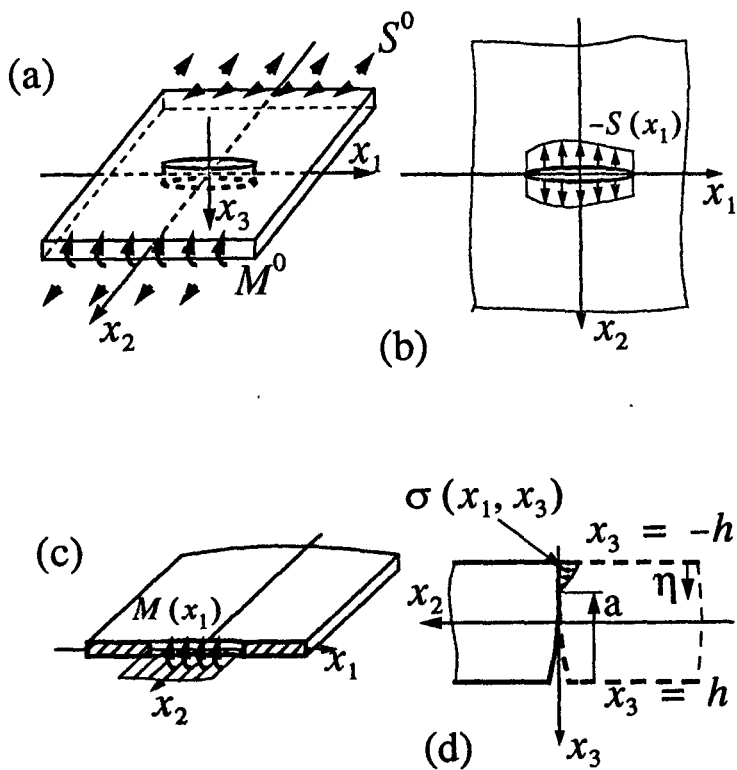


FIGURE 1. SINGLE CRACK CLOSURE

Following Rice and Levy (1972) the expressions can be written as follows (see Fig. 1d). If v and ϕ denote the additional displacement and rotation (Fig. 2a) of one end of the strip relative to the other due to the introduction of the crack,

$$\begin{aligned} v(x_1) &= \frac{1}{E'} \left(\alpha_{11}(\zeta)S(x_1) + \frac{3}{h}\alpha_{1m}(\zeta)M(x_1) \right) \\ \phi(x_1) &= -\frac{3}{E'h} \left(\alpha_{m1}(\zeta)S(x_1) + \frac{3}{h}\alpha_{mm}(\zeta)M(x_1) \right) \end{aligned} \quad (1)$$

in which $\zeta = a/2h$, while $a \equiv a(x_1)$. By elastic reciprocity, $\alpha_{\lambda\mu} = \alpha_{\mu\lambda}$. The quantities v , ϕ , S and M are the same as in the bending-plane coupled problem (4) or (5). In terms of the closure contact problem,

$$\begin{aligned} v(x_1) &= \frac{1}{2h} \int_{-h}^h u_2(x_1, 0^+, x_3) dx_3 \\ \phi(x_1) &= -\frac{3}{2h^3} \int_{-h}^h x_3 u_2(x_1, 0^+, x_3) dx_3 \\ S(x_1) &= \int_{-h}^h \sigma(x_1, x_3) dx_3 \\ M(x_1) &= \int_{-h}^h x_3 \sigma(x_1, x_3) dx_3 \end{aligned} \quad (2)$$

where $u_2(x_1, 0^+, x_3)$ is the crack opening displacement, and $\sigma(x_1, x_3)$ is the stress distribution in the closure strip. The asymptotic stress distribution for a narrow contact strip as $a \rightarrow 2h$ is presented below. If S^0 , M^0 and the crack length, 2ℓ , are given, the above equations together with the integral equations present the closed system of the equations for the problem under consideration.

The asymptotic solutions central to this point are achieved by first providing a wide-ranging ($0 \leq \zeta = a/2h < 1$) description of the coefficients, $\alpha_{\lambda\mu}$, as functions of the ratio $e_f(x_1) = M(x_1)/S(x_1)$. From Dempsey et al. (1995), it is apparent that the most suitable form is

$$\alpha_{\lambda\mu}(\zeta) = \frac{\pi\zeta^2}{(1-\zeta)^2} \Lambda_{\lambda\mu}(\zeta), \quad \zeta = \frac{a(x_1)}{2h} \quad (3)$$

where a is the crack length in this plane problem (in the coupled plane-bending problem, $a = a(x_1)$ is the depth of the crack opening). The compliance functions $\Lambda_{\lambda\mu}(\zeta)$ are defined fully in the paper by Dempsey et al. (1995).

INTEGRAL EQUATIONS FOR THE SINGLE CRACK

Consider the crack on the x_1 -axis: $-\ell < x_1 < \ell$, $x_2 = 0$ (Fig. 1). Using known fundamental solutions for plane and bending problems one can express

the force S_{x_2} and the moment M_{x_2} at $x_2 = 0^+$ by the superposition principle (in this case $S^0 \equiv S_{x_2}^0$ and $M^0 \equiv M_{x_2}^0$), giving

$$\begin{aligned} \frac{Eh}{\pi} \int_{-\ell}^{\ell} \frac{v(\xi)}{(\xi-x_1)^2} d\xi &= -S^0(x_1) + S(x_1) \\ -\frac{Eh}{\pi} \int_{-\ell}^{\ell} \frac{\phi(\xi)}{(\xi-x_1)^2} d\xi &= \dot{\nu}(-M^0(x_1) + M(x_1)) \end{aligned} \quad (4)$$

in which $\dot{\nu} = 3(1+\nu)/(3+\nu)h^2$, $-\ell < x_1 < \ell$ and S^0 and M^0 are the initial force and moment acting in the intact plate, and S and M are the crack surface interaction force and moment; v is the crack opening displacement, and ϕ is the crack face rotation (Fig. 6). Note that $S_{x_1}^0$ and $M_{x_1}^0$ exert no influence, as usual; in addition, it is assumed that the shear force $S_{x_1 x_2}^0$ and the twisting moment $M_{x_1 x_2}^0$ are both zero.

The inverse form of the integral equation formulation used by Rice and Levy (1972) can be derived from (4). They can be expressed for $x_1^2 < \ell^2$ as

$$\begin{aligned} v(x_1) &= \frac{\pi}{Eh} \int_{-\ell}^{\ell} [S^0(\xi) - S(\xi)] L(x_1, \xi) d\xi \\ \phi(x_1) &= -\dot{\nu} \frac{\pi}{Eh} \int_{-\ell}^{\ell} [M^0(\xi) - M(\xi)] L(x_1, \xi) d\xi \end{aligned} \quad (5)$$

Three different regions may be in existence along the crack line: crack closure, open non-contacting crack faces, and crack faces in full contact.

LIMITING CASES AND ASYMPTOTES

The nature of the problem under consideration depends, to a large extent, on the ratio $e_f^0 = M^0/S^0$. Different scenarios are outlined here that serve to identify the influence of e_f^0 .

Consider the case of a long through-the-thickness crack subjected to a compressive in-plane force initially located such that $0 \leq |e_f^0| \leq h/3$. In this case, $S^0 \leq 0$ and there is complete closure of the through crack. $a \equiv 0$, $v = \phi = 0$, and $\sigma(x_1, x_3) \leq 0$ is negative for $-h \leq x_3 \leq h$. The equations in (4) and (1) are satisfied by $S = S^0$, $M = M^0$ and by the fact that the parameters $\alpha_{\lambda\mu} = 0$ (since $\zeta = 0$). For this range of e_f , an intact infinite layer would experience only compressive stresses through the depth. Alternatively, consider the plane problem of two semi-infinite layers (of thickness $2h$) laid end to end and subjected to smooth compressive contact by far-field forces S^0 whose line of action is restricted to vary between $-h/3 \leq x_3 \leq h/3$. In this case, complete closure would again result and the above parameter values apply.

Consider next the case of either a long surface crack with $K = 0$ or a long through-the-thickness-crack under closure. The in-plane force and moment

combination is such that while crack opening takes place ($a > 0$), $h/3 < |e_f^0| < h$. As $l/a \rightarrow \infty$, the solution is simply that for the edge-cracked strip described above in (1) for $S = S^0$, $M = M^0$. In other words, while the quantities S , M , v and ϕ can be obtained and are functions of crack length $2l$, the limit as $l/a \rightarrow \infty$ exists. For long cracks and for $h/3 < |e_f^0| < h$, the solution is obtained by simply considering a plane problem (Fig. 1d). This solution is valid everywhere on the crack line except small (as compared to the crack length) vicinities of the crack tips, $x_1 = \pm l$.

Now consider the case $|e_f^0| \geq h$ which has no plane problem limit. This fact is readily apparent because the value of $|e_f| = |M/S|$ cannot be greater than unity. Clearly, given a zero stress intensity factor at $x_3 = a(x_1)$ and $e_f \leq -h$, the edge-cracked strip would not remain in equilibrium as $l/a \rightarrow \infty$. This leads directly to the conclusion that, in this coupled case, the interaction force S , and moment M cannot tend to the applied force S^0 and moment M^0 , respectively, as the crack length $2l$ increases. However, from (5), it is evident that in-plane (averaged) crack opening displacement v and rotation ϕ increase under a constant force, S and moment M , as the crack length increases. Under this increase, (1) can only be satisfied by an associated increase in the coefficients, $\alpha_{\lambda\mu}$. The latter is possible only if the ratio $|e_f/h|$ (generally less than unity) tends to unity. Thus, as the crack length increases the ratio $|e_f/h|$ tends to unity; the larger the value of l , the less the difference $h - |e_f|$. This is true everywhere on the crack line $-\ell < x_1 < \ell$ except in the vicinity of the crack tips ($x_1 \sim \pm l$), on a scale relative to the plate thickness.

Knowledge concerning the limiting behavior of e_f allows one to separate the plane contact problem (1) from the coupled plane-bending problem (4) (or (5)). First, note that the averaged crack opening displacement is zero at $x_3 = e_c$; that is,

$$\bar{v}(x_1, x_3) = v(x_1) - x_3\phi(x_1) = 0 \text{ for } x_3 = e_c \quad (6)$$

Clearly, $e_c = v/\phi$. To determine the limiting closure behavior for long cracks, the procedure is to first let $e_f = \pm h$, and hence, $e_c = \pm h$ in (4) [(5)], then substitute the crack opening displacement and rotation so obtained into (1) to find the difference, $h - |e_f|$. The closure behavior and associated stress distribution are determined in this manner below.

CLOSURE FORCE AND MOMENT DISTRIBUTION

Consider now the case in which $e_c = \text{const}$; that is, $v(\xi) - e_c\phi(\xi) = 0$ and from (4)

$$S(x_1) = \frac{S^0(x_1) + \nu e_c M^0(x_1)}{1 + \nu e_c e_f}, \quad M(x_1) = e_f S(x_1) \quad (7)$$

From this, neglecting any shortcomings in the crack tip regions, and assuming the crack segment under consideration to be subjected to closure, one can express the interaction force and moment as follows, given that $M = e_f S$, $e_f = -h$, $e_c = -h$,

$$S(x_1) = \frac{S^0(x_1) - \nu h M^0(x_1)}{1 + \nu h^2} \quad (8)$$

By the result in (8), the formulation by Young and Sun (1992), (νh , $e_f e_c = h^2$), is justified for long cracks. At the same time, note that such a formulation is valid not only for the case $M^0 = \text{const}$, $S^0 = 0$ but for a general distribution of the in-plane force, S^0 , and bending moment, M^0 , along the crack line. However, the crack does have to be long, and the variation has to be slow on the scale of the plate thickness.

Now consider a more general problem in which a (multi-segment) portion is subjected to closure. In this case, the difference $v(\xi) - e_c\phi(\xi)$ with $e_c = \pm h$ is nonzero only in the open crack segments (called hereafter 'open crack area' or OCA) because $v(\xi) - e_c\phi(\xi) = 0$ in the closure region. It is assumed that $e_c = \text{const}$ in the closure region; that is, either $e_c = +h$ or $e_c = -h$. This more general case may be described by

$$\begin{aligned} & \frac{Eh}{\pi} \int_{OCA} \frac{(v - e_c\phi)}{(\xi - x_1)^2} d\xi \\ & = \begin{cases} -S^0 - \nu e_c M^0, & x_1 \in OCA \\ -S^0 - \nu e_c M^0 + (1 + \nu e_c e_f)S, & x_1 \notin OCA \end{cases} \quad (9) \end{aligned}$$

where $e_c = e_f = \pm h$. The open segments may be viewed as cracks. Note that the difference $v - e_c\phi$ is zero in the closure segments and intact regions.

Now let there be a single open segment only; in this case, (9) can be solved (Slepyan et al., 1995) assuming S^0 and M^0 to be known. The interaction force outside of the 'crack' is thus given, for ($x_1 \notin OCA$), by

$$\begin{aligned} S(x_1) &= \frac{S^0(x) + \nu e_c M^0}{1 + \nu e_c e_f} \\ & - \frac{\text{sgn } x}{\pi \sqrt{x_1^2 - l^2}} \int_{OCA} \frac{S^0 + \nu e_c M^0 \sqrt{l^2 - \xi^2}}{1 + \nu e_c e_f} \frac{d\xi}{\xi - x_1} \quad (10) \end{aligned}$$

To solve (9) for several open crack segments, the equivalent of (5) for several collinear cracks must be used. Note that the transition points between the open and closed segments, excluding the 'real' crack

tips at $x_1 = \pm \ell$, must be associated with zero stress intensity factors at these points. This requirement serves to locate these points.

The solution in (7) and (8) for the closure force and moment distribution is independent of the crack tip coordinates and the evolution of the contact (closure) region. Therefore, this solution is valid for any collinear system of cracks with $e_f = h$ (or $e_f = -h$) over each crack (that is, each crack has to be long). Clearly, the limits $-\ell$, ℓ in the integrals in (4) need only cover the extent of closure, similar to the considerations in (9) with respect to the OCA. Then, if e_c is constant on the closure segments, the closure force and moment are expressed by (8) because $v - e_c \phi = 0$. Thus, in this case of a collinear system of cracks under closure, and the unilateral contact conditions on these long crack surfaces, the interaction is independent of the details of the actual crack lengths and spacing on this line. At the same time, the crack opening displacement and rotation depend on the specifics of the collinear crack distribution.

CONTACT STRIP WIDTH DISTRIBUTION

The above asymptotic equalities, $e_f = e_c = \pm h$, developed to describe the coupled plane-bending cracked-plate problem, are suitable for the determination of the closure force and moment, but are not suitable for the determination of the stress distribution in the contact area. With this goal in mind, it is first necessary to find the asymptote for the contact strip width $2h - a$, where a is the crack depth portrayed in Fig. 1d. From an asymptotic representation of the coefficients $\alpha_{\lambda\mu}$ in (1), Slepyan et al. (1995) revealed that the required contact width, $b(x_1)$, can be asymptotically expressed as

$$b(x_1) = 2h - a = 2h(1 - \zeta) = -\frac{\pi \Lambda_0 k_f}{E'} \frac{2hS(x_1)}{v(x_1)} \quad (11)$$

In this formula, the force S is defined by (8), and the displacement v can be found by (5)₁ for a single crack and a collinear crack system. Note that this asymptotic formula is valid in contact region(s) where $b/2h \ll 1$, and that it does not hold in the vicinity of the crack tips ($x_1 \sim \pm \ell$), where $v(x_1) \rightarrow 0$.

The contact width function b in (11) is shown in Fig. 2b for various values of the half-crack length to plate thickness ratio $\ell/2h$ ($\nu = 0.3$). The latter ratio is chosen to facilitate comparison with Fig. 11 in the paper by Joseph and Erdogan (1989). Fig. 2b is for the case of zero initial force and a uniform moment distribution: $S^0 \equiv 0$, $M^0 = M_0^0$, where $M_0^0 \neq 0$ is a constant. From (7), it is apparent in this case that $S = S_0$ is also a constant. Since S_0 also appears in the expression for $v = v_*$, in this particular instance, the closure force does not actually appear in the con-

tact width expression $b = b_*$. Noting that v_* is given by (5)₁ and that b_* is given by (11), it is found that

$$v_*(x_1) = -\frac{S_0}{Eh} \sqrt{\ell^2 - x_1^2}$$

$$\frac{b_*}{2h} = \frac{0.7554(1 - \nu^2) 2h}{\sqrt{1 - (x_1/\ell)^2}} \frac{1}{\ell} \quad (12)$$

As has already been discussed, the asymptotic expressions in this paper are expected to lose validity in the vicinity of the crack tips $x_1 \sim \pm \ell$. This remark notwithstanding, the agreement between the analytical result in (11) that is plotted in Fig. 2b and the numerical calculations plotted in Fig. 11 in the paper by Joseph and Erdogan (1989) is remarkable, especially for larger values of $\ell/2h$.

CONTACT STRESS DISTRIBUTION

Consider the closure contact problem (Fig. 1d) under the force, S , applied along the line of action $x_3 = e_f < 0$. The stress distribution can be expressed as

$$\sigma(x_1, x_3) = f\left(\frac{2h}{2h - a}, \eta\right) \frac{S}{2h - a}, \quad \eta = \frac{h + x_3}{2h - a} \quad (13)$$

In this qualitative expression, the crack depth a is defined by e_f . In terms of the η -coordinate, the extent of contact is invariable and remains equal to unity as $(x_3 + h)/(2h - a)$ tends to infinity under the condition $a \rightarrow 2h$. This limit corresponds to the contact of two elastic quarter-planes contacting along a zone of contact of unit length $0 \leq \eta < 1$ (Fig. 2c) under the force $S/(2h - a)$ applied at infinity along the line of action $x_3 = e_f$. The asymptotic closure stress distribution is a function solely of η and directly proportional to S/b , where $b = 2h - a$. Such a contact problem is the same as the corresponding problem for an elastic half-plane with a semi-infinite crack perpendicular to the surface (with a zero stress intensity factor). Significantly, the desired closure contact stress is unique and valid in general under the condition $b \ll 2h$.

Suppose the closure stress distribution, in terms of η , is denoted by $\Sigma(\eta)$ (as compared to $\sigma(x_3)$). This closure stress is well approximated by the simple expression

$$\Sigma(\eta) \approx 1.8(S/b)(1 - \eta)^{4/5}, \quad \sigma_{\max} \approx 1.8 \frac{S}{b} \quad (14)$$

A closed form solution to the closure stress distribution is available from the paper by Slepyan et al. (1995), who studied the problem of a semi-infinite crack lying on the bisector of an elastic wedge of angle 2α subjected to a far-field load and moment. The

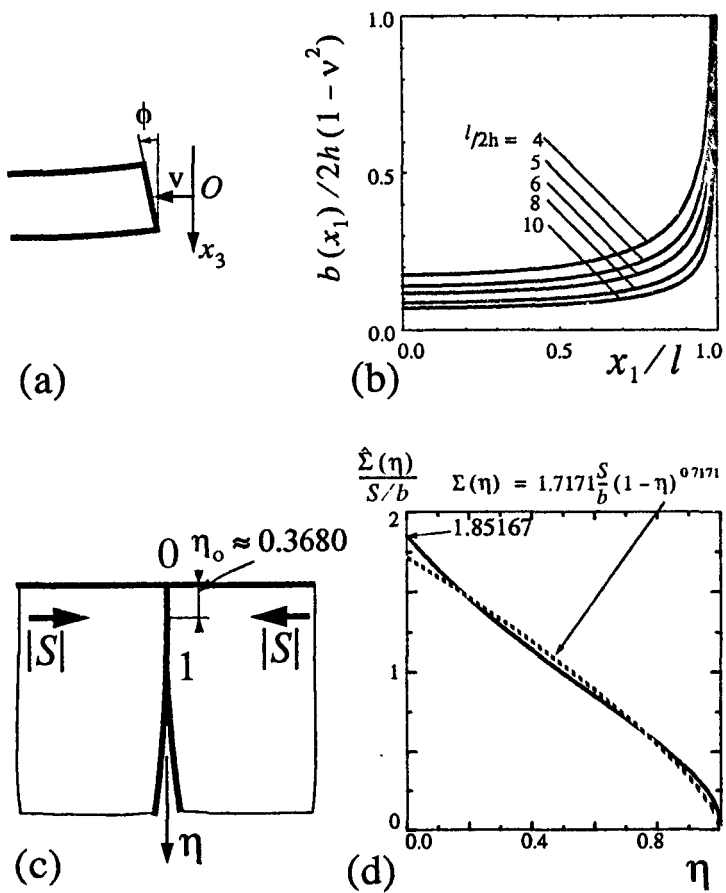


FIGURE 2. CLOSURE COORDINATES AND DISTRIBUTIONS

accurate closure stress distribution and the approximate expression in (14) are plotted in Fig 2d. Note that this asymptotic stress distribution is valid for a radial system of cracks as well as the single crack. In fact, this stress distribution is unique and universal for any slowly curving crack or crack system under closure with narrow contact width

RADIAL CRACKING

Progressive radial cracking of plates subjected to crack-face closure is studied. The same as above the cracks are assumed to be relatively long in the sense that the three dimensional contact problem can be described via a statically equivalent two-dimensional idealization. The number of cracks is supposed large enough to permit a quasi-continuum approach rather than one involving the discussion of discrete sectors (Hellan, 1984). The formulation incorporates the action of both bending and stretching as well as closure effects of the radial crack face contact. Fracture mechanics is used to explore the load-carrying capacity and the importance of the role of the crack-surface-interaction. For a given crack radius, the closure contact width is assumed to be constant. Under this condition, a closed-form solution is obtained for the case of a finite clamped plate subjected to a concentrated force. Crack growth stability considerations predict that the system of radial cracks will initiate and grow unstably over a significant portion of the plate radius. The closure stress distribution is determined exactly in the case of narrow contact widths and approximately otherwise.

Consider, briefly, vertical loading under a downward concentrated load: under increasing loads, a surface crack would initiate at the bottom of the plate. This crack would then propagate up through-the-thickness as well as radially. At some juncture, further cracking would ensue such that eventually a multiply-radially-cracked zone has been developed. This paper assumes at the outset that such a zone has developed. Ultimately, in the present scenario, circumferential cracking would be caused by tension on the top surface of the plate.

The crack face interaction that occurs after a number of radial cracks have 'popped in' produces a wedging action that allows the plate to carry an additional load (until circumferential cracking or penetration occurs). This wedging action, or crack face interaction, should be more evident for thicker sheets. Actually, the crack face interaction is a complicated three-dimensional contact problem. The contact pressure distribution is unknown and acts over an unknown area. The constraint that the contact pressure be positive (compressive) or zero, thus excluding tensile tractions on the crack faces, in itself makes

the problem nonlinear (even for small deformations and linearly elastic material behavior). In this paper, the contact strip width, as well as the closure stress distribution, is determined. The influence of the number of cracks is included in these calculations.

The classification of the closure contact situation (in the through-the-thickness direction) of the radial crack faces leads directly to several important generalizations. Since the contact is of the 'receding' type (Dundurs, 1975), the contact area changes discontinuously from its initial to its loaded extent and shape on application of the first increment of load. Further, if the nature of the loading does not change but increases in magnitude only, and if the cracked zone radius does not change, the extent and shape of the closure contact does not change. The final special property of receding contacts is especially important in the context of the problem under consideration in this paper: the intensity of the closure stress distribution will increase, without change in form, in direct proportion to the load.

The general problem under consideration is based on both the coupled plane-bending problem as well as the plane crack closure problem. The first sub-problem is viewed as an axisymmetric multi-sectored quasi-continuum thin plate problem. The latter is an elasticity problem which induces an additional self-equilibrated stress distribution on the crack surfaces. The 'inner' contact problem is matched to the 'outer' plate problem by matching the 'outer' circumferential extension and rotation (quantities that can be expressed in terms of certain averaged integrals of the inner crack opening displacement) with the kinematic (Kirchhoff-Poisson) requirement that planes remain plane and normal to the neutral axis. The latter kinematic condition is imposed over a horizontal 'plane' at $z = e_c$ in the cracked zone ($0 \leq r \leq R$, $0 \leq \theta \leq 2\pi$) on which the plate is considered to be rigid. In other words the axisymmetric 'zero circumferential displacement condition' is imposed only at one z value. Note that the associated value of e_c depends on the cracked zone radius R . An additional kinematic condition is specified to ensure rotational compatibility along the θ -lines bisecting each wedge sector formed by n radial cracks. The parameters e_f and e_c may be looked upon as 'outer' or remote loading and kinematic variables, respectively, while the crack length a in the thickness direction is the inner contact variable. It is especially important to note that the closed form solution is derived assuming e_f and e_c to be constant for a given cracked zone of radius R . The strength of the formulation then resides in the fact that e_f and e_c can (and do) vary with each and every radius R .

The solution development incorporates two areas: the crack closure area and the intact area. Disconti-

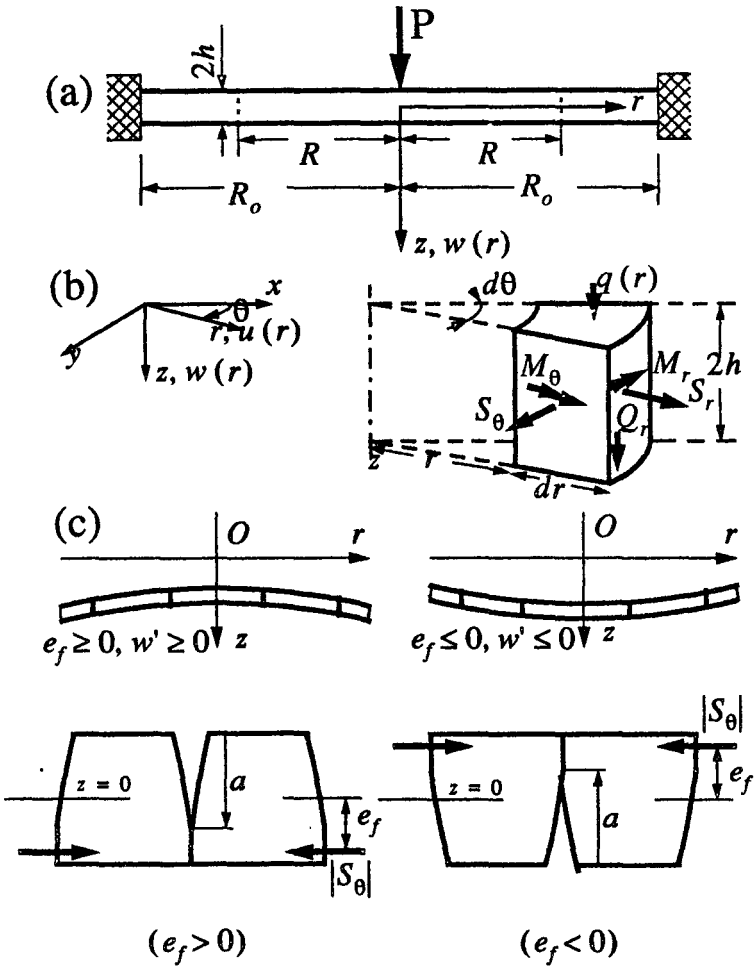


FIGURE 3. "RADIALLY CRACKED CLAMPED CIRCULAR PLATE"

nities or 'jumps' in M_θ and S_θ at the closure-intact interface produce the total energy release rate; the expression for the latter is derived by taking a variation of the crack closure area. This energy release is assumed to be uniformly distributed amongst a finite number of cracks. The latter number is assumed to be specified. In the following, the complete formulation of the problem is given. Different factors considered include the merits of a solution with no central hole (which at first sight might appear to be simpler) and the energy release rate obtained by the quasi-continuum formulation.

'FEW' VERSUS 'MANY' CRACKS

The viewpoint adopted in this formulation forms one extreme in which one supposes that the large number of cracks formed permits a quasi-continuum axisymmetric approach rather than one involving the discussion of discrete sectors. In this section, it is shown that this approach is plausible, even for rather few cracks

To this end, consider the plane star crack in an infinite elastic thin plate of thickness $t \equiv 2h$ with a central hole of a vanishingly small radius r_0 under the radial pressure $\sigma_r = -F/(tr_0)$. In this case, the force which acts at the vertex of each wedge in the star crack problem is given by $P_n = 2F \sin(\pi/n)$ where n is the number of the radial cracks; the number of cracks here is finite and no quasi-continuum axisymmetric assumption is required. The stress intensity factor for this problem is available on page 8.18 in Tada et al. (1985). The total energy-release-rate, denoted here by G_n , is given by

$$G_n = \frac{nK_I^2}{E} = \frac{4F^2 n}{t^2 ER} \sin^2\left(\frac{\pi}{n}\right) \left(\frac{2\pi}{n} + \sin\left(\frac{2\pi}{n}\right)\right)^{-1} \quad (15)$$

Now consider the same problem but let there be a large enough number of cracks such that the quasi-continuum axisymmetric assumption is tenable. It is easy to show that, under the latter formulation, the total energy-release-rate is equal to

$$G_\infty = \lim_{n \rightarrow \infty} G_n = \pi F^2 / (t^2 ER) \quad (16)$$

The ratio $\mathcal{E}_n = G_n/G_\infty$ turns out to be remarkably close to unity even for $n = 2$ (this is actually only one crack, and only in polar coordinates does it look as two cracks): $\mathcal{E}_2 = 0.811$, $\mathcal{E}_3 = 0.968$, $\mathcal{E}_4 = 0.991$; for higher n this ratio rapidly approaches unity (in fact, $1 - \mathcal{E}_n \sim \pi^4 / (45n^4)$ as $n \rightarrow \infty$).

This result reveals, at least in the case of plane crack problems, that the energy release rate may well be rather insensitive with respect to the crack number. Moreover, the quasi-continuum model may es-

timate the energy release rate rather well, and hence also the radius of the cracked zone.

A RADIALLY CRACKED CLAMPED PLATE

The quantities $w(r)$ and $u(r)$ denote the vertical and radial displacements of the plate in the central plane ($z = 0$) respectively, and $u_r(r, z)$ is the radial displacement for arbitrary z ($u(r) \equiv u_r(r, 0)$).

$$u_r(r, z) = u(r) - zw'(r) \quad (17)$$

Note that $w' \equiv dw/dr$. S_r and S_θ denote the in-plane radial and tangential forces, respectively, per unit length and M_r and M_θ denote the radial and tangential bending moments. In addition, let Q_r denote the radial shear force per unit length. In the equations to follow, E, ν, ρ, h denote the plate's Young's modulus, Poisson's ratio, density and half-thickness, respectively.

The radially cracked plate configuration (Fig. 3) is separated into the following regimes: the crack closure area (the inner region $r < R$), and the unbroken or intact plate (the outer region, $R < r < R_o$). The cracks are assumed to be uniformly distributed for $r < R$. The in-plane interaction force S_θ is compressive in the crack closure area. The formulation here prescribes that S_θ acts at $z = 0$. In addition to this in-plane force, a moment M_θ acts at the same radial location on $\theta = \text{constant}$. This force and moment are statically equivalent to the force S_θ acting at $z = e_f$ (Fig. 3c). The latter force is statically equivalent to the crack closure forces acting within the crack closure regime. The plate closure parameter e_f caused by the wedging action can occur either below or above the neutral axis, depending on whether the plate is subjected to uplift ($w' \geq 0$) or is being pushed down ($w' \leq 0$), respectively.

The solution to the problem is based on the relations for the Kirchhoff-Poisson bending plate. The key to the formulation is the coupling between the in-plane (u, S_r, S_θ) and out-of-plane (w, M_r, M_θ, Q_r) quantities (Fig. 3b). This plane-bending coupling occurs solely through the expressions for M_θ and e_f :

$$\begin{aligned} M_\theta &= -S_\theta e_f, & S_\theta &\leq 0, \\ e_f &= (u - e_c w')/r \\ &= (S_\theta - \nu S_r)/2Eh - e_c(M_\theta - \nu M_r)/EI \end{aligned} \quad (18)$$

where $I = 2h^3/3$.

An analytical expression for the central displacement of the plate (Dempsey et al., 1995) is remarkably simple:

$$\begin{aligned} EIw(0) &= EIw_o + \frac{PR^2(1+\nu)^2}{16\pi(1+\gamma)} \\ &+ \frac{PR^2}{4\pi} \left(\frac{b^2 - 2(1-\nu)\ln\zeta + (1-\nu^2)\ln^2\zeta}{(\zeta^2 + b^2)(1+\gamma)} \right) \end{aligned} \quad (19)$$

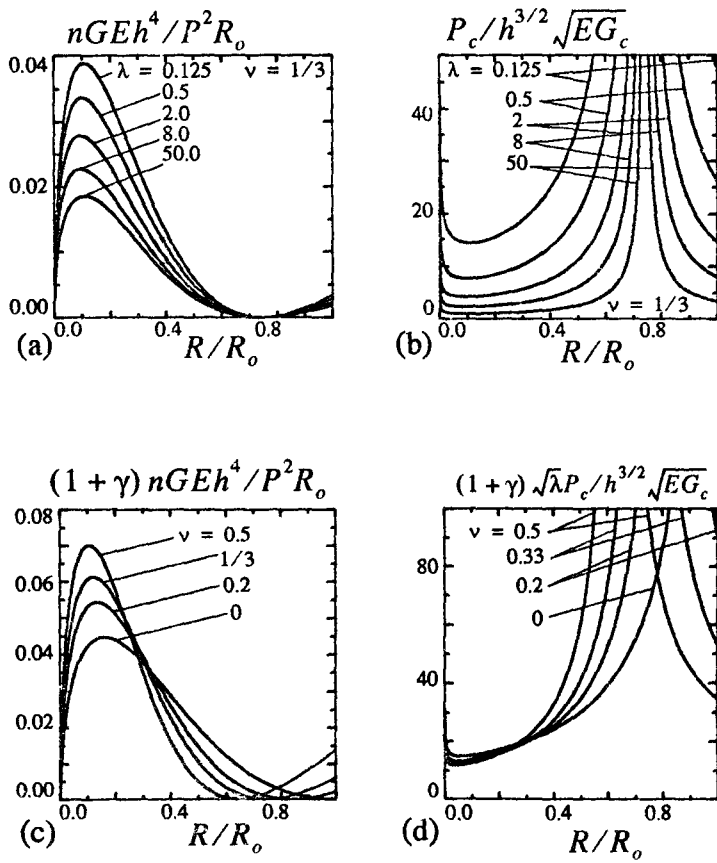


FIGURE 4. ENERGY RELEASE RATE G AND LOAD BEARING CAPACITY P_c

where u_0 is the central displacement of the intact plate, $\gamma = 3e_{c\epsilon_f}/h^2$, $b^2 = (1 - \nu)/(1 + \nu)$, $\zeta = R/R_0$.

In the formulation adopted, the energy-release-rate is found based on the axisymmetrical problem as the difference between the work done by the forces and moments which act at the $R + \Delta r$ and R boundaries of the annulus during this interface coordinate variation, from the one hand, and the strain energy increase at the same area under the variation, from the other hand. At the same time, a finite number of the radial cracks, n , is to be taken into account for the energy consumption calculation. Let G denote the energy-release-rate per crack in the radially cracked zone; presuming the formation or existence of n cracks, it follows from the model considered (Dempsey et al., 1995) that

$$nG = \frac{\pi R}{2h} \left\{ \frac{S_0(R^+)}{2Eh} [S_0] + \frac{M_0(R^+)}{EI} [M_0] \right\} \quad (20)$$

Significantly, the above expression differs from that in the paper by Hellan (1984). It is important to note here that (20) has been derived without specifying any relationship between S_0 and M_0 .

The plots in Figs 4a & 4b portray the normalized total energy release rate and the critical load, respectively. The unbounded behavior in the plot of the critical load (Fig. 4b) is directly associated with the zero energy release rate in Fig. 4c. A radius R_c ($R_c/R_0 = 0.7412$ for $\nu = 1/3$) at which $G = 0$ imposes an insurmountable barrier to crack propagation, as revealed by the critical loads tending to 'infinity' for various values of $\lambda = R_0/nh$ in Fig. 4b. Note in Fig. 4b that radially cracked zones smaller than a certain critical radius (hereafter called r_c) will propagate unstably. This extent of instability extends over increasingly larger distances, the higher the value of λ (and, qualitatively, the fewer the number of cracks). If the pre-existing cracked zone radius is greater than r_c , stable crack growth will be encountered at the outset. Eventually, however, crack growth stability will be experienced, and for relatively short crack lengths (compared to the plate diameter)

The unbounded behavior evident for very short crack lengths in Fig. 4b is indicative of the behavior discussed earlier in the paper in the section on localized loading. Regardless, radial cracking within a very small radius is patently unrealistic. Actually, considerations of surface cracks and slanted crack fronts are clearly involved.

Figs 4a & 4b reveal that the total energy release rate and critical load are significantly influenced by the value of λ ; for a fixed value of R_0/h , λ is proportional to $1/n$. The total energy release rate increases with the number of cracks (which is clearly expected)

and the load bearing capacity increases as the number of cracks increases. Once again, the load limiting mechanism will be circumferential cracking or penetration due to shear. Although it is not obvious, λ typically varies little in any specific practical scenario. In this case, the conclusion put forward in the section entitled 'Few' Versus 'Many' Cracks is found to be true.

The function $(R_0/G)(dG/dR)$, a widely used crack growth stability indicator (Gurney and Hunt, 1967; DeFranco and Dempsey, 1994), plotted versus R/R_0 reveals that the crack growth stability behavior is not influenced by closure effects. The normalized plots in Figs. 4c & 4d portray the significant dependence on Poisson's ratio; for $\nu = 0$ cracks can apparently propagate all the way to the clamped plate boundary.

FUTURE RESEARCH

Based on these results, it now remains to consider the role of fluid support in the case of an ice sheet, the influence of the crack number in the case of the radial crack system, and the configurational stability under conditions of crack closure. In the latter topic, the stability of the symmetrical configuration needs to be examined as well as the stability of bars and plates with the contact type of boundary conditions or interfaces. Ice-ridge formation and propagation is of course an example of such a problem in the nonlinear crack closure mechanics framework.

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REFERENCES

- DeFranco, S. J. and Dempsey, J. P., 1994, "Crack Propagation and Fracture Resistance in Saline Ice" *Journal of Glaciology* 40, pp. 451-462.
- Dempsey, J. P., Adamson, R. M. and DeFranco, S. J., 1995, "Fracture Analysis of Base-Edge-Cracked Reverse-Tapered Plates," *International Journal of Fracture* (in press).
- Dempsey, J. P. and Zhao, Z. G., 1993, "Elastohydrodynamic Response of an Ice Sheet to Forced Sub-Surface Uplift," *Journal of the Mechanics and Physics of Solids* 41, pp. 487-506.
- Dempsey, J. P., Slepyan, L. I. and Shekhtman, I. I., 1995, "Radial Cracking With Closure," *International Journal of Fracture* (in press).
- Dundurs, J., 1975, "Properties of Elastic Bodies in

- Contact" *Mechanics of Contact between Deformable Bodies*, de Pater, A. D. and Kalker, J. J., ed., Delft University Press, pp. 54-66
- Gurney, C. and Hunt, J., 1967., "Quasi-Static Crack Propagation," *Proceedings of the Royal Society*, Vol. A361, pp. 254-263.
- Hellan, K., 1984, "An Asymptotic Study of Slow Radial Cracking," *International Journal of Fracture*, Vol. 26, pp. 17-30.
- Herning, F. S., 1980, "Sixth Order Analysis of Crack Closure in Bending of an Elastic Plate," *International Journal of Fracture*, 16, pp. 289-304.
- Jones, D. P. and Swedlow, J. L., 1975, "The Influence of Crack Closure and Elasto-Plastic Flow on the Bending of a Cracked Plate," *International Journal of Fracture*, 11, pp. 897-914.
- Joseph, P. F. and Erdogan, F., 1989, "Surface Crack Problems in Plates," *International Journal of Fracture*, Vol. 41, pp. 105-131.
- Li, Y. N. and Bazant, Z. P., (1994), "Penetration Fracture of Floating Plate Ice: 2D Analysis and Size Effect," *ASCE Journal of Engineering Mechanics* 120, pp. 1481-1498.
- Rice, J.R. and Levy, N., 1972, "The Part-Through Surface Crack in an Elastic Plate," *ASME Journal of Applied Mechanics*, Vol. 39, 185-194.
- Slepyan, L. I., 1990, "Modeling of the fracture of sheet ice," *Mechanics of Solids* (translation of *Izvestiya AN SSSR: Mekhanika Tverdogo Tela*) 25, pp. 155-161
- Slepyan, L. I., Dempsey, J. P. and Shekhtman, I. I., 1995, "Asymptotic Solutions For Crack Closure," *Journal of the Mechanics and Physics of Solids* (in press).
- Sodhi, D. S., 1995, "Breakthrough Loads of Floating Ice Sheets," *ASCE Journal of Cold Regions Engineering* 9, pp. 4-22.
- Sodhi, D. S., 1995, "Wedging Action During Vertical Penetration of Floating Ice Sheets," *ICE MECHANICS - 1995*, edited by J. P. Dempsey and Y. D. S. Rajapakse (to appear).
- Il Tada, P. C. Paris, and G. R. Irwin, 1985, *The Stress Analysis of Cracks Handbook*. Del Research Group, St. Louis.
- Young, M. J. and Sun, C. T., 1992, "Influence of Crack Closure on the Stress Intensity Factor in Bending Plates -- A Classical Plate Solution," *International Journal of Fracture*, Vol. 55, pp. 81-93.
- Young, M. J. and Sun, C. T., 1993, "On the Strain Energy Release Rate For a Cracked Plate Subjected to Out-Of-Plane Bending Moment," *International Journal of Fracture*, Vol. 60, pp. 227-247.

THE RUSSIAN ICE- INFORMATION SYSTEM FOR THE ARCTIC

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ABSTRACT

The paper considers the questions related to hydrometeorological support to economic activities in the Arctic on the basis of the existing automated ice-information system for the Arctic (ALISA). The infrastructure of the system including the blocks of data collection, analysis and presentation to the users, the scheme and structure of the information flows, technology for its procession for the realization of purpose-oriented system functions is described. The questions of further improvement of the information system using modern technical means for information collection and analysis on the basis of high technologies in the medium of geoinformation software are discussed. Examples of output products of the ALISA system that are used for resolving specific applied and research objectives in the Arctic are presented.

In the middle of the 1970s the Arctic and Antarctic Research Institute (AARI) in cooperation with specialists developing means and methods for remote sensing sounding of the Earth, has initiated the work for creating the Automated Ice-Information System for the Arctic (ALISA).

The ALISA system which was used first as an experimental system from 1986 and from 1990 became fully operational, includes the Center of Ice and Hydrometeorological Information (CIHI) set

up at the AARI and the Territorial Administrations of Rosgidromet as the main operational structural divisions. This allows the users of all levels from the Ministries and Shipping Companies to the institutions and ships in the Arctic to receive meteorological and ice information, including short-range (one-three days) and medium-range (three-eight days) forecasts for the required zone, as well as for the whole of the Arctic Ocean areas if necessary.

The ALISA system uses the following sources of ice and hydrometeorological information:

- the Earth's satellites transmitting information on the underlying surface in the visible (TV), infra-red (IR) and radio (SHF) spectrum ranges;

- aircraft and helicopters of visual and instrumental ice reconnaissance;

- icebreakers and ships, polar stations;

- drifting ice and stationary automated buoys.

As a result of regular validation observations carried out at special polygons and in different expeditions, the information properties of satellite and airborne remote sensing means are determined and systems of interpretation indications are developed. It is found that the ice cover characteristics and their accuracy recorded by these means, are governed by their spectral ranges and resolution. For a sufficiently full description of the ice cover properties it is necessary to use a complex of means operating in different areas of the electromagnetic wave spectrum on different media.

Hence, composite charts of ice situation are compiled on the basis of all information obtained in the retrieval subsystem. A

methodological principle for preparing such charts is the use of all available information taking into account the information properties and accuracy of the geographical reference of data of each specific means.

Ice information procession in the ALISA Center is performed using professional and personal computers and developed software. The procession process includes automated geographical reference of satellite images and their partial automated interpretation compiling separate ice charts of actual (observed) ice situation, preparation of calculation-analytical composite ice charts using data on current meteorological situation, development of ice forecasts with different periods in advance.

The output information of the ALISA Center and the territorial centers (separate and composite ice charts, forecasts) are disseminated to users in the form of graphical charts by facimile communication channels in the letter-digital format "KONTUR".

The KONTUR format provides an automated input, storage and transmission of information on all variables characterizing the ice cover state, completely preserves the accuracy in delineating the boundaries of zones and the position of linear and point targets. At the information reception point when special software for IBM compatible computers is used, there is an automated reconstruction of an ice chart in a hard copy form. As compared to a facimile transmission, it is more noise-resistant and reduces the communication line load by 2-3 times. Thus, for the future it is advisable after equipping all users with personal computers and corresponding software to make this method of the information distribution the main one and to use the facimile

method as a reserve one.

Since detailing of operational charts, both separate and composite, is insufficient for choosing motion in the ice, it is reasonable to use satellite images received onboard an icebreaker or a ship in a self-contained voyage.

The AARI has developed a special portable reception station for satellite information which can be installed without any considerable assembling work onboard any icebreaker for the period of specific operation or activities on a complicated route segment.

Further improvement in the ALISA system is conducted in the direction of searching and introducing new technical means for data collection and procession, improving the automated methods for geolocation and interpretation of data, supplementing the results of direct observations by calculations, creating and maintaining operational and regime banks of hydrometeorological data, converting the system to geoinformation technologies. Thus, in the framework of updating a space system Meteor-3 for addressing the objectives of the system, operation of spacecraft equipped by a set of radiophysical instruments, including SLAR, is envisaged.

The AARI has developed and successfully tested in flight an airborne SLAR with a cm range and a high spatial resolution (5-7 m) and a swath width of 2 x 15 km. The station is equipped with a system for operational information procession, aboard aircraft (helicopter and light airplanes of the AN-2 type).

The AARI prepares for introducing into exploitation a receiving station for high resolution satellite information by radiochannel 1.7 GHz. Also, the CIHI of the AARI installed and

introduced into use a station for receiving data of Arctic buoys over the region of Western Arctic. The equipment has been supplied to the AARI in the framework of cooperation with the USA under the International Arctic Buoys Programme. The data on the buoy drift in combination with the sea ice drift vectors from satellite images (especially radar images) allow maintaining a dynamic chart containing data on ice compacting and diverging that are most important for navigation.

Currently, the creation of the geoinformation system of polar regions of the Earth (GIS PRE) has been initiated in the framework of the ALISA system. As basic software, the system Arc/INFO is used which is one of the leading information products at the world market and which is successfully used for work with spatially distributed data. This work aims at increasing timeliness, reliability and quality of hydrometeorological data provided to the user.

The ALISA system is also developed toward increasing a number of controlled environmental parameters, including creation of the ecological monitoring block. The technologies of remote sensing control of contamination and thermal state of water and ice surface are being developed.

The increased cost of renting aircraft under conditions of a relative decrease in financing resulted in a dramatic reduction of all airborne activities and even in complete termination of some of them, in particular, of regular ice reconnaissance. Hence, satellites have become the main remote sensing means for observations of ice situation in the seas and oceans.

As a result of processing satellite images in the visible, IR and SHF ranges, the following information on the ice cover

state can be obtained.

Thus, most of navigation characteristics and ice targets are identified by satellite data. However, some quite important characteristics (stages of development of first-year ice, snow cover, stages of melting, pressures) cannot yet be determined or are determined only under certain conditions. This governs the increased role of ice observations onboard icebreakers and ships which are obviously insufficiently used to date.

The Provision on Hydrometeorological Support to Arctic navigation should necessarily include the responsibilities of navigators to fulfil regular ice observations and report data to the Headquarters of Sea Operations where they should be generalized and reported to the HMC of the Arctic Administrations and the ALISA Center.

Also, the role of calculation methods which should supplement direct satellite observations increases. To enhance their accuracy and reliability, it is necessary to more fully use ice drift data and at the present time we pay a great deal of attention to this question. Using satellite images, especially radar images which do not depend on illumination and meteorological conditions, a regular drift determination is possible. Programmes have been developed that are used in research, methodological and regime studies. The technology for constant ice drift determination which provides tracking the history of the ice cover formation in each delineated zone is currently finalized to be included into operational activities of the Center.

Monte Carlo Simulation to Estimate Northern Sea Route Transit Time and Cost
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As part of a 18-month Reconnaissance Study, the U.S. Army Corps of Engineers constructed a Monte Carlo-based FORTRAN model to calculate transit time and costs for cargo shipments between Murmansk and the Bering Strait, using the Northern Sea Route (NSR). The Reconnaissance Study was intended to assess the potential of the NSR to benefit U.S. marine trade and to indicate which U.S. ports should be considered for improvements such as channel dredging and construction of breakwaters, ice control, or other harbor structures. Using the model, we compare the costs of shipping via the NSR with those of alternative routes, which then allows us to predict future commodity movements. The computer model is a way of organizing and quantifying the extensive data that were assembled during the study.

Interest in the NSR is currently high and there have, no doubt, been other efforts to model its utility. To our knowledge, however, there was no such software available in the public domain that could be used for our purpose. Some recent empirical data on NSR trafficability have been published by the International Northern Sea Route Programme (INSROP) and Russia's NSR Administration in an effort to foster greater international interest. These data have primarily been in terms of average ship speeds for various routes, months of the year, and broad categories of ice conditions. The problem with making projections based on these data is that few foreign ships have made the voyage and complete information on their experiences is not readily obtainable for analysis. To overcome the scarcity of data, we employ a Monte Carlo method to select the environmental conditions encountered on a voyage, and predict transit time based on expected vessel speeds under those conditions.

The Arctic and Antarctic Research Institute (AARI) in Russia has collected weather, ice, and oceanographic data in the Arctic Basin for many decades. Russian researchers have developed probability-of-occurrence relationships for a multitude of environmental parameters that affect polar navigation. These extensive data, published in atlases, monographs, reference books and articles are the cornerstone of our model. The large amount and form of the Russian data on the route's environmental conditions allowed us to construct a model that predicts NSR passage based on combinations of their probabilities of occurrence.

Our model lets the environmental conditions determine a base ship velocity which we then modify with slowing factors or the need for icebreaker escort. The base velocity is obtained from empirical estimates that are stored in lookup tables. This velocity and the slowing factors can easily be modified for ship types with different capabilities for sea keeping and ice navigation. The strength of our model lies in its ability to predict transit speeds for times of the year when few, or if any voyages have occurred. Predictions can be made if the modeled ship's speed is reasonably estimated for the range of conditions encountered on the NSR. These speed estimates can be based on NSR experience or on sea trials under similar conditions in other polar regions.

For each voyage, the ice, sea, and atmospheric conditions are used to determine the speed of a vessel between data and decision nodes along the route. Data nodes are mesh points where the navigation conditions are set for the next trip segment. These are generally spaced less than 250 nm apart along the commonly used shipping lanes. Decision nodes are similar to data nodes but with the additional feature of marking where two or more route choices exist; for example, where a choice is made to follow the coastal route or a more northerly variant. For each data node, we assembled probability distributions for ice thickness, concentration, and pressure, wind speed and direction, wave heights, occurrence of fog, snow storms, and topside icing. The magnitude of each condition, or the mere existence of each condition (in the case of fog, snowstorm, and icing) is established by a random selection, or a "roll of the die" based on its probability distribution. For example, if there is a 20%

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historical probability of fog occurring, then the random selection of fog is weighted 80% in favor of clear conditions. After a particular set of conditions is set, it is held constant for 8 hours or until the next node is reached, whichever occurs first.

The program proceeds in the following manner:

- 1) At each decision node, the choice of direction is first set by the probability-weighted roll of the die.
- 2) At every mesh point, a base ship speed is retrieved for whatever ice concentration and thickness is "rolled" by the die
- 3) This speed is reduced by a slowing factor to account for the weighted selection for ice pressure.
- 4) More severe ice conditions (e.g. 100% concentration or 1.5-m-thick ice at 75% concentration) will trigger the need for an icebreaker escort with its own overriding velocity.
- 5) The wind speed and direction are "rolled" and if ice concentration is less than 30%, then the wave height is also selected.
- 6) We then "roll" through the weighted probabilities of several parameters that affect visibility (fog, icing, and snow) to establish whether they are occurring. The code checks an internal clock to see if it is day or night. Slowing factors ranging between 0.5 and 1.00 are randomly selected for each of these visibility factors. Only the slowing factor having the greatest effect is applied.
- 7) Finally, the speed is adjusted to account for the permanent and wind-induced ocean currents.

Four different months were modeled to cover the easiest (August), intermediate (June and October), and most difficult (April) transit periods. Three different ice-strengthened ship types were modeled: a Norilsk-class multipurpose cargo ship, a Strelakovsky-class dry bulk freighter, and a Lunni-class tanker. We assumed an Arktika-class icebreaker escort in our simulations, but other types could easily be modeled. Travel east or west can be modeled.

For daily vessel costs, we relied on standard Corps of Engineers estimates of daily rates for conventional ships plying the conventional routes, which we modified to account for ice strengthening and Arctic operations. We assumed 20% greater capital costs, 25% greater average fuel consumption, and twice the insurance cost of warm water operations. These figures can be easily modified for different ships or as more NSR shipping information becomes available. Average transit time and cost were obtained by simulating a large number of voyages. The program takes approximately 2 mins to simulate 500 voyages on an IBM-PC 486-33 with a math co-processor.

Results show that non-stop transits from Murmansk to the Bering Strait during August (the easiest period of navigation) averaged about 14 days for the three ship classes, with a standard deviation of 1.2 days. The average vessel speed was 9.4 knots. About 20% of the time, an icebreaker escort was required. The current version assumes an icebreaker to be instantly available when needed. We have not programmed for in-port time or administrative delays that may occur. For our simulated April transits, voyages averaged 24.5 days, with a standard deviation of 1.8 days. This is the period when navigation conditions are most difficult, and an icebreaker escort was required approximately 90% of the time. Mean vessel speed for April was only 5.6 kn.

The model calculates transit times and costs for these extreme periods as well as for the marginal periods of June and October to allow commodity movement projections to be made for various lengths of shipping season. This work will enable the Reconnaissance Study to project U.S. port throughput based on 60-day, 120-day, and year-round NSR shipping.

We believe that our ice, sea, and atmospheric data are adequate to simulate the important environmental conditions that affect navigation. Weaknesses in the current version are shipping costs and speeds. For example, we did not include NSR fees and tariffs that may be assessed for foreign ship passage because they seem to be unsettled at this time. Our analysis includes only ship operating and ownership costs (including replacement of the vessel after its useful life) and therefore can only be a relative indicator at this time. We believe that our estimated vessel speeds are reasonable for the conditions expected but these could be improved with input from experienced NSR captains and ice pilots. Additional and more reliable information on these factors will enhance the model's overall result.

A SYSTEM OF SPECIALIZED ICE FORECASTS FOR SHIPPING IN THE ARCTIC

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ABSTRACT

Specialized ice forecasts are used for addressing specific goals of shipping in the ice. They include data on the expected ice conditions on the most favorable navigation route and take into account the influence of these conditions on operation of ships. A multilevel system of specialized ice forecasts with regard to generalization and advance period covers major directions in the organization of shipping in the Arctic and envisages a gradual detailing of ice and operating indicators with a decrease in the advance period of forecasts.

1. Introduction

The increase in the intensity and volume of transportation along the Northern Sea Route has required setting up a system for planning of sea operations. The prognostic information on the ice cover state has become the basis for planning shipping in ice. Along with traditional ice information for general use which represents the distribution of ice cover on the whole over the seas or a forecast for ice phenomena at specific points, the AARI develops the direction of specialized ice information for shipping.

This information presents a set of ice, operating and ice-navigation indicators reflecting ice conditions on the route of ships and a quantitative assessment of the effect of these conditions on the success of different navigation types [5].

2. Specialized ice forecasts for shipping

The need for forming a new direction in forecasting - specialized ice forecasts for shipping, was governed by the fact that general use ice forecasts not always allowed an accurate determination of ice-navigation characteristics with a required period in advance and time interval.

Creation of the methods for specialized ice forecasting was a result of many years of research studies by the AARI's specialists of ice conditions on the NSR and estimates of their influence on the possibility of shipping.

At present it is clear that specialized ice forecasts are closely connected with general use ice forecasts, supplement them and make them more detailed [1,2,3,5].

The development of specialized ice forecasts includes the use of a complex of all available hydrometeorological information - regime data, actual hydrometeorological data, the results of numerical and physical-statistical forecasts. The composition and content of prognostic specialized data are governed, on the one hand by the need for a practical use of this information for the organization and planning of shipping, and on the other hand, by the

existence of physical grounds to forecast the required characteristics with a required period in advance and an interval [1,8,10].

Meanwhile, there are two ways to obtain specialized prognostic ice information. The first envisages application of a specialization algorithm (for example, the method for a quantitative assessment of the difficulty of ice navigation [6,7]) to general purpose prognostic ice information, forecasting distribution of ice cover characteristics in navigation regions. This technique restricts advance period of specialized information to that of existing general purpose ice forecasting methods and the information error will consist of that of general-purpose forecasts and that of the method for a quantitative assessment of ice navigation difficulty.

The second technique is based upon direct forecasting of ice navigation indication. In that case, the advance period of specialized ice forecasts could be coordinated only with specific tasks of navigation, error depending only on that of specialized forecasting methods.

Traditionally, planning of marine operations along the NSR has several stages: preliminary and general from 1 to 6 months in advance, tactical - up to 1 month and operational regulation - approximately up to 10 days in advance. The stages and objectives of planning of shipping are considered below.

At present methods for specialized ice forecasts for separate NSR segments and navigation periods covering basically all planning stages have been developed.

2.1. Forecasting methods for preliminary and general planning of shipping

The method for forecasting the type of winter navigation 4-5 months in advance and mean monthly ice-navigation indicators from 1 to 3 months in advance is used for addressing the objectives of preliminary and general planning of sea operations [8].

The method was developed in 1991 for the NSR segment - western ice edge in the Barents Sea - Dikson Island, on which regular winter voyages are carried out at the present time. Forecasts cover the navigation period from February to May. They have a physical-statistical basis using the technique of generalizations by types. Background and mean monthly ice-navigation indicators are being forecasted, as well as corresponding ice and operating characteristics referring to the optimal navigation variant. The forecast is issued at the AARI.

2.2. Forecasting methods for operational-tactical planning of shipping

To date two methods are developed for forecasting ice-navigation characteristics of mean 10-day navigation conditions along the segments of the NSR western region (to 130°E) for summer 1 month in advance [8].

The first method was developed in 1984. This method allows one to forecast the type of ice navigation conditions (easy, medium, heavy) for the first, second and third 10 day periods of the months for three segments of the NSR western region:

- western ice edge - Dikson island,
- Dikson island - Cheluskin Cape,
- Cheluskin Cape - Tiksi Inlet.

In accordance with the type forecasted the ice and operating characteristics of navigation conditions by the optimal variant are determined.

The method uses physical-statistical dependencies on the generalized characteristics of ice navigation conditions. Additionally, the forecasts of the ice cover extent and the areas of the ice mass over the navigation region are used. The forecast is prepared for the summer navigation period - June-September. The forecast is 1 month in advance with a detailed presentation by 10-day periods.

The second method evolved in 1993 develops the possibilities for forecasting ice-navigation indicators of navigation conditions on an operational-tactical time scale. It allows forecasting the type of ice conditions of navigation and the position of an optimal variant [9].

It was necessitated by the need to forecast the additional characteristics of navigation conditions, in particular, the position of the optimum navigation variant, and by the possibility to improve the methods of the division into types and forecasting ice navigation conditions. To improve the division of ice navigation conditions into types the new parameter of the division into types - $\Sigma\Delta t_{ice}$ - a total increase in the calculated time consumption due to navigation in specific ice zones for a nuclear-powered icebreaker of the "Arktika" type was used.

Parameter $\Sigma\Delta t_{ice}$ is determined as a difference between the calculated total transit time for the NSR segment of the "Arktika" in real ice situation by an optimal variant and the transit time of the "Arktika" on the same way in open water. The criterion $\Sigma\Delta t_{ice}$ has allowed one to obtain a more objective estimation of the ice navigation difficulty, as compared with the $\Sigma\Delta t_{ice}$ earlier, which makes the new division of ice conditions into types more universal.

The method is developed for the segment Dikson island - Cheluskin cape of the western NSR region. The forecast is prepared in summer (June-September) with a 10-day interval and one month in advance.

The method of forecasting the value $\Sigma\Delta t_{ice}$ is based on physical-statistical dependencies, expressed by regression equations. The forecasting of the 10-day type of ice navigation conditions (easy, medium, heavy) on the basis of $\Sigma\Delta t_{ice}$ allows one to pass to the types of ice and operating characteristics of navigation conditions. The forecast of the position of the optimal variant is based on empirical-statistical inertial dependencies.

3. Stages and main objectives of planning sea operations along the NSR

In recent years the development of the marine transportation system has reached a qualitatively new level. A need for arranging and planning regular coastwise and transit shipping along the whole of the NSR in summer and all-year-round shipping in the western NSR region has arisen [4].

The whole complex of objectives for organization and planning of shipping in the Arctic region are divided into the following stages:

- perspective planning of shipping (estimates for the period from 3 to 25-30 years);
- preliminary planning of marine operations (3-6 months in advance);
- general planning of marine operations (1-3 months in advance);
- tactical planning of marine operations (10-30 days in advance);
- operational regulation (management) of marine operations (1-10 days in advance).

A specific range of objectives are addressed at each stage.

Perspective planning includes:

- designing and construction of icebreaking and transport fleet;
- designing and equipment of ports, places of moorage and inloading;
- determination of possible directions of cargo transportation in the Arctic region.

The objectives of a preliminary planning of marine operations are as follows:

- determination of the general directions and order of marine cargo transportation in the Arctic;
- preparation of the plan for the navigation period and its stages;
- updating of the plan of marine operations by the navigation stages;
- development of preliminary plans of nonstandard marine operations.

General planning of marine operations includes:

- preparation and updating of the plan-schedule of marine operations including supply operations;
- development of the plans of nonstandard marine operations.

Tactical planning of marine operations includes:

- correction of the plan-schedule of marine operations;
- updating of the plan of nonstandard marine operations;
- planning of a specific marine operation of a wide range (transportation, supply, some nonstandard operations, etc.).

A complex of objectives of operational regulation (management) of sea operations include:

- updating of the plan for a specific marine operation (5-10 days in advance), designation of icebreakers and convoy composition;
- distribution of icebreakers on the route segments, determination of the convoy formation points;

- management of a specific marine operation (including nonstandard marine operations) 1-5 days
- in advance;
- selection of the places for a possible stationing of vessels on the NSR segments at the deterioration of ice situation.

The objectives of each planning stage allowed determining the types of the required ice information and its spatial and temporal scales (Fig. 1) [10].

A characteristic feature of the stages of planning specific navigation (beginning from the stage of preliminary planning) is their interrelated and successive character.

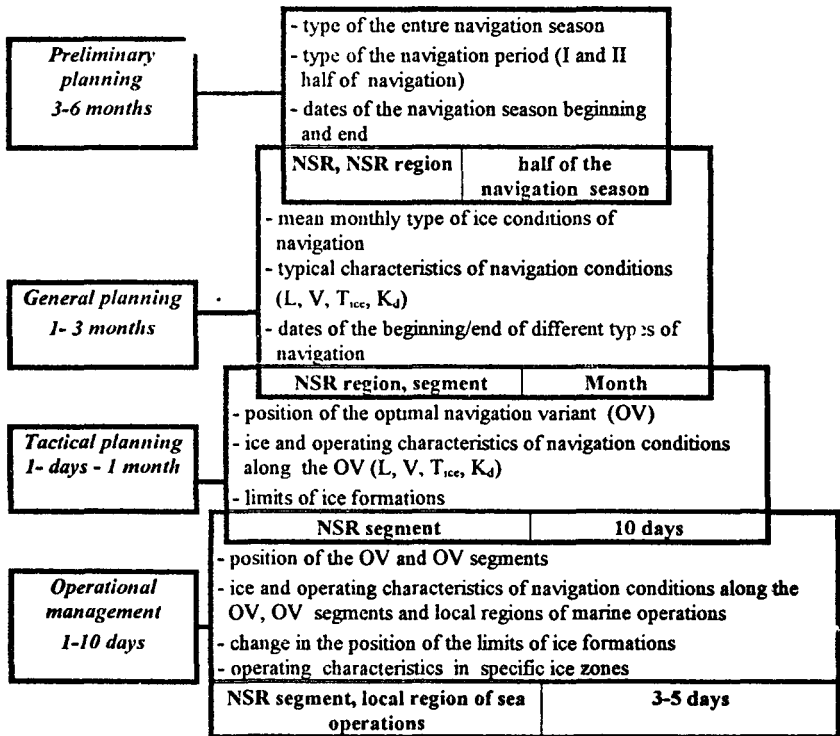


Fig. 1. Types of specialized prognostic ice information and their spatial-temporal interval for the stages of shipping along the NSR.

It is natural that the functioning of such a complicated planning and management system of the fleet activities, including tens of icebreakers, hundreds of transportation vessels, tens of ports and supply points, is impossible without a smoothly functioning system of prognostic

information: ice, hydrometeorological, and specialized ice information. This was a precondition for creating a concept for a multilevel system of specialized ice forecasts.

First of all, independently of the time scale they have a common purpose - reliable, regular and safe shipping along the NSR. Secondly, all directions are united by a common organization principle. The planning aims of a higher time level appear, in turn, to be a preliminary plan of the objectives of a lower time level, thus, the principle of information detailing at each successive stage is implemented. The objectives of operational management are a composite component of the objectives of tactical planning.

4. A multilevel system of specialized ice forecasts for shipping

At the present time the concept of a multilevel system of specialized ice forecasts by generalization and advance time covers four planning stages of sea operations: from preliminary planning to operational management [10].

This concept is implemented at the Laboratory for Ice Navigation Studies of the SSC the AARI. The system is based on the principle: from the forecast with a large period in advance to the forecast of a smaller period in advance but more detailed. A specialized ice forecast is the main structural component of the system.

Each component of the system meets the requirements of its level of the organization and planning of shipping. Here, the common nature of initial information (its specialized) form and the common physico-statistical basis of forecasting method made it possible to obtain interdependent parameters for different levels of the system. Thus, the transition to the next level of the system of specialized forecasts is accompanied by the increase in the number and detailing of ice-navigation indicators existing at a higher level. Such approach allows gaining impression even when forecasting the most generalized indicators (for navigation on the whole) of their most probable interpretation in the characteristics on a smaller scale.

The preliminary planning objectives include forecasting of the most generalized ice-navigation indicator - the type of navigation 5-6 months in advance referring to the whole of the NSR and its two regions (western and eastern).

The general planning objectives include forecasting of the type of ice conditions of navigation by regions and segments of the NSR (5-6 segments) with a monthly interval and 3 months in advance.

The tactical planning objectives include forecasting of the type of ice conditions and of the position of the optimal navigation variant by the NSR segments with a time interval of 10 days and one month in advance. The type of ice navigation conditions has a number of ice-operating characteristics referring to an optimal navigation variant: the length of the route in different ice formations (ice massif, ice of different concentration and age categories, polynyas, etc.), times and motion velocity for different types of ships and convoys, dates of the beginning-end of navigation and unescorted navigation for specific types of ships.

And finally the operational management objectives include forecasting of an optimal navigation variant with a time interval 3-5 days and up to 10 days in advance referring to the NSR segments and their separate parts.

A multilevel system provides for a common cycle of specialized prognostic ice information for shipping. A preliminary forecast for the entire navigation period is made specific for its first half and includes specialized prognostic information for one month and detailed prognostic information for the first 10-day period. In 10 days a forecast for the next three 10-day periods is prepared. After the second 10-day period there is a possibility by using such flexible schedule to update the forecast for the next calendar month. At the end of each month the forecast can be updated for a stage (half) of the navigation season. Thus, there is a continuous cycle of specialized ice information that is capable to meet the objectives of shipping at all time levels of planning operations of the fleet.

A number of the structural components of the system - specialized ice forecasts with a different period in advance and a different time interval have already been developed and introduced into practice (Table 1).

Table 1. Methods for specialized ice forecasting, used for shipping support in the western NSR region

Time scale of shipping organization	Methods of specialized ice forecasts developed and used in practice	
	Winter	Summer
Preliminary planning 3-6 months	Navigation type forecast 4-5 months in advance	-
General planning 1-3 months	Forecast of mean monthly types of ice conditions for the NSR segment 3 months in advance	-
Tactical planning on 10-day period - 1 month	-	Forecast of 10-day types of ice conditions and positions of an optimal variant by the NSR segments 1 month in advance
Operational management 1 day - one 10-day	-	Forecast of ice conditions period of navigation up to 10 days

Thus, it suggests a possibility for creating a common multilevel system of specialized ice forecasts for the whole of the NSR.

At the first stage a multilevel system of specialized ice forecasts can be developed and put into practice for the western region of the NSR. At the second stage the system should be expanded and extended to the eastern region of the NSR and provide all users along the NSR with a continuous cycle of prognostic specialized ice information.

At present one can state that 20-25% of studies, referring mainly to the western NSR, are fulfilled for establishing a multilevel system. To set up a complete system of specialized ice forecasts for the western NSR region requires the development of new, and improvement of the existing, forecasting methods (Table 1). For the winter period the forecasts for all levels of tactical planning and operational management are necessary. For summertime - for the levels of preliminary and strategic planning. Specialized ice forecasts up to 30 days in advance (for the level of tactical planning) should by all means envisage forecasting of the position of the optimum navigation variant. At present ice-operating characteristics for the optimum navigation variant are predicted without indicating of its position. For the level of operational management it is necessary to forecast specialized characteristics not only for the segments of the routes, but also on a smaller space scale.

With the formation of databases and the addition of initial data, search for new typical features in forecasting and estimating the influence of ice conditions on ship motion, separate methods of ice forecasting are being improved which allows us to hope that a flexible and effective system of specialized ice forecasts for shipping will be created for the whole of the NSR.

REFERENCE

1. Buzuev A.Ya., Brovin A.I., Kolbatov P.V., Fedyakov V.Ye. "Specialized ice forecasts for navigation support", VDNKH USSR, Ser. Gidrometeorological support to the economy. Moskva, Transport, 1987, p. 11.
2. Volkov N.A. "The Arctic navigation planning and long-range forecasts", The Arctic and Antarctic problems, issue 18, Leningrad, Gidrometeoizdat, 1964, pp.40-47
3. Gordienko P.A. "Study of ice conditions and ice shipping", Arctic and Antarctic problems, issue 50, Leningrad, 1977, pp. 70-75
4. Zaika B., Batskikh Yu. "The cargo transportation problems in the Arctic". Marine fleet, No. 5, 1987, pp. 13-15
5. Brovin A. "The concept for the evolvement of specialized ice information for shipping in the Arctic", Proceedings of the IAHR'94, vol. 2, pp. 941-949.
6. Buzuyev A.Ya., Fedyakov V.Ye. "A comprehensive allowance for the characteristics of the ice cover state in the development of recommendations for navigation". In: Questions of enhancing the strength and reliability of sea port constructions. Soyuzmorniiiproject, M., Transport, 1983. pp. 89-97.
7. Brovin A., Fedyakov V.Ye., Frolov S. "Description of the Empirical-statistical method for a quantitative assessment of the difficulty of ice navigation (the "QAD" model)". INSROP Working Paper I.5.5, Planning and Risk Assessment, 1995, Sec. 3.
8. Brovin A., Yulin A. "Specialized ice forecasts for shipping along the Northern Sea Route", INSROP Working Paper No. 10 - 1995, I.6.1, Operational Tools, Sec. 5, pp. 91-109.
9. Brovin A., Yulin A. "Specialized ice forecasts for shipping along the NSR", INSROP Working Paper, I.6.1, Operational Tools, II stage, Sec. 5, (in press).
10. Brovin A., Frolov S., Yulin A. "A concept of a system for specialized ice information support to successive planning of marine operations along the NSR", INSROP Working Paper, I.5.5, Planning and Risk Assessment, II stage, Sec. 1, (in press).

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