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ASSESSMENT OF RELIABILITY AND SAFETY OF SHIPPING ALONG THE NSR (EASTERN REGION) UNDER DIFFERENT TYPES OF ICE CONDITIONS

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ABSTRACT

Marine fleet has always been the main type of transport in the zone of the Northern Sea Route. The selection of technical means of marine transport (first of all - types of icebreakers and ships) and methods for their exploitation is governed by natural conditions of the seas of the Siberian shelf. Ice cover is the major one among them. In fact, in spite of the impressive results of scientific-technical progress in the arctic shipbuilding, the rather complicated ice conditions that are formed episodically on different segments of the NSR, considerably delay the transportation process and result in ice damages.

There are objective difficulties in describing natural conditions, processes of ship/ice interaction, features of their exploitation in different regions and different seasons.

As a result, up to now the questions of estimating the reliability of shipping along the NSR, a risk for navigating of ships of specific type and the state at prescribed combinations of the ice cover characteristics were poorly developed. The solution of these questions is often subjective on the basis of speculative conclusions and from own experience. The paper discusses the possibilities for a quantitative estimation of the reliability and risk of shipping by the example of the eastern segment of the NSR. This study is based on a comprehensive
features of the distribution of characteristics on the navigation route, ship's hull/ice interaction processes, specific characteristics in the study region of the NSR. In the opinion of the authors, a comprehensive approach which combines efforts of specialists in different branches of knowledge can result in objective quantitative estimates of the reliability and risk of Arctic shipping in any of the regions of navigation.

1. Main features of the ice regime and the division of ice distribution into types in the Eastern region of the NSR.

The ice cover of the Arctic Seas is a multiparameter medium. More than 10 elements non-uniformly distributed in space are centered in its thin layer.

Depending on the time of the year and specific climatic conditions, the ice cover can contain an incomplete set of elements which govern its structure and state at a given time instant. Stability of the ice cover with regard to external factors depends on the presence and persistence of the most thick ice and the regional features of each sea. The ratio of the most small mean monthly ice amount to the most large amount is assumed to be a degree of ice cover stability. The oceanic massif of old ice has a considerable influence on the character of its distribution in the Arctic Seas. This effect is most pronounced in the seas open for ice exchange with the Arctic Basin, and first of all, the seas of the eastern region (Fig. 1). Zones of prevailing old ice and their inclusions are branches of the oceanic massif of old ice. These zones constantly vary during the annual cycle and govern the interannual variability in geographical location and intensity. That is why, the geographical position and orientation of the old ice branches serve as the main criteria in the classification of the ice distribution fields in the Arctic Seas.

Second in ice stability is naturally first-year ice prevailing by the area of extent and amount. The existing differences in the conditions of its formation, development and decay in the seas create diverse ice distribution patterns and hence, is a principal basis for ice classification.
Fig1. Stability of ice cover (—), amount of multi-year ice (—) and the share of multi-year ice in ice cover preservation for the Arctic Basin and the seas (...)

The structure of the distribution fields of mean multiyear amount of first-year thick ice illustrates quite well the regional features. For example, in February (Fig. 2) thick cores of first-year ice are only formed in the Kara and Laptev Seas. And zones of first-year ice in the south-western Kara Sea and the northern half of the Barents Sea presents branches of the Kara core, not being in fact independent. This is important for understanding the dimensions of the regions where some uniform phenomena and properties are evident. Such cores of first-year ice are observed neither in the East-Siberian, nor the Beaufort Sea, since they supplement old ice. This is the difference between the seas of the western and eastern Arctic which should be taken into account for classificating ice distribution and delineating the regions for subdividing them into types. Also, zones of fast ice that are steadily preserved during the winter-spring period and which then create local massifs: Severozemel'sky, Yansky and Novosibirsky (see Fig. 2) should be taken into account. The areas of close first-year ice related to the oceanic massif form, in turn, a number of branch massifs (Fig. 3).

The above considerations serve as a basis for subdividing the ice distribution into types.

In particular, for identifying types of the ice distribution in the seas of the eastern Arctic the following criteria have been used:
Fig. 2. Spatial pattern of the first-year thick ice for February.

Fig. 3. Spatial pattern of the first-year thick ice for 3rd 10-days period of July

1. The geographical position of the oceanic massif of old ice and its periphery reflecting the role of ice of the Arctic Basin in the development of ice conditions along the NSR; zones of prevailing first-year ice reflecting the character of the development of the processes of ice growth and melting in the annual cycle within the region; zones of young ice reflecting the extent of relation between local sea regions and thermal conditions of the atmosphere, convective processes in the sea and local wind flows; ice edge reflecting complicated processes of interaction between systems of warm and cold currents, as well as atmospheric circulation.
2. Similarity in the configuration of the boundaries of the delineated ice zones and their closeness to each other within 50 km by range and 60-70% of the length.

3. Orientation of the branches of oceanic massif.

4. Area of ice massifs and fast ice.

Using the indicated criteria, all fields of ice distribution in the Chukchi, East-Siberian and south-eastern Laptev Sea over a 50-year observation series were combined into types.

Various ice distribution patterns were grouped into 6 types by each 10-day period (Fig. 4). And type I included fields of ice distribution where old ice was located far from the coast in the Arctic Basin. At type II the branch of the oceanic massif of old ice is directed from the north toward the New-Siberian Islands. At type III the massif branch is directed toward the New-Siberian straits. At type IV old ice is located in the center of the East-Siberian Sea most frequently blocking the Anon island. At type V the old ice branch is located in the eastern East-Siberian Sea and in Long strait and at type VI it covers considerable areas in the Chukchi Sea, blocks the Chukchi coast and sometimes flow to Bering Strait to the Anadyr' Bay.

Hence, the first two types govern exceptionally favorable background ice conditions for shipping; types III and IV reflect background conditions close to mean multiyear ones and most complicated navigation conditions correspond to types V and VI. In summertime all ice massifs of the seas in the eastern Arctic of type VI are, for instance, preserved up to the late fall, blocking the mainland coast, the anomalies in their areas reaching 30% even in early September.

Calculation of the occurrence frequency in persistence of the initial type during one 10-day period allowed differentiating all types into three groups with a characteristic distribution for each group (Fig. 5) with the probability of the initial types being preserved for several 10-day periods (Fig. 6).

Thus, if the ice distribution at types I and II do not create ice conditions dangerous to some extent for navigation, as they are not related to either of the ice massifs, then the prevalence in the development of other types causes serious difficulties for ships navigating in different regions of the Arctic Seas. For example, type VI usually governs the most complicated ice conditions in Long strait and the Chukchi Sea as observed in 1983.
Fig.4. Variability of the total concentration for 6 typical ice cover patterns synthesised for the 2nd ten days period of August for the Eastern sector of the Arctic.

Each type has inherent specific features in the development of ice processes in the region under consideration. Hence, to estimate the ice distribution type, predict its stability of transformation to another type is important in terms of practice and science. However, knowledge of the ice distribution type is necessary, but it is insufficient for estimating the reliability of shipping on some or other segment of the NSR. It is necessary for each type to find specific distribution features in the ice cover characteristics (concentration, thickness, amount of hummocking, pressures, etc.) on the optimal navigation variant, estimate the influence of any combination of these characteristics on operating parameters (velocity, probability and duration of stays due to natural conditions, etc.). An approach to addressing these problems is discussed below.
Fig. 5. Probability (%) of preservation of the initial type from the number of combinations with the current type for the year /1/ and from the total number of combinations with all types for May-October 1949-1990 period /2/ as a function of time (in 10-day intervals).

Fig. 6. Occurrence of preservation of the initial type of the ice cover distribution (%) and probability of its transfer to the other types (%) for 10-days interval in advance.
2. Natural conditions on the navigation route and taking into account their influence on shipping

Navigation of ships in the study region can be in fast ice and drifting ice.

In fast ice after a preliminary breaking of the channel (sometimes with a simultaneous ship routing) there is a possibility for using it many times (up to the break-up) which significantly enhances the reliability and safety of navigation. Here, it is important to determine operating parameters \( (V_{io}, \Sigma T_i) \) connected with making the channel (or its "renewal" in winter).

In drifting ice on the route segments where concentration \( > 9-10 \), pressures can predetermine the course of operations. Thus, the issues of the reliability of shipping in fast ice or drifting ice should be discussed separately.

2.1. Estimate of the reliability of shipping in drifting ice

Detailed evidence on the distribution of drifting ice on the optimal navigation variant in each 10-day period for the entire series of regular ice observations on the segment Shelagsky cape-Bering strait served as initial data.

It is clear that these data can be prepared for other segments and confined to the specific type of ice distribution (see section 1).

Then, characteristic features in the distribution of pressures of different intensity were determined (from data on the duration and stability of on-shore flows - Table I). Finally, calculations of the parameters of navigation difficulty were performed on the basis of an empirical model of ship motion in the ice \( (V_{io}, T_s, \Sigma T_i) \).

For estimating time \( (T_s) \) necessary for waiting for improved ice situation (to be exact - a decrease in wind-induced pressures), the following preconditions are used:

### Table I

<table>
<thead>
<tr>
<th>Pressure in arbitrary units</th>
<th>0-1</th>
<th>1</th>
<th>1-2</th>
<th>2</th>
<th>2-3</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration ( T_{io}/T_p ) at ( T_p ) 2 days</td>
<td>0.20</td>
<td>0.30</td>
<td>0.30</td>
<td>0.10</td>
<td>0.07</td>
<td>0.03</td>
</tr>
</tbody>
</table>

a) The calculated velocity \( V_{io} < 1.0 \) knots serves as a criterion of ice conditions under which escort of even one ship is basically impossible.
b) The probability of a ship (convoy) being in any ice zone \( (P_i) \) is determined by the ratio of the calculated motion time in prescribed ice zones \( (T_i) \) to the total time for navigating along the study segment \( (\Sigma T_i) \), i.e.

\[
P_i = \frac{T_i}{\Sigma T_i}
\]

These preconditions are used for obtaining the dependencies of probable delays of an icebreaker (convoy) due to waiting for improved ice conditions at different duration of on-shore air flows in the general case - preservation of pressures (Table 2).

<table>
<thead>
<tr>
<th>Type of navigation conditions</th>
<th>Power of Icebreaker, thous. h.p.</th>
<th>75</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>December-May</td>
<td>July</td>
<td></td>
</tr>
<tr>
<td>Easy</td>
<td>6</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Medium</td>
<td>9</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Heavy</td>
<td>10</td>
<td>5</td>
<td>39</td>
</tr>
</tbody>
</table>

The route Shelagsky cape - Bering strait

Table 2

Mean delays ("time of halting", \( T_i \)) of icebreakers of different power in ice depending on the duration of the action \( (T_p) \) of on-shore winds \( (T_e, \%) \).

Total motion time along the route \( (\Sigma T) \) is determined as a difference between the duration of the calendar period (in this case - 10-day period, \( T_p \)) and the time for forced halting due to natural conditions \( (T_e) \), i.e.

\[
\Sigma T = T_p - T_e
\]

A quotient from dividing the total time by the time for escorting one ship gives a number of escorts which can be made by a specific icebreaker for one 10-day period.

On the basis of the above scheme, a calculation algorithm has been prepared and realized for all icebreakers used on the route during a self-contained voyage (see Table 3 for calculation examples) and escort of ships of a specific ice category.

On the whole, there is quite a good agreement between the calculation results and full-scale data.

Eventually, the calculated probability of a guaranteed escort of a different number of ships for each 10-day period at prescribed icebreaking support is a measure of reliability of shipping in drifting ice. Also, the probability of unescorted navigation is
estimated and of such natural conditions under which icebreaker cannot escort even one ship for one 10-day period.

2.2. Estimate of reliability of shipping in fast ice.

The reliability of shipping in fast ice is considered on the basis of the probability of escorting a definite number of ships within a specific time interval (naturally at fast ice preservation). This value varies s. p-wise (increases) from the instance of making a channel to the subsequent escort of ships in it. Hence, the question of the reliability of shipping in fast ice should be considered in two stages: when navigating in continuous fast ice and for moving in the channel made earlier.

In the latter case the motion velocity is sufficiently stable and changes little over a comparatively wide range of values of the characteristics of fast ice state (thickness, amount of hummocking, etc.).

Hence, the velocity of ship escort in the earlier made channel relative to the problem addressed can be taken into account for a specific region and the period on the basis of mean calculated ice thicknesses (with a correction for mean amount of hummocking), Table 4.

Thus, the reliability of shipping in the given case will only be governed by the length of the channel in fast ice.

It is more difficult to estimate the reliability of shipping in continuous fast ice. Experience gained indicates that here different situations are possible from a "rapid run" along a narrow (5-50 m) frozen crack up to the rather ineffective motion. In particular, on June 17-19, 1987 the icebreakers "Yermak" and "Kapitan Khlebnikov" tried to make the channel from the north to the near-mouth area of the Kolyma river, but then stopped due to the rather poor progress in fast ice. There are many similar examples in the experience of ice navigation.

In order to estimate the climatic (based on the use of the entire observation series) reliability of shipping in continuous fast ice, it is necessary in addition to the most probable ("background") characteristics, to take into account their variability and hence, the distribution of the motion velocity (and times) both for a continuous motion and by ramming. In view of the above considerations, a procedure for estimating the reliability of navigation in continuous fast ice was developed which included:
Table 3

Probability (%) of a number of self-contained travels possible by ice conditions, for one 10-day period by icebreakers of different power through drifting ice on the route Bering strait - Shelagsky cape

<table>
<thead>
<tr>
<th>Month</th>
<th>one 10-day period</th>
<th>Possible number of travels for one 10-day period</th>
<th>Type of icebreaker</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NP</td>
<td>1-5</td>
<td>6-10</td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>0</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>July</td>
<td>1</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>11</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>11</td>
<td>24</td>
</tr>
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<td>July</td>
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</tr>
<tr>
<td>July</td>
<td>1</td>
<td>8</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Note: NP(not possible) - icebreaker does not have enough time to overcome the ice zone for one 10-day period
Ice-free - ice zone is absent
- calculation of mean values of the indicators of navigation difficulty (operating velocity, time consumption) from the data of "background" characteristics of fast ice (by the segments with their equal values and on the whole along the fast ice route);
Table 4

Calculated velocity of ULA ship escort in the channel ($V_{ie}$) in fast ice (during the "warm period" June-September)

<table>
<thead>
<tr>
<th>Type of icebreaker</th>
<th>Mean ice thickness (taking into account the amount of hummocking)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>140</td>
</tr>
<tr>
<td>&quot;Arktika&quot;</td>
<td>9.6</td>
</tr>
<tr>
<td>&quot;Yermak&quot;</td>
<td>7.6</td>
</tr>
<tr>
<td>&quot;Kapitan Sorokin&quot;</td>
<td>4.9</td>
</tr>
</tbody>
</table>

- calculation of the values of possible deviations from mean values (due to operating by ramming, etc.) from the data on the distribution of hummocked formations, inclusions of old or younger ice, etc.;

- generalization of the calculation results over the entire series of regular ice observations, determination of quantitative indicators of the climatic reliability of icebreaker navigation in continuous fast ice in a self-contained voyage or at a simultaneous escort of one ship.

As an example, let us present the calculation results for all icebreakers of the "Arktika" type (Table 5). Similar calculations were performed for all icebreakers now in operation. This allows estimating the level of the reliability of shipping in continuous fast ice.

Table 5

Climatic probability ($P$, %) of time consumption (by intervals, $\tau$, day) for making a channel by the "Arktika" type icebreaker and escorting one ULA ship (end of May-June, north-eastern Kara Sea and B.Vil'kitsky strait)

<table>
<thead>
<tr>
<th>$\tau$, day</th>
<th>2</th>
<th>2-3</th>
<th>3-4</th>
<th>4-5</th>
<th>5-6</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$, % of a self-contained icebreaker motion in continuous fast ice</td>
<td>20</td>
<td>29</td>
<td>29</td>
<td>14</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>$P$, % of icebreaker motion with a simultaneous escorting of a ship</td>
<td>9</td>
<td>12</td>
<td>26</td>
<td>26</td>
<td>15</td>
<td>12</td>
</tr>
</tbody>
</table>
3. An approach to estimating a risk of shipping

The presented structure of data on the conditions of ice navigation along the NSR makes possible theoretical forecasting of the reliability of shipping taking into account the risk. A convenient presentation form of the data on ice conditions allows characterizing these conditions by a limited number of parameters. For these parameters it is possible to plot the probabilistic distribution laws dependent on the season and the region. Below, the probability $P_{u}$ with which the cargo will be delivered to the destination point for the time less than $T_{o}$, is assumed to be the reliability of shipping

$$P(T<T_{o}) = P_{u}$$

The value $Q_{o} = 1 - P_{u}$ is the risk of the cargo carrier who has undertaken to transport cargo for the time not more than $T_{o}$.

Let us consider in more detail the calculation algorithm $P_{u}$ for a given ship on a specific segment of the NSR which is divided into $n$ segments. On each of the segments there is possible the appearance of $m$ types of ice conditions with a probability $P_{u}$ which depend on the season (10-day period), $i = 1, n$; $j = 1, m$

$$\sum P_{u} = 1$$

Each of the types of ice conditions is described by $l$ parameters $x_{1}, x_{2}, \ldots, x_{l}$. In turn, each of these parameters is prescribed by the probability density function $p_{i,k}(x_{j}, \ldots)$, whose characteristics depend on the region and the season.

Having these initial data and using the methods for stochastic computer modelling with software developed at the AARI, we obtain the probability distribution functions of the ship passing $i$-region for the time less than $t$, $P_{i} = P(t<T_{o})$.

Naturally, in the general case the functions $P_{i}$ will depend on the type of ship, shaft power, ship loading, etc. Each of $P_{i}$ will depend on $P_{u}$, since the initial data contain the probabilities of transition from one type of ice conditions to another for each region. A set of $P_{i}$ allows calculating the sought value $P_{u}$.

The presented algorithm for estimating the reliability takes into account only ship performance in the ice, since the notion of reliability is defined relative to the time of travelling along the prescribed segment. However, a tendency for reducing total time consumption results more frequently in ice conditions in the increase in the volume of
damages of the hull structures. Repairs of damages or accidental withdrawal from operation, losses from cargo spoiling reduce the cost-effectiveness of marine transportation system or can make it unprofitable. Therefore, it is necessary to formulate the notion of reliability relative to the profit of the transport operation:

$G_0 = G(C < C_0)$.

$G_0$ - the probability that the income from the transport operation $C$ will exceed some threshold level $C_0$ with which the cargo carrier agrees. Respectively, the risk of cargo carrier is $F_0 = 1 - G_0$.

The task set is more composite as it contains several interrelated blocks:

1. Calculation of profit at a fixed time of travelling along the segment and calculation of the probability of travelling for this time.
2. A probabilistic estimate of damages of a specific ship in typical ice conditions. The formulation and solution of this problem with application examples are presented in more detail in one of the papers of this conference.
3. Calculation of $G_0$ values for a prescribed series of $C_0$ and navigation conditions.

The suggested expanded methods for estimating the reliability of shipping in the ice can be used for economical planning of transport operations in the ice with a prescribed composition of cargo and icebreaking fleet, as well as for a justified purpose of insurance fee for insuring economical and technical risks of sea ice transportation.
AN INVESTIGATION ON FRACTURE MECHANICS AND ICE LOADS DURING CUTTING FRESHWATER ICE BY INDENTERS SIMULATING PROPELLER BLADES

PART 2: FLAT VERTICAL INDENTERS

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ABSTRACT

The report describes experimental results from tests in which natural freshwater ice was cut by vertical indenters simulating propeller blades of different shapes. The description includes the involved test set-ups and the observed features of ice fracture mechanics in different areas along the cutting edge. The report contains ice load and indenter / ice contact zone data for various kinematic conditions, including the so-called "pure cutting". The results are compared to those of the horizontal indenter series reported at POAC-93. It is also demonstrated how the obtained data may be applied for propeller blade ice load computations.

INTRODUCTION

Due to the lack of experimental data all propeller / ice interaction studies were till now made on the grounds of their authors' speculative assumptions and therefore aimed at evolving only some rough evaluation methods for the integral forces arising on propeller blades. A brief review of such developments may be found in [1,2] where it was also said that it would be necessary to investigate detailed features of ice fracture mechanics under various kinematic conditions of interaction for propeller blades of geometrical configurations differing both section-wise and shape-wise. Only that could make it feasible to generate an improved method for computing ice loads on propulsors and to find proper algorithms for propeller blade design in order to reduce these loads.

To achieve that goal, a new technique was suggested and applied in a wide-scale test series in which natural ice specimens were broken by flat indenters simulating blade leading edges and shape contours. The principal feature of this approach was that it allowed to get data not only on the physical aspects of the involved process, but as well to obtain information on the value of contact pressures under conditions as close as possible to full-scale environment.

An earlier report [1] has described the first phase of the project and offered a rather simple numerical model permitting to estimate the blade, ice contact zone area and arising there ice loads. The present report adds data acquired subsequently from tests with natural ice blocks and flat vertical indenters which simulate different propeller blade shapes.
1. AIMS AND METHODS OF TEST DATA ANALYSIS

The aims of the tests in which natural ice blocks were broken by vertical indenters simulating propeller blades were:

- to clarify physical aspects of ice fracture patterns under conditions simulating realistic blade/ice interactions;
- to identify variations in cutting force components as functions of the interaction conditions, including ice crystal orientation;
- to establish relations between the variations in typical ice failure areas and indenter/ice contact zones depending on indenter shape and interaction conditions;
- to determine contact loads in the contact zones.

The experiments were made in the laboratories of Kiev Civil Engineering Institute on the there available dynamometric test set-ups [1,3]. The measurements included the axial \( P_x \) component of the ice cutting force (the component acting along the velocity vector of the indenter), the normal \( P_n \) and side \( P_s \) components. Also registered were the indenter/ice contact zone sizes, ice temperatures and ice unconfined compression strength. The patterns of cutting force variations were observed through the traditional procedure, i.e. maintaining all but one variable components constant. The only component was varied throughout the relevant exercise.

The process of ice cutting by blade-simulating indenters was arranged in a half-restricted manner which allowed the ice block no sideways expansion (Fig.1). To simulate this interaction regime, characterising continuous milling, it was necessary to prepare ice block surface before. It was made by some preliminary thin cuts of the ice block by the tested indenter. It's necessary to do, due to side's expansions of the cutting path when it's depth is small [1]. The cutting forces varied in a saw-tooth pattern with random amplitudes and periods, both depending on interaction parameters and reaching their maxima at the instant a main ice chip (spall) separated. Subsequent analytical evaluations were made with the mean maximum values, because the practical aim of this investigation was to obtain information about mean contact pressures, arising at the characteristic contact zones at the moment of chipping (spalling) main ice fragments. In this way it's necessary to collect enough number of chipping cycles and corresponding force cycles. It depended on the interaction process and in some cases (big \( h/b \) values) required to use two or three ice blocks. The required numbers of test runs and relative errors were found with the help of Student's function.

The experimentally logged forces were described as suggested in [3]:
\[ P_s = P_f + P_s + P_L + P_B = p_f \cdot b \cdot h + K_1 \cdot p_s \cdot h + K_2 \cdot p_L \cdot h^2 + p_B \cdot b \cdot h \]  \hspace{3cm} (1)

where:
- \( P_f \) is the ice cutting force at the front cutting edge;
- \( P_s \) is the force due to sideways fracturing;
- \( P_L \) is the force due to side expansions;
- \( P_B \) is the force due to the bluntness of the cutting edge or (and) its deformation (for sharp edge).

The tests have revealed that in such half-restricted conditions there were no sideways chips (spalles) and expansions. Therefore, the relevant component was \( P_L = 0 \). As at the cut bottom the ice was crushed and sheared only by one side edge, therefore \( K_1 = 1 \). The final expression chosen for the analysis was formulated as:

\[ P_s = \left( p_f + \frac{P_s}{b} \right) \cdot b \cdot h + P_B \]  \hspace{3cm} (2)

By means of relation (2) the integral force \( P_s \) was divided into components differing not only in absolute values but in ice-destruction mechanics in these specified zones. For determining an ice contact pressures it is necessary to know the dimensions of the contact zones (Fig. 2): along the leading cutting edge "\( \alpha_f \)"; along a zone of tip sections "\( \alpha_s \)" and in indenter's bluntness zone "\( \alpha_b \)". The knowledge of the force and geometry parameters for different parts of ice-indenter interaction area makes it possible to calculate the contact pressures (Fig. 2):

- at the leading cutting edge:
  \[ p_{fs} = \frac{p_f \cdot \cos \mu}{\alpha_f \cdot \left( 1 - \frac{b_f}{b} \right) \sin (\delta_f + \mu) \cdot \sin \varphi_f} \], where \( \varphi_f = \frac{a_r \cdot \sin \delta_f}{h_i} \)  \hspace{3cm} (3)

- at the tip sections:
  \[ p_{ts} = \frac{P_s \cdot \cos \mu}{a_s \cdot b_s \cdot \sin (\delta_f + \mu)} \], where \( a_s = \frac{h_i}{\sin \delta_f} \)  \hspace{3cm} (4)

- at the indenter's bluntness zone:
  \[ p_{bs} = \frac{P_B \cdot \cos \mu}{a_B \cdot b \cdot \sin (\delta_f + \mu)} \].  \hspace{3cm} (5)

The nature of \( P_B \) for sharp indenters and its dependence of the interaction parameters is not quite clear up till now and should be investigated in future. The ice cutting tests were made with nine indenters (Fig. 3). Contact zone shapes and sizes were established using carbon paper shielded with a thin lavsan foil.
2. ICE FRACTURE MECHANICS AND INDENTER TEST RESULTS

Under the half-restricted test conditions fragmented ice chips (spalls) were separating along the whole cutting portion of the indenter except at the tip. The chipped fragments appeared along the leading edge as individual pieces (spalls) at different instants. With the growth in the ratio of the cut thickness ($h_c$) to the indenter penetration depth ($b$) the number of the chips (spalls) forming along the cutting edge decreased. The contact zone started immediately at the cutting edge. In the same zone a breaking crack appeared together with the formation of every subsequent chip fragment. Regardless of the indenter shape, the crack was directed at an angle $\theta \approx 28^{\circ} - 30^{\circ}$ from the cutting path (Fig.2). The observed fracture pattern and values of $a_F$ and $\varphi$ were exactly the same as seen earlier at the cutting edges of horizontal indenters [1].

When an indenter penetrated into the ice, the shape of the free cutting surface corresponded to outline of the indenter's cutting edge.

Ice fracture mechanism in the vicinity of the tip coming close to the cut bottom was different from the above-described picture. Because of the confined effect of the surrounding ice mass, the tip sections couldn't chip off any ice fragments in front of them and had to cut the ice interacting with it across the whole thickness of the sheared and crushed layer. The indenter front edge contact zones ($b_s$) and ($a_F$) variation pattern may be seen in Fig.4. The values of ($b_s$) and ($a_F$) were independent of cutting length ($b$). The examples of measured axial ($P_x$) and normal ($P_N$) cutting force components are shown in Fig. 5.

The performed test result analysis allows to conclude that outside the tip zone the cutting faces behave in the same manner for both horizontal [1] and vertical indenters. This conclusion is also supported by the specific forces $P_F$ which coincide for both indenter types. It was experimentally proven that the shape of the flat indenters which simulated propeller blades produced virtually no effect upon the axial component ($P_x$) of the cutting force.

While assessing the measured normal components ($P_N$) of ice cutting forces on shape-simulating indenters (for propeller blades these forces are directed along the radius) it was found that the shape of the cutting edge had a significant effect on ($P_N$) values. Those forces were found to be the lowest for the indenters with straight edges. The least favourable shape has turned out to be the one of indenter No. 9 which has as well manifested rather high elastic deformations when interacting with the ice blocks.
3. "PURE" ICE CUTTING BY MODEL INDENTERS

This assumed condition of propeller/ice interaction when the involved cutting indenter moves in the ice with a zero angle of attack (cutting angle $\delta_c$) at a significant distance from the edge of the floe was originally formulated in the model suggested by Jagodkin [4] who considered such a condition to be the least energy-consuming since the ice forces and the resulting moments opposing the propeller rotation were believed to be in the case minimum. When attempting to generate a new propeller/ice interaction numerical model [2], that assumption caused certain doubts and it was decided to verify it experimentally.

The cutting test series involved three of the indenters: No.2, No.6 and No.9. (Fig. 3). The observed fracture mechanism may be described as follows:

- when the distance from the indenter to the free side face of the ice block was less than 40 to 50 indenter thicknesses, the ice was chipped off in large fragments (Fig. 6) similar to those typical for the usual ice cutting pattern; the indenter itself bended towards the chips (large spalls);

- when the indenter was set symmetrically in respect of the ice block side faces, it sometimes initiated a crack or itself got into a hidden crack running through the ice at a certain angle to the indenter path; that caused the tool to suffer some deformation following the crack propagation direction (Fig. 7);

- in uniform ice blocks symmetrically arranged indenters brought about a sizeable amount of fine "ice powder" at the lower portion of the tool; the "powder" travelled upwards forcing the ice to chip off at the sides in the shape of layers propagating at about $35^\circ$ to vertical side faces of the indenter (Fig. 8, 9).

It should be remarked that the latter of the above-described conditions required the greatest force to overcome the ice resistance.

Test results are shown in Fig. 10. It may be seen there that regardless of whether the ice was spalled in layers or crushed through, the axial cutting force component ($P_x$) had practically no relation with the shape of the blade. At the same time the normal component ($P_n$) changed quite significantly and reached its maximum on indenter No.9.

It was generally observed that ice resistance to penetrating tools increased with the transition from layer spalling to crushing through the ice at a large distance from the free side of the floe.

Local faults (cracks) in ice blocks caused their global failures. The load levels then dropped noticeably lower.

Contact pressure $p_s$, calculated by dividing force components $P_x$ and $P_n$ on subsequent projection of contact surfaces:

$$p_s = \frac{P_x}{t \cdot b_s}; \quad p_n = \frac{P_n}{t \cdot l_s}$$

were $t$ is the thickness of the indenter; $b_s$ - cutting contact depth;

$l_s$ - horizontal projection of the contact zone

In this tests $b_s = (0.6 + 0.7) b$. 

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CONCLUSIONS:

- Ice fracture mechanics and specific ice loads within the working zone of a vertical indenter cutting edge (outside the tip vicinity) do not depend on the indenter shape and completely agree with the results of horizontal indenter test series;
- At the tip of the vertical indenter, the ice is crushed by shearing and crushing forces and its interaction with the cutting faces occurs across the whole thickness of the cut layer;
- The indenter contour shape has virtually no effect upon the axial ice force component \( P_x \) but significantly influences the vertical one \( P_y \);
- The "pure cutting" condition takes more energy than chipping; however, an important role here belongs to inner flaws in the ice which may drastically reduce the ice load level;
- Analysis of this experimental results allow to introduce important corrections to the ice/blade interaction model [2]; the blade now should be divided into the "cutting part" and "tip part", were force components should be calculated in accordance with described ice fracture mechanics.

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   "An Investigation on Fracture Mechanics and Ice Loads during Cutting Freshwater Ice by Indenters simulating Propeller Blades. Part 1. Flat Horizontal Indenters".
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   "Method for Calculating Ice Loads Encountered by Propeller Blades".
3. Vetrov Y.A.
4. Jagodkin V.S.
Fig. 1  Half restricted ice cutting. 1 - ice; 2 - indenter; 3 - chips (spalles).

Fig. 2  Typical ice fracture areas and indenter / ice contact zones.
Fig. 3  Tested indenters and contact zones.
Fig. 4. Indenter/ice contact zones.

Fig. 5. Horizontal $P_x$ and vertical $P_N$ ice force components vs thickness of cutted ice layer $h$. $b=50$ mm, $\delta_p=35^\circ$. 

---

$h_x$ [mm]

$h, [\text{mm}]$

$P_x, [\text{N}]$

$P_N, [\text{N}]$

$a)$

$b)$

---

---

---

---
Fig. 6 "Pure" cutting: $h/t < 50$; $t$ - indenter's thickness, Indenter No. 1

Fig. 7 "Pure" cutting. Deformation of the Indenter No. 1 by the global crack.
Fig. 8 "Pure" cutting. Indenter No. 6.
Fig. 9 "Pure" cutting. Indenter No. 9.
Fig. 10. "Pure" cutting. Horizontal $P_x$ and vertical $P_N$ ice force components vs cutting depth ($b$).

- Indenter 2
- Indenter 6
- Indenter 9

- Global failures of the ice block

Fig. 11. "Pure" cutting. Contact pressure for indenters N 2, N 6, N 9.

- $P_{kr} = P_x/A_y$
- $P_{kr} = P_N/A_x$
THE MATHEMATICAL MODELS OF INTERACTION OF AIR CUSHION ICEBREAKING PLATFORMS WITH THE ENVIRONMENT

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ABSTRACT

The mathematical models of stability of air cushion icebreaking platforms and resistance to their movement at destruction of solid ice cover are being considered. The principles of their constructions are described, calculation results are given.

The present work considers the air cushion icebreaking platforms (ACIP) which during the past 20 years have been of interest as power-saving means of ice destruction and of prolongation of the navigation periods. They are characterized by relatively low speeds (upto 10 km/h), extremely low air consumption (the flow clearance is practically equal to zero and ACIP "sits in a pit"), application of non-receiver aerodynamic design and a single-level flexible skirt (FS) and absence of sectioning of the air cushion (AC). Because of these features of ACIP the classical theory of high-speed air cushion vehicles is inapplicable to them.

The problems of stability and resistance at destruction of solid ice cover are the most urgent ones for ACIP.

The mathematical models of ACIP stability are developed based on the following assumptions verified by the experimental data:
- external FS outline at ACIP difference remains constant;
- there is no redistribution of air pressure in AC at difference since there is no AC sectioning).

Then, it is possible to consider ACIP as a displacing vessel with draught \( h_0 = \frac{p_{ac}}{\rho_w g} \) (\( p_{ac} \) - air pressure, \( \rho_w \) - water density) at which the water-proof bottom remains parallel.
to the free water surface at the vessel difference (Fig. 1). Similarly to classical Euler's theorem at ACIP difference on infinitely small angle $\delta \psi$ for point of intersection of equal-volume waterlines $F$ is obtained:

$$X_F = -0.5 \frac{L_{ac}^2 B_{ac}}{L_{WL} B_{WL}}$$

(1)

where $L, B$ - sizes of AC in plan.

Following this analogy, the resulting force of the air support $P$ shall be considered as applied in the centre of gravity of the air hollow $C$. As it is visible from Fig. 1, due to the FS slope (for $\alpha$-angle) the ratio of air volumes additionally entering water and outcoming from it at difference, is such that point $C$ is shifted to the downing side. As a result of this the pair of forces $gD$ ($D$ - ACIP mass) and $P$ begins to create the restoring moment. It is also visible that at the difference the hollow size in plan is increased. Therefore, the condition of equal volumes inevitably results in the reduction of its depth (the ACIP is upcoming):

$$h = h_0 / \cos \psi - (X_F - 0.5 L_{ac} + h_0 \tan \psi) \sin \psi$$

(2)

The ACIP difference upto the finite angle around the axis, identified via (1), will not be equal in volume due to the considerable FS slope. Therefore, it is necessary to correct the $X_F$ value. Then, the process of ACIP difference can be presented as two stages (Fig. 2): the turn of the vessel around the conventional axis (due to the fact that the flow clearance is equal to zero it is convenient to accept point $A$ for this) and vertical motion of the vessel (by updating of $h$ value).

The restoring moment is presented in the following form:

$$M_r = gDl. \text{ The non-dimensional shoulder of the restoring moment is adopted as a stability measure: } \overline{T} = M_r / gDL_{ac}. \text{ As it is visible from Fig. 2: } \overline{T} = \Delta \overline{x}_c - \Delta \overline{x}_g, \text{ where } \Delta \overline{x}_c = \Delta x_c / L_{ac}, \Delta \overline{x}_g = \Delta x_g / L_{ac}. \text{ For the most wide-spread rectangular ACIP with the knee-like form of FS the stability mathematical model is developed in the analytical form.}

Originally the task is solved in the flat statement (an infinitely wide vessel). Here $\Delta \overline{x}_c$ is nothing but the abscissa of the centre of gravity of the air hollow longitudinal section (trapezium). The basis of dependences for descriptions of trapezium geometrical characteristics is the expression of linear elongation of the air hollow bottom at difference:
\[ \Delta L_{ac} = \tan \psi / \tan(\alpha - \psi). \]  \hfill (3)

It is fair for \( \psi \) angles under consideration, which do not exceed the angle of the ACIP bottom entry into the water.

Taking into account the ACIP width finiteness (a three-dimensional task) required (as calculations have shown) at \( B_{ac}/L_{ac} < 4 \) is executed by description of characteristics of air volumes connected to board FS elements. The \( \Delta \bar{x}_c \) expression for a three-dimensional air hollow is obtained by the usage of these dependences and the result of the flat task solution.

For ACIP of a non-rectangular shape in the plan (round, with a cut for a tug vessel bow etc.) or with a loop-segment or any other type of FS, the analytical model becomes too bulky. Therefore, for such platforms the numerical model is developed. In it the FS surface is generated in the form of theoretical lines and all air hollow characteristics are determined by numerical integration.

The value \( \Delta \bar{x}_g \) in both models is determined in the following way:

\[ \Delta \bar{x}_g = 0.5 \left( \cos \psi + 2 \frac{Z_g}{L_{ac}} \sin \psi - 1 \right) \]  \hfill (4)

where \( \bar{Z}_g = Z_g / L_{ac} \) is a non-dimensional elevation of the ACIP centre of gravity above the FS bottom edge.

The stability models are realized in the form of packages of application software for IBM PCs. However, for stability express assessment of a rectangular ACIP with a knee-like FS without a PC employment the simplified model is developed. The simplification is achieved by obtaining the dependence for the absciss of centre of pressure of an infinitely wide ACIP (a flat task) hovering above the rigid screen. The ACIP width finiteness is taken into account by introduction of the \( K_b \) factor, and softness of screen (water) - by the introduction of the \( K_p \) factor:

\[ \bar{p} = 0.5 K_p K_b \sin \psi \cdot \tan \left( \alpha - \psi \right) - \bar{Z}_g \cdot \sin \psi \]  \hfill (5)

Expressions for \( K_p \) and \( K_b \) are obtained by approximation of numerical experiment data executed on a PC for a number of ACIP projects. It consists of comparison of results of 1-calculations from the analytical model and (5) for different \( p_{ac} \) and \( \psi \) (\( K_p \)) and solutions of three-dimensional and flat tasks (\( K_b \)):

\[ K_p = 1.00 + 2.03 (0.0086 - 0.0831 \bar{h}) \psi - 0.1 (\psi - \psi_k)^{1.25} \]  \hfill (6)
\[ K_b = (1 + 0.190/B_{ac}) (1.072 - 0.0247 \psi) \]  \hfill (7)

where \( \psi_k = \arctg \left( \frac{H_k - \bar{h}}{\bar{h}} \right) \) - angle of FS knee entry into water.
The results of stability calculations from analytical and simplified mathematical models executed for ACIP "102-LP" are given in Fig.3 and demonstrate satisfactory coincidence of models with one another. The comparison of results of stability calculation from the analytical model and full-scale experiment data for ACIP "102-LP-M" is given in Fig.4 where their satisfactory concurrence is visible.

The mathematical model of ACIP resistance at destruction of the solid ice cover is developed with the employment of the following scheme of the motion process: hovering near the ice field edge (Fig.5,a), up-coming to the ice field with the change of both ACIP posture and ice deflection (Fig.5,b), occurrence of the cracks system in ice alongside with the growth of its deflection and the ice-floe break in the area of bow FS (full-scale observations) at \( L_c = L_{cr} \). The cyclic nature of ACIP motion is obvious. Therefore, the model is constructed for one such cycle of \( L_{cr} \) length.

At any moment of the cycle (Fig.5,b) the ACIP interacts simultaneously with solid ice cover, ice-floe and water. Then, it is logical to present its total resistance as a sum of components:

\[
R = R_{ic} + R_{if} + R_{hd}
\]

In its turn, the solid ice resistance is:

\[
R_{ic} = R_{ac} + R_{ic}^{fr}
\]

where \( R_{ac} \) is resistance of "up-coming to the wall" formed by ice field edge; \( R_{ic}^{fr} \) is resistance of FS friction from the ice field.

The ice-floe resistance is presented in the form:

\[
R_{if} = R_{if}^{fr} + R_{if}^{d},
\]

where \( R_{if}^{fr} \) is resistance of FS friction on the ice-floe; \( R_{if}^{d} \) is dynamic component (power consumption for carrying away of immobile ice-floes into the translational and rotary motion).

The principle of \( R_{ac} \) determination is clear from comparison of drawings 6,b and 6,a. For resultant forces of distributed loads \( p_{ac} \) and \( q_{hs} \) (\( R'_{ac} \) and \( T_{hs} \) accordingly) is written in the following way (Fig.7):

\[
R_{ac} = R'_{ac} - T_{hs}
\]

While integrating the loads which "disappeared" from the bow in hight (\( p_{ac} \) - on \( h \), \( q_{hs} \) - on AF) and width of vessel, we receive:
The nature of $R_{ic}^{rr}$ component is obvious if we consider FS breaking by the ice in point A (Fig.7):

$$R_{ic}^{rr} = f P_{ac} S_{fr}$$

where $f$, $S_{fr}$ - factor of friction and area of contact FS with ice. While dividing the $S_{fr}$ area into bow and side zones it is easy to receive the following expression:

$$R_{ic}^{rr} = f \rho_w g h \left[ \frac{Bac/2}{-Bac/2} \left( Z_A - Z_B \right) dy - \frac{1}{2} h B_{ac} \right]$$

As it is seen from (12) and (14) the $R_{ic}$ component to a considerable extent depends on the posture of ACIP ($Z_A, Z_f, Z_0$) up-coming to the ice.

The ACIP posture shall be determined by using the same approach as in the stability model (Fig.7). The resultant air pressure force ousting the water, $P_w$, is applied in the centre of gravity of the air hollow volume $V_{ac}$ (point $C_w$). and the one of the support forces stipulated by the ice cover, $P_1$, - in centre of gravity of its $S_1$, "area covered" by ACIP (point $C_1$).

The system of ACIP balance is:

$$\Sigma Z = 0; \Sigma M_{y'} = 0$$

where $Z$ - projection of forces on axis $Z$; $M_{y'}$ - moments of forces relative to the cross axis $y'$, passing through point $O'$. The first equation of the system (15) has the form:

$$P_w + P_1 - g D = 0$$

If for items of (16) we write:

$$P_w = V_{ac} \rho_w g; g D = V_0 \rho_w g; P_1 = P_{ac} S_1 = h \rho_w g \int_{-Bac/2}^{Bac/2} L_c dy.$$

(V_0 - hollow volume at hovering above the water), we obtain:

$$V_{ac} + h \int_{-Bac/2}^{Bac/2} L_c dy - V_0 = 0$$

The second equation of the system (15) is written while neglecting the moments from horizontal forces in view of a small size of their shoulders:
After receiving the obvious expression for $X_{c1}$ we write:

$$P_w X_{cw} - P_1 X_{c1} - gDx_g = 0 \quad (18)$$

The analytical solution of the system (17), (19), reduced to the two unknown values $Z_0$ and $\psi$ (Fig. 5, b) is extremely difficult. Therefore, it is solved numerically by the method consecutive approximations. At first the ice cover is accepted as non-deflected, then based on the found $h$ and $L_c$ the ice deflection is taken into account (numerical solution by the method of finite elements of V.V. Knyazkov for a three-dimensional task). After the ice cover deflection the values of $Z_A, Z_D, Z_F$ are changed, i.e. conditions of ACIP balance are infringed. Therefore, the vessel posture parameters $Z_0$ and $\psi$ are specified. It leads to the change of $h$ and $L_c$, i.e. to refinement of $W$ and etc.

The calculation based on (12), (14) is conducted for a number of vessel positions along the X axis ($X_o$, in Fig. 5, b). At each step after preliminary determination of the ice elastic line and ACIP posture from (17), (19) the analysis of ice cover condition is performed to reveal its breaking. The current value of $p_{ac}$ is compared to the load $P_{Acb} = f(L_c)$, that is the minimum one required for ice destruction received V.V. Knyazkov for a half-infinite plate with a cut. The value of $L_c$ at which $P_{Acb}$ is reduced to $p_{ac}$ is accepted as equal to $L_{cr}$ (the end of the cycle). The numerical dependence $R_{ic}(L_c)$ is thus determined. In Fig. 8 an example of calculation is given. However, for use of $R_{ic}$ in (8) it is reasonable to replace this dependence by some integrated characteristic:

$$R_{ic} = \frac{L_{cr}}{\int_0^{L_{cr}} R_{ic}(L) dL} \quad (20)$$

For determination of $R_{if}^{fr}$ the approach of V.A. Zuyev is used. Accepting the ice-floes length as equal to $L_{cr}$ and averaging the value of $R_{if}^{fr}$ per cycle we receive the following:

$$P_{if}^{fr} = fghL_{cr}(\Pi_{ac} - B_{ac} - L_{cr})(\rho_w - \rho_i)^2 / \rho_w \quad (21)$$

where $\Pi_{ac}$ - AC perimeter along the bottom FS edge, $\rho_i$ - ice density.

Taking into account the complexity of theoretical determi-
nation of $R_{1r}^d$ and $R_{hd}$ (at small speeds of motion) and especially their mutual influence it is reasonable to identify their sum, $R^d$, by approximation of results of ACIP model tests in the ice-floes (having excluded $R_{1r}^f r$ from them earlier). Such dependence is offered by V.A. Zuyev:

$$R^d = R_{1r}^d + R_{hd} = 0.42 \frac{g D \text{Fr}_v h}{L_{ac}}$$

(22)

where $\text{Fr}_v$ - Froude number on the air hollow volume.

To compare the results of $R$-calculation based on the described model with rather scanty and non-systematic full-scale data the non-dimensional characteristics of $F = \frac{R}{\rho_{ac} B^3 \sqrt{V_o}}$ is used. In Fig. 9 such comparison for two ACIPs is given: "ACT-100" and "107P". As it is visible from the figure the convergence of calculation and experimental data can be admitted as a satisfactory one.

Fig. 1. Scheme of ACIP difference round the real axis $F$ at its hovering over the water
Fig. 2. Scheme of ACIP difference round the conventional axis A

Fig. 3. The results of stability calculation on analitical and simplified models, executed for ACIP "102LP"

Fig. 4. The result of stability calculation on analitical model and full-scale experiment data for ACIP "102LP-M"
Fig. 5. Scheme of ACIP interaction with solid ice

Fig. 6. The action of air and water pressures over water and ice cover

Fig. 7. Scheme of forces, acting on the ACIP at up-coming to the ice field
Fig. 8. The results of calculation of ACIP resistance and posture at solid ice cover break

Fig. 9. The results of resistance calculation and full-scale data for ACIP "ACT-100" and "107P"
APPLICATION OF MIXED MODELS OF FINITE ELEMENTS METHOD FOR SOLVING ICE-COVER CURVATURE PROBLEMS

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ABSTRACT

In this article application of mixed models of FEM for investigating ice deformation as semi-infinite plate curvature on elastic basis being under transverse load (point force applied to the edge, equally located forces on the edge, load applied to the edge on different load areas, load equally distributed along the rectangle area) is considered.

INTRODUCTION

For evaluating navigation of ships in ice conditions and evaluating hull strength of ice-breakers it is necessary to determine the amount of force needed to break the ice-cover. On the other hand usage of ice-cover support for carrying out construction work from ice is also of practical interest.

By the present moment a great number of investigations has been carried out resulting in approximate calculation formula which was obtained after a range of different assumptions being made. Nevertheless we believe that it's possible to make further improvements in calculations.

Application numerical methods, and for example, FEM, makes possible to avoid numerous drawbacks of analytical methods dealing with both complex boundaries and load application areas and other problem peculiarities.
THEORETICAL FORMULATION

In this article application of mixed models of FEM for investigating ice deformation as semi-infinite plate curvature on elastic basis being under transverse load (point force applied to the edge, equally located forces on the edge, load applied to the edge on different load areas, load equally distributed along the rectangle area) is considered. Schemes of plate loading are shown in fig.1.

Figure 1. Schemes of loading for plate
A simple flexible triangle element of mixed type shown in Fig. 2, a was taken to solve this problem. Vector of generalized coordinates of the element

\[ \{ q \}_e = \{ W_1, W_2, W_3, M_{n1}, M_{n2}, M_{n3} \}, \]  

contains apices flexures \( W_1 \) and normal bending moments \( M_{n1} \) in the middle of its sides. Triangle element of mixed type was obtained by Herrmann [1] on the basis of Reissner's mixed variational principle. Reissner's functional in its nature is two-pole, including simultaneously both displacement and stress fields within the element as a whole. Compared to rigid, equilibrium and hybrid flexible elements mixed models easily satisfy compatibility requirements on the boundary of adjacent elements and do not require numerical displacement differentiation to define bending moments, because bending moments are included in vector of element generalized coordinates.

Reissner's functional with regard to the elastic basis is

\[
\Pi(e)_R = \int \int_{A(e)} \left( (M_{x,x} + M_{xy,y})W_{,x} + (M_{y,y} + M_{xy,x})W_{,y} - \frac{12}{Eh^3} \left[ (1 + \mu)M_{xy}^2 + \frac{1}{2}(M_{x,x}^2 + M_{y,y}^2) - \mu M_{x}M_{y} \right] + \frac{1}{2} \rho \bar{g} \bar{w}^2 \right) dx dy - \oint_{S_1(e)} \phi_w w_m s_{M_{ns}} ds - \oint_{S_2(e)} \phi_{\bar{w}} \bar{V}_n s dS - \oint_{S_3(e)} \phi_{\bar{w},n} \bar{M}_n s dS,
\]

where \( h \) - plate thickness, \( E \) - elastic modulus, \( \mu \) - Poisson's ratio, \( \bar{q} \) - normal pressure; lower indices after comma are derivatives; set values are marked by bars.

In the functional (2) the first contour integral is calculated for the element anticlockwise, the second and the third contour integrals are calculated for those boundary parts along which effective shearing force \( \bar{V}_n \) and normal angle of rotation \( \bar{w}_n \) values are given.

Bending and twisting moments and shearing force in regard to natural axes (Fig. 2, a) are bound with values respective \( x,y \) axes by the following dependences.
Figure 2. Triangular element of mixed type (a) and form of mesh (b).
\[ M_n = M_x \cos^2 \beta + M_y \sin^2 \beta + M_{xy} \sin 2\beta; \]
\[ M_{ns} = 1/2 (M_y - M_x) \sin 2\beta + M_{xy} \cos 2\beta; \]
\[ Q_n = Q_x \cos \beta + Q_y \sin \beta. \]

For angle \( \beta_1 \) between normal \( n_1 \) and axis \( x \)
\[ \sin \beta_1 = \left( x_i - x_j \right)/l_1; \quad \cos \beta_1 = \left( y_j - y_i \right)/l_1, \text{ where } l_1 - \text{element side length}; \quad j = i + 1 \text{ with } i=1,2 \text{ and } j=1 \text{ with } i=3; \]
\[ l_1 = \sqrt{(x_1 - x_j)^2 + (y_1 - y_j)^2}. \]

To provide compatibility of the element by flexures and normal bending moments along its boundaries simple approximation is adopted based on the linear law of flexure changing and element bending moments constancy

\[ w = [1, x, y] \left\{ \begin{array}{c} a_1 \\ a_2 \\ a_3 \end{array} \right\}, \quad \{ M_x, M_y, M_{xy} \} = \{ \mu_1, \mu_2, \mu_3 \} \quad (4) \]

Constants \( a_i \) are expressed as usual by apices flexures and coefficients \( \mu_i \) are bound with moments \( M_{n1} \) by the first equation of system (3). By way of approximations (4) initial functional (2) after a number of transformations and subsequent minimization comes to the relationship

\[ [k]^{(e)} \{q\}^{(e)} = \{f\}^{(e)}. \quad (5) \]

Matrix of rigidity-elasticity here is \([k]^{(e)}\) and element load vector \([f]^{(e)}\) is

\[ [k]^{(e)} = \begin{bmatrix} k_n & k_{WM} \\ k_{WM}^T & k_{MM} \end{bmatrix}; \quad [f]^{(e)} = \begin{bmatrix} qA^{(e)}/3 \\ qA^{(e)}/3 \\ 0 \\ 0 \end{bmatrix}, \quad (6) \]
where

\[
[k_n] = \left( \rho e g A^{(e)} / 12 \right) \begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix} - \text{matrix of elastic basis;}
\]

\[
[k_{WM}] = - \left( 12 A^{(e)} / E h^3 \right) [\alpha]^T [B] [\alpha] - \text{matrix of elastic compliance;}
\]

\[
[\alpha] = \begin{bmatrix} \cos^2 \beta_1 & \sin^2 \beta_1 & \sin 2\beta_1 \\ \cos^2 \beta_2 & \sin^2 \beta_2 & \sin 2\beta_2 \\ \cos^2 \beta_3 & \sin^2 \beta_3 & \sin 2\beta_3 \end{bmatrix}^{-1}
\]

\[
[B] = \begin{bmatrix} 1 & -\mu & 0 \\ -\mu & 1 & 0 \\ 0 & 0 & 2(1+\mu) \end{bmatrix}
\]

\[
\]

\[
[\beta] = (1/2A^{(e)}) \begin{bmatrix} -\sin \beta_1 & \cos \beta_1 \\ -\sin \beta_2 & \cos \beta_2 \\ -\sin \beta_3 & \cos \beta_3 \end{bmatrix}
\]

\[
[B] = \begin{bmatrix} B_1 & B_2 & B_3 \\ c_1 & c_2 & c_3 \end{bmatrix}
\]

\[
B_1 = y_2 - y_3; \quad B_2 = y_3 - y_1; \quad B_3 = y_1 - y_2; \quad c_1 = x_3 - x_2; \quad c_2 = x_1 - x_3; \quad c_3 = x_2 - x_1.
\]

\[
[\gamma] = \begin{bmatrix} -1/2 \sin 2\beta_1 & 1/2 \sin 2\beta_1 & \cos 2\beta_1 \\ -1/2 \sin 2\beta_2 & 1/2 \sin 2\beta_2 & \cos 2\beta_2 \\ -1/2 \sin 2\beta_3 & 1/2 \sin 2\beta_3 & \cos 2\beta_3 \end{bmatrix}; [1] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

\[A^{(e)} - \text{element area;}
\]

Full functional of the plate being investigated as a system of finite elements

\[
\Pi^e_R = \sum_{e=1}^{E} \Pi^{(e)}_R
\]

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allows after variating according to the unknown parameters $w_1$ and $M_{n1}$ to obtain a soluble algebraic system

$$[k] \{q\} = \{f\}$$

(7)

It is convenient to represent equation's coefficients (7), (rigidity-elasticity matrix) and free members (load vector) in nondimensional form obtained dividing respective values by characteristic linear dimension $l_o$ and substituting to the right part of the load intensity $q_o$

$$l_o = \frac{4\sqrt{D}}{k}, \quad q_o = \rho_b g l_o$$

(8)

where $D = \frac{Eh^3}{12(1 - \mu^2)}$ - cylindrical rigidity,

$k = \rho_b g$ - elastic base coefficient.

In case of solution (7) non-dimensional flexures $w_1 = w(x_1, y_1)$ and non-dimensional moments $M_{n1} = M(x_1, y_1)$ are obtained. Relation between non-dimensional and dimensional values of calculation results is established by the following relationship

$$w_1 = \frac{w_1}{q/k}, \quad M_{n1} = \frac{M_{n1}}{q/\alpha^2}$$

(9)

where $q$ - applied load intensity:

$\alpha = 1/l_o$ - ice cover characteristics.

Moment values are further used to find stress fields $\sigma_x$, $\sigma_{xy}$, $\tau_{xy}$ according to the well-known formulas. Limit tensile stress value at the top or bottom surface of the ice plate was adopted as rigidity criterion.

$$\sigma_p = \frac{6 M}{h^2}$$

(10)

where $M$ - bending moment.

As far as in the method in question the semi-infinite calculation domain is substituted by the area of finite dimensions, there arises a problem of mesh $l_s$ dimension, where outer edges could be considered remote in infinity. Ratio of applied force $P$ to the total elastic basis $P_b$ snapback force could serve as a criterion of such remoteness. For infinite
plate P/P_b = 1. Computational analysis for infinite plate case has shown that mesh area could be considered as infinite when l_s/l_o > 5. Flexural and moment errors in the centre are 1.1% and 0.3% respectively. For further calculations the following assumptions are made: l_sx/l_o = 6.0 and l_sy/l_o = 6.0, number of pitches along both axes being 20, which equals to the number of elements - 800 (symmetry along OY axis being considered, fig. 2.b).

To evaluate further the results of numerical realization of ice-cover stress-strained problem it becomes necessary and correct to check whether calculation results correspond to the accurate solution. This solution [2] was obtained for the case of concentrated force. Comparison of flexure and moment distributions at the edge and symmetry axis with those obtained in the accurate solution (fig. 3) shows satisfactory convergence.

![Graph](image)

Figure 3 Comparison of flexure and moments with accurate solution.

(---) - exact solution; (*) - numerical solution; 1 - axis of symmetry (ax=0); 2 - free edge (ay=0).
1 - two point forces applied to the edge;
2 - equally located forces on the edge;
3 - load applied to the edge on different load areas.

b) - load equally distributed along the rectangle area:

$q/\sigma_p h^2 a^2$

Figure 4. Dependence of breaking force on dimensions and forms of loading area.
MAIN RESULTS

The results obtained show that increase of load zone dimensions results in the total force increase (fig. 4). The area near load, which is limited by the first maximum rise of ice cover up is usually called flexures cup. Increase of load zone dimensions results in widening of flexure cup. Plate curvature with this diminishes, thus lowering level of stresses in ice. That's why amount of load $P$, necessary for ice breaking is increased.

In case of two-point load (fig. 1, b) when $a a < 1.8$ flexures reach their maximum value when $a x = 0$. When $a x > 1.8$ - maximum flexure is observed at the point where forces are applied. When $a a > 3.0$ action of forces upon stress-strained elements is significantly decreased what manifests in ice cover curvature increase under forces resulting in certain deceleration of total forces speed growth.

Dependences of the breaking load from loading zone dimensions for different schemes are given in fig. 4.

CONCLUSION

In this article only a small part of the obtained results is present. However, it's enough to confirm acceptability of FEM mixed models in this class of problems.

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Designing peculiarities of structures for icebreakers and ships for navigation in ice.

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Structures damages analyses for icebreakers and vessels for navigation in ice show that fifty percent of damages occur below the waterline. They are concentrated in the area below strengthened ice belt plates and in the bilge and bottom structures (Fig. 1).

Fig. 1. Typical forms of damages for web framing and outer shell plating at bilge and bottom areas of ship bow.
1-web of a floor; 2-crack; 3-area of swell; 4-buckling of a stiffener.

Analyses of information on ice damages that was accumulated during previous thirty years proves that shallow waters occur to be one of the causes for structures damages of icebreakers and for transport ships in the process of navigation in ice. It was revealed as well that the highest frequency of impacts against ice is usual for the bilge area and small dents have been found in this area in great numbers. Contacts of horizontal part of bottom with ice are rare but results of such contacts are more severe because there is possibility to run over an ice floe that is frozen to the ground, ice floes may get beneath the ship bottom because of suction, there may be impacts against ice floes that are coming up to the surface (when on deep water). Therefore it is permissible to make a conclusion that problem of bottom structures strength mostly concerns ships which are in self-dependent navigation in ice.

Without any consideration of values of loads that may act in these situations we shall analyse the problem of equal strength of components of bottom structures because in many cases components which serve as supports for ordinary framing are damaged in the first turn. Direction of loads passing from outer shell plating to longitudinal or transverse components of primary framing and further to web framing is implied here. One more peculiarity associated with local character of the loads occurs to be their ability to be implied directly to any element of the structure without passing through the above mentioned
succession of loads 'passing over. Special attention is to be paid to buckling strength of bottom framing made of panels.

Analysis of revealed damages of icebreakers and designing experience obtained in the process of structures modernization for icebreakers and ships for ice navigation permits to formulate several rules which are to be realized in bottom structures design of vessels designed for self-dependend ice navigation.

Firstly, from the point of view of diminishing of ice resistance and outer shell wear due to friction on ice it is better to use longitudinal framing system because, when a goffers of the outer shell appear, their larger dimensions will be oriented lengthways and so they will less oppose motion of the ship in ice.

Secondly, in view of small value of bending moment in longitudinal components of bottom structures primary framing (due to more close arrangement of floors) and for resistance to significant shear forces framing elements may be made of thicker stripes to simplify arrangement of their crossings with web framings. Where bulb steel or angle sections are used, their bulbs and face sides may be cut down to thickness of the web to simplify their crossing with floors arrangements and finally, it is necessary to make lower portions of floors and stringers webs of greater thickness arranging such webs of two parts in order to prevent buckling of those parts of web frames that are adjacent to the outer shell plating when they are subjected to intensive local loads.

The problem of framing designing for bottom structures of icebreakers and ships for ice navigation are to determine geometrical parameters of webs lower portions strengthening and to find correlation between dimensions of longitudinal primary framing and outer shell plating thickness for fixed spacing of web frames.

When lower part of a web girder is crashed a fold-goffer appears. Its location depends on several factors, viz. height and breadth of the panel, its thickness, and on correlation of these parameters. Calculation's forms of panel web buckling in dependence of its breadth 'a' are given in Fig.2a. It is obvious that center of buckling 'h' dependence on panel's breadth is nearly linear. Results of experiments carried out by the authors and full scale measurements of deformed web frames are shown in Fig.2b. They show correlations of 'h' with web thickness 's' and with 'h/h' (beams height in the range between h = 220 mm [8] and h = 2200 mm). Observations of the process of beams loading with a local pressure carried out during the experiments show that after an appearance of a folder (goffer) position of its top with respect to unloaded face plate does not change. At the same time goffer's breadth diminishes due to appearance of one or two folds. Therefore, distance between the swell center and unloaded edge was calculated in accordance with formula h=hs-h' (see Fig.2.b) because in all tests and full scale measurements forms of goffers were different (one or two folders). Correlation h=f(s) is approximated by formula h=9·s+s^2, mm, where s-thickness of the web, mm.
There are two different ways to increase local strength of high web frames. According to one of them, a stiffener is to be arranged in the center of probable swell (folder) on the web, i.e., at distance \( h \) from the outer shell plating. It permits to ensure buckling strength of the web loaded with local pressure up to the stress value equal to the yield point of the material.

This approach is based on the well-known fact from experiments that when high girders [10] or even beams of primary framing are loaded [11] an effect of division of the web in two parts (upper and lower) may be observed. When stresses reach the yield point each of these parts begins to function independently. If this phenomenon is taken into account, arrangement of a stiffener in the specified place permits to separate lower portion of loaded web as an isolated beam that would function in conjunction with a strip of plating. This way it is possible to increase the ultimate strength of lower part of a frame made of panels, although possibilities of this approach are limited because thickness of the panel remains the same.

\( \text{Fig. 2 Correlation of center of swell position with parameters of the panel.} \)

a) calculations with application of FEM;
b) generalization of experimental data, results of calculations, and results of damaged framing inspections.

Another way of web strength increasing is realized by means of increase of web thickness in its lower part up to the height \( H \). In this case the stiffener is to be arranged along the upper edge of the panel with increased thickness with the purpose to ensure its buckling strength against a side swell due to local load as that of a beam. Determination of optimal parameters
Fig. 3 Schemes of loads determination for web frames (a) and primary ones (b)

For this beam (height and thickness of the web, dimensions of the face plate) may be carried out with application of I.G. Bubnov's correlation for an I'-beam. S.P. Timoshenko's formula [9] may be used for verification of buckling strength against side swelling.

In order to ensure sufficient bending strength of an I-beam it is necessary to make its height not less than determined by the formula

\[ H = 1.16 \times \sqrt{W / S_{\text{min}}}. \]  

(1)

To resist the shear force sectional area of beam's web is not to be less than determined by the formula:

\[ S = 20 \times N / \sigma_0. \]  

(2)

where \( S_{\text{min}} \) - minimal thickness of web frames according to the Rules of Russian Register[1].

\( W \) - section modulus, cm³; \( N \) - shear force, kN;

\( \sigma_0 \) - yield point of material of the web, MPa;

\( S \) - sectional area of the web which exists to the shear force, cm².

When web height is calculated by the formula (1) for minimal thickness, the thickness is to be increased in accordance with the formula (2), sectional areas of shell's plate connected to a web and of the face plate being included in the area \( S \) value.

Preliminary calculations show that there is no need for verification of beam's web buckling strength when it is subjected to local pressure and shear force combined action because greater value of thickness is necessary to ensure shearing strength. Design schemes of bottom structures with strengthened lower parts of floors and stringers in accordance with the second approach are shown in Fig. 3. Several versions of compound web framing strengthened in accordance with the second approach are shown in Figure 4. When bulb flat symmetrical (or unsymmetrical) steel or unequal angles are used, it is recommended to cut their face plates to make possible "putting on" of strengthened web.
frames on top of ordinary framing (see Fig.4b). It seems reasonable to use spreadsheet that enable to obtain the required diagrams immediately after calculations, when extensive determination of scantlings for portions of web frames with increased thickness is to be carried out. Some results of calculations which have been carried out in order to determine values of $H, S_{fl}, b_1$ are given in Fig.5. All regulations with respect to strength, buckling strength, and minimal web thickness of the lower part of a floor in accordance to the Rules of Russian Register [1] have been complied with.

Correlation between scantlings of primary framing beams and thickness of outer shell plating may be obtained on the assumption that they may withstand to the utmost pressure of the same value. Intensity of the utmost pressure for outer shell plating may be determined from Standards of strength [7] as follows:

$$P = 4.0 \cdot K_1 \cdot \sigma_b (S_{sh} / a)^2 \text{ MPa}, \quad (3)$$

where $S_{sh}$-outer shell plating thickness reduced by the value of wear, cm (results of investigation of outer shell plating wear rates for icebreakers and vessels for ice navigation are given in References [12,13]);

$\sigma_b$-yeld point of shell plating, MPa.

![Fig.4 Structures with strengthened lower portions of web flaming]

- a) version with unsymmetrical face plate of a web girder;
- b) arrangement of primary framing component with symmetrical bulb crossing with lower portion of uncreased thickness of web girder;
- c) version with symmetrical face plate of a web girder.
a—length of smaller side of the supporting contour, cm. 

$$K_1 = 1 + 1.8 \left( \frac{a}{a_1} \right),$$

$$a_1$$—length of greater side of the supporting contour, cm.

Fig. 5 Diagrams for determination of height of lower portion of web framing on the base of external pressure and spacing of frames.

For ordinary framing on the base of its bending strength the utmost pressure is:

$$P = 16 \sigma_y W_0 K_1 \left( \frac{a}{a_1} \right), \text{ MPa},$$

where \( \sigma_y \) — yield point of framing material, MPa; 

\( W_0 \) — the utmost section modulus of a girder in conjunction with a strip of plating, cm³; 

$$K_1 = \frac{3}{3 - \left( \frac{a}{a_1} \right)},$$

the utmost load for ordinary framing girders loaded with a shear force

$$P = 1.15 \sigma_y \left( \frac{a}{a_1} K_3 \right), \text{ MPa}; \quad (5)$$

where \( S \) — sectional area of a girder or of welds cm², which connect girders that have been cut with basic structures resisting the shear force (see Reference [7]).

Equate pressure values obtained by formulae (3), (4), (5) it is possible to find such correlation between plating thickness and scantlings of primary framing components that would ensure their equal strength. Correlation between height of primary
framing girders hp and thickness of webs tp is to comply with
the regulation that the utmost condition of the girder comes
when bending moment and shear force act simultaneously. The utmost
loading condition formulated in Reference [7] is recommended
because it is in good correlation with results of full scale
experiments with girders [5]. Besides that from the point of
durability of ice resistant coating it is recommended in
Reference [12] to keep ratio of ordinary framing spacing to outer
shell plating thickness not more than 26. This recommendation
takes into account ability of ice resistance coatings to bear
deformations.

It is necessary to mention that according to experimental
data [5] and to estimations of loads applied to damaged
structures it has been proved that outer shell plating is of
great importance for ability of primary framing girders to
withstand shear forces. In order to take into account this fact
it is recommended increase web height, when it is designed on the
base of shear force, on the value which is equivalent to three
thicknesses of the outer shell plating plus thickness of the
face plate, if there is one. This recommendation is formulated in
the standards of strength [7].

For estimation of reaction in the place of an primary
framing component crossing with a web girder diagrams for
the utmost reaction R that is possible in this place may be used
the diagrams are given in Reference [3]. Value of reaction R in
the crossing may be determined by means of scheme shown in
Fig.3. One diagram for determination of reaction in the
crossing of a strip beam with a web girder is shown in Fig.6.
There are design parameters of the strip beam at the bottom of
Fig. 6. Fragment of a web girder with increased thickness of
lower part of its web arranged in the bilge area is shown in
Fig.7. This area is specific because it is necessary to put
primary framing components normally to the outer shell. The
problem of "turn" of primary framing cross sections in the areas
with variable angle of flare is solved if each primary framing
component is cut on parts with length of (3 - 4)*a1 and
these parts are joined on floors webs with their bulbs only. Load
pass over from one part to another is ensured this way. Such a
solution may be recommended for ship bow area where problem of
general strength is not of primary importance. Besides that
due to specific arrangement of ordinary framing in the bilge area
its components are to pass through openings in thicker
portions of webs.

Recommended arrangement of web frames of structures
subjected to local loads is protected by the licence N 1331720
"Ship hullframing", authors: Babtsev V.A., Shemendiuk G.P.,

Redistribution of material's weight towards areas of local
loads application enables to retain structures weight and
dimension parameters while reliability of the structures becomes
Fig. 6. Diagram for determination of reaction R in the crossing.
1 - 160*16; 2 - 180*8; 3 - 200*20; 4 - 220*22; 5 - 240*24; 6 - 260*26; 7 - 280*28; 8 - 300*30.

Fig. 7. Recommended arrangement of lower portion of a web frame strengthening.

higher. More complicated technology of structures assembling in the process of ship construction will be compensated in the future exploitation due to diminished volume of repair work. The last fact is primary importance for shiponers. Exploitation experience of icebreakers "Ermak", "Admiral Makarov", "Captain Sorokin" proves that only this approach enables to escape regular damage of bottom structures.

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Results of statistical analysis of satellite data on discontinuities in ice cover in the south-western Kara Sea and their possible use for planning sea operations during the winter-spring period

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Abstract
On the basis of satellite data for the south-western Kara Sea, generalized characteristics of discontinuities in ice cover were calculated for some months from December to May by grid squares 50x50 km and presented in the form of charts. By analysing the obtained data, it was found that in the regions of ice navigation along the routes Kara gate - Dikson and Zhelaniya cape - Dikson the modal direction of discontinuities is close to the general direction of the motion route of ships. Favourable conditions for using the discontinuities here are also provided by their significant density and large occurrence frequency in the directions of a modal interval. The length of discontinuities along the route in a 50x50 km square is 35-40 km, on the average. It is concluded that planning of sea operations should take into account the regime characteristics of discontinuities along with other ice cover characteristics influencing ice performance of ships.

The presence of discontinuities is a typical feature of the Arctic Seas in winter. They occur due to spatial inhomogeneity in the drift velocity field and are formed as cracks, leads, fractures or relatively narrow extended zones with increased degree of fracturing and slightly reduced ice concentration. Sometimes discontinuities form an ordered system - a polygonal grid that divides ice cover into quite large separate blocks /1/.

In practical respect, an interest in discontinuities is mainly governed by their large significance for navigation /2/. Being potential routes for easier navigation, discontinuities are often used for escort of ships by icebreakers in complicated ice conditions. Thus, already in 1954 in the middle of October the transport ship "Yenisey" was escorted from Pevek to the eastern boundary of multiyear ice to the Chukchi Sea through compact ice using a system of discontinuities. At the end of May-beginning of
June 1978 during the voyage of the nuclear icebreaker "Sibir'" with a transport ship "Kapitan Myshevsky" along the high-latitudinal route from the Barents Sea to Bering strait, the motion route was selected taking into account channels and cracks. In anomalously difficult ice conditions which had formed in October-November 1983 in the eastern Russian Arctic, escort of transport ships by icebreakers in heavy ice at the eastern approaches to Long strait was by using systems of discontinuities.

As follows from these examples, data collection on discontinuities, their procession and generalization is important for shipping. For the Kara Sea this problem is resolved by establishing a database on discontinuities which is supplied by a package of processing and service software. Such decision is most effective, since it allows quite a quick determination of generalized statistical characteristics for any prescribed periods both for the whole of the sea and for its local regions.

Initial data input is made from satellite images received in direct transmission regime. Images in visual and IR-ranges of satellites "Meteor" and "NOAA" were used. The length and orientation of the segments of discontinuities within which changes in direction do not exceed 10° are entered on computer media by the grid squares 50x50 km. Information on the sea was taken for the intervals that are equal to 1-5 days. Data refer to discontinuities whose lower threshold width is 500 m, since this is the minimum width of leads and fractures that are decoded on satellite TV and IR images /3/.

At present the database includes data from December to May for various years beginning from 1979. Regrettfully, not all months have equal volumes of initial data.

Using the database, the following characteristics of discontinuities were calculated for the south-western sea for separate months by means of the package of processing software:

- specific length (measure of density of discontinuities) - mean length of leads and fractures over an area of 1 km²;
- modal orientation - the direction to which a maximum density of the orientation of discontinuities corresponds (along with the first mode the second mode, next in significance, was
determined):

- the occurrence frequency of the modal interval - a percentage ratio of the length of discontinuities whose direction falls into the modal interval, to the total length of all discontinuities in the square (a modal interval is assumed to be equal to 30° and corresponds to the condition - modal direction ± 15°).

All characteristics are obtained in the form of charts, but here it is not possible to illustrate the fields for each month. Therefore, the examples given below will only be for April, when ice cover reaches its maximum development.

Results of calculating the specific length show that the density of discontinuities is rather variable in space. In the field of specific length values there are zones with increased and decreased number of discontinuities (Fig. 1). The largest specific lengths are observed in the central region of the sea. With approaching the land or fast ice boundary, the density of discontinuities decreases. This typical feature is preserved for the entire period from December to May.

Temporal changes in the specific length are rather large. In early winter the density of discontinuities is quite large. In December-January the specific length is 19 m/km², on the average, over the entire calculation area (this corresponds to a total length of discontinuities of 47 km in a square of 50x50 km) reaching 40-50 m/km² in zones of enhanced values (the total length is 100-125 km in a square). Then the density of discontinuities decreases and in February-March the specific length is equal to 12-14 m/km², on the average. In April the number of discontinuities increase and the specific length becomes close to its values in December-January. In May, in connection with a total decrease in ice strength, the density of discontinuities becomes even larger and the specific length is equal to 24 m/km², on the average (the total length is 60 km in a square). Statistical distributions of the specific length obtained for each month showed that the fraction of sea area with a length of discontinuities of 55 km and more in one square is 32% in December-January, 12% in February-March, 47% in April and 58% in May.

Modal orientation of discontinuities (ωm) is quite ordered.
(Fig. 2) indicating the ordering of the systems of discontinuities. In Fig. 2 the length of the segments characterizing the orientation is proportional to the occurrence frequency of the directions of discontinuities falling into the modal interval $\left( \alpha_m \pm 15^\circ \right)$.

The number of squares with a bi-modal distribution of the orientation of discontinuities is close to 50%. Uni-modality is most pronounced in the sea region adjacent to the Yamal peninsula and the Bely Island. Here, the orientation of the first mode is steadily preserved from month-to-month (February is the only exception) insignificantly varying from square-to-square. Mainly it is close to the direction south-west–north-east. This means that the prevailing direction of discontinuities in this zone coincides with the general direction of the motion of ships passing here along the route Kara Gate–Dikson.

The second region where the modal orientation of discontinuities is of interest, is located south-east of the northern tip of Novaya Zemlya where ice navigation along the route Zhelaniya cape–Dikson is quite frequent. The prevailing direction of discontinuities in this region also corresponds, to a great extent, to the direction of ship motion.

The field of occurrence frequency of the direction of discontinuities falling into the modal interval (modal occurrence frequency) is characterized like the specific length field, by the presence of zones with its increased (65-80%) and decreased (35-50%) values. The values of modal occurrence frequency averaged over the whole of the sea for monthly intervals are equal to 55-60%. The sea area fraction with a modal occurrence frequency of 50% and more is 70% in December-January, 63% in February, 71% in March and 60% in April-May. These figures indicate once again a comparatively stable orientation of discontinuities in the winter-spring period.

As follows from the results of the analysis undertaken, the obtained generalized data can be taken into account for providing support to shipping. The possibility of using discontinuities in the south-western Kara Sea is not only governed by the coincidence of their prevailing direction with the direction of the navigation routes of ships, but also by a considerable
density of leads and fractures and a high occurrence frequency of modal orientation. Thus, on the basis of mean values of the specific length and modal occurrence frequency for April and May, it is found that the length of the discontinuities en route is 35-40 km in one square, on the average. Let us remind that these values only refer to sufficiently large discontinuities more than 500 m wide.

It is also necessary to note that when the generalized characteristics are taken into account together, February turns out to be the least favourable month for using the discontinuities. The total length of the segments of the discontinuities en route in the vicinity of the Kara Gate - Dikson route is only 15-20 km in a square in February.

Thus, the generalized values of the specific length, modal orientation and modal occurrence frequency can be used for estimating possible voyages of ships in close ice. For planning sea operations it is desirable to take into account the regime characteristics of discontinuities along with other ice cover characteristics influencing ice performance of ships.

Also, in addition to regime information on discontinuities on the basis of the database it is possible to obtain diagnostic estimates of the systems of discontinuities in the cases when there are no satellite data due to the presence of clouds over the whole of the sea or some of its regions. In such cases it is sufficient to find a field of discontinuities in the database which has formed in the presence of the atmospheric pressure field similar to the current one. In spring of 1995 the diagnostic charts of discontinuities prepared on an operational basis were reported to the Murmansk Shipping Company.

REFERENCES


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Figure Captions

Fig. 1. Mean values of the specific length of discontinuities in the south-western Kara Sea in April.

Fig. 2. Modal orientation of discontinuities in the south-western Kara Sea in April.

Fig. 3. Mean occurrence frequency of the modal interval in the orientation of discontinuities in the south-western Kara Sea in April.
Fig. 2
MAPPING OF THE BARENTS AND KARA SEAS BY STRENGTH AND BEARING CAPACITY OF FIRST-YEAR ICE

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In connection with increasing requirements of the engineering practice related to the organization of transportation in the Arctic in winter, exploration of hydrocarbon fields on the Arctic shelf, etc., there is a need for analyzing regional variability of such ice characteristics as strength and bearing capacity by generalizing data of theoretical and experimental studies of ice physical-mechanical properties obtained in recent years.

In most cases the ice cover of the shelf zone is formed by the ice of congelation, infiltration and intrawater formation differing in structure and physical characteristics. Seasonal changes as affected by thermometamorphic processes sharpen these differences in the ice cover resulting in considerable changes in its strength characteristics.

According to numerous experimental data, the main factors on which the mechanical properties of sea ice cover depend are ice temperature and salinity. Mean values of these characteristics weighted by ice thickness can be calculated if the thicknesses of the snow and ice cover, air temperature, temperature and salinity of the near-ice water layer are known. From known mean ice temperatures and salinities one can calculate the volume of the liquid phase which according to the cellular sea ice model of A. Assur is the main initial parameter for determining mechanical characteristics.

Using the available multiyear data on mean monthly values of air temperature \((t_a)\) and near-ice water layer \((t_w)\) for definite ice thicknesses \((H_i)\), one can determine the mean monthly ice temperature according to the Nazintsev's formula \((t_i)\):

\[
\frac{t_a \cdot H_i \cdot \lambda_s + t_w \cdot H_s \cdot \lambda_i}{t_w} = \frac{t_w}{2 \cdot (H_i \cdot \lambda_s + H_s \cdot \lambda_i)} + \frac{t_a}{2}.
\]
where $\lambda_s$ - heat conductivity of snow; $\lambda_i$ - heat conductivity of ice. The thickness of the snow cover ($H_s$) can be expressed by the following analytical dependencies /1/:

$$
H_s = 8.827 \cdot 10^{-3} \cdot H_t^{1.555} \quad \text{- for fast ice;}
$$

$$
H_s = 3.089 \cdot 10^{-3} \cdot H_t^{1.555} \quad \text{- for drifting ice.}
$$

Mean salinity of the ice cover ($S_i$) can be calculated by the formula /2/:

$$
S_i = S_w \cdot (1-b) \cdot \exp(-a \sqrt{H_i}) + S_w \cdot b,
$$

where $S_w$ salinity of the near-ice water layer. It is proposed to assume the dimensionless coefficients "a" and "b", according to /2/ to be equal to $a=0.5$; $b=0.13$.

The liquid phase volume ($V_b$) is determined according to the formula of Frankenstein-Garner /3/:

$$
V_b = S_i \cdot 10^{-3} \cdot (0.532 - 49.185 \cdot t_i)
$$

On the basis of comparing the representative statistical results of recent measurements of the ice strength of the Kara Sea, the Sea of Okhotsk and the Bering Sea with the values of the ice strength calculated by different methods, it is found that optimal results for the Arctic Ocean Seas are obtained by calculating sea ice flexural strength using cantilever beams by the formula of Truskov-Polomoshnov modified by us /4/:

$$
\sigma = 1,94 \cdot 10^{-3} \cdot H_i \cdot 6 \cdot k(t_i,S_i) \cdot k_d,
$$

where $\sigma = 57 + 0.4 \cdot S_i - 8 \cdot t_i - 600v_b$ [4], $k$ - a dimensionless coefficient of the transfer from the uni-axial compressive strength to the flexural strength of cantilever beams

$$
k(t_i,S_i) = a_0 - a_1 \cdot t_i + a_2 \cdot t_i - a_3 \cdot t_i + a_4 \cdot t_i \quad \text{at } t_i > 10^0C
$$
\[ k(t_1, S_1) = b_0 - b_1 \cdot (t_1+8) + b_2 \cdot (t_1+8)^2 - b_3 \cdot (t_1+8)^3 + b_4 \cdot (t_1+8)^4 \] at \( t_1 < -10^\circ \text{C} \)

Here the coefficients \( a_1 \) and \( b_1 \) are obtained by analyzing the experimental data for ice of different salinity: 2, 4, 6, 8, 10 and 12 per mil.

The coefficient \( k_d \) in the ratio (1) presents the dynamics coefficient that takes into account the ice structure at different conditions of the ice formation.

In accordance with the data in /5/ and unpublished results of the work of Tyshko K.P. for fast and drifting ice of the Kara Sea the indicated coefficients are obtained in the following form

\[
k_d = \frac{0.85 - 0.47 \cdot H_I}{5.64 \cdot \exp(-0.135 \cdot |t_1|)} + 1
\]

\[
k_d = \frac{0.85 - 0.47 \cdot H_I}{3.62 \cdot \exp(-0.098 \cdot |t_1|)} + 1
\]

The block-scheme for calculating flexural ice strength by means of this method is given in Fig. 1. The deviation of the ice strength values thus calculated from the measured values does not exceed 6%.

The dynamic elasticity modulus \( (E_d) \) can be calculated by the formula suggested by B. Frederking and U. Hasler:

\[
E_d = E_o \cdot (1 - \sqrt{\nu_b})^4
\]

where \( E_o = 9.21 \cdot (1 - 0.00146 t_1) \).

The statistic elasticity modulus \( (E_s) \) of sea ice can be determined by the formula:

\[
E_s = E_i \cdot (1 - \sqrt{\nu_b})
\]
where, according to Gold

\[ E_1 = 5.69 - 0.064t_1 \]

For determining the Poisson's coefficient \((v)\) B. Weeks and A. Assur recommend to use the formula:

\[ v = 0.333 + 0.06105 \cdot \exp(t_1/5.48) \]

which gives the following values: \(0.333 < v < 0.394\).

\[ \tilde{\sigma}_f = \frac{1.94 \cdot 10^{-3}}{\sqrt{H_1}} (57 + 0.4\tilde{S}_1 - 8\tilde{t}_1 - 600\tilde{v}_b) k(\tilde{t}_1, \tilde{S}_1) k_d \]

Fig. 1. A block-scheme for calculating flexural ice strength using cantilever beams.

The bearing capacity of the ice cover, i.e. its property to resist destruction under the impact of different loads, is considerably affected by the duration of the application and character of loads. Usually, three typical modes of ice loading are identified: dynamic at which elastic properties of ice are fully revealed and non-elastic result in energy dissipation; static when the inertia forces can be neglected; the persistent loading mode at which ice plastic properties are fully revealed. The ice cover for most static problems with a comparatively small time of the load
application can be considered as an elastic uniform plate lying on an elastic base of a hydraulic type. One distinguishes between the loading capacity of the ice floe up to the formation of the first through cracks \( P_{KP} \) and the full bearing capacity \( P_p \).

The analysis of the bearing capacity of the ice cover that is based on the theory of the flexure of elastic plates allows obtaining only an approximate description of what really takes place, especially at prolonged loading. A strict calculation of the destructive forces and an estimate of the influence of cracks on the ice loading capacity should be made in this case taking into account creeping in the presence of a temperature gradient by ice thickness and other factors.

Restricting himself to the case of a short-term (several seconds) static loading, Bernstein S.A. obtained a relatively simple equation for determining the loading capacity of an ice floe before the formation of first cracks /6/.

\[
P_{KP} = \frac{6f \cdot H_2}{3 \cdot (1+v) \cdot C(\alpha)}.
\]

It was suggested to determine the coefficient \( C(\alpha) \) from the diagram given in the above work which causes some inconvenience. Numerous modifications of this formula (for instance /7/, etc.) are related to the presentation of the coefficient \( C(\alpha) \) in the more suitable analytical form. For a convenient use of this formula in the computer program, we suggest the following approximation of this coefficient

\[
C(\alpha) = (1,02317 - 1,56695 \cdot \ln \alpha) \cdot 10^{-2}.
\]

The correlation coefficient \( r=0.99 \) at \( 0.1 \leq \alpha \leq 0.7 \). Thus, the calculation formula has the following form

\[
P_{KP} = 100 \cdot \frac{6f \cdot H_2}{(1+v) \cdot (3,07 - 4,70 \cdot \ln \alpha)}.
\]

That is why, in the results given below, the loading capacity
of an ice floe before the formation of first through cracks was calculated using a modified formula of Bernstein (it was assumed that the load is uniformly distributed over a circle with a radius of 3 m).

Using the developed algorithm for calculating physical-mechanical parameters of the congelation sea ice by its temperature, salinity and the volumetric content of brine, charts of mean multiyear values of strengths and the bearing capacity of first-year ice in the Barents and Kara Seas were compiled. Figs. 2 and 3 give an example of such charts.

All information on the charts is represented not by isolines, but in a digital form which corresponds to a recently formed tendency for preferring digital charts rather than using traditional charts and enables linking the two ice state parameters that are mapped (strength and bearing capacity) to the three gradations of its thickness (probabilities of encountering ice of different thickness are given in special handbooks). This allows reducing the number of the chart sheets to a minimum: November-April; May and October; June. From July to September the ice strength does not exceed 0.1 MPa which results in a loading capacity less than 100 kH and charts for this season are not calculated.

The flexural strength in MPa - a group of digits in the upper left-hand corner of the square; the bearing capacity in kH - in the lower right-hand angle. Upper digits refer to thin first-year ice; middle - to the ice of medium thickness; bottom - to thick first-year ice. When necessary, the interpolation between the neighboring values of the parameters is assumed.

The calculated information is prognostic and depending on the character of input hydrometeorological data (mean multiyear or measured (expected) for a definite date) it can be either regime-climatic or operational.

In the first case it is useful at the planning stage: for designing off-shore structures on the shelf of the Arctic Seas - ice warfs, routes, aerodromes, as well as oil rigs, platforms, oil and gas pipelines.

In the second case, it can be used for escort of icebreakers, unloading activities on the ice, making channels and holes, as well as for strengthening warfs and runways.
Fig. 2 Calculation mean multiyear failure strength (MPa) and bearing capacity (kN) of first-year (of the thin, of the middle thickness and of thuck) ice.
Fig. 3 Calculation mean multiyear failure strength (MPa) and bearing capacity (kN) of first-year (of the thin, of the middle thickness and of thuck) ice.
REFERENCES


Expanding of large-scale activities for oil and gas exploration and production in the shelf zone of ice-covered seas is impossible without taking into account data on ice cover (wind-induced and tidal ice drift, ice compacting, pressures and diverging, geometry of drifting ice floes, etc.). Ice information is also necessary for providing support to transportation, Navy operations and for other users.

Information on the ice state can be obtained by using different technical means. Side-Looking Alborne Radar (SLAR) Stations play a particular role as they can be used under any weather conditions. Application of SLAR "Toros", "Nit" installed on-board high-altitude aircraft and "Okean" satellite has allowed obtaining unique information on the ice state in the Arctic Seas and the Arctic Basin. This information can be used for solving a number of research objectives. However, data of "Toros" and "Nit" do not provide spatial resolution required for the survey of local regions for supporting construction of off-shore structures in the shelf zone of the seas. Thus, the need for creating a digital side-looking radar station with high spatial resolution, absolute calibration that can be installed onboard low-altitude aircraft has arisen. It is obvious that the indicated technical means will allow addressing the objectives that are usually resolved by means of aerophotography of ice cover, but will not depend on the visibility conditions. Also, due to a large depth of radiowave penetration, one can identify ice cover features on a radar image that are illegible when using other remote sensing means.

As a result of addressing this problem, the AARI has developed a digital SLAR with the following characteristics:
- operating range of wave lengths X-range
- polarization horizontal
- swath width up to 14 km
- angle resolution 0.01 rad.,
- resolution by the distance range 7-10 m
- flight altitude from 300 to 2000 m
- accuracy of the geographical reference
  of images by means of the satellite
  navigation system 50 m

The station provides real-time viewing of images on the monitor
screen of the on-board computer directly in flight, storage of
images on magnetic disc for further procession and display.

Flight tests of the station were performed in July-August 1994
and in March-April 1995. The goal of the tests was as follows:
- determination of real parameters of the station and their
  comparison with the calculated ones;
- absolute calibration of the station;
- determination of the informative content of radar images of
  ice cover, water surface, forest zones, etc., obtained by means of
  the station constructed.

For absolute calibration of the station angle reflectors with a
side of 40 cm (effective scattering area - 105 sq.m) and a sphere 25
cm in diameter (effective scattering area - 0.05 sq.m) were used as
point targets. In spite of the difference in their effective
scattering area by 33 Db, the indicated targets are clearly
displayed simultaneously on radar image.

Fig. 1 presents a fragment of the radar image in the Gulf of
Finland in the vicinity of the dam. The survey was conducted on 6
April 1995 from an altitude of 600 m. The frame size is 3640 m (by
horizontal) and 3100 m (by vertical). The image shows ice conditions
in the region of the dam's gate.

The results of the work made indicate that it is desirable to
use a helicopter high resolution SLAR for ice cover mapping allowing
one to obtain the following characteristics:
- ice distribution in the local region at different wind
  situations;
- ice concentration and age categories, its evolution with
time;
- fast ice, its freeze-up, the largest extent, break-up and
decay;
- leads and fractures, their geometry, stability with time,
  statistical characteristics;
- geometry of drifting ice floes, partial distribution of ice
  area by ice floe size at different stages of the ice cover
  existence;
- geometry of grounded ice formations and their formation features;
- ice drift.

In conclusion it should be mentioned that installation of SLAR at low-altitude aircraft (helicopters, AN-2 aircraft) makes the use of the station economically profitable.

Fig. 1 A fragment of the radar image in the Gulf of Finland in the vicinity of the dam.
THE PECULIARITIES OF THE KARA AND BARENTS
SEA ICE COVER FORMATION AND SCHEMATIC
MAPPING OF ITS STRUCTURE AND MAIN
PHYSICAL PROPERTIES

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Multイヤr investigations of Kara and Barents sea ice cover have
allowed to point out the most important peculiarities of ice
formation mechanisms, spatial and temporal variability of its
structure. In ice cover of these seas the regions with prevailing
calm or dynamic ice formation conditions are clearly expressed.

The variety of dynamic ice formation mechanisms in Kara sea
depends on hydrologic regime complexity and first of all intensive
Ob-Yenisei fresh water masses drain. In fresh and sea water contact
zones also as on open water areas in autumn and winter ( coastal
polynyas, fractures and cracks in drift ice ) are created the most
favourable conditions for these processes. It can be explained by
the fact of their close relation both water supercooling and heat
transfer from open water areas. As the result in these regions
prevail such structural types of ice as slush, grease and frazil
ice. In sea ice cover they form a desorientated structure with
isometric shape of crystals and low salinity.

In Barents sea the dynamic ice formation processes prevail
everywhere in ice edge zone and also in the regions of intensive ice
exchange with adjacent Kara and White seas. That is why in the
southern-east part of the sea from i-nd Kolguev till str. Karskie
vorota is observed the most intensive formation of these ice types.

For the central parts of both seas more stable ice formation
conditions are typical and as a consequence in middle and low layers
of ice cover here develops orientated structure with the crystal
growth in the direction of their basal planes ( 0001 ) and
anysotropy of ice physical properties.

On the data base obtained as the result of multiyear
investigations of Kara and Barents sea ice structure has been
carried out its schematic mapping with distinguishing predominant
ice structure regions. The main information to create this mapping
method was the distribution of the multiyear average monthly values of air temperatures and ice thickness. On every map with ice thickness average monthly values was plotted the data of its crystal structure typical for this period. To make it easier to solve this problem all the structural ice classification / 1 / has been divided into two main parts: types of cogelation ice with prevailing parallel-fibrous crystals ( B1,B2,B3,B5 ) and dynamic ice with isometric form of crystals ( B4,B6,B7,B8,B9 ). It had been taken into account also that at such division the physical properties of these ice groups differ radically. The degree of dynamic ice formation in every distinguished region was defined by dynamic coefficient Kd, that is

for the firstyear ice

\[ Kd = (1 - \frac{Hcon}{Hob}) \times \frac{Hcal}{Hob} + (\frac{Hob}{Hcal} - \frac{Hcon}{Hob}) \]  \hspace{1cm} (1),

for the multiyear ice

\[ Kd = 2.5 \times (1 - \frac{Hcon}{Hob}) \]  \hspace{1cm} (2).

where
\[ \text{Hcon} - \text{thickness of congeloation ice layer,} \]
\[ \text{Hob} - \text{observed ice thickness at average monthly means of air temperature,} \]
\[ \text{Hcal} - \text{calculated on Zubovs method / 8 / ice thickness at average monthly means of air temperature.} \]

Every means range of Kd approximately corresponds to determined percentage range of dynamic types ice presence in total thickness of ice cover ( Table 1 ).
Table 1

The type of ice formation as a function of dynamic coefficient Kd

<table>
<thead>
<tr>
<th>Kd</th>
<th>Amount of dynamic type ice in total thickness of ice cover, %</th>
<th>Type of ice formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.5</td>
<td>0 - 20</td>
<td>Congelation</td>
</tr>
<tr>
<td>0.5 - 1.0</td>
<td>20 - 40</td>
<td>Congelation prevails</td>
</tr>
<tr>
<td>1.0 - 1.5</td>
<td>40 - 60</td>
<td>Congelation-dynamic</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>60 - 80</td>
<td>Dynamic prevails</td>
</tr>
<tr>
<td>&gt; 2.0</td>
<td>80 - 100</td>
<td>Dynamic</td>
</tr>
</tbody>
</table>

Composed sketch-maps of ice formation dynamic coefficient distribution for every month from October to April have allowed us to follow the dynamics of its variability during the whole autumn-winter period. (Distribution of Kd in December in Barents sea and in March in Kara sea are shown on Fig.1).

The schematic mapping of weighted average monthly values of ice temperature was carried out in accordance with obtained results mentioned above. In different works devoted to such calculations is often assumed that ice temperature increases quite linear to its thickness that permits to use simple term average monthly value instead of weighted average monthly value. The variations range of these values for the first year ice of different thickness is well known /3/. That is why the main idea of this work was to see the seasonal variability of ice temperature as a function of ice and snow thickness and air temperature just for every distinguished region with predominant crystal structure of ice. The growth velocity of different structural types of ice at the same air temperature can differ considerably. For slush, frazil ice and shuga it depends first of all on compactness of crystals in volume unit or shuga porosity (relative amount of water in its mixture with ice crystals). The laboratory experiments have allowed us to ascertain the temporal variability of thickness, upper and lower surface...
Fig. 1. Distribution of dynamic ice formation coefficient:
a) in December in Barents Sea and b) in March in Kara Sea.
temperatures of different structural types of ice under the effect of constant air temperatures from the moment of ice cover appearing till the beginning of ice melting and also to calculate the equilibrium ice thicknesses in air temperature range from -5 to -55 °C / 7 /. (On Fig.2 these interdependencies are present for air temperature -10 °C ). On these data the method of schematic mapping of average monthly values of ice temperature was based.

If there is snow on ice cover the temperature of the upper ice surface and its average monthly value is often calculated on the base of assumption that the heat fluxes in ice and snow are equal / 2 / that is

\[ T_{up} = \left( T_a H x K_s + t x h x K_i \right) / \left( H x K_s + h x K_i \right) \]  \hspace{1cm} (3)

where \( T_s \) - temperature of the upper ice surface,
\( T_a \) - air temperature,
\( H \) - ice thickness,
\( K_s \) - heat conductivity of snow,
\( t \) - sea water temperature at the ice-water boundary,
\( h \) - snow thickness,
\( K_i \) - heat conductivity of ice.

But in equation (3) also as in well known Stephan expression for ice-water boundary place changes as the result of ice formation the temperatures of upper and lower ice surfaces are approximated correspondently by air and water temperatures. In this case re-distribution of vertical ice temperature as a consequence of heat transfer from water to ice and crystallization process is not taken into account. Nevertheless these processes are the main reason of the upper surface temperature of ice variability during its growth ( Fig.2b ) and neglect this fact can lead to noticeable errors in calculations especially at the beginning of ice formation.

That is why temperature of the upper ice surface was calculated in some stages. First of all for every distinguished region of Barents and Kara seas was determined the thickness of snow as a function of ice thickness / 4,5 /. Using the data of snow thickness were obtained equivalent values of air temperature or temperature of the upper ice surface \( T_{eq} \). That is those air temperatures that had
Fig. 2. Temporal variability of ice thickness growth (a), temperature of upper (b) and lower (c) surfaces of congelation and shuga ice formed at air temperature -10°C and values of shuga porosity 0.8(2), 0.6(3), 0.4(4) and 0.2(5).
(1 - result of calculation on Zubov /8/ method).
directly caused ice growth without snow or temperature of the upper ice surface with snow cover on it but without heat flux from ice-water boundary. To calculate Teq. the values of equilibrium ice thickness for average monthly temperatures were used i.e. at the condition of absence of heat flux from the water-ice boundary. the only one, when this calculation using the equation (3) is correct.

The further calculations of the upper ice surface temperature were fulfilled according calculation method of the temporal variability of the thickness growth of different structural types of ice /7/ by such a way:

1. Using the values Teq., Kd and nomograms of temporal variability of ice thickness growth of different structural ice types was determined equivalent time (with accuracy one day) of ice growth in every sea region. (An example of temporal variability of thickness growth of different structural ice types at air temperature -10 °C is shown on Fig. 2a). Here it is necessary to point out that Teq. might be both smaller or larger than the real age of ice cover. But this fact had not any noticeable effect on vertical ice temperature re-distribution because average monthly air temperature values were used. In addition to that shuga porosity under ice cover was defined on the base of laboratory experiments as a function of total shuga thickness layer and freezing level.

2. Using Teq., Kd, Psh. and nomograms of temporal variability of upper ice surface temperature at a constant air temperature the values of upper ice surface temperature have been obtained.

3. Since the temperature of the lower ice surface becomes close by temperature of sea water freezing somewhere in a 30 days (Fig. 2c) (the dynamical types of ice have this period from 8 to 20 days) in our calculations it approximated by the sea water freezing temperature except the beginning of ice formation when these data were taken from the nomograms of the temporal variability of lower ice surface temperature.

In addition to that at the growth of dynamical types of ice according the laboratory experimental results the temperature of its lower surface was supposed equal to -2.1 °C at the Psh. variations 0.6 - 0.8 and -2.2 °C when Psh. decreased to 0.2 - 0.4 at the sea water salinity 34 - 35%/oo. In case of water salinity lowering the temperature of the lower ice surface also decreased and in
dependency of shuga porocity values was somewhere 0.25 - 0.30 °C lower than sea water freezing temperature.

Taking the average values between upper and lower ice surface temperatures has allowed us to compose the scetch-maps of monthly average ice temperatures distribution in Kara and Barents seas for the autumn-winter period from October to April. ( On Fig.3 distribution of average ice temperatures in December in Barents sea and in March in Kara sea is presented ).

The schematic mapping of the weighted average values of ice salinity in both seas was carried out on the base of obtained data of monthly average ice temperatures, spatial distribution of sea water salinity and more used interdependencies of weighted average ice salinity and its thickness, velocity growth and air temperature. When these investigations began the linear dependencies of N.T. Chernigovskovo and B.A.Savelieva /6/ of ice thickness increase during its first day of growth versus average values of its salinity and air temperature were used. But on the base of following analysis of laboratory experimental results obtained in AARI these formulas have been transformed in a such way:

\[
\Delta H = -0.325 \times \text{Ta} - 0.45 \\
\Delta H = 0.56 \times S - 1.74
\]

where \( \Delta H \) - increase of ice thickness for the first day of its growth,
\( \text{Ta} \) - air temperature,
\( S \) - ice salinity.

The physical characteristics of ice calculated according (4) are correct only for initial period of its formation because do not take into account the effect of brine drainage during its growth. Nevertheless they are necessary for the further calculations of weighted average ice salinity as a function of vertical ice temperature changes. So the temporal variability of the upper ice layer salinity may be approximated as

\[
\text{Sup} - \text{So} x ( \text{To/T} )^{1/2}
\]
Fig. 3. Distribution of the monthly average ice temperature:
a) in December in Barents sea and b) in March in Kara sea.
where $S_0$, $T_0$ - temperature of the upper ice surface and salinity of the upper ice layer after first day of its growth at the constant air temperature.

$T$ - temperature of the upper ice surface of observed thickness formed at a constant air temperature.

The analysis of the real salinities ratio of the upper and lower layers of different structural ice types predetermined the kind of relation between them as

$$S_I = S_{up} - 0.5 \times \left( \frac{H \times T}{H_{eq} \times T_0} \right)^{1/3} - 3n \text{ at } H < H_{eq}$$  \hfill (6)

$$S_I = \frac{H}{H_{eq}} \times \left( S_{up} - 0.5 \times \left( \frac{H \times T}{H_{eq} \times T_0} \right)^{1/3} - 3n \right) \text{ at } H > H_{eq},$$

where $H_0$ - ice thickness after first day of its growth at a constant air temperature,

$H$ - ice thickness formed at a constant air temperature,

$H_{eq}$ - equilibrium ice thickness for given air temperature when snow cover is absent,

$n$ - relative amount of ice mass in its mixture with water in shuga.

By such a way calculations of salinity in upper and lower ice layers were based on suggestion of its variability under the effect of the vertical ice temperature re-distribution during its growth at a constant air temperature.

To calculate the weighted average values of ice salinity different types of its vertical distribution were used that are typical for different structural types of ice.

It is necessary to point out here that obtained results are correct only for ice formed from the sea water with salinity 34 - 35‰. That is why the results of calculations for a coastal regions where the effect of the river fresh water is strong as for example for Ob-Yenisei Bay were corrected by following way
Fig. 4. Distribution of monthly weighted average ice salinity:
   a) in December in Barents sea and b) in March in Kara sea.
\[
\bar{S}_1 - \bar{S}_{34} = 0.28 \times (34 - \bar{S}_w)
\]

where \( \bar{S}_1 \) - weighted average ice salinity.
\( \bar{S}_{34} \) - weighted average ice salinity formed from the sea water with salinity 34 \(^o/oo\).
\( 24 < \bar{S}_w < 34 \) - sea water salinity.

On such a way corrected data have been composed schematic maps of monthly distribution of weighted average values of ice salinity. (On Fig. 4 distribution of monthly weighted average ice salinity in December in Barents sea and in March in Kara sea are shown).

The sketch-maps of monthly distribution of dynamic ice formation coefficient, temperature and salinity of ice may be used for the further mapping of physical and mechanical properties of Barents and Kara sea ice.
SEASONAL VARIABILITY OF DYNAMIC ICE FORMATION AND PROBABILITY OF APPEARING ICEBREAKER BOARD ICE STICKING IN THE WESTERN PART OF NORTHEN SEA WAY

Tyshko K.P., Cherepanov N.V., AARI.

Natural investigations of icebreaker board ice sticking (or in a short way simply ice sticking) carried out on board of such icebreakers as "Lenin", "Sybir" and "Arctica" have shown that the main condition of this phenomenon to appear is presence under ice cover frazil ice layer. This layer thickness that mostly consists of crystals with diameter not more than 5 mm can achieve some meters. As the result of ice sticking at the icebreaker board occurs such ice form usually called ice "cushion" that impedes to its propulsion and forces to stop it. Somewhere on 80 - 90% of its thickness that may achieve 6 - 8 meters ice "cushion" consists of such crystals holding on the surface of this layer large ice pieces.

According the results of ice "cushion" composition study has been made a conclusion that ice sticking mechanism should be closely connected with dynamic ice formation conditions because just under their effect forms frazil ice layer. This conclusion is also confirmed by such fact that in most cases this process is observed in consolidated ridged ice that is a consequence of ice cover shearing and open water areas formation.

In addition to this main conclusion as a consequence of laboratory investigations and natural observations on sea ice cover also some conclusions else have been made about the mechanism of ice sticking appearing:

1. Ice sticking may appear at quite different hydrometeorological and ice conditions.

2. Ice "cushion" appears mainly in those regions where frazil ice and shuga formation prevail; coastal regions where fresh water flow occurs and most dynamic parts of ice cover: sides of drift ice floes, regions of flaw polynyas, edge zones.

3. Vertical distribution of temperature gradient on icebreaker
board and electric aspect of its interaction with ice can not be the main reason of ice "cushion" appearing.

4. Thermohaline layering of under ice cover layer of frazil ice can in certain extent promote this phenomenon.

5. Contact mechanism between frazil (shuga) ice and icebreaker board must be in agreement with following results of natural observations:

   a) this contact disappears when icebreaker increases its speed;
   
   b) there is no regulation of frazil ice crystals with large pieces of ice and icebreaker board in ice "cushion"; the contact between them is liquid;
   
   c) different but not symmetrical forms of ice "cushion" even when icebreaker moves forward in the same part of ice cover;
   
   d) ice compacting promotes ice "cushion" formation and its diverging and breaking open lead to disappearing of this phenomenon.

Thus on the base of this conclusions during laboratory modelling of ice sticking mechanism first of all it was taken into account that the frazil ice formation can proceed both in supercooled water (for example, in a regions of fresh and sea water contact) and after heat transfer from open water areas in winter time. As the result of these investigations done in a such way two models of this phenomenon have been proposed. In the first of them the contact between ice crystals and icebreaker board appears in a moment of its entering in a zone of such ice when the surface water layers are supercooled that leads to rapid realization of supercooling energy (Thermodynamical model). Because of no possibilities in laboratory conditions to create a two-layers sistem consisted of snow-ice mixture and supercooled water layers this physical model realized by two ways. In a first of them during ship-model propulsion in a supercooled water the snow crystals were scattered in front of it (Fig.1a). In other experiments snow-ice mixture that consisted of frazil ice and snow crystals and small pieces of ice was placed in one laboratory tank while in another was prepared supercooled sea water. Then during ship model propulsion in a snow-ice mixture in front of it supercooled water was spilled through the rubber hose. In both cases the hull of the ship model was covered with rather
even layer of snow-ice mixture (Fig. 1b).

The mechanism of the second model of ice "cushion" formation is provided by hydraulic forces acting in a process of taking sea water on board through special tanks (ice boxes). In icebreaker hull they have small holes or notches near those the first contact layer of ice "cushion" forms. This layer filtering sea water grows in no time predominantly in vertical direction until reaches the low surface of ice cover (Hydraulic model). In this case the force pressing ice crystals to the icebreaker board may be defined by the pump pressure value, which is

\[ H = H_{ex} - H_{en} + (P_{ex} - P_{en})/g + (Z_{ex} - Z_{en}) + (V^2_{ex} - V^2_{en})/2g \]  

(1),

where

- \( H_{ex} \) - pressure on exit of the pump,
- \( H_{en} \) - pressure on entrance of the pump,
- \( Z_{ex}, Z_{en} \) - heights of the divert and lead pipelines,
- \( V_{ex}, V_{en} \) - velocities of flow on exit and entrance of the pump,
- \( P_{ex}, P_{en} \) - pressure of deliver and vacuum on entrance of the pump.

Thus ice crystals accumulated on the icebreaker board near ice boxes form the initial layer of the "cushion".

When this mechanism was studied in laboratory the wooden ship model with metallic hull was used. In the lower part of the hull small holes with diameter 2-3 mm were made that had the common outlet on the upper surface of the ship model. In this outlet with diameter 8 mm was inserted the metallic tube with rubber hose on it for taking water (Fig. 2a). In this way the real ice boxes functioning was simulated. The model was placed in sea water flow with salinity 35% and was remained fixed by special holder. Similar to natural conditions of ice sticking appearing the ice-snow mixture consisted of frazil ice and snow crystals was placed in this flow. Ice "cushion" was formed as soon as taking of water through rubber hose began (Fig. 2b) and in 1-2 min all the ice-snow mixture was accumulated round the model. In addition ice "cushion" was loaded with ice pieces with dimensions some cm which mass in considerable extent exceeded the mass of crystals. The "cushion" immediately came off the model when water taking was stopped.
Fig. 1. Laboratory equipment for investigations of ice sticking mechanism (a) and ice "cushion" on the hull of ship model (b).
Fig. 2. Laboratory hydraulic model of ice "cushion" formation: a) appearance of ship model and b) ice "cushion" on board of ship model.

1 - holes in board of the model for taking water,
2 - common outlet of the holes in the hull of the model,
3 - tube for taking water,
4 - tube for air supply to prevent ice "cushion" formation.
In both laboratory models of ice "cushion" formation ice and snow crystals came into contact with hull of ship model without ice cover on the surface of the tank. But in both cases it is supposed that ice cover breaking open and icebreaker stop occur when compactness of frazil ice under ice cover attains its critical value. This supposition is confirmed by ratio of forces that appear when this process starts. Thus the main characteristic of ice cover strength when ice "cushion" forms is the shear strength. The natural observations in Kara sea ice cover have shown that in zone of ice "cushion" formation in considerable extent prevail ice with small grained crystals of the structure types B7, B8 / 2 /. For this ice the shear strength at the temperature -2 °C is not more than 0.10-0.15 MPa / 3 /. The strength of liquid film interaction of two ice crystals with account their contact area achieves 0.012 MPa / 5 /. When the unit volume contains the maximum of ice crystals with diameter 2-3 mm (about 17-18) the strength of their contact may amount to 0.22 MPa. In these circumstances the strength of liquid film interaction of ice crystal with icebreaker board may be somewhere 0.008 MPa / 4 /. As it was mentioned above in thin ice cover "cushion" forms when speed of icebreaker in not more than 5-6 knots. When it increases this contact disappears and during the further propulsion of icebreaker "cushion" does not form. This fact is easily explained if consider the variations of dynamic pressure of water flow on a places of ice crystals contact with icebreaker board. The value of this pressure on the unit area may be defined as

\[ P = \frac{g}{2}v^2 \]  

(2)

where \( g = 102 \text{ kg x sec}^2/\text{m}^2 \) - mass density of water, 
\( V \) - velocity of flow.

So when speed of icebreaker does not exceed 5-6 knots the dynamic pressure of flow is equal 0.004 MPa. This value is less twice than contact strength of ice crystals with icebreaker board. If icebreaker increases its speed up to 10 knots the dynamic pressure of flow also will increase up to 0.012 MPa and as a consequence the formation of ice "cushion" becomes impossible.

Every of presented mechanisms of ice "cushion" appearing is certainly related with dynamic ice formation. The dynamic degree of
ice formation conditions is characterized both the presence in ice cover the layers with isometric crystals form and ratio of calculated and real ice thickness in the renovation process of sea ice cover in different periods of its growth. The higher dynamic degree of ice formation conditions the greater probability of ice sticking appearing. On the base of all obtained multiyear data analysis has been carried out the schematic mapping of ice formation conditions dynamic degree in the western part of Northen Sea Way. It has been done using the method created earlier for the same mapping of Karça and Barents sea ice cover /7/. (On Fig.3. distribution of dynamic ice formation coefficient on the western part of Northen Sea Way in march is shown). If consider probability of ice sticking appearing as a function of dynamic degree of ice formation it is necessary to point out that one can not use this criterion equally to all age gradations of ice. As natural investigations have shown ice "cushion" can not form in young floes of ice breccia where not completely regelated large pieces of ice and frazil crystals are not so strong that not crack during icebreaker propulsion. This conclusion is also correct at the same extent for ice cover with thickness up to 20 cm where probability of ice sticking is negligible. It can be explained by such fact that dynamic ice formation coefficient for young ice is always near its maximum meanwhile as thick layers ( with thickness some dozens of cm ) of frazil ice and shuga under such ice cover and large strength of it enough to be whole after passing of icebreaker are observed extremely rarely. It is well known that the regelation of frazil ice and shuga at air temperature -15OC and lower proceeds rather quickly /8/. At different compactness of the crystals ice layer with thickness 20 cm forms during the time from some hours up to 1-2 days. Besides it has a small viscosity at such temperatures and easily cracks under the effect of percussion action (passing of icebreaker ). In this connection the only condition of ice "cushion" formation in young ice cover with shuga layer under it is the high (for winter) air temperature. So at air temperatures higher than -10 OC and correspondent ice temperature near 0OC its viscosity /6/ and the period of shuga regelation considerably increase. But because the probability of such conditions when all these facts coincide is negligible it has been suggested to express the probability of ice sticking appearing through dynamic ice formation
Fig. 3. Distribution of dynamic ice formation coefficient on western part of Northern Sea Way in March.


Coefficient only for ice with thickness more than 30 cm.

All the estimation system of probability of ice sticking appearing as a function of dynamic ice formation coefficient may be accepted on the base of ice formation types variations in every distinguished sea region. Such estimation system (Tabl.1) has been worked out according the results of natural investigations of ice "cushion" formation carried out not only on navigable way but also in regions near it.

Table 1

The probability estimation of ice sticking appearing as a function of dynamic ice formation coefficient

<table>
<thead>
<tr>
<th>Kd</th>
<th>Probability estimation of ice sticking appearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 1.0</td>
<td>Ice conditions for ice sticking appearing in region are absent.</td>
</tr>
<tr>
<td>1.0 - 1.4</td>
<td>Probability of ice sticking appearing in region is equal 50% i.e. the necessary ice conditions that this phenomenon appear may be or not with equal probability in this region.</td>
</tr>
<tr>
<td>1.4 - 1.6</td>
<td>Probability of ice sticking appearing in region is equal 100% i.e. the necessary ice conditions that this phenomenon appear are present in region but the probability of their presence on navigable way is equal 50%</td>
</tr>
<tr>
<td>&gt; 1.6</td>
<td>Probability of ice sticking appearing on navigable way is equal 100%</td>
</tr>
</tbody>
</table>

The estimation system of probability of ice sticking appearing presented here is undoubtely very schematic. The main reason of it is both lack of natural data of this phenomenon and its exceptional locality. Nevertheless if to accept it appears a good chance to analyse the seasonal variability of ice "cushion" formation on the base of ice formation types variability not only on the western part of the Northern Sea Way but in any sea region.
REFERENCES

USE OF INDIRECT TECHNIQUES FOR SEA ICE TEMPERATURE AND SALINITY MEASUREMENTS

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In connection with a wide development of the activities for designing off-shore structures to be constructed and used on the shelf of the Arctic Seas, the questions of assessing sea ice strength characteristics in these regions on an operational basis become quite important. Main factors that govern the mechanical properties of sea ice cover are its temperature and the liquid phase volume.

Theoretical studies performed in recent years have shown that at an insignificant surface and internal radiation scattering in the ice, its brightness temperatures at the vertical ($T_v$) and horizontal ($T_h$) polarizations are related to effective temperature ($T_{ef}$) of the snow-covered ice by the following ratio:

$$T_{ef} = T_{eq}' \left( 1 + 2m - T_a - T_v \right) / (2T_h - T_v),$$

where:

$T_{eq}' = T_{eq}^2 / (2T_h - T_v)$

$$m = |r_v| - |r_h|, r_v, r_h - reflection coefficients (by amplitude) of vertical and horizontal polarizations.

Calculations performed for real temperature and salinity distributions in the ice have shown $|m| \leq 0.3$ at the incidence angles more than 50°. The latter allowed suggesting the realizability of the method for estimating ice cover temperature on the basis of polarization microwave measurements.

As a first step in resolving this problem, we carried out special laboratory studies of radiothermal radiation of simulated sea ice and considered theoretical questions of the correction of obtained results that takes into account real characteristics of antennas and contribution of background microwave radiation.

Experimental studies aimed to specify the coefficients in the ratio (1), find the limits for applicability of the ratio and
determine errors in calculating ice cover temperature.

For taking into account the contribution of background radiation, methods that are based on the use of partial scattering coefficients were applied. These coefficients allow reconstructing the true brightness temperature of the laboratory ice under study calculating it by formula:

\[
T_b, r(\theta) = \frac{T_b, m(\theta) - T_b, b(\theta)}{1 - \beta(\theta)} (1 - \beta(\theta))
\]

where \( T_b, m(\theta) \) - the brightness temperature that is measured by radiometer;
\( T_b, b(\theta) \) - the brightness temperature of background radiation;
\( \beta(\theta) \) - partial scattering coefficients;
\( \theta \) - the angle of view.

As an example, fig. 1 (a, b, c) gives the calculated, experimental and reconstructed dependencies of water brightness temperature on the angle of view.

![Fig. 1. Dependencies of water brightness temperature on the angle of view](image)

a) — — calculations;        c) — — reconstruction;
b) — — measurements;        d) — — taking into account sky radiation.

As can be seen from the diagrams, the reconstruction permitted improving the agreement between calculations and the experiment.

Taking into account the sky brightness radiation in accordance
with equation

\[ T_b(\theta) = T_b - r(\theta) - R(\theta) \cdot T_b - s(\theta) \]

where, \( R(\theta) \) - the reflection coefficient of the underlying surface which allows further improvement in the consistency of the calculated and experimental values (see Fig. 1 d).

A good agreement between the results of model calculations and full-scale data indicates that in this case the internal scattering of radiation in the laboratory ice can be neglected and that surface scattering is much less than absorption. Thus, it can be suggested that the ratio (1) is mainly fulfilled. It is only necessary to optimize the value of the parameter \( m \).

Assuming \( m' = 2 \cdot m \) and \( a = 2 \cdot T_h - T_v \) in (1), we obtain

\[ T_{ef} = T_{sh} \frac{1 - m' \cdot T_v / a}{1 - m' \cdot T_{sh} / a} \]

By using full-scale measurements for optimization, the following mean values of the parameter \( m' \) were obtained for different incidence angles and wavelengths:

<table>
<thead>
<tr>
<th>Incidence angle (degrees)</th>
<th>( m' ) (0.8 cm)</th>
<th>( m' ) (2.1 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.603</td>
<td>0.482</td>
</tr>
<tr>
<td>45</td>
<td>0.306</td>
<td>-0.050</td>
</tr>
<tr>
<td>50</td>
<td>-0.203</td>
<td>-0.677</td>
</tr>
<tr>
<td>55</td>
<td>-1.267</td>
<td>-1.688</td>
</tr>
</tbody>
</table>

Table 1 presents the results of calculating \( T_{ef} \) and their comparison with measured temperature at the snow/ice boundary (\( T_{snow/ice} \)).

Comparison of the calculated data with the experimental values shows the difference between them not to exceed 1 - 1.5°C, on the average.

It is obvious that the obtained coefficients \( m' \) are optimal only for experimental conditions. Small difference values prove the
validity of the physical grounds that are used in the parameteric model under development. Additional full-scale measurements are necessary for the model to be used in sea ice temperature measurements.

Table 1

<table>
<thead>
<tr>
<th>Wavelength 0.8 cm</th>
<th>Wavelength 2.1 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td></td>
</tr>
<tr>
<td>Field 1</td>
<td>Field 2</td>
</tr>
<tr>
<td>( T_{ef} )</td>
<td>( T_{\text{snow/ice}} )</td>
</tr>
<tr>
<td>40</td>
<td>269.8</td>
</tr>
<tr>
<td>45</td>
<td>269.7</td>
</tr>
<tr>
<td>50</td>
<td>269.8</td>
</tr>
<tr>
<td>55</td>
<td>269.7</td>
</tr>
</tbody>
</table>

As mentioned, the second parameter governing strength characteristics of sea ice cover is the volume of the liquid phase in ice. Experiments on ice samples have shown the perspectiveness of determining its SHF dielectric permeability by the characteristics of the pulse radar signal of a nanosecond duration that passed through the sample or was reflected from its boundaries. And the dielectric permeability is unambiguously related to a relative volume of the liquid phase in ice by ratios:

\[
\varepsilon' = 3.22 + 20.6 \times 10^4 \cdot \frac{v}{\sqrt{f}} ,
\]

\[
\varepsilon'' = 0.1 + 13 \times 10^4 \cdot \frac{v}{\sqrt{f}} ,
\]

where \( \varepsilon' \) and \( \varepsilon'' \) - actual and false parts of relative composite dielectric permeability of first-year sea ice, \( v \) - the relative volumetric content of the liquid phase in the ice in unit fractions, \( f \) - the frequency in Hz at which the dielectric permeability was measured in the frequency range from 10 to 500 MHz.

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This fact has allowed developing an instrument for determining the relative volumetric content of the liquid phase in sea ice by remote sensing means. This is a nanosecond pulse reflectometer with two wide-band antennas placed above ice. Instantaneous values of the signal reflected from the ice are introduced into a computer. Here, also a reference signal reflected from a steel sheet is entered. The computer separates the signals from the upper and lower ice boundaries, determines the time interval between these signals and ice thickness. Also, a reference signal and the signal from the lower ice boundary are expanded to Fourier series and the values of false parts of the ice composite dielectric permeability at harmonic frequencies are determined from the ratios of harmonic moduli. The liquid phase content in the ice is calculated using the above mentioned empirical equations of the relationship between a relative liquid phase volume and composite dielectric ice permeability.

Model tests of the instrument included recording of the reference signal, recording of real signals reflected from melting freshwater ice that simulates sea ice, computer synthesis of the signals reflected from sea ice of different thickness with different liquid phases by the reference signal, a computer analysis of synthesized and real signals and computation on their basis of a composite dielectric permeability of the ice and a relative volumetric content of the liquid phase in the ice.

The instrument envisages a possibility for connecting with a portable computer for obtaining the results of measurements directly on the site of antenna installation. For this purpose there is a built-in eight-discharge analogue-digital converter and the software for data read-out in computer has been developed.

Tests demonstrated a satisfactory operation of the instrument as a pulse radioreflectometer for the frequency range from 70 to 350 Mhz.

The use of wide-band antennas and computer procession of signals allow a separate observation of the signals from the upper and lower ice boundaries at its thickness from 0.2 m to 0.4 m.

The instrument permits either measuring ice thickness if the values of the real component of ice dielectric permeability are known a-priori or obtaining the values of this actual component in the frequency band of the signal of the instrument if the thickness is known. In both cases the instrument allows obtaining values of
the false component of ice dielectric permeability in the frequency band of the signal used.

The results of analysing computer synthesized signals reflected from the ice of different thickness with a different liquid phase content show a possibility for calculating a relative volumetric content of the liquid phase in sea ice with an absolute error of 1% at the change of the measured value from 1% to 10% and adequate physical and mathematical models. In spite of the fact that adequacy of most models used is confirmed by earlier experimental studies in this field (V. Vanta, M.I. Finkel’shtein and others), still the final conclusion about the capabilities of the instrument requires full-scale tests.

On the whole, the obtained results serve as a basis for finding empirical dependencies relating mechanical and electrophysical sea ice characteristics and governing the possibility for developing a method for determining mechanical characteristics of sea ice cover with the use of data collected by remote sensing means of its active-pasive sounding.
METHOD AND DEVICE FOR ICE STRENGTH MEASUREMENT

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Introduction.

The natural ice is a multiparametric system. Its mechanical characteristics and strength depend on the structure that, in turn, is determined by the conditions of water freezing, by the age of ice, by temperature and stress during the loading procedure, by influence of solar radiation and so on. The natural ice is high stratified material, its sublayers can be of different temperature and density. It is known also that the mechanical properties of ice depend on the testing conditions, including temperature, strain rate and type of the stress state. The nature of the ice itself and the complex character of the problems under investigation make it impossible to obtain and to use rheological relations that provide exact description of the ice behaviour for the wide range of the boundary conditions. That is why it is necessary to determine of ice mechanical characteristics and strength immediately in the place of its deposition. Spatial maps describing the most practically important properties of ice should be plotted on the basis of these measurements for each regions. The maps could be used further for the solution of practical glaciological problems. Taking it into account we can conclude that development of the express-method for measurement of ice mechanical properties and strength is a high-priority task.

The problem formulation.

Traditional methods for testing of ice specimens cut out of the ice cover demand application of large presses displaced indoors. Preparation and transportation of the specimens for these testing is very laborious and expensive procedure. To eliminate it, it is necessary to develop simple tests that can provide reliable and exact data immediately in the place of ice deposition.

Penetration technique is the only method that allows to solve this problem. There are numerous works concerning this method. One modification of this method based on hammering in of the rod with conical tip has been proposed for the first time by Lord Haefeli [1]. However this method gives no possibility to obtain original mechanical properties of ice because penetration of the conical indenter causes ice fracture that can not be reproduced and controlled. That is the main disadvantage of this method.

The other type of penetration method is the procedure including collision of a rigid spherical body and the ice surface. There is a set of variants of this procedure based on measurement of such integral characteristics as height of rebounding, depth of penetration, diameter of the crater formed. The most exhaustive investigations in this direction have been carried out by D.Ye. Heisin et all (1976) [2]. As the result of these investigations the modification of the original structure of ice inside and outside contact zone has been revealed. These integral characteristics describe simultaneously parameters of the material and characteristics of the fracture process that makes difficult to obtain the properties of the original material. The efforts aimed at mechanical characteristics determination by recording and processing of the impact deformation curve were unsuccessful because there were no devices and experimental technique for such quick processes registration.

Application of piezoelectric accelerometer gave the possibility to obtain oscillograms of the collision between the rigid indenter and ice plate [3]. Express-method and portable device for measurement of ice physical and mechanical characteristics and strength have been developed on the basis of this work.
Physical foundation of the method.

The device including rigid spherical indenter and piezoelectric accelerometer has been used for this investigations. Piezoelement is electrically connected with the correcting preamplifier that ensures the shape of the electric signal to be one half-wave, the boundary conditions for the collision are chosen that give the possibility to consider the material under investigation as the elastic-plastic half-space. If the initial velocity of collision \( V_0 \) is smaller than 100 m/s it is possible to consider the impact to be quasistatic and to use the Hertz model of elastic contact (Fig.1).

The main relationships. Deceleration of indenter caused by its collision with the ice plate is proportional to the voltage at the accelerometer output.

\[
\ddot{x}(t) = n \cdot \frac{1}{RC} \int_0^t U(\tau) d\tau,
\]

where \( n \) is conversion coefficient of the measuring line, \( C \) and \( R \) are the capacity and the resistance of the electric circuit, \( U \) is voltage, \( \tau \) is time.

Thus, using the values of voltage in the measuring circuit with known parameters \( C \) and \( R \) for the indenter with mass \( m \), it is easy to determine instantaneous acceleration

\[
\ddot{x}(t) = n \cdot U,
\]

and instantaneous reaction

\[
P(t) = n \cdot U \cdot m = m \cdot \dot{x}(t).
\]

We can obtain instantaneous velocity \( X \) and instantaneous depth of penetration \( X \) by successive integration of (2). It is easy to determine characteristics of deformation for the indenter with known tip shape and size. For example for spherical indenter stress averaged over the area of contact is equal to

\[
\sigma_t = \frac{3}{3} \frac{P}{\pi \cdot a^2},
\]

where \( a \) is Hertzian radius of contact zone,

\[
s = \frac{3P (1 - \mu^2) R}{4E}.
\]

Pressure distribution in the contact zone is
\[ \sigma_r = \sigma_0 \sqrt{1 - \left(\frac{a^2}{r^2}\right)} \]  

(6)

In accordance with the Hertz theory the stress that causes radial crack initiation can be used as a characteristic of the material hardness

\[ \sigma = \frac{3}{2} \frac{P_r}{r^2} \]  

(7)

where \( P_r \) and \( a \) are the stress and the radius of contact zone corresponding to the instant of the crack initiation.

Elastic modulus can be obtained from (3) and (5) for \( R \gg X \)

\[ E_o = K \bar{X} X^{\frac{1}{2}} \]  

(8)

where \( K = 0.172(m/R^2) \) is the constant describing indenter parameters, \( X \) and \( \bar{X} \) are maximal acceleration and maximal penetration of the indenter at quasielastic stage of penetration (see collision oscillogram), for ice \( \mu = 0.35 \).

From (2) and (3) it is possible to obtain \( P(X) \), work of elastic deformation and specific energy of ice fracture. The ideas used for this calculation are based on explicit physical ideas. For example, area under the curve \( P(X) \) is equal to the work of indenter during the impact. Separate regions of this impact impulse describe the loss of energy for deformation or fracture in accordance with dominant mechanism at each region.

It is possible, however, to use simplified approach for ice strength measurement based on application of correlation dependences, for example the dependence between the limit stress \( \sigma \) (standard compression strength tests) and the amplitude voltage \( U, V \), determined by penetrometer for the same specimens.

**Impact impulse oscillogram.** Typical impact impulse oscillogram for the collision of spherical indenter and massive ice plate is shown in Fig.2. Three regions I, II, III with different types of deformation mechanisms are revealed at the oscillogram.

Contact is predominantly elastic at the initial stage of deformation (\( E_o \) is the elastic modulus). It is confirmed by the linear character of the oscillogram at the region OA. Linear character of deformation takes place also at the region AB where elastic deformation prevails also but shelling fracture arises inside the layer of maximal tangential deformation [4], thin layer of damaged ice appears (snow sublayer) as a result of this type of fracture. Presence of plastic deformation component causes change of the tangent angle of segment AB in comparison with the segment OA. The regions OA and AB can approximately be considered together if some effective modulus \( E_w \) will be introduced then the region I can be considered as a region of linear deformation.

In the point \( B \) stress reaches the critical value and intensive process of fracture with growth of radial cracks begins in addition to the elastic deformation process and shelling. Ice fracture is accompanied by crushing and compaction of ice. Ice crushing can be confirmed by appearance of high frequency component (it is not shown in Fig.2); ice compaction causes growth of resistance of the compacted mass. That is why at the region BCDE we observe the diminishing and then the rise of amplitude that corresponds to the diminishing and subsequent rise of acceleration. The acceleration can decrease and increase several times, the duration of the periods depending on the
energy of collision. To a first approximation the region II can be described by the segment of the straight line parallel to the abscissa axis and then the segment can be considered as the region of plastic deformation.

The snow sublayer influences the character of the curve EF during unloading. The dependence is non-linear at the region III. This non-linearity during unloading confirms that the attempts to determine material elastic properties by the rebounding are not sufficiently correct.

Thus each point at the oscillogram corresponds to some deformation process. That allows to propose methods of material properties evaluation to determine the loss of impact energy for each of these processes.

**Generalized deformation relation.** Fig.3 illustrates the dependence of mean stress on the instantaneous velocity for various impact velocities (curves 1-7), the limiting curve position corresponding to the maximal initial velocity. This fact can be explained by the possibility of the snow sublayer to reach the optimal thickness under the fixed experimental conditions. For example when the energy of the impact increases the process of the snow layer pressing out is intensified and in some instant the layer thickness diminishes. However, action of the stresses causes damage of the ice and the thickness of the snow sublayer increases as a result of shelling. Such dynamic equilibrium is easy maintained in this system because the energy necessary for the snow sublayer pressing out is rather great. Rheological properties of this sublayer determine the tangent of the yield plateau for curves $\sigma(X)$, the center of this plateau ($\sigma_c$ and $X_c$) is the point of similarity. All curves $\sigma(X)$ can be presented as one generalized curve relatively this point that makes it easier to determine the energy loss for elastic and plastic deformation.

**Specific energy of fracture.** The value of the specific energy of fracture is commonly determined as the relation of the irreversible loss of impact energy to the mass of ice in the crater produced by this impact

$$\epsilon_s = \frac{W_o}{\rho V},\quad (9)$$

where $\rho$ is the ice density, $V$ is the crater volume. The energy loss determination was the most uncertain step in calculation of specific fracture energy because the fracture includes the process of snow sublayer formation. Using the dependencies $P(X)$ and $\sigma(X)$ we have the possibility to estimate the energy loss in accordance with plastic $W_p$ and elastic $W_e$ deformation mechanisms more precisely. The results of such calculations for congelation ice are given in Table 1.

<table>
<thead>
<tr>
<th>$W = \frac{m V^2}{2}$, J</th>
<th>0.592</th>
<th>1.72</th>
<th>3.01</th>
<th>4.38</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_o = m \frac{\dot{V}^2}{2} W$, %</td>
<td>45</td>
<td>20</td>
<td>16</td>
<td>19</td>
</tr>
</tbody>
</table>

Таблица 1.
It follows from the table that the most part of the impact energy (more than 55%) is lost in the dissipative processes. The energy of elastic deformation for $W \geq 1 \text{ J}$ is constant within the accuracy of the experiment. This stabilization is caused by snow sublayer formation. For small impact energy ($10^{-14} \text{ J}$) the rebounding coefficient in accordance with [5] is close to 0.9, while our consideration revealed its diminishing from 0.2 to 0.15 with the increase of the impact energy.

The value of specific energy of mechanical crushing for fresh-water ice is from 3 to 10-20 kJ in accordance with [10]. For the given case (congelation ice under the temperature -10 °C) specific energy of mechanical fracture $\varepsilon = (6.7 \pm 0.5) \text{ kJ/kg}$ that is within the order of magnitude of this value. However the present work provides higher accuracy of energy loss estimation.

**Effective elastic modulus** can be calculated from relation (5) and experimental dependence $X(r)$. Thus for $X=0.32 \text{ mm}$, $a=4.92 \text{ mm}$ in accordance with (5) we have

$$E = \frac{3(1-\mu^2)P}{2Xa^2} = \frac{3(1-0.35^2)1.76 \times 9.81}{2 \times 0.32 \times 10^{-3} (4.92 \times 10^{-3})^2} = 3 \times 10^3 \text{ MPa},$$

that is close to the dynamic modulus obtained by acoustic method

$$E_d = \rho V_p = 916.8 \times 3245 = 9.6 \times 10^3 \text{ MPa},$$

it is much greater than the effective elastic modulus, obtained in quasistatic uniaxial compression tests.

**Factors that influence the measurement results.** The results confidentiality caused by the work of piezoelement in the region of linear deformation, measuring line calibration can be carried out immediately in the field conditions [7,8].

1. For each region of the oscillogram it is possible to determine the thickness of ice corresponding to the results obtained by this method. For example the thickness of the layer that influence the result in determination of the modulus $E_\varepsilon$ and the local hardness $\sigma$ is

$$h = \frac{1}{2} V_p \tau = 0.5 \times 3200 \times 0.4 \times 10^{-3} = 0.84 \text{ m},$$

where $V_p$ is the velocity of longitudinal wave, $\tau$ is the impact duration.

2. The ice surface layer is subjected to the action of solar radiation and atmospheric conditions. If this action is not the special object of investigation, it is necessary to remove this layer before the measurements. It is worth to take into account that, as a result of the layer removal, internal stresses are also removed or diminished that can influence the results of measurements.

<table>
<thead>
<tr>
<th>$W_\varepsilon$</th>
<th>55</th>
<th>80</th>
<th>84</th>
<th>61</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>7.3</td>
<td>7.2</td>
<td>5.6</td>
<td>6.6</td>
</tr>
</tbody>
</table>
3. Surface roughness if it is greater than some critical value can influence the results of measurements because of the crushing of asperities. It is known that a damaged layer arises due to surface processing by cutting tools. It includes asperities at the surface and the microcracks at the interface between the layer and the bulk material, the thickness of the damaged layer four times greater than the height of the asperities [8]. The removal of the asperities and the healing of the microcracks take place in polishing. Use the solution of correspondent contact problem [9] to evaluate the permissible value of roughness and technology of the surface preparation [10].

Contact pressure during the contact interaction of a punch and half-plane with thin layer rigid attached can be determined from the integral equation of the second kind

$$K_1 \left[ q(x) - q(0) \right] - \frac{1}{\pi} \int_{-a}^{a} q(\xi) \ln \left| \frac{x-\xi}{\xi} \right| d\xi = g(x) - g(0),$$

(11)

where $K_1 = h(1-2\mu)/(G, 2(1-\mu))$, $\Theta = G,/(1-\mu)$, $h$ is the thickness of the layer, $G, \mu$ are elastic constants for the layer, $q(x)$ is contact pressure distribution, $-a \leq x \leq a$; $g(x)$ is displacement of the half-plane surface caused by punch action.

The first term in the left part of (8) can be considered as the surface displacement caused by the presence of thin layer, the second one is the foundation displacement. Consider the influence of the first term to be minimum if

$$\left( h \frac{(1-2\mu)}{2\Theta (1-\mu)} \right) \left( \frac{1}{\pi} \int_{-a}^{a} q(\xi) \ln \left| \frac{x-\xi}{\xi} \right| d\xi \right) < 1,$$

(12)

Suppose that $\mu_1 = \mu_2 = 0.35$, $G, = (4/9)G_2$, we obtain $h < 3.4 \times 10^2 a$. Hence, to ensure the accuracy of the measurements better than 1% for the penetration depth near 1 mm, the height of the asperities should be smaller than 0.01 mm. The surface machined by the cutting tool with tip radius equal to 0.3 mm and then polished satisfies this condition. Ice is rather "soft" material, then the conditions can be easy satisfied if sharp cutting tool with cutting velocity approximately 3 m/min is applied.

**Penetrometer**

The device general characteristics. Portable device of impact action (Penetrometer) is designed for express estimation of mechanical characteristics and strength of ice immediately in the place of ice deposition or in the laboratory conditions. The base model of the device is intended for registration and processing of impact impulse that is material instantaneous reaction caused by penetration of tips of various shapes. Several modifications of the device are designed. Thus the model W-ICE [Fig 4) is intended for measurement of the ice local strength $\sigma_r$. It can also be used for measurement of elastic modulus Eo and specific energy of fracture $e_u$, the programs of primary signal processing are changed by electronic block replacement.

**Technical description.** For the W-ICE type device the accuracy of measurement of electric impulse is 5%. The result reproducibility for homogeneous material is 1%. Time for one measurement is 2-3 seconds. Mass of the device with electric power supply source is 2 kg. The device can be used within the temperature range from -20 °C to +30 °C. Overall dimensions 400·150·55 (mm).
The device design. The device is of pistol type (Fig. 4), the control buttons (pull button 8, fix button 6, power switch 7) are placed at the grip. The result of the measurement is indicated by the display at the upper part of the case cover 9. The rod with spherical tip (indenter) moves partially out of the barrel. Measurement is carried out during the collision of the indenter with the material under investigation. The radius of the tip $R$ is equal to 40mm. The position stop 4 with support ring 3 is used for impact velocity fixation. The electronic block and electrical power supply are mounted inside the case.

Measurements. Electrical power supply is turned on. Indenter is moved in the barrel by small axial effort. The limit position is fixed by the button 6. The device is placed in accordance with the task of investigation for example in the vertical direction, the support ring being in contact with the surface of the material under investigation. Pull button is pressed, the result of measurement is indicated by the display during the impact of the indenter and surface of the body under investigation.

The following condition should be valid during the measurement

$$M/m > 10^8,$$

where $m$ is the mass of the indenter, $M$ is the mass of the specimen;

$$L/R = 10...15,$$

where $L$ is the size of the specimen along each of the axes, $R$ is the radius of the tip. The difference between the temperature of the tip and the surface of ice as a rule should be smaller than 2-3 °C. Special attention should be paid to the temperature difference when precise measurements are carried out.

Experimental results.

Preliminary testing. Reproducibility of the results obtained with penetrometer W-ICE has been estimated during the laboratory tests under the temperature $-5 \, ^\circ C$, for specimens made of coarse-grained ice with diameter 250mm, height 60mm and also under the room temperature for the plasticine specimens of the same size. Plasticine was used as model plastic material that allows to produce homogeneous structure. The results of experiments are presented in Table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_1$, MPa</th>
<th>$\sigma_2$, MPa</th>
<th>$\Delta \sigma$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice A3</td>
<td>50.1; 49.5; 47.1; 48.6; 48.3</td>
<td>48.7 ± 0.7</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>-5 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice A9</td>
<td>55.8; 54.6; 54.9; 56.7; 55.5; 55.5; 54.3</td>
<td>55.3 ± 0.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>-20 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasticine</td>
<td>17.6; 17.8; 17.9; 17.9; 17.7</td>
<td>17.8 ± 0.1</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>+20 °C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The ice hardness obtained in our experiments is in good correlation with results of [12] for loading time $10^{-4}$ c. The results scattering for homogeneous material (plasticine) is 0.6%, for coarse-grained ice it is smaller than 1.5 %. The device W-ICE makes it possible to reveal ice mechanical characteristic variation caused by temperature variation that confirms once more the possibility to
use the device in the field conditions.

Conclusions

The method is proposed that allows to obtain deformation properties and strength of ice from the measurement and processing of the impact impulse parameters, arising in collision of the rigid indenter and the ice plate. The base model of the device for the method realization is designed. The scattering of the results obtained by device W-ICE is 0.5% for the homogeneous material and it is 1.5 % for coarse-grained ice.

The method can be used in the laboratory and field conditions. It is determined instantaneous impact velocity, energy of elastic and plastic deformation and specific energy of fracture.

The present work allows to consider the penetration method as the promising one for the terrestrial monitoring of great ice masses.

References.

10. Alexandrov V.M., Mkhitaryan S.M. Contact problems for bodies with thin coatings and interlayers, Nauka, Moscow, 1983.
Fig. 1. Scheme of Herzian contact.
Fig 2. Impact oscillogram for collision of spherical indenter and ice plate.

$U \propto \ddot{x}$

$U$ is the voltage, mV; $T$ is time, ms.
Fig. 3. Dependence of mean pressure $\sigma$, MPa, on the instantaneous velocity $\dot{X}, \text{m/s}$ for initial impact velocities $V_0, \text{m/s}$ equal to 0.48(1), 0.59(2), 0.83(3), 0.99(4), 1.4(5), 1.87(6), 2.23(7). Ice temperature $-9.8 \, ^\circ\text{C}$ (8) is the dependence of reduced stress on reduced instantaneous velocity.
Fig. 4. The view of device W-ICE

1-indenter, 2-barrel, 3-support ring,
4-position stop, 5-grip, 6-fix button,
7-power switch, 8-pull button, 9-case.
ABSTRACT

For ridge sail height two distribution hypotheses have been suggested. The first, of the form $\propto \exp(-cf^2)$, was proposed by Hibler et al (1972) and the other, of the form $\propto \exp(-ch)$, by Wadhams (1980). In laser profilometer surveys the latter has been in most cases found the fit the data excellently. However, the profilometer data refers to two-dimensional ridge cross-sections while in the derivation of the Hibler distribution the reference was to ridge segments or links. The height variation of ridge links has been measured in the Baltic. The results strongly suggest that correctly interpreted the two hypotheses imply each other.

1. INTRODUCTION

Ridge sails form horizontally a complex two-dimensional geometry. As no generally accepted two-dimensional statistics exists ridging is usually quantified by linear transsects across the ridge field. The two basic components of the linear statistics are the ridge sail height and ridge spacing distributions. There are two commonly used models for sail height (or keel depth). The first was proposed by Hibler et al (1972) and according to it the sail heights distribute as

$$f_1(h) = \frac{2}{\pi \mu} \exp \left\{ -\frac{1}{\pi} \left( \frac{h}{\mu} \right)^2 \right\}$$

(1)

The expectation of (1) is $\mu$. As ridge data sets normally have a cutoff $h_o$ for sail height the tail of (1) above this value is applied. This changes the expectation in a nonlinear fashion.
Another distribution hypothesis is the negative exponential proposed by Wadhams (1980),

\[ f_2(h) = \frac{1}{\mu} \exp\left\{ -\frac{h}{\mu} \right\} \]  

(2)

The expectation of is likewise \( \mu \). Separating the tail above the cutoff simply shifts the distribution and changes the expectation to \( \mu + h_0 \).

These distributions have been fitted to data in a routine fashion and variable results have been found. The virtue of the exponential distribution is its analytical simplicity and easy fitting to the data. The results are not bothered by the cutoff. For the Hibler distribution the choice of cutoff and reference level is crucial; if these are adjusted, the properties of the distribution change. Thus the Hibler distribution has two independent parameters although the zero level of the data set is usually applied, wherever it refers.

On the other hand, the Hibler distribution can be derived by an argument borrowed from statistical physics. In the 1972 paper Hibler et al. decomposed the ridge field into ridge segments or links and derived (1) by assuming that all arrangements of ridge links constrained by a constant total volume of deformed ice are equally likely. To obtain (1) one must assume also that the cross-sectional area of a link has a quadratic dependence on ridge height. It is clear that cross-sectional area and height are to be defined as averages over the link length. For (2) no explanation has thus far presented.

In most papers following Hibler (1972) it is left undiscussed what is the reference of 'ridge height'. Ridges are can be several km long and a sail segment has a certain maximum, minimum and mean height. The sail height variation can be large and even massive ridges can contain gaps. As ridges are classified visually the reference is either to the maximum height or to general massivity, related to the mean height of a certain segment. On the other hand, as the sail height is measured along a linear track the reference is to a narrow sail cross section which for laser profilersmeters is two-dimensional. The recorded height value is a random sail height sample and has certain relations to the mean or maximum height of the corresponding segment.

In the following the statistical relations of cross-sectional height to the mean height of ridge sail segments, called ridge links, is examined. As segment statistics exists for sails only, ridge keels are not considered.
2. STATISTICAL DESCRIPTION OF RIDGED ICE FIELDS

In a heavily ridged ice field the ridges join to a complex network. From above this is observed as the totality of ridge sails. Also in rubble fields, where the ice underside is an unstructured ice mass, sails can often be discerned.

Following Hibler (1972) the complex horizontal geometry of ridge sails is decomposed to a large number of ridge segments or links. These are assumed to be units the geometry of which is constrained by the local deformation history of the ice field. Two adjacent short segments of a pressure ridge can be assumed to have formed in a compressive event the direction and magnitude of which are the same for both segments. The segments are expected to have about the same volume which sets a constraint to the variation of sail height and keel depth. On the other hand, two segments from ridges far away from each other have independent local deformation histories and their properties are correlated through the large scale dynamics and ice thickness only.

If one observes ridge formation in the field it constitutes a local deformation event where the sail has well defined end points. It is thus meaningful to say that the ridge field consists of individual ridges where the statistics of each ridge is constrained by the characteristics of the corresponding deformation event. If ridge links are identified with individual ridges the link length $L$ is a random variable. However, this is not possible in practice. Therefore all links are assumed to have the same length $L$ which is of the same order as the shortest individual ridges.

As the ridge field is decomposed into links, three distributions are associated to it. Given a cutoff value $h_0$ for the ridge sail height, then if per unit area

$$ F(h) = \frac{\text{length of ridge sail exceeding } h}{\text{length of ridge sail exceeding } h_0} $$

define the ridge sail height distribution as

$$ f(h) = -\frac{\partial F(h)}{\partial h}. $$

Within each ridge link sail height variation exists. The size of the link is measured by the mean sail height $s$ of the link. Define, per unit area, the ridge link size distribution $g(s)$ by

$$ G(s) = \frac{\text{number of ridge links exceeding } s \text{ in size}}{\text{total number of ridge links}}, \quad g(s) = -\frac{\partial G(s)}{\partial s} $$
and for each ridge link size the distribution of height variation within the link, $k(h,s)$, as

$$K(h,s) = \frac{\text{length of link sail exceeding } h}{L}, \quad k(h,s) = -\frac{\partial K(h,s)}{\partial h}$$

These distributions are related to each other as

$$f(h) = \int ds \, g(s) \frac{k(h,s)}{K(h_0,s)}, \quad s = \int dh \, k(h,s)$$

(3)

If $h_0=0$ the expectations of $g(s)$ and $f(h)$ are equal. If the distributions $f(h)$ and $k(h,s)$ are known, (3) is an integral equation for the unknown $g(s)$.

3. PROFILING MEASUREMENTS OF A RIDGE FIELD

Consider a measurement of a ridge field along a linear track (Figure 1). The device can observe the surface or underside only, like laser profilometers and sonars, or sound through the ice, like AEM (airborne electromagnetic) systems and impulse radars, and it has a certain physical footprint and measuring frequency. How a ridge link is observed depends on the footprint and the measurement method. An AEM system footprint is tens of meters and the calculated ice thickness can be interpreted as a weighted average within the footprint (Multala et al. 1995). Therefore the result is likely to be correlated with the ridge link size. A sonar beam width is typically from $2^\circ$ to $10^\circ$, corresponding to footprint diameter increase of 3.5 to 17.5 m per 100 m distance increase. The measurement system may record the first returning signal, like many sonars do, and refer to the maximum within the footprint, or it may calculate the output from several signals. All these things matter when the data is interpreted.

A typical footprint diameter increase for a laser profilometer is 0.3 m per 100 m and it resolves the ridge structure to the scale of block thickness. It produces two-dimensional cross sections from the ridge. As a laser profilometer is flown across a ridge link sail, the cross-sectional maximum is a random sample from the height distribution $k(h,s)$ of the link. If the ridge field has homogenous statistics over a large region, the sail height distribution obtained from it is $f(h)$. This cannot be a priori assumed to be equal to the link size distribution $g(s)$.  


Figure 1. A schematic illustration of a profiling measurement. The ridge field is decomposed into ridge links with length $L$.

4. SAIL HEIGHT DISTRIBUTION

In the Baltic negative exponential sail height distributions have been found in laser profilometer surveys (Leppäranta 1981, Lewis et al 1993, Lensu 1993, 1995). The surveys have restricted to the most heavily ridged sea area, the Bay of Bothnia, and the exponentiality has been confirmed almost beyond doubt. This may be associated to the fact that the Bay of Bothnia constitutes more or less a single ice regime with little variation in level ice thickness. The mean ridge height ($0.5$ m cutoff) is almost constant $0.7$ m that does not vary much interannually.

In Arctic and Antarctic areas there is room for dispute between the negative exponential and Hibler distributions (Table). Several explanations can be suggested. The Arctic and Antarctic surveys cover often large regions. It is conceivable that the exponentiality holds regionally but the regional distributions, having different mean values, do not superpose in a way that would enhance this property. The superposing of exponential distributions result to distributions that have some similarity with the Hibler distribution. The tail of the Hibler distribution has qualitative similarities to the

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negative exponential. It has been suggested that the ridge search procedure effects (Wadhams 1980) or simply that both distributions are approximate models (Dierking 1995).

It is, however, noted that exponential distribution applies to all data sets obtained by a profilometer. Devices with larger footprint produce distributions that are usually well fitted by the Hibler distribution. The same applies to the quantification of ridge heights from stereo pairs. Visual classification is bound to refer to some sail segment or its maximum. It is remarkable that the keel draft distribution in Wadhams (1980), obtained by a wide beam sonar, was found to obey Hibler distribution while the sail heights measured by a profilometer along the same track obeyed exponential distribution. On the other hand, keel draft measured by a narrow-beam sonar is excellently modelled by the exponential distribution (Wadhams and Davy 1986).

**Table:** Ridge sail height measurements in the Arctic and Antarctic. The footprint diameter is included when reported.

<table>
<thead>
<tr>
<th>Source</th>
<th>Region</th>
<th>Method /lp</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hibler et al 1972</td>
<td>Arctic</td>
<td>Visual observations</td>
<td>Good fit with Hibler, exponential not considered</td>
</tr>
<tr>
<td>Hibler et al 1974</td>
<td>Western Arctic</td>
<td>Laser profiler</td>
<td>Hibler acceptable, exponential not considered</td>
</tr>
<tr>
<td>Tucker et al 1979</td>
<td>Chukchi and Beaufort Seas</td>
<td>Laser profiler</td>
<td>Exponential better than Hibler, both acceptable</td>
</tr>
<tr>
<td>Wadhams 1980</td>
<td>Central Arctic</td>
<td>Laser profiler</td>
<td>Good fit with exponential; keel depths along the same track fitted Hibler</td>
</tr>
<tr>
<td>Kreider and Tho 1981</td>
<td>Beaufort sea</td>
<td>Stereographic photography</td>
<td>Exponential slightly better than Hibler, both acceptable</td>
</tr>
<tr>
<td>Sayed and Frederking 1991</td>
<td>Canadian Arctic shear zone</td>
<td>Stereographic photography</td>
<td>Lognormal at the shear zone edge, Hibler in the Interior pack, exponential not considered</td>
</tr>
<tr>
<td>Weeks et al 1989</td>
<td>Ross Sea</td>
<td>Laser profiler 0.05</td>
<td>Good fit with negative exponential, Hibler not considered</td>
</tr>
<tr>
<td>Granberg and Leppärinta 1990, 1993</td>
<td>Weddell Sea</td>
<td>Laser profiler 0.2</td>
<td>Good fit with negative exponential, Hibler not considered</td>
</tr>
<tr>
<td>Lytle and Ackley 1991</td>
<td>Eastern Weddell Sea</td>
<td>Acoustical Sounder 1.3</td>
<td>Hibler better than exponential in all cases</td>
</tr>
<tr>
<td>Dierking 1995</td>
<td>Weddell Sea</td>
<td>Laser profiler 0.08</td>
<td>Exponential better for low ridging intensity, Hibler for high ridging intensity</td>
</tr>
</tbody>
</table>
5. THE DISTRIBUTION \( k(h,s) \): LONGITUDINAL RIDGE PROFILES

The measurements of longitudinal profiles of ridge segments are few. These would be available, for example, from stereographic pairs but the ridge height has been measured from these along linear tracks only (Table). Hibler and Ackley (1975) measured longitudinal profiles from ridge shadows in the Beaufort Sea in order to model the probability for a vehicle to find a gap enabling it to cross the sail. The height was quantified from images in 5 m intervals and with the accuracy of ±0.25 m. No specific effort to find the best possible model for the height distribution was made. It was assumed to be multivariate normal distribution and the covariance matrix was calculated from the data. The mean height was 1.9 m, the standard deviation 0.7 m, and a large variation over short distances can be seen in the profiles.

In Lensu (1994a) a longitudinal profiling of a 1460 m long Baltic ridge in 4.4 m average interval is reported. The measurements were made with a laser theodolite and the accuracy was 0.01 m. The results are shown in Figure 2. Mean height was 0.8 m and maximum 2.5 m. The normal distribution was acceptable (Figure 2 b) while the negative exponential distribution was not (Figure 2 c). However, the best fit was obtained with the squared exponential distribution (Weibull distribution with index 2, Figure 2 d). In Lensu (1994b) six longitudinal profiles are reported. The measurements were made with a laser levelling device in 1 or 1.5 m constant intervals and 0.01 m accuracy. The profile lengths varied from 99 m to 191 m. In chi-square analysis the Weibull hypothesis was valid for 4 ridges and rejected for one and the indices of best fit varied from 1.8 to 2.8. Squared exponential (index 2) was valid for three ridges and rejected for one. The negative exponential was rejected in all cases.

Since each measurement referred to an identifiable singular ridge they can be assumed to be samples from the ridge link height distribution \( k(h,s) \). The results suggest that the cross-sectional area is distributed exponentially along the link which for the quadratic dependence on ridge height gives squared exponential height distribution,

\[
k(h,s) = \frac{\pi}{2s} \exp\left\{-\frac{\pi}{4s}h^2\right\}.
\]

In the measurements it was also found that the ridges contained gaps where the sail completely disappeared and that the distribution \( k(h,s) \) was defined for all nonnegative values of \( h \).
Figure 2. Sail height distribution of a 1460 m long Baltic ridge. a) Histogram of sail heights. b) Probability plot of sail height. c) Decreasing cumulative distribution of sail height. d) Decreasing cumulative distribution of sail height squared.
6. RIDGE-LINK SIZE

For given \( f(h) \) and \( k(h,s) \) the link size distribution \( g(s) \) can be solved from (3). Since the distributions \( k(h,s) \) were observed to be defined for all nonnegative \( h \) the same is assumed on the ridge height distribution \( f(h) \). The negative exponential \( f(h) \) is assumed to be extrapolated down to zero. However, it is not known whether this applies or not. For generality a form of \( k(h,s) \) comprising a larger family of distribution hypotheses is assumed, namely a powered gamma distribution with mean value \( s \),

\[
k(h,s) = \frac{\rho h^{a-1}}{\Gamma(a/\rho)} \exp \left\{ - \left( \frac{h \Gamma((1+a)/\rho)}{\Gamma(a/\rho)} \right)^a \right\} \left\{ \frac{\Gamma((1+a)/\rho)}{\Gamma(a/\rho)} \right\}^a .
\]

The Mellin transform of \( k(h,s) \) with respect to \( h \) is

\[
M(h(k,s)) = \int_0^\infty dh h^{z-1} k(h,s) = \frac{\Gamma((a+z-1)/\rho)}{\Gamma(a/\rho)} \left( \frac{\Gamma(a/\rho)}{\Gamma((1+a)/\rho)} \right)^{z-1} s^{z-1} .
\]

and that of the exponential distribution \( f(h) = (1/\mu) \exp(-h/\mu) \) is

\[
M(f(h)) = \Gamma(z) \mu^{z-1}.
\]

As these are applied to the integral equation (3) for the link size distribution, the Mellin transform of \( g(s) \) can be solved as

\[
M(g(s)) = \frac{\Gamma(z) \Gamma(a/\rho)}{\Gamma((a+z-1)/\rho)} \left( \frac{\Gamma((1+a)/\rho)}{\Gamma(a/\rho)} \right)^{z-1} \mu^{z-1}
\]

For Weibull distributions \( a=\rho \) and for squared exponential distribution \( a=\rho=2 \) in which case

\[
M(g(s)) = \frac{\Gamma(z)}{\Gamma((z+1)/2)} (\Gamma(3/2))^{z-1} \mu^{z-1} = \Gamma(z/2)(\Gamma(1/2))^{z-2} \mu^{z-1}
\]

Comparing (6) and (7) (change \( s \) to \( \mu \)) reveals that the link size is distributed as

\[
g(s) = \frac{2}{\pi \mu} \exp\left\{ - \frac{1}{\pi} \left( \frac{s}{\mu} \right)^2 \right\}
\]

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It is thus found that if the ridge height distribution \( f(h) \) is exponential and the link height distribution \( k(h,s) \) squared exponential then the link size distribution follows Hibler distribution (1).

7. DISCUSSION

The results suggest that the two distribution hypothesis are not rivals but rather two sides of a coin that moreover imply each other when correctly interpreted. The Hibler distribution is to be considered as more fundamental one since it can be derived with some general arguments. It also refers to entities that correspond to what is understood by a 'ridge' in the field. The applicability of negative exponential distribution appears as a secondary feature. It follows also that devices with large footprint sample values more closely following the Hibler distribution. The burden of explanation is transferred from \( f(h) \) to the distributions \( k(h,s) \). In a simple configuration this would mean the derivation of \( k(h,s) \) in a process where a rectangular ice sheet is used up to produce a pressure ridge link.

The main problem in the application of Hibler distribution is the adjustment of reference level and cutoff. The distributions \( k(h,s) \) are defined down to zero elevation which implies that \( f(h) \) is, too. On the other hand, ridge link size can be assumed to have a certain physical minimum value \( s_0 \) which is probably related to the parent ice thickness. This means that the system of the three distributions can be expected to start to collapse near \( s_0 \). This implies further that the exponentiality of \( f(h) \) is not expected to hold for small values of \( h \). This is supported by the observation that the exponentiality of \( f(h) \) can to some extent extrapolated downward to produce estimates of ridge density but the extrapolation to zero raises the ridge density to unrealistic values.

More extensive measurements of longitudinal ridge sail elevation would be needed to clarify these matters. Resolving stereographically the topography of a, say, 1 sq. km of ridged ice field would provide all three distributions and their interrelations. This would also give the distribution \( f(h) \) below the cutoff value necessary in profilometer data analysis and make possible the calculation of ridge densities that would correspond to those observed in the field or measured from aerial photography.

It should be remembered that \( f(h) \) refers to the relative length of ridge sail in a certain area and that the height distribution obtained with a profilometer can be identified with it only if the ridge field is homogenous over the area of survey. In the Baltic heights exceeding 2 m are seldom observed in profilometer surveys but
commonly in the field. This is in accordance with the interpretation of \( f(h) \) since the tail probability of finding them is of the order of 0.001. For typical Baltic ridge densities (3-5 ridges/km) this means that few meters of ridge sail exceeding 2 m is found within easy reach (500 m) in the field. Extrapolation upwards implies that typically one ridge exceeding 3 m is found per 100 sq. km and one exceeding 4 m per 30 000 sq. km. This is also in accordance with observations (Lensu 1995).

If the ridge field is homogenous w.r.t. height, as appears to be in the Bay of Bothnia, then the stereographic measurement of 1 sq. km would correspond to a profilometer survey of several hundred km. This indicates that an effective ridge survey would consist of stereographic mapping for the distributions \( f(h), g(s) \) and \( k(h,s) \) together with a laser profilometer flight for ridge spacing distributions. This could be completed by a search of maximal ridge heights which cannot be expected to be found by either method.

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FILTERING SURFACE BY ICE FLOES

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ABSTRACT

We discuss a mechanism of filtering ocean waves in the marginal ice zone modeled by regular ice floe bands. Computed surface gravity wave frequency spectrum has well defined regions of transparency and attenuation. Boundaries of the first forbidden (gap) region correspond to the wavelengths of the order of a typical size of the ice floes.

1. INTRODUCTION

The sea ice cover is inhomogeneous in its composition and properties. The structure classification of the sea ice is given in [1]. Ice floes constitute one of the main types of sea ices. These floes are separate pieces or blocks of ice that float on the surface of ocean. Zones of broken ice usually appear in a marginal zone of drifting ice and in the regions where the gradient of the drift velocity is large. Certain types of the young sea ice can also be included in the class of broken ice.

The main characteristics of broken ice are compactness (concentration of the ice on the ocean surface) and thickness. The compactness of an ice cover may vary rather rapidly under the impact of wind, sea currents and tides. The characteristic times of such processes appreciably depend on the intensity of external action. Usually, these times are not less than several ten minutes. They are much greater than characteristic periods of sea swells which transfer the energy from open ocean areas into waves under the ice cover. Therefore, when considering problems associated with the propagation of surface waves, we can assume the compactness to be a stationary parameter of the ice cover.

The authors of [2,3] demonstrated that the spectral composition of flexural-gravity waves in the Arctic Ocean is inhomogeneous and contains several frequency bands that correspond to the waves with maximum energy. Such a spectrum is rather differing from the sea spectrum at the open water. As was shown in [4], the frequency spectrum of
surface waves that propagate under the sea cover with a periodic set of fractures features frequency gaps, while the low-frequency part of this spectrum is somewhat similar to the spectrum of ocean swell. The boundaries of these gaps are determined by rigidity of the ice sheet. If the frequency of a wave propagating under the ice cover falls within such a gap, this wave exponentially decays. The purpose of this work is to study the dependence of spectral properties of surface waves on compactness of the ice cover, in particular, to find the relationship between the characteristics of this gap and real parameters of ice floes, such as thickness and elasticity.

2. FORMULATION OF THE PROBLEM

Let us consider a broken ice cover that consists of separate blocks of ice, floating on the ocean surface. We assume that the characteristic horizontal scale of ice blocks is much greater than the thickness of these blocks. Therefore, each of these blocks can be modeled by a thin plate. Sea roughness gives rise to sufficiently rapid deformation of the ice blocks. Hence, parameters of the waves considerably depend on the elastic properties of ice. Thus, as a model of ice floes, we can consider a set of elastic plates floating on the surface of a fluid layer.

The propagation of surface waves in a fluid under ice floes is accompanied by dissipation of the wave energy on the edge of each ice block. The coefficient of a surface wave transmission through the edge of ice depends on the angle $\theta$ between the edge line and the wave front [5]. The transmission coefficient reaches its maximum in the case of normal incidence, when $\theta = 0$. If the angle $\theta$ is greater than a certain critical one, which depends on rigidity of the ice cover, the transmission coefficient is equal to zero. Therefore, we can find the upper estimate of the filtering properties of ice floes with respect to surface waves by solving the problem of waves propagating through the zone of ice floes where
ice edges are parallel to the front of incident waves.

To perform model calculations, we consider the following formulation of the problem. Suppose that bands of ice float on the surface of a fluid layer with a finite depth \( H \). We assume that the edges of these bands are parallel to the horizontal \( y \)-axis: \( x = jl, \ x = (j + N)l, \ 0 < N < 1, \ j = 0, \pm 1, \pm 2 \cdots \) (see Fig. 1). Between ice bands, the fluid surface is assumed to be free. Each of the ice bands is modeled by a thin elastic plate with free edges. It is required to determine conditions that ensure the existence of nondecaying surface waves propagating in the direction perpendicular to the edges of plates.

Let us consider the approximation of shallow water. This corresponds to the case when the depth of fluid is less than a characteristic wavelength of running waves. Within the framework of the linear approximation, the equations of shallow water under an elastic plate are reduced to the set of equations [4]

\[
\begin{align*}
\frac{\partial \eta}{\partial t} + H \Delta \varphi &= 0, \quad \frac{\partial \varphi}{\partial t} + g \eta + \frac{Eh^3}{12\rho(1 - \nu^2)} \Delta^2 \eta = 0, \\
\Delta &= \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}
\end{align*}
\]

Here, \( \varphi \) corresponds to the potential of velocities in fluid at \( z = 0 \), \( \eta \) is the coordinate of the fluid surface relative to the horizontal equilibrium position, \( E \) is the Young modulus, \( \nu \) is the Poisson ratio, \( h \) is the thickness of the ice plate, and \( \rho \) is the density of fluid.

Below, we will study motions that depend only on \( t \) and \( x \). Let us introduce dimensionless variables, which will be designated by symbols with primes (in what follows, we will omit them), \( t' = t, \ x' = x \) and \( T^2 = t^2/(gH) \). Eliminating \( \eta \) from (1), using dimensionless variables, and assuming that the dependence of the solution on \( t \) is described by the factor \( \exp(i\gamma t) \), we can write

\[
\begin{align*}
\gamma^2 \varphi + (1 + D \frac{\partial^4}{\partial x^4}) \frac{\partial^2}{\partial x^2} \varphi &= 0, \quad x \in (j, j + N) \\
\gamma^2 \varphi + \frac{\partial^2}{\partial x^2} \varphi &= 0, \quad x \in (j + N, j + 1)
\end{align*}
\]

Here,

\[
D = \frac{Eh^3}{12\rho g(1 - \nu^2)l^4}, \quad j = 0, \pm 1, \pm 2 \cdots
\]

In dimensionless variables, the edges of ice blocks are positioned at the points \( x = j \) and \( x = j + N \). Therefore, contact-boundary conditions should be satisfied at these points. According to these conditions, cutting forces and moments applied to the edges of the plate should be equal to zero,

\[
\frac{\partial^4 \varphi}{\partial x^4} = 0, \quad \frac{\partial^5 \varphi}{\partial x^5} = 0, \quad x = j, j + N
\]
Invoking the conditions of continuity for pressure and fluid rate, we find that
\[
\lim_{x \to j+N+0} \varphi = \lim_{x \to j+N-0} \varphi, \quad \frac{1}{\partial x} \lim_{x \to j+N+0} \varphi = \frac{1}{\partial x} \lim_{x \to j+N-0} \varphi
\]
(4)
\[
\lim_{x \to j+0} \varphi = \lim_{x \to j-0} \varphi, \quad \frac{1}{\partial x} \lim_{x \to j+0} \varphi = \frac{1}{\partial x} \lim_{x \to j-0} \varphi
\]
(5)
Thus, the problem under consideration is reduced to deriving conditions that ensure the existence of limited solutions to the chain of equations (2) subject to boundary conditions (3) - (5) within the interval \( x \in (-\infty, +\infty) \).

3. METHOD OF SOLUTION

Within any interval \( x \in (j, j+1) \), the solution to (2) - (4) can be written as
\[
\varphi = C_1^r \varphi_1 + C_2^r \varphi_2
\]
(6)
\[
\varphi_1 = e^{i\lambda_r (x-j)} + \sum_{k=3}^{6} C_{rk} e^{i\lambda_k (x-j)}, \quad x \in (j, j + N)
\]
\[
\varphi_2 = C_{+r}^r e^{i\gamma_r (x-j)} + C_{-r}^r e^{-i\gamma_r (x-j)}, \quad x \in (j + N, j + 1), \quad r = 1, 2
\]
Here, \( \lambda_{1,2} \) and \( \lambda_{3-6} \) are the real and complex roots of the dispersion equation \( \gamma^2 = \lambda^2 (1 + D\lambda^4) \). The constants \( C_{1,2}^1 \) and \( C_{1,2}^2 \) satisfy the set of linear equations that can be derived from (3) and (4),
\[
\lambda_i^+ + \sum_{k=3}^{6} C_{rk} \lambda_k^i = 0, \quad \lambda_i^+ + \sum_{k=3}^{6} C_{rk} \lambda_k^i = 0
\]
(7)
\[
\lambda_i^+ e^{i\lambda_k N} + \sum_{k=3}^{6} C_{rk} \lambda_k^i e^{i\lambda_k N} = 0, \quad \lambda_i^+ e^{i\lambda_k N} + \sum_{k=3}^{6} C_{rk} \lambda_k^i e^{i\lambda_k N} = 0
\]
\[
\lambda_i e^{i\lambda_k N} + \sum_{k=3}^{6} C_{rk} \lambda_k e^{i\lambda_k N} = \gamma (C_{+r} e^{i\gamma_r N} - C_{-r} e^{-i\gamma_r N})
\]
\[
\lambda_r e^{i\lambda_k N} + \sum_{k=3}^{6} C_{rk} e^{i\lambda_k N} = C_{+r} e^{i\gamma_r N} + C_{-r} e^{-i\gamma_r N}
\]
The values of \( \gamma_1 \) and \( \gamma_{1+1} \) are related by the expressions that follow from (5),
\[
C_{+r} e^{i\gamma_r} + C_{-r} e^{-i\gamma_r} = C_{1+1}^+ (1 + \sum_{k=3}^{6} C_{1k}) + C_{2+1}^+ (1 + \sum_{k=3}^{6} C_{2k}),
\]
(8)
\[
\gamma (C_{+r} e^{i\gamma_r} - C_{-r} e^{-i\gamma_r}) = C_{1+1}^+ (\lambda_1 + \sum_{k=3}^{6} \lambda_k C_{1k}) + C_{2+1}^+ (\lambda_2 + \sum_{k=3}^{6} \lambda_k C_{2k})
\]
The set (8) has two solutions for \( C_{1,2}^{1+1} \), that correspond to \( r = 1 \) and \( r = 2 \). Let us use these solutions to define a matrix
\[
T = \begin{pmatrix} C_{1,2}^{1+1} \bigg|_{r=1} & C_{1,2}^{1+1} \bigg|_{r=1} \\ C_{1,2}^{1+1} \bigg|_{r=2} & C_{1,2}^{1+1} \bigg|_{r=2} \end{pmatrix}
\]
The matrix $T$ is an analog of the monodromy operator [6] in the theory of differential equations with periodic coefficients. The elements of $T$ coincide with the coefficients with which the basis functions $\varphi_{j+1,2}^2$ enter the solution within the interval $x \in (j+1, j+2)$ under the condition that, within the interval $x \in (j, j+1)$, the solution is given by $\varphi_1^2$ or $\varphi_2^1$. The functions $\varphi_{1,2}^1$ and $\varphi_{1,2}^+1$ are equivalent to each other up to a shift by the period. Therefore, the moduli of the eigenvalues of matrix $T$ determine the type of solution within the interval $x \in (-\infty, +\infty)$. If the modulus of the eigenvalue is greater or less than unity, then the solution to the considered problem exponentially increases or decreases as $x$ tends to $+\infty$ or $-\infty$. Provided that the moduli of the eigenvalues of $T$ are equal to unity, the considered problem has a solution that is limited everywhere in the region of motion.

The eigenvalues of $T$ depend on the frequency $\gamma$ of the wave and on the rigidity $D$ of the ice cover. From the physical point of view, the ranges of parameters $\gamma$ and $D$, where the moduli of the eigenvalues of $T$ differ from unity, correspond to waves that decay while propagating in the zone of ice floes. The decay of waves is due to dissipation of the wave energy on the edges of ice blocks. The ranges of parameters $\gamma$ and $D$, where the moduli of the eigenvalues of $T$ are equal to unity, correspond to waves that propagate under the ice floes without energy loss.

4. RESULTS OF NUMERICAL SIMULATIONS

In this study, we use the shallow-water approximation to describe wave motion in the ocean. When deriving the corresponding equations, we assume that dependence of the vertical velocity of particles in fluid on the depth is close to a linear function. For a fluid with an arbitrary depth, the dependence of vertical velocity on the vertical coordinate $z$ is described by the factor $\sinh(kz)$ (we assume that the origin of coordinates is positioned at the bottom), where $k$ is the wave number. Thus, we can apply the shallow-water approximation when the quantity $kz - \sinh(kz)$ is small. For example, let us assume that $kz - \sinh(kz) = 0.3$. In this case, we have $kz \approx 1.2$. Therefore, we will assume that the ratio of the fluid depth to the quantity reciprocal of the characteristic wave number does not exceed 1,

$$H \leq \frac{1}{\gamma}$$

According to the experimental data [6], the Young’s modulus $E$ of the sea ice cover ranges from $3.5 \times 10^9 N/m^2$ to $10^{10} H/m^2$. Note that a decrease in $E$ down to $4 - 5 \times 10^9 H/m^2$ is observed only within the periods of melting and destruction of the ice. Otherwise, $E \approx 8 - 10 \times 10^9 H/m^2$. The Poisson ratio $\nu$ varies within the range from 0.3 to 0.45. Thickness of the ice cover may be as large as several meters. Therefore, we can accept the estimate

$$\frac{EH^3}{12\rho g(1-\nu^2)} \leq 10^6 m^4$$

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Figure 2.

Figure 2 shows the plot of dependence $D(h, l)$. It can be seen that $D$ rapidly decreases with the growth of $l$. Therefore, within a sufficiently broad interval of parameters $l$ and $h$, we can assume that $10^{-5} < D < 1$.

We performed numerical simulations of the moduli of eigenvalues of $T$ within the intervals $10^{-5} < D < 1$, $0 < \gamma < 20$. As can be seen from (8), the upper boundary $\gamma = 20$ corresponds to a case when $H < l/20$, i.e., the depth of fluid is 20 times smaller than the characteristic scale $l$ of the problem (see Fig. 1). Setting $h \approx 3m$, we find that $l \approx 1000m$. Under these conditions, the upper estimate for the depth of fluid and for the wavelength divided by $2\pi$ is $50m$.

Figures 3 - 6 display curves of the constant modulus for one of the eigenvalues of matrix $T$ in the $(\gamma, N)$ and $(\gamma, D)$ planes. Light regions correspond to the moduli of the eigenvalues greater than unity. Dark regions represent the moduli of the eigenvalues less than unity. Within gray regions, which are predominant in Figs. 3 - 6, the moduli of the eigenvalues are equal to unity. The modulus of another eigenvalue is equal to unity within the same regions. The considered eigenvalues correspond to counterpropagating waves. As is evident from physical considerations, if the wave cannot propagate without energy loss, then it should decay along the direction of its propagation. Therefore, in those regions where the modulus of one of the eigenvalues is less than unity, the modulus of the other eigenvalue is greater than unity. The boundaries of frequency gaps correspond just to the boundaries between gray regions and light or dark regions.

Figure 3 shows frequency gaps in the wave spectrum for various $\gamma$ and $N$ at $D = 0.001$. This figure displays curves the constant modulus for one of the eigenvalues. If condition (9) is satisfied, then $l \approx 100m$ and $H \leq 100m/\gamma$. The horizontal axis in Fig. 3 represents $\gamma$ in relative units. For example, number 100 corresponds to $\gamma = 20$. The numbers along the vertical axis display the quantity $N$ expressed in percent, e.g., number 80 corresponds to $N = 0.8$. It is seen that, for moderate $N$, the ice cover is totally transparent for surface waves. The growth in $N$ leads to the appearance of gaps in the spectrum. Note that a
continuous increase in $N$ results in jumpwise shifts of the first gap to the low-frequency region. This effect is associated with arising new gaps.

Figures 4 - 6 display curves the constant modulus for the eigenvalue in the plane of $\gamma$ and $D$ for $N = 0.8$. The horizontal axis represents $\gamma$ in relative units within the same interval as in Fig. 3. The vertical axis corresponds to the relative rigidity $D$ in various intervals. Number 0 indicates an initial point of the interval, and number 100 corresponds to the terminal point of the interval. In Fig. 4, $D$ varies within the interval $10^{-5} < D < 10^{-4}$ and in Fig. 5 within the interval $10^{-4} < D < 10^{-2}$. Finally, in Fig. 6, $D$ varies within the interval $10^{-5}$ to $10^{-2}$, the widths of gaps considerably increase. As $D$ varies within the interval $10^{-2} < D < 1$, the boundaries of gaps remain virtually unchanged. The first gap lies in the vicinity of $\gamma = 8$. Assuming that condition (4.2) is satisfied, we find that $l = 100m$. In accordance with (4.1), the depth of fluid should satisfy the condition $H \leq 12m$. The wavelength of decaying waves is estimated as $2\pi 12m \approx 72m$. It can be seen that this wavelength is close to the quantity $1N$, which is proportional to the characteristic size of ice blocks.

5. CONCLUSIONS

In this paper, we investigated a model problem concerning the propagation of surface waves through a periodic set of elastic bands of ice floating on the surface of a shallow water. The investigations show that the frequency spectrum of waves features frequency gaps. Waves whose frequencies fall within these gaps cannot propagate without loss in such systems. The first frequency gap corresponds to waves whose wavelengths are approximately equal to the characteristic size of floating blocks of ice. We can assume that this or close criterion holds for fluid of an arbitrary depth.

Analysis of an analogous problem for fluid of an arbitrary depth encounters additional mathematical difficulties because, in this case, we should satisfy condition (5) of joining solutions along the entire depth rather than at a single point.

The quantity $N$ involved in the analysis of the problem at hand is an analog of the compactness of a broken ice cover. Broken ice may contain pieces of ice with various horizontal dimensions. If the above hypothesis is true, then the boundaries of the first frequency gap should correspond to the pieces of ice with maximum dimensions. Smaller pieces have only a slight impact on the propagation of waves with large wavelength. Note that the small ice pieces dissipate the energy of waves with short wavelength. Such waves can effectively propagate in ice fields consisting only of large blocks. These waves correspond to gray regions in Figs. 4 - 6 to the right of the first frequency gap along the axis of frequencies $\gamma$.

This publication was made in the framework of the Protocol for Cooperative Research between the Hydrophysics Scientific Council, RAS, and Istituto per lo Sfruttamento Biologico delle Lagune, CNR, Italy. A.V. Marchenko and K I. Voliak express their gratitude to the International Science Foundation and Russian Government (Grants MFE300 and
JJ4100), as well as to the Russian Foundation for Basic Research (Project Code 93-02-16203) for support during the study. R. Purini thanks also the Italian Antarctic Project (PNRA) and the Physics Committee of CNR for partial support to the paper.

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ELABORATION OF THE AUTOMATED SYSTEM FOR INTERPRETATION OF SEA ICE IR IMAGES

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For some reasons the potential capabilities of the methods and instruments for remote sensing of sea ice from space have not been fully used. In many respects, this can be attributed to poorly developed procedures for an automated interpretation (decoding) of satellite images of sea ice. At present, IR-images of sea ice are interpreted either by means of visual or calculation methods that are based on physical models. Visual methods subjective by nature, provide inaccurate information being strongly dependent on experience and the psychophysical state of specialists involved in interpretation. The interpretation indications that are being used and are obtained from restricted data of subsatellite observations are expressed in verbal language and are difficult for automation. The calculation methods are easier for automation, however, their realization requires initial data on a large number of environmental parameters forming their own thermal radiation of snow-ice cover. Also, due to technical-economical restrictions or the absence of developed measurement methods, it is difficult and frequently impossible to derive necessary information on environmental parameters simultaneously with IR-image recording. That is why, the use of each method separately does not provide a satisfactory solution of the problem of interpreting an IR-image of sea ice.

The solution of this problem requires formalization of the procedure for combining these methods into a single set of methods providing a possibility for an active work under conditions of inaccuracy and uncertainty of initial data. An analysis of the existing approaches to resolving this problem has shown that it is promising to develop the systems based on artificial intellect technology, in particular, the automated systems for supporting the decision-making and expert systems.

One of the most important objectives of interpreting IR-radiometry data on sea ice cover is to estimate ice concentration and spatial distribution by thickness. In practice for ice mapping the thickness is usually shown in the form of age gradations whose
limits were found on the basis of visual ice reconnaissance.

As a result of multiyear studies performed at the AARI, an expression relating surface temperature of snow-covered ice to its thickness was obtained /1/. It was found that in addition to the ice temperature, its surface temperature also depends on some parameters, most important among them being: thickness and heat conductivity of snow cover, wind speed, air temperature and counterradiation of the atmosphere. Simultaneous measurements of the indicated parameters are difficult, being sometimes impossible. That is why, one has to be based not on the results of their measurements, but on estimates obtained either by averaging the values of multiyear observations or by extrapolating some ground observations. Therefore, practical realization of potential possibilities of the IR-radiometry method in ice cover studies requires resolving the problem of inaccuracy and uncertainty of information about the specific values of environmental parameters that govern their own thermal radiation in real situations.

Additional difficulties arise when interpreting satellite IR images. They are connected with the need to take into account the parameters characterizing the extinction of optical radiation by the atmosphere.

Partly, these problems were resolved in the methods for interpreting data of IR-radiometry of ice cover developed at the AARI /2/. By introducing two dimensionless generalized factors whose values are functionally connected with the ice thickness, the transition to relative measurements is made. As a result, the number of parameters that are necessary to determine, decrease and the accuracy of estimates of ice concentration and age increases. But, since for calculating dimensionless generalized factors by means of these methods one uses mean values of environmental parameters, the problem of taking into account the information uncertainty, remains unresolved.

To some extent, these difficulties are eliminated by using climatic databases that contain information of the extent of the snow cover on the ice and the characteristics of wind flows. This is being done in the system under development. However, from experience, it is not always justified to be based only on the averaged regime characteristics that are contained in climatic databases. The actual values of environmental parameters can
significantly differ from their mean values in real situations. In such cases the only source of required information are data, obtained on the basis of expert estimates which are, as a rule, of an approximately qualitative character. Hence, there is naturally a problem of formalizing expert conclusions and determining the nature of uncertainty and taking it into account when analyzing the influence of variable environmental parameters on the results of interpretation. That is why, along with such traditional functions as preliminary procession of initial images, the system under consideration includes calculation of the geographical image basis; initialization of climatic databases. It envisages procedures for an interactive input of snow cover values, characteristics of wind flows; prescription of the parameters of fuzziness of initial data and taking it into account in the process of interpreting IR-radiometry data. This can be seen in Fig. 1 which presents a structural scheme for interpreting IR-images of ice cover.

A distinguishing feature of the functioning of the system is the need of operating under conditions of a priori uncertainty and inaccuracy relative to initial data. This causes the use of some specific means and methods for presentation, analysis and allowance for uncertainty.

An analysis of specific operation of remote sensing equipment has shown that possible interpretation of uncertainty and a theory of fuzzy sets are more adequate to the physical sense and semantics of the problems of remote sensing sounding, than the probability theory. It is believed that since initial data are fuzzy by their nature, the restrictions should be described by fuzzy sets and the results of the output and decision-making procedure for diagnostics of ice types should reflect the uncertainty in data. Then, the use of fuzzy intervals eliminates the need for establishing accurate values of the boundaries dividing ice age gradations. Thus, boundary values of ice age gradations are presented not in the form of clear (accurate) numbers but as fuzzy numbers /3/. At such interpretation the problem of decision-making about an area of the IR-image of sea ice under study belonging to some age gradation or other is reduced to comparing fuzzy numbers, one of them reflecting a fuzzy boundary value separating adjacent age gradations, and the second - a fuzzy value of the brightness of the investigated area of the IR-image of ice. In other words, the decision-making procedure is reduced to the
of the initial expert system variant for processing
IR-images for ISM PC interpretation of sea ice
types by thickness (age gradation)

Start initialization includes initialization, geographical image bases
(calculation, initialization of climatic database)

Initial image visualization

YES ← Query for interactive input
(NO) of snow cover extent
values and wind flow
characteristics

YES ← Interactive division of
the initial image into zone
and input of characteristic
snow cover extent and wind
flows by information points
prescription of FP

Interpolation of input
archived parameters into
image CB

Calculation of relation
parameters brightness-
thickness, calculation of
FP of the output results

Visualization of the calculated field of ice
thickness: - of most probable age gradation (AG)
- extreme AG
- probabilities of most probable ice AG

Choice and visualization of the climatic
analogue of calculation

A qualitative comparative analysis
of the calculate and climatic
fields of ice thickness

Request for repeated
calculation → YES

NO

Output

Fig. 1

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choice what of the two fuzzy numbers should be considered to be larger (or smaller).

Schematically, let us show an algorithm for estimating ice age gradations and taking into account the uncertainty of information on the environmental state by the example of taking into account possible variations in snow cover on the ice. This is related to the fact that snow cover on the ice is one of the most important parameters that govern thermal radiation proper of the snow-ice cover. At the same time in practice the decoding of IR-images of ice cover is most difficult when obtaining information on snow cover thickness. This is due to significant spatial-temporal variability in its thickness distribution and the absence of methods and instruments for measuring the snow cover on the ice from aerospace media.

At the first stage the approximate values of snow cover thickness are transformed to fuzzy numbers in the form of L-R functions /3/. Then, according to the rules of fuzzy arithmetics the dimensionless parameter $\xi$ is calculated which allows taking into account the influence of the snow cover:

$$\xi = \frac{\lambda_s}{\lambda_1} \left( \frac{\lambda_s}{\lambda_1} + \frac{h_s}{H_i} \right),$$

where $h_s$ and $\lambda_s$ the thickness and coefficient of snow heat conductivity, $H_i$ and $\lambda_i$ the thickness and coefficient of ice heat conductivity.

Then, a fuzzy value of the approximated snow cover thickness ($H_a$) is calculated by the formula:

$$H_a = \frac{H_i}{\xi},$$

At the next stage a fuzzy value of the dimensionless factor $\theta$ is calculated:

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where $T$ - the surface temperature of snow-covered ice whose thickness is to be determined, $T_2$ and $T_w$ - the surface temperature of thick first-year or second-year ice and water, respectively, $k$ - the heat exchange coefficient of ice surface/ atmosphere, $T_a$ - the air temperature, $I_e$ the effective radiation of snow-covered ice surface, $I$ - the absorbed solar radiation, $I_{e2}$ the effective radiation of thick ice surface.

On the basis of the IR-image to be decoded, the brightness values of pixels that correspond to open water surface $\alpha_w$ and thick first-year or multiyear ice surface $\alpha_2$ are determined. With the assumption that ratios of temperature differences are equivalent to ratios of differences of corresponding image brightnesses, the fuzzy ice brightness value $\alpha_o$ whose thickness is necessary to determine is calculated by the formula

$$\alpha_o = \beta(\alpha_2 - \alpha_w) + \alpha_w$$

On the basis of known reference situations the fuzzy brightness values of the IR-image that separate ice age gradations are calculated. The belonging of the study area of the IR-image to some or other ice age gradation is determined by comparing fuzzy numbers describing the brightness of the study area with fuzzy numbers corresponding to the boundaries separating ice age gradations. The procedure for comparing fuzzy numbers is based on calculating the ranking indices whose values for a specific pair of fuzzy numbers allow the decision of what number of the two is larger. From ranking indices known in literature the ranking indices suggested in /3/ were chosen. The theoretical formulas for calculating the ranking indices of fuzzy numbers have the following form:

$$H_1(A,B) = \sup \min \{ M_a, M_b \}, \quad a \geq b$$

$$H_2(A,B) = \sup \inf \min \{ M_a, 1-M_b \}, \quad a \leq b$$
\[ H_3(A,B) = \inf_{a, b \leq a} \sup_{b} \max \{ 1 - Ma, Mb \}, \]

where \(Ma\) and \(Mb\) the functions of belonging of fuzzy sets \(A\) and \(B\).

The need for taking into account possible variations in the snow cover on the ice is illustrated in Fig. 2 where the dependencies of a dimensionless factor \(r\) on the ice thickness are given at mean snow depths (curve 1), minimum possible (curve 2) and maximum possible snow depths (curve 3). As is seen, in the cases of actual values of the snow cover on the ice deviating from mean values there appear significant errors in diagnostics of the ice thickness.

An example of comparison procedures for fuzzy brightness values of the IR-image is given in Fig. 3 and in Table 1. Fig. 3 presents functions of belonging of fuzzy brightness values that correspond to the boundaries separating neighbouring ice age gradations \(N_0.05\) (dark nilas - light nilas), \(N_0.1\) (light nilas - grey ice), \(N_0.3\) (grey-white-white ice) with fuzzy brightness values of the three image fragments under study \(N_1, N_2, N_3\).

<table>
<thead>
<tr>
<th>Results of comparing fuzzy numbers in pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_1)</td>
</tr>
<tr>
<td>(N_0.05; N_1)</td>
</tr>
<tr>
<td>(N_1; N_0.05)</td>
</tr>
<tr>
<td>(N_2; N_0.05)</td>
</tr>
<tr>
<td>(N_0.05; N_2)</td>
</tr>
<tr>
<td>(N_3; N_0.1)</td>
</tr>
<tr>
<td>(N_0.1; N_3)</td>
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</tbody>
</table>
Fig. 2 Dependency of \( \beta \)-factor on sea ice thickness

Fig. 3 Functions of belonging of fuzzy brightness values of the IR-image
Table 1 presents results of comparing fuzzy values of corresponding brightnesses in pairs by ranking indices of fuzzy numbers. When the condition $H_1(A,B) > H_1(B,A)$ is fulfilled, the decision about $A > B$ is made. The comparison indices of fuzzy sets have a definite model semantics and are indicators characterizing the extent of assurance that estimates of belonging of the study image fragments to some or other age gradation are not a result of variations in environmental parameters, for example, of the snow cover on the ice. Thus, there is a possibility for numerical assessment of the reliability of the decision-making procedure for diagnostics of ice types and obtaining approximate but most reliable conclusions in terms of available information, about the age categories of ice cover.

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SUMMARY
of Report "Air monitoring of ice conditions In the Arctic seas"

The authors V.I. Chernook, V.B. Zabavnikov, V.Yu. Bogomolov
( Russia, Murmansk, PINRO )

The development of the Arctic requires development of active navigation in the seas surrounding this region. For increase of speed of steering of ships and maintenance of safety of navigation it is necessary not only to improve the quality of meteorological, hydrological and ice forecasts, but, in a not smaller degree, knowledge of a real ice conditions, information about which, with the best efficiency, may be obtained by surveying from the aircrafts.

For considerably increased, recently, requirements to quality, productivity, effectiveness of reception and the transfers of the information about the ice cover conditions it is necessary to expand the means of realization of ice air surveyes and researches, as well as operational characteristics of a measuring equipment, means of processing and transfer of received data. Besides, problems of updating of planes capable to execute work over the arctic Seas are decided.

For reception of maximally possible volume of the information, high quality and the efficiency of interpretation of data about ice conditions it is necessary to execute remote sensing of a marine surface in several spectral ranges of electromagnetic waves, that can be ensured by complex use of the equipment, working in various areas of spectrum.

The important place among tool methods of remote sensing of marine drifting ice at present belongs to a multiband complex of side-looking air-born radar (SLAR), enabling to execute sensing of the sea surface from heights of flight from 1000 up to 9000 meters at any speeds of a plane, irrespective of a condition of atmosphere such as clouds, fog, mist and etc., as well as time of day.

The specified features are extremely important for air sensing in the Arctic seas, where unstable weather conditions and prolonged period of a pole night and dark time of days are frequently marked. Thus the complex SLAR works in three ranges of lengths of waves - centimetric, decimetric and meter band.

The processing of radar-, IR- and videoimages is executed as onboard a plane - operatively, as thematically - on coastal centres, for that a specialized hardware-software complex is used. It includes:
- computer of the type IBM PC-486:
- Device of input of the images;
- Printer;
- Standard and specially developed software that consider specific character of the problems to be solved.

For automatic control of the data acquisition, their integration and processing in real coordinates and time an onboard operative computer system is used. The basis of its hardware is an IBM-compatible computer on the basis of 486 processor with SVGA display, hard disk drives, printer and set of devices of communication with a measuring equipment. An advanced software, enabling to execute the most diverse functions depending on solvable problems is developed.

For operative communication and exchange by the information with vessels, coastal centres and headquarters of marine operations, as well as the transfers of files of initial data, including the received images, the air carriers are equipped with AM and FM radios. Besides the transfer of data may be executed through satellites of "Inmarsat" series.

The air surveys of the seas of the arctic region with use of methods of multiband remote sensing, principles of which are stated above, during a number of the last years is regularly executed by the experts of PINRO from a board of plane - laboratory IL-18 D "Pomor", on which means visible, IR- and radio band of waves are installed and successfully maintained. A wide circle of scientific and applied problems is thus decided, among which special place take air research on air monitoring of ice conditions of the Arctic seas. These work are executed basically with the purposes of:
- Maintenance of safety of navigation of ships of Murmansk marine Shipping company to Northern Pole and on a line of NSR;
- Maintenance of safety of navigation of fishing vessels in coastal zone of marine drifting ice;
- Information service of organizations of Defence Ministry;
- Maintenance of safety of oil and gas extraction and transportation of raw material in the outlying seas of the Russian North.

All information on ice conditions is processed as onboard plane - laboratory (operatively), as on ground (thematically) with the help of modern computer systems and software in real coordinates and time. All this, and first of all the integrated approach of air surveys, permits to receive qualitatively new information, expediently distinguished from data, received at ice investigations, using only one of the methods of remote sensing (only radar-tracking or only visual or any other).
AIR MONITORING OF ICE CONDITIONS in the ARCTIC SEAS

The authors V.I. Chernook, V.B. Zabavnikov, V.Yu. Bogomolov. (Russia, Murmansk, PINRO)

INTRODUCTION

The development of a vast Arctic region of Russia requires development of active navigation in outlying seas of the Arctic Ocean. For good safety navigation it is necessary to have, on the one hand, qualitative meteorological, hydrological and ice forecasts, and, on the other hand, reliable operative knowledge and data on a real ice conditions, information about which can be obtained by surveying from coastal stations, from ships and by realization of sensing from board of space-borne platforms.

As long-term experience and practice of researches of marine drifting ice and realization of so called marine Arctic operations show, the best efficiency, quality and representation of obtaining of the operative information about a real ice conditions are reached by realization of surveys from air- and space-borne platforms. Thus the preference is given to data received by air surveys since the information here has more authentic, operative character and has higher resolution.

The first regular air surveys of marine drifting ice have begun to be executed in 1930 from the moment of active development of a line of Northern Sea Route (NSR). Then the air surveys were executed only with use of visual observations.

For past more than 60-years period of air researches of marine drifting ice in the Arctic pool, so called ice investigations, a way from simple visual air surveys to application of complex technologies, based on use of instrumentall complicated multiband air surveys of sea surface and processing of obtained data on modern onboard computer systems, based on personal computers (PC), was passed.

To obtain the maximally possible volume of information, high quality and efficiency of interpretation of data about ice conditions, it is necessary to execute remote sensing of marine surface in several spectral ranges of electro-magnetic waves, which can be ensured by complex use of the equipment, working in various parts of spectrum.

Thus still there is an urgent problem of rational organization and optimization of fulfilment of ice air surveys, that permits to receive at minimum costs necessary and qualitative volume of information about characteristics and distribution of marine ice.

Air surveys of the seas of the Arctic pool with use of methods of multiband remote sensing is regularly executed during a number of the last years by the experts of PINRO from a board of plane - laboratory IL18 D "Pomor", on which visible, IR and radio equipment are installed and successfully maintained. A wide circle of applied sciences problems is thus solved, among which special place take air researches on monitoring of ice conditions of the Arctic seas.

This work are executed basically with the purposes of:
- Maintenance of safety of navigation of ships of Murmansk shipping company to Northern Pole and on a line of NSR;
- Maintenance of safety of navigation and fishery of fishing vessels at edge zone of marine drifting ice;
- Information service for organizations of defence ministry;
- Maintenance of safety oil and gas extraction and trans-
portation of raw materials in outlying seas of the Russian North.

All information on ice conditions is processed as onboard plane - laboratory (operatively) as on ground (thematically) with the help of modern computer systems and software in real coordinates and time.

MEANS And METHODS OF REMOTE SENSING OF MARINE DRIFTING ICE FROM BOARD OF AIRCRAFT

As was already marked, originally aerial ice investigations had visual character. Due to high resolution and usually to large experience of the hydrologists-observers the visual surveys are still carried out, as an element of ice aerial survey, at present. Purely the visual surveys are executed from heights of 200-300 meters or below the bottom layer of clouds. It is thus not required any significant reequipment of planes. During realization of the visual aerial surveys the observers can determine all main characteristics of ice cover.

Together with this, visual aerial surveys of marine ice are executed in a comparatively narrow strip of view, amounting from 2 up to 20 heights of flight, at minimum distance between surveying tacks of 30 kms, that results in significant errors of interpolation between them and miss of those or other objects, describing condition of the ice cover. Besides, the visual surveys in a large degree depend on light conditions and weather, subjectivism and experience of the observers, as well as on significant errors of quantitative evaluations of ice conditions.

For these reasons, at present, visual ice aerial surveys can not satisfy fully to the growing inquiries of practice. Therefore, for the last 30-35 years growing development is received by instrumental means and methods of determination of ice conditions.

In order to get complex and detailed information on ice cover condition wide introduction in practice of realization of ice aerial surveys of means and methods of remote sensing in the various areas of electro-magnetic spectrum is necessary. For this purpose, in the last years equipment working in visible, IR and radio ranges of waves is applied.

Here, first of all, one should include following measuring complexes: - Visible range - photo and video equipment of various systems; - IR range - IR-radiometers and thermovisions of various types and systems; - Radio range - radiometers, side looking air-born radars (SLAR) and radars with synthetic aperture (SAR), ice thickness meters.

The aerial photography is conventional and rather precise method of reception of information about the ice cover condition. The main advantage of aerial photography is high resolution and affinity of the image to the natural one, perceived by human eye. But its essential defects are duration and complexity of processing of the photos that sharply reduces effectiveness of work, dependence on weather conditions.

Various video equipment finds growing application at ice aerial surveys. In the last years their resolution has conside-
rably increased, color-transfer was improved weight and dimensions have decreased, simplicity and reliability in management and operation have increased. The advantage of video survey as compared with aerial photography consists in an opportunity of recording of the images on magnetic tapes, operative inputting of them in a onboard computer and automated processing.

For maintenance of safe navigation among marine drifting ice it is necessary to know the characteristics of ice-hummocks, which are determined on photo-, video and IR-images and with the help of laser profilometer.

Data on space distribution of temperature as of ice, as of water surface are received with the help of thermovisions. This information permits to predict terms and centres of ice forming and natural thawing, as well as position of an ice edge.

The thermal aerial survey in a range of lengths of waves 8-14 mm, permits to execute ice exploring in a dark time of days and in conditions of a polar night, determining thus, with a sufficient degree of reliability, presence of cracks and fractures, hummocking and condition of snow-and-ice cover, as well as age characteristics of ice.

In the last years for determination of radio brightness temperature of natural objects passive UHF-radiometers have become to be applied advantage of which is small dependence on weather conditions. The drawbacks of determination of temperature in comparison with IR equipment.

However, the leading place among the listed remote sensing equipment belongs to a complex of multiband radar-tracking stations, the application of which permits essentially to increase width of a strip of view and, hence, surveyed area in dozens of times, thus to ensure considerably higher economic efficiency of ice aerial surveys, fulfillment of which thus does not depend on weather conditions and is executed from heights of flight of 1000-9000 meters.

The radar-tracking complexes in comparison with panoramic plane radar stations have following advantages:
- By order higher resolution;
- Considerably larger range of detection of objects;
- Opportunity of reception of the images in a rectangular system of coordinates, that facilitates their comparison to the video and photo images.

The one-frequency radar surveys have restrictions, connected with ambiguity of decoding of signals, for exception of which it is expediently to use a complex of multiband radar-tracking stations.

The information, arriving from radar-tracking complex, is processed and displayed onboard a plane and is registered for the subsequent processing in an analog and digital form. Thus the information contents of radar images rather great and is characterized by large volumes of data. In this connection there is necessity of automated processing of the radar images in real coordinates and time, that is successfully decided with use of personal computers (PC).

For measurement of thickness of a marine ice a special radar instrument is used, the principle of action of which is based on irradiation of ice with probing radio impulses and measurement of a time interval between the signals, reflected from the top and bottom borders of ice. It also essentially assists at instrumental evaluation of ice concentration.
The best efficiency and quality of ice aerial survey is reached by complex use of listed above measuring means and automated processing of the information thus received. The specified principle is successfully realized by the experts of PINRO onboard plane - laboratory IL-18 D "Pomor", which is equipped with some of the above listed measuring complexes.

BRIEF INFORMATION On PLANE - LABORATORY IL-18 D "POMOR"

The plane-laboratory IL-18 D "Pomor" has following main specifications:
- Maximum range of flight 5500 kms.
- Maximum duration of flight up to 12 hours.
- Range of speeds 300-700 k.ms / h.
- Range of heights of flight 100-7500 m.

The plane-laboratory has 4 places for realization of visual observations, equipped with blisters. Accuracy of navigation, determination of a current position of a plane and objects on a sea surface are executed with the help of a navigating complex, which gives data about time and coordinates, as well as about speed, course and height of flight.

The complex consists of:
- Positioning system of precise navigation GPS R-900 or MX-200;
- Altimeter;
- Navigator.

GPS permits to determine coordinates with accuracy not worse then 100 m, speed and height of flight does with accuracy 1 m/c and 10 m respectively. The system stores in memory 999 points of a scheduled route and specifies deviations from them. Navigator is realized on base of PC AT-386 / 486 and displays on a screen of a monitor a route of flight, coastal line, all navigating parameters and current results of discrete sensing of marine surface, simultaneously recording them on a magnetic carrier.

As an equipment, working in visible range of spectrum, aerial photo cameras are used on "Pomor" intended for close-up and perspective photography, as well as video equipment, used for observing and perspective video surveys. As photo equipment cameras AFA-41/10, AFA-41/20, RA-39 and A-39 are used, and cameras of standards VHS and SVHS are used for video survey.

For work in IR spectral range the plane - laboratory is equipped with IR-radiometer and thermovision AGA-780. The specified equipment works in a spectral range 3-5 mkm and 8-14 mkm respectively, at viewing angles of 7 and 20 degrees.

As a measuring equipment at microwaves sensing ( radio range ) on "Pomor" a multiband radar-tracking complex is used, consisting of side looking air-born radars ( SLAR ) and synthetic aperture radar ( SAR ). SLAR includes RBO-0.8 ( sensing to one side ) and RBO-3 ( sensing to both sides ), possessing length of waves of radiation 0.8 cm and 3 cm respectively and the space resolution 30 * 30 m and 20 * 50 m and strip of view of 15 km and 40 kms respectively. SAR senses to one side and have lengths of waves of radiation 23 cm and 180 cm, and strips of view of 15-120 km ( is set by the operator ) and 45 kms and space resolution 20 * 50 m and 100 m respectively.

Besides, on the plane - laboratory there are all opportu-
ties for installation and operation of the additional equipment necessary at realization of ice aerial surveys (ice thickness meters, profilometers, scanners and etc.).

For operative communication and exchange by the information with vessels and coastal centres, as well as for transfer of files of data, including files of images, "Pomor" is equipped by a complex of radio communication equipment of SW and USW ranges.

The processing of SLAR, IR and video images onboard plane-laboratory is executed with the help of a specialized hardware-software complex, consisting of:
- PC of the type IBM PC-486;
- Device for input of the images;
- Printer;
- Standard and specially developed software, depending on specific character of the problems to be solved.

For automatic control of the data acquisition, their integration and processing in real coordinates and time, the onboard operative informative system (BOIS) is used. The basis of hardware of BOIS is a IBM-compatible computer on the basis of 486 processor, with SVGA display, HD and floppy drives, printer and a set of devices of communication with a measuring equipment. The advanced software permits to execute the most diverse functions depending on problems to be solved.

ORGANIZATION And REALIZATION OF AIR MONITORING of ICE CONDITIONS OF ARCTIC SEAS. ACQUISITION, PROCESSING And PRESENTATION OF RECEIVED INFORMATION.

At organization and realization of complex aerial surveys with the purpose of monitoring of ice conditions, first of all, technical specifications of plane-laboratory, synoptical situation, time of day and season of a year are to be taken into account.

Three last circumstances are caused by the fact that, along with all-weather SLAR and SAR systems, at realization of ice monitoring a IR equipment are applied, use of which is limited by meteorological conditions (clouds, mists, fogs, deposits etc.), as well as various photo and video surveys, visual observations, which successfully and qualitatively can be conducted only at favorable weather conditions and in a light time of day.

Thus, before the beginning of work, the analysis of current meteorological situation is executed and synoptical forecast on a region of aerial survey is accepted with prospect from a day and under. Thus the flight is mainly carried out in a light time of day with a general direction, taking into account rotation of Earth, i.e. from east to west.

The route of air survey is created so that at minimum flight time one could determine ice conditions with maximum complete and authenticity. The character of the created route depends on goals of flight, expected ice and meteorological conditions in a region of the air survey and features of the region of work. Some variants of tacks is thus predominarily applied: Π-shaped, oblique-angled, fan-shaped and spiral. However, main are the first two, others are applied as auxiliary, additional. Operating height of flight is chosen proceeding from technical possibilities of the equipment, mission tasks and real meteorological conditions in a region of survey and can make 100-7000
The data acquisition at realization of aerial survey with the purpose of monitoring of ice conditions is executed along a chosen route from the moment of arrival in a given region of work up to a moment of departure from it. Thus the periodicity of sensing of sea surface by means of equipment, working in discreet mode, is chosen proceeding from features of a region of researches and mission tasks. The visual observations, aerial photography and video survey are executed continuously on a route of flight while permit light conditions, visibility and meteorological conditions. The radar sensing during aerial photography is carried out continuously. Thus all data are output on a display of a computer and printer, as well as are recorded on a disk for the subsequent ground processing.

The processing of an aerial survey results with the purpose of monitoring of ice conditions is executed in two stages:
- Preliminary processing with the purposes of correction of the primary information and presentation of it in a form convenient for the subsequent analysis;
- Thematic processing with the purposes of the analysis and interpretation of materials of aerial survey with the subsequent synthesis of maps for the consumers.

Both stages are based on automated data processing on a computer in an interactive mode, that assumes participation in this process of an applied expert - researcher (hydrologist or physicist). The majority of procedures of preliminary processing of the information is reasonably well formalized and logically programmed. Thus by now, the methods and software, enabling to decide the following problems, were developed:
- Correction of instrumental and other distortions;
- Calibration or normalization of the images;
- Geographical binding of remote data;
- Transformation of the images into a cartographical projection.

The preliminary processing should be made on the ground stations of the information consumers. Thus for effective use of the remote sensing information the operators of receiving stations dispose advanced and adequate functional-and-service environment, which is maintained by the necessary software.

After completion of preliminary processing of materials of aerial survey that was acquired during air monitoring of ice conditions, their thematic processing, including decoding and interpretation of data, is made, that is determination of ice concentration, age structure and other characteristics of the ice cover.

Radar images and images, received in a visible area of spectrum are subjected to decoding.

Decoding attributes of radar images are subdivided on direct and indirect. The tone and tone structure of the object image, its form and sizes belong to direct ones. Thus the texture of the image is frequently used, for it is a subclass of a tone structure.

The tone of radar images depends on electrical and physical properties of ice, roughness and humidity of a surface, angle of inclination and direction of irradiation of that or other area of the ice. Also at decoding and interpretation the attribute of form is applied.

Position, mutual connection of objects, and also traces of their activity belong to indirect decoding attributes. So, for
example, typical indirect attributes are: polynias on lee side of grounded hummocks, channels, formed by icebreakers.

Except direct and indirect decoding attributes, sometimes logic ones, imposing space and temporary restrictions, are used. As characteristic example of it, the impossibility of formation of young ice in summer can serve.

Radar image of each kind of ice has features, stipulated by the fact that a surface of ice cover, depending on conditions of its formation, duration of existence and phase of development, has a wide range of roughness and physical properties. Due to this, at radar sensing, the detection of marine ice of all aging stages, from shuga and nilas up to long-term ice is possible. However, selection in a mass of one-year ice of their intermediate stages is a very difficult problem.

The unequivocal interpretation of the radar information about ice cover is not always possible. Therefore for maximum elimination of this defect additional data, having independent character and received by other means of remote sensing and as a result of visual observations, are involved.

As a result of processing of a complex of materials, received at air surveys, directed on realization of air monitoring of ice conditions, the generalized ice information is prepared, which is presented to the consumers, more often as maps of various scale, on which the ice conditions is displayed by accepted international ice designations and symbols. Besides, photo, video, thermal and radar images are added to the maps, presenting in details the ice conditions on certain, the most interesting areas of researched aquatorium.

There is an additional opportunity of reception of thematic electronic maps for direct perception or inclusion of them in other systems of computer processing. The resulting electronic maps can be displayed in given scale, in various cartographical projections with any degree of detailed elaboration. The format of presentation of data allows further thematic processing of a map in order to obtain various parameters, for example, quantity and distribution of objects of a given type, perimeters and areas of given zones.

Described principles and methods of realization of air monitoring of ice conditions in the Arctic seas, as well as ways of acquisition, processing, analysis, interpretation and presentation of received data, permit to have the characteristics and parameters of the ice cover, necessary for effective and safe navigation in the ice.

CONCLUSIONS

Further development and the activization of navigation on a line of NSR put forward the increased requirements to ensuring of safety of navigation among marine ice. This problem can be successfully solved only at comprehensive perfection and development of technical means and methods of remote sensing of marine ice, among which the important place is allocated for automation of processes of data processing, joint interpretation and decoding of the images and discrete data in various parts of
electro-magnetic spectrum. The specified problems, during a number of the last years, purposefully and successfully are being solved by the experts of PINRO. The achieved results pass check and tests at realization of air surveys.

As our own experience and modern world practice and tendency of development of use of aircraft at realization of remote sensing show, the best efficiency of air monitoring of ice conditions can be achieved at fulfillment of surveys from small and average planes not requiring large financial costs on their service, possessing small fuel consumption and capable of basing on ground airfields.
OPERATIONAL TRACKING OF THE OIL POLLUTED ICE IN THE ARCTIC SEAS AND THE ARCTIC OCEAN.

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ABSTRACT

Due to active exploration of the Arctic Sea shelf a probability of drifting ice pollution increases. A technique of contaminated ice operational tracking is proposed. It includes the use of satellite data, data from Argos drifting buoys and model simulations. A technique for ice drift determination from successive satellite images is presented. Model calculations can be used when there are no real ice drift data. Trajectories and positions of polluted ice are determined operationally with the use of real data or model calculations.

INTRODUCTION

At present a probability of sea and drifting ice surface pollution increases due to the development of active exploration on the Arctic Sea shelf. Sea ice constantly moving under the influence of winds and currents can carry pollutants over a considerable distance from the pollution source.

Numerical calculations of contaminated ice dynamics are carried out with the use of real drift velocity field.
Ice drift in the Arctic seas is determined from satellite images by means of identification of the same ice floes on successive satellite images and their coordinates determination.

Sea ice dynamics can be determined from visual, IR and radar satellite images. Satellite radar images are the most useful for sea ice monitoring because of their independence on light and weather conditions. Detailed ice drift patterns can be retrieved from successive ERS-1 SAR images, but on limited areas (100 x 100 km). Therefore, only radar images from the "Okean" satellite can be used for regular ice tracking because of their considerably wide swathwidth (450 km).

ICE DRIFT DETERMINATION FROM SUCCESSIVE SATELLITE IMAGES

The algorithms and software elaborated at the AARI, allows us to determine ice drift in interactive mode from successive images, covering the same area. Satellite images, geolocated with the use of orbital data and ground control points, are visualised on the screen of the computer and geographical coordinates of any point can be determined in interactive mode. As a rule, giant ice floes, fractures are delineated on these images. Some characteristic elements are recognised on both images and their geographical coordinates are determined.

Experience in using satellite images for determination of ice drift vectors and study of ice movement peculiarities in different areas of the Arctic Ocean has been gained [1, 3-5]. In particular, we studied the possibility of regular
ice tracking from successive AVHRR NOAA images [1]. Images received onboard the research vessel "Polarstern" for the period August-September 1993 for the Laptev Sea were analysed and ice drift patterns were determined. Time intervals between successive images varied from 2 to 42 days, but a considerable number of ice drift vectors were retrieved only for time intervals from two days to two weeks. The results of comparison with ARGOS buoy data showed a good coincidence both in velocity and direction.

Detailed spatial coverage of ice drift data was obtained for the eastern and western Laptev Sea in August and September. But it was impossible to retrieve any data for the central Laptev Sea due to clouds covering this area.

A series of 80 "Okean" images covering the Laptev Sea and nearby areas since the autumn freeze-up till early summer was selected for the analysis. Ice drift was determined for this period. An example of retrieved ice drift vectors is presented in Fig.1c,d. Examples of ice movement in the Barents and Kara seas are shown in Fig.1a,b.

ICE DRIFT DETERMINATION FROM DRIFTING BUOY DATA

Automated buoys with sensing elements for atmospheric pressure and air temperature were used for ice tracking in the Arctic Basin. Deployment of buoys on drifting ice was implemented in the framework of "The Arctic Buoy" program since 1979. Argos satellite system determines buoy positions with 500 m accuracy[8]. Buoy data, processed by the Argos Service, are transmitted all over the World via the Global Telecommunication System. Operational computer
processing of the buoy information is carried out at the AARI. Weekly and monthly charts of ice drift velocity in the Arctic Basin are composed. An example of such ice chart is shown in Fig. 2. When necessary, ice drift charts can also be presented as buoy displacements for any time interval more than twenty-four hours.

MODEL ICE DRIFT CALCULATIONS

Ice drift simulations can be fulfilled equally with real ice drift determination. At present, sea ice dynamics model elaborated by S.A. Kolesov [6, 7] is widely used in the AARI. Being relatively simple, it calculates ice drift velocity field in the Arctic Basin with a 200 km step. In the Arctic seas the grid step varies from 10 km in small areas (Baydaratskaya inlet) to 50-55 km for big water areas. Verification of the model was carried out with the use of Automated Buoy data in the Northern Kara Sea and in the Arctic Basin and showed, that model described main ice drift peculiarities quite well. Parallel implementation of numerical simulations allows us to use them as the main source of information in the periods when there are no real drift data. Dirty ice tracking can be carried out with the use of real drift velocity fields or model calculations. From time to time contaminated ice position can be estimated more accurately with the use of aircraft. Deployment of an automated buoy on a dirty ice floe for its subsequent tracking is also possible.

Forecasting calculations of dirty ice movement are carried out in the model 5-6 days in advance with the use of
atmospheric pressure forecasts, issued at the European Centre for medium-range weather forecasts. Estimates of anticipated transfer can be done on the basis of the charts of expected atmospheric pressure within homogenous circulation periods and with the use of regime data.

Proposed technology can be used for setting up a system for operational polluted ice tracking in the Arctic.

REFERENCES.


OPERATIONAL TRACKING OF THE OIL POLLUTED ICE
IN THE ARCTIC SEAS AND THE ARCTIC OCEAN.

(The Arctic and Antarctic Research Institute, St.Petersburg,
Russia)

Fig.1 The results of ice drift determination from
successive "Okean" satellite images for different parts of
the Arctic.

b) Kara Sea (30.12.1994 - 08.01.1995)
c) Laptev Sea (05.11.1987 - 10.01.1988 - 29.03.1988 -
06.05.1988)
d) Laptev Sea, drift of zones (28.10.1987 - 30.01.1988
- 06.05.1988).

1- drift of ice floes, identified on satellite images;
2- drift of contaminated ice floe, calculated with the
use of satellite data;
3- drift of the same ice floe, determined from
numerical simulation.

Fig.2 Ice drift velocity in the period January 24 - 30,
1995.

1 - buoy number (25565), direction (arrow) and velocity
(20.48 km/day) of its drift.
2 - isotach.
3 - boundary between areas with different ice drift
velocities and directions.
4 - centre of anticyclonic ice circulation.
IMPACT OF PRODUCTION AND PROCESSING OF HYDROCARBON-CONTAINING RAW MATERIALS FROM THE SHTOCKMANOVSKOYE FIELD UPON THE BARENTS SEA BIOTA

by

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The project of the Shtockmanovskoye field development envisages not only production of raw material but also construction of a methanol plant in the area of Teriberka. Exploitation of the two will inevitably result in pollution of sea water over a vast area.

The purpose of this research work was to study the impact of gas condensate and methanol, upon marine organisms of various trophic levels and also on hydrochemical regime of the Arctic waters.

MATERIAL AND METHODS

Under experimental conditions, using criteria of marine organisms survival and such physiological characteristics as intensity of photosynthesis, level of gas exchange, hematological, histological characteristics etc., toxic effect of condensate and methanol upon these organisms (protozoans, unicellates, planktonic and benthic crustaceans, gastropods and bivalves, roe and larvae of sea urchins, juvenile fishes) is estimated.

Besides, a process of sea water self-cleaning of gas condensate under conditions similar to natural ones was studied. An attempt to estimate how some natural factors (temperature, insolation and biological utilization) contribute into intensity of hydrocarbons removal from both the surficial film and water column was made under model (summer/spring) and laboratory conditions.

RESULTS AND DISCUSSION

As experiments have shown, the possibilities of the Arctic Ocean waters self-cleaning of gas condensate hydrocarbons are rather limited. Evaporation was the main factor of removal of low-boiling fractions. At the 10-th day, more than 85 % of initial content of condensate evaporated under day-light and 20° C temperature (and about 65 % evaporated under darkness). In a low-temperature series, this index constituted 60 % in average. This allows to compare gas condensate (taking light fractions content into account) with diesel fuel, for which the similar dynamics of evaporation was revealed (Izmailov, 1988). Contribution of light reaction fluctuated in the range of 8-25 % in dependence of exposition conditions. At temperature increase, the intensity of self-cleaning increased as well. But concerning the low-temperature conditions of the Polar Arctic Basin, the contribution of this factor is assumed to be unimportant. A role
of micro-organisms in transformation of both film hydrocarbons and dissolved components was not noticeable in the period of observations. Thus, the dissolved fractions of gas condensate decrease mainly at the expense of self-oxydizing and re-adsorption on a film.

Studying the impact of analysed compounds upon physical and chemical properties of sea water we have found that gas condensate in concentrations above 2.5 mg/l, and methanol - above 0.5 mg/l, promoted faster biochemical oxygen consumption, increase of permanganate oxydation, changed gas balance and depressed the processes of nitrification.

During toxicologic studies it was revealed that planktonic and benthic crustaceans at early stages of their development, and also unicellates turned to be the most sensitive to impact of condensate. Already at concentrations of 0.05 and 0.1 mg/l a considerably high level of death of juvenile amphipods Gammarus finmarchicus and copepods Acartia longiremis was registered. Much higher toxicity of emulgated solutions of gas condensate compared to unemulgated ones was registered. Besides, emulgated solutions will be more typical for the nature.

During the experiment, the sufficient sensitivity of a photosynthetic apparatus of cells of green alga Rizosolenia sp. to impact of condensate was revealed (Fig. 1). Reliable decrease of photosynthetic reactions intensity was registered already at the 6-th day of exposition in gas condensate concentrations of 0.1-100.0 mg/l. Photosynthesis indices have been fluctuating later on with maximum restoration and approaching to control values at the 15-th day. Such fluctuations of photosynthesis intensity are natural and often revealed in experiments under intoxication by substances, which impact is unspecific (Veselovsky and Veselova, 1990; Novikov, 1992). Impact of condensate on the increment of total abundance was much less active. Reliable decrease of experimental algae abundance compared to the control one was observed under concentration of 10.0 mg/l and higher.

Gastropods (Littorina obtusata), mature amphipods and young cod (Gadus morhua) were the most resistant species to the impact of gas condensate. Minimally active concentration for them in chronic experiments was that of 2.5 mg/l. At this level of pollution and higher, a real decrease of survival of adult molluscs and departures from the norm in their embryo development was noted, as well as the abnormal reproduction of amphipods and change in blood picture and histological features of cod (Table).

By the character of its intoxication methanol manifested itself as a neurotoxic poison with narcotic properties. Clinical pictures of acute intoxication of hydrobionts of different systematic locations were similar to each other and characterized by the increase of excitability of experimental specimens in the beginning of intoxication and further depression, and followed by narcosis and death of animals.
Rizosolenia sp. turned out to be the most sensitive species. Delay and complete stoppage of growth of the alga was registered at methanol concentrations of 5.0 mg/l and over (Fig. 2). These concentrations destroyed functioning of photosynthetic apparatus of cells, that was proved by the sufficient fluctuations of a value of photosynthesis effectiveness, which constituted 5 and 50 mg/l at the 23-d day (183.7 % and 169.7 %, correspondingly), and 66.2 % and 34.2 % at the 33-d day. Such range exceeds the normal limits of possible variability registered for algae photosynthesis (Shulyakovskiy, 1985; Veselovsky and Veselova, 1990) and justifies on toxic influence of methanol in the given concentrations.

Protozoans, adult crustaceans and molluscs, as well as young cod turned out to be more resistant to the methanol impact. Ciliates Euplotes baron were the most stable species. Negative influence on their function of reproduction was noted under content of methyl alcohol of 1000.0 and higher, and death of protozoans was revealed at higher concentrations. Death of planktonic crustaceans Idotea fuscata was observed in concentrations 5000.0 mg/l and higher, benthic representatives Gammarus finmarcellus - 30 000.0 mg/l, gastropods Littorina obtusata - 25 000.0 mg/l and young cod - 15 000 mg/l. There were no deaths of fish in the chronic experiment, but in concentration of 5000 mg/l the alcohol changed the architecture of gill apparatus, that could ruin osmoregulation system and cause lethal outcome.

Embryo and juvenile stages of the studied organisms development were the most vulnerable, that can be connected with the sufficient relative surface, weak protection of intensively dividing cells and high intensity of their metabolism. Compared to adult specimens, larvae of amphipods, as well as gastropods and sea urchins Strongylocentrotus drobachiensis were found to be highly sensitive (Table).

CONCLUSIONS

Comparative analysis of obtained data shows that gas condensate is much more toxic for hydrobionts than methanol. The recommended allowable concentrations of gas condensate, not influencing the functioning of the sea biota in the sea masses, is 0.01 mg/l and those of methanol - 0.5 mg/l.

The increase of the Barents Sea pollution by oil hydrocarbons and methanol in the result of the Shtockmanovskoe field exploitation can lead to sufficient structural changes in communities of hydrobionts. Reduction of abundance and even a complete elimination of some highly sensitive species of plankton crustaceans and algae and planktophages - the main food object of fish - will cause negative changes in the ichthyofauna composition. Both the increased sensitivity of specimens at early stages of ontogenesis and influence of gas condensate and methanol on processes of reproduction will impact negatively the population of relatively stable to them organisms and can be a reason of a degradation of the sea communities.
REFERENCES


Table. Some limiting parameters of toxic impact of gas condensate (GC) and methanol on marine organisms.

<table>
<thead>
<tr>
<th>Organisms and parameters</th>
<th>MUC*, mg/l</th>
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<tr>
<td></td>
<td>GC : Methanol:</td>
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<tr>
<td>Algae (Rizosolenia sp.):</td>
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<tr>
<td>increment of abundance</td>
<td>1.0</td>
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<td>photosynthesis</td>
<td>0.1</td>
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<td>Protozoans (Euplotes haron):</td>
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<tr>
<td>reproduction</td>
<td>2.5</td>
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<td>Crustaceans:</td>
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<td>survival of:</td>
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<td>Idotea furcata</td>
<td>-</td>
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<tr>
<td>Acartia longiremis</td>
<td>0.05</td>
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<td>young specimens of</td>
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<td>Gammarus finmarchicus</td>
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<tr>
<td>Gastropods (Littorina obtusata):</td>
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<tr>
<td>survival and embryogenesis</td>
<td>0.5</td>
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<tr>
<td>Sea urchins (Strongylocentrotus droebachiensis):</td>
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<td>embryogenesis</td>
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<td>Fish (Gadus morhua morhua):</td>
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<tr>
<td>hystological parameters</td>
<td>0.5</td>
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<td>blood parameters</td>
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* MUC - maximum unactive concentration
Fig. 1. Influence of different concentrations of gas condensate (mg/l) on change of photosynthesis effectiveness of alga cells, % of control.

Fig. 2. Influence of different concentrations of methanol (mg/l) on dynamics of algae cells abundance.
THE INFLUENCE OF EMERGENCY OIL SPILL
ON THE PECHORA SEA ECOSYSTEM

by

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In accordance with the project "Timan-Pechora", several variants are
assumed to transport fresh oil by on-land and underwater oil pipe li-
nes from the Varandeiyskaya group of the field to a terminal located in
the Pechora Sea and further oil loading on board of a tanker. It is
supposed to build a terminal in the site nearest to the shore with the
depth more than 20 m.

The continuous local pollution of water environment is probable during
exploitation of oil transports. Accidents happen rarely during oil
transportation or at a terminal during oil loading, and therefore can
not be foreseen, as a rule, but damage all marine complexes. The main
consequence of accidents is oil pollution which can be followed by ex-
plosions and fires, as well as by distribution of toxic substances ac-
tive on the surface and used for oil spill removal.

We investigated the influence of emergency oil spill in the area of
the sea terminal on the ecosystem of the Pechora Sea, including Islands
Dolgy, Natveev, Golets, Bolshoi Zelenets and Mali Zelenets.

Modelling of emergency oil spills in the tidal seas, it was concluded
that when 0.3-10 thou.t of oil spill into the water, a spot forms du-
dring 6-14 hours, that is comparable with duration of a right semi-di-
urnal high tide. In the majority of coastal areas of the tidal seas,
oil spots move by the close elliptic trajectories, since the determi-
nining factor is tidal currents (Potanin and Tersiev, 1978; Potanin and
Shcherbakov, 1987).

Regime calculations of oil spots drifting under the influence of cur-
rents after the emergency oil spill in the area of a terminal (89o10'N
58o05'E) were carried out for one tidal cycle. During one tidal cycle,
a centre of a spot will move by 1.2 - 1.7 km from the pollution source by elliptic trajectories eastwards, i.e. to the Dolgy Island. Consequences will depend on the volume of the spilled oil and hydrometeorological conditions.

At emergency oil spill, the pollution influences the status of the euphotic layer. The neuston organisms, which are very sensitive to pollution and present the early stages of ontogenesis of main commercial fish species (nawara, herring, Arctic flounder), concentrate in the surface layer. In the areas of Islands Dolgy, Matveev, Bolshoi and Mali Zelenets, the spawning grounds of Clypea harrangus pallasi n.gumoroi, Rabinergon and nawara are located. Young fish of these species fatten there as well in the shallow waters. Larvae of herring and nawara distribute at small depths in the coastal areas of the mentioned islands till the middle of August. Young fish of these species fatten there as well. The affect of larvae and young fish by fresh oil and their death are possible.

Oil spill spreading over the shore of the Dolgy Island can disturb dwelling conditions of Atlantic walrus included in the Red Book and rookeries in the southern part of the island.

Big concentrations of water-fowls including those from the Red Book are observed in summer-autumn on the Dolgy Island and nearest islands. Oil pollution of the sea will cause irrereplaceable losses in populations of Avesiformes.

In summer-autumn, the density of beluga, bearded seal and ringed seal in this area is small; single animals occur mainly. Therefore, one can assume that water pollution with oil will not damage mass concentrations of these animals.

Freezing period in the coastal zone of the Pechora Sea lasts 8-9 months a year. At accidental spill of oil on the ice in the area of the sea terminal, the oil can spread over the ice, under the ice and in the water.

A scheme of continuous currents of the south-eastern part of the Pec-
hora Sea in winter coincides in general with calculated schemes of currents in the surface layer in the iceless period. We can assume that oil spot, spilled under ice in the area of a terminal, will move under ice in the direction coinciding with that of the under-ice currents. Oil, spilled under ice, sticks in hollows of its low surface, then is sorpted by ice and distributes over a smaller square than on the sea surface free from ice. The oil accumulated by ice can appear in some time on the surface of the ice coverage under the influence of a mechanism of the vertical migration. In this case, ice is a platform for further oil degradation (Annon., 1988). Due to regime data in the surveyed area, ice drift predominates in the northern and north-eastern directions with mean velocity of 5-10 cm/s. In this case, the drifting ice can be considered as a mechanical factor of the sea self-cleaning (in areas of oil accumulation) and hydro-sphere pollution (in areas of melting).

In the case of emergency oil spill in winter, the pollution in the area of a terminal can damage mammals, ringed seal mainly, since animals stay constantly nearly the ice edge.

A measure of the pollution influence on marine environment and biota will depend on how urgently the oil spill will be removed.

REFERENCES


Baydaratskaya Bay ice cover and necessity of its accounting during marine hydrotechnical construction

Characteristic feature of coastal areas ice cover structure of freezing seas is obligatory presence on the ice both on drift and fast ice big hummocked formations. On the stationary ice these hummocked formations (stamukhas) affect the formation, stability and duration of fast ice, change the speed and direction of coastal currents, increase the fluctuation of surface wind, promote the redistribution of snow cover in the marine coastal part. Big number of stamukhas, rounding the fast ice boundary make difficult the delivery of cargo from supplying vessels into unequipped locations via fast ice. Stamukhas displacement during their generation and destruction causes the soil ploughing. These stamukhas properties define the necessity to account their importance during marine hydrotechnical construction. For instance, one of the main features of hydrotechnical supplying of works during oil and gas resources development on the freezing seas shelf is the elaboration of recommendations, accounting the influence of hummocked formations on the sea bottom.

On the drift ice the hummocked formations increase the volume and mass of ice floes, affect the drift speed and direction, i.e. increase the kinematic energy of drift ice.

The main task of ice investigations, carried out by SE AMIGE and other organizations in Baydaratskaya Bay from 1988 to 1993 was the receiving of field data on morphological and morphometrical characteristics of hummocked formations (stamukhas) in order to determine their penetration as well as dynamics and physical and mechanical properties both drift and fast ice.

Baydaratskaya Bay is situated on the south of Kara Sea and is fully located behind the Polar Circle (Fig.1). Depths in the coastal of the bay vary from 2 to 8 m and in the central part from 15 to 20 m, and on the north upto 25 m. Baydaratskaya Bay is covered by ice during considerable part of the year. The fast ice is predominated close to the coasts and the drifting ice - in the central part.

The icing in the bay begins in October, firstly in shallow parts and then it also extends on the more deep areas. Stable icing occurs at the end of October. By the middle of November the ice thickness reaches 10-15 cm and by the end of the month the gray-white ice, 15-30 thickness are already appeared. The ice grows approximately 7 months, from October to May. In May its thickness achieves maximum values of 170-200 cm, and sometimes more - upto 220 cm (SE AMIGE's observations).

In the Baydaratskaya Bay coastal shallow water areas the immovable ice cover (fast ice) is formed in November. Near the eastern coast the fast ice width achieves 20-22 km and coincides with isobath 18-20 m; near the western - 7-9 km and it passes near isobath 10-20 km. During offshore winds, behind the fast ice is formed the polynya, which can remain long time as zone of
free water or zone of young ice. Close to western coast of the bay the fast ice is often fractured and it is taken off into central part. In some years the stable fast ice is not observed here during all winter period. Near Yamal coast the fracturing of fast ice is occurred rarely only in period of formation.

Between fast ice in Baydaratskaya Bay are located drift ice floes, which sizes can achieve 25-30 km. Drift ice concentration is mainly 9-10 points. According to ice investigations in period from 1972 to 1985, the Baydaratskaya Bay was completely covered by immovable ice only once (in April). In 1989 the immovable ice is also formed on the whole square of the bay, but such situation has existed for a short period - 3-4 days. Then, the ice was fractured by storm winds and the part of it was taken off to north-west.

Ice cover destruction in Baydaratskaya Bay begins in May with appearance of puddles. Fast ice is fracturing under the influence of wind and sea level deviation after decreasing of ice thickness upto 100-120 cm. On the average it takes place at the end of June. Complete removal of the bay from ice is observed at the end of July. Duration of free ice period is 60-68 days, i.e. marine transport and investigating works in Baydaratskaya Bay can be carried out from the vessels without ice class only during 2-2.5 months but in some, most warm years, this period can last 90-100 days.

Ice floes drift investigations in Baydaratskaya Bay in winter 1988-1989 distinguished cyclonic circulation in the ice flow of Baydaratskiy massive (Fig.2). Maximum drift speed was 86 cm/s. Average daily drift speed at gentle wind close to western coast was 4-6 cm/s, close to eastern - 2-4 cm/s.

The removal of the bay from the ice may occur either due to ice melting on the site or its out flow from the bay under the wind and currents influence.

Because of irregularity of floes, wind and currents, influence of nearest coasts and differences in roughness of low and upper ice surface, the drift of individual ice has an irregular character. It results in intershearing and intercollising of ice. As a results we observe the change of ice cover concentration which promotes ice compression, fractures, deformation, as well as hummocking and rafting.

Deformation processes are mostly developed along the fast ice edge, where they are influenced by wind and currents. Jammed brash barrier - compacted sheet of ice cake and small ice cake, formed due to multiple hummocking and rafting, corresponds to deformed ice. In the coastal zone and close to fast ice edge, the thickness of jammed brash barrier can achieve 5-10 m and even the bottom.

It must be also noted, that in the coastal zone both eastern and western coast of Baydaratskaya Bay the annual ice piles on shore take place. The piles height varies from 1 to 3 m. During strong frosts the freezing of above ice together with soil is occurred. On melting and ice destruction some part of the frozen ice is taken out into the sea. In the future this fact can evoke the beginning of the shore abrasion.

Drift ice hummocking in Baydaratskaya Bay is 2-3 points on average (upto 60% of area is covered by hummocks). Hummock height reaches 3-4 m at average height 1.5-1.7 m. External barriers on fast ice edges have 8-10 m height, Levdiev and Litke islands. Hummocks underwater keels on drilling results reached 12-15 m and more. Fast ice hummocking varies from 0 to 5 points. On the fast ice some hummocks barriers are observed. On the western fast ice the first hummocks barrier corresponds to 2-3 m depth, the second to 5-7 m and the third to fast ice edge (Fig.3). On the eastern - the first hummock barrier corresponds to 1-2 m depth, the second to 5-
6 m, the third to 8-9 m (Fig.4). Hummocks ridges and barriers can make difficult the cargo offloading via fast ice and drilling from ice as well as the pipe-lines stacking.

During the hummocking on small depths and intense compression the foot (keel) of hummocks can reach the soil. Single hummocks and whole ridges, sitting on the shoul, are named "stamukhas".

In Baydaratskaya Bay the stamukhas formation lasts continuous time, beginning from November-December and finishing in March. In this case the autumn origin stamukhas are generated from gray-white first year thin ice (30-70 cm), and the winter origin stamukhas are generated in February-March at the depth 10-15 m from medium-first year ice (70-120 cm). Most definitely such dependence is observed near eastern coast of the bay. As a rule, the autumn origin stamukhas are firstly formed close to the shore on the under-water bars (2-3 m depth), then, when external boundary of the fast ice shifts to depth 5-6 m, the second period of stamukhas formation from fast ice 30-50 cm thickness and more is observed.

As a rule, the autumn stamukhas are destroyed more quickly, together with the fast ice destruction after the fracturing of fast ice and carrying out of ice to the central part of the bay, the stamukhas of winter origin continue to be retained for a while on the soil in the places of generation. Then, due to wave action and water warming the above-water part of stamukhas are destroyed. Stamukha becomes more light and in definite time it can begin to drift, transforming into "floe berg". Stamukha drift in this case can be accompanied by soil ploughing.

About 20 stamukhas have been studied in coastal part of Baydaratskaya Bay during their investigations in order to determine the morphometric and morphologicai properties. Drilling has been used during investigation of stamukhas internal structure and determination of their penetration into soil, and topographic survey has been used for study of geometrical characteristics. As a results of these investigations the following stamukhas characteristics have been received: sizes (width, length, height), basement square, volume of under-water and above-water parts, stamukhas mass, structure density (coefficient of filling) and also the depth of stamukhas exaration into soil. In Baydaratskaya Bay the biggest of observed stamukhas was the stamukha with the height of above-water part of 18 m (Fig.5). The basement square of the one of stamukhas was more than 23,000 m² and the mass of its above-water part about 50,000 tons at the coefficient of filling 0.72.

Analysis of all our materials according to stamukhas linear and areal characteristics in Baydaratskaya Bay shown, that more often in this area are occurred stamukhas, having the configuration of elongated ovals. The stamukha configuration is always determined according to proportion of basement axes sizes, measured on reciprocally perpendicular directions. This proportion, named by S.M. Lossev and U.A. Gorbunov (AANII) as "index of elongation", was changing for Baydaratskaya Bay stamukhas from 0.14 to 0.95 at average value of 0.53, i.e. the stamukhas configuration was changing from highly elongated to circle. Analysis of all stamukhas structure within investigated area shown, that the bigger stamukha square the more elongated oval is. So, the biggest stamukhas had the coefficient of elongation, equaled to 0.14; 0.22. Such dependence between stamukha basement square and index of its elongation for Baydaratskaya Bay, according to our calculations, is well approximated by expression:

\[ \xi = 1 - 0.00562 \sqrt{F}, \]

\( \xi \) - index of elongation,
\( F \) - stamukha square.

From this expression follows, that at \( F \to 0, \xi \to 1 \). It also follows that in Baydaratskaya Bay the maximum stamukha basement square is close to 30,000 m². It is clear, that such conclusions
may be approximate. For example, according to investigation data obtained by SakhNIPI in Sakhalin Bay maximum stamukhas basement square doesn't exceed 8,000 m².

Results of stamukhas drilling shown, that the penetration depth of stamulchas consolidated part into soil reaches 0.8-1.3 m. Diving inspection of bottom surface near stamukhas and depth measuring around them shown here the scores 0.5-0.7 m depth. The scores length varies from some meters to 10-20 m.

Investigation by RLS, carried out in 1988 directly in the zone of planned pipe line crossing, shown that in the limits of investigation area the negative forms were widely distributed. They present on the plane the lines of different length, width and direction. Above scores in the investigating area were differentiated on the depth from 8-10 m to 20 m (Fig.6).

Among these formations were distinguished the scores, relatively separated each from other, as well as score systems. The basis present on the plane the parallel lines system. In some cases the scores can loop, onlapping on themselves or on the nearest scores. In the other cases they are distinguishing as relatively uniform lines on the considerable distance. The width of separate scores reaches 10-15 m and the width of systems 40-60 m. Maximum scores depth is about 2 m, on average it deviates from 0.5 to 1.0 m.

We haven't yet the definite idea about the score formation genesis. Hypothesis, that given scores are produced by icebergs is improbable. So, according to materials of AANII, S.Petersburg, the icebergs appear on south-east of Kara Sea highly rarely.

It is early to assume the relict origin of these formations within the absence of data on composition of recent sediments, their thickness and absolute age in score of ploughing, as well as data about substrate composition, where these scores are ploughed. It is quite probable that these formations present the scores of ice ploughing, produced by stamukhas during their big keels draught during the ice floes drifting.

As a conclusion of above said it may be stated, that we have collected sufficiently much materials on Baydaratskaya Bay ice cover. However, some characteristics of ice condition have not interpreted yet sufficiently completely. Further engineering investigations, connected with pipe lines stacking, need to pay particular attention to study the stamukhas drift after fast ice destruction, to carry out the measurement of drift ice hummock under-water keels, as well as to carry out the investigation to determine the horizontal shearing of fast-ice.
The most prominent use for crude oil is in the production of liquid motor-fuels and heating fuels. A major investment has been made by society in automobiles, trucks, locomotives, and aircraft, which need liquid hydrocarbon fuels. Industry has discovered large reserves of natural gas in the Arctic. It has been difficult to use methane for transportation vehicles or as a feedstock for petrochemical production. This is due to the gaseous nature, and the chemical stability, of methane. Thus, economics of natural gas production and distribution have been limited and less profitable. Natural gas is transported by pipeline or LNG tanker ship, and the cost of both methods is higher than for oil. A plasma converter technology has been developed which converts natural gas directly into hydrocarbon liquids, which are usable as both petrochemical feedstocks and as fuels. The growth of the "newly-developing economies" of the world, especially in Asia, is creating a need for liquid fuels at modest prices. Supply of such fuels from natural gas, using the inexpensive plasma converter process, would contribute to economic growth. Plasma converters do not make use of catalysts, high temperatures or pressures. Rather, they use low pressure, any surface material, and locally-intense regions of high energy density associated with ionic impact. In a time interval of 1 picosecond, methane ions and neutrals are combined to form higher hydrocarbon molecules. This is a direct conversion of methane into higher hydrocarbons, using low-density plasma interactions with surfaces. The technology is not highly selective; many output product gases and liquids are produced, a kind of synthetic crude oil useful for hydrocarbon fuel applications. Recent estimates of the cost of production using this technology suggest that the product will be at the $12 to $19 per barrel level. Details of the technology are given in the report by Sackinger et al. (1993). The basic technology of the process is in the use of an array of many small tubes, which are co-parallel and provide a large surface area for interactions. A superimposed electric field, in the direction of the axes of the tubes, provides energy to the ions. When an ion strikes the inside wall of a tube, it locally excites the neutral molecules on the surface, and a variety of chemical conversions take place. In past experiments, over 1.3 million tubes were used, with each tube 12 micrometers in diameter. There is a statistical distribution of emission energies, emission angles, number of ions emitted, number of neutrals emitted, and the ratios of chemical species produced, in the impact events. The effect is the rapid chemical conversion of methane to higher hydrocarbons at the impact sites. The ion-driven processes at a surface have not been studied in detail for such a case, but it is believed at this time that the most probable ions are H+, CH3+, CH2+, and CH+. Once higher hydrocarbon neutrals are created, a wider variety of ions containing C-C bonds, C=C bonds, and C≡C bonds are possible. Conversion of methane into higher hydrocarbons was noted in every case when the electric field was above 4 volts/diameter (333 volts/millimeter). For case 1, operated at a pressure of 1.13 x 10⁻¹ kPa, an evolution of the mass spectra is displayed, indicating the progressive production of higher hydrocarbons, at least as high as C8. In these batch experiments, higher hydrocarbon production rose very rapidly initially, giving the impression that a continuous-flow conversion device would have an appreciable conversion in throughput times of fractions of seconds. Details of the 36 experiments are given in Sackinger et al. (1993). Conversion of methane into higher hydrocarbons, plus hydrogen, requires the addition of energy, due to the different chemical bonding of the products. This may be calculated in kilowatt-hours, for each kilogram of methane.

supplied. However, the hydrogen is made available and can be burned, yielding energy which can help supply the energy for the reaction. The burning of the hydrogen can provide more than enough energy for the reaction. The equipment cost is the most important, and can be estimated to be US$0.01 per kilowatt-hour. We can summarize these considerations by estimating that electrical power costs will be in the range of $10 to $40 per tonne of methane feedstock. Feedstock costs vary with the location, and are as low as $25 per tonne in the oilfield (or perhaps even less, and even negative if the gas is not marketable). Tankers or pipelines may be used to carry the synthetic product mix to downstream locations. It is a simple concept to convert the natural gas of any gas field, or the produced gas of any oil field, into \textsuperscript{C}_5 - \textsuperscript{C}_{10} molecules, with this kind of technology.

The application of this technology to the huge gas deposits of the North could include those in Alaska, Siberia, Canada, Greenland, and Svalbard. In the latter three areas, onshore and offshore gas could be produced at any arbitrary rate desired, could be continuously transformed into synthetic crude oil, and could be shipped by normal-draft tanker ships during summer and by ice-reinforced tankers in winter. Shallow-draft tankers can be used in Siberia, arriving whenever ice conditions permit. When on-site storage facilities for synthetic crude oil are full, gas production and conversion can be turned off with no damage to the reservoir. The shipment distance to Pacific Rim Asian markets is shorter than Arabian Gulf alternatives. Details of the economics of shipment will be discussed.

Introduction

In the beginning of 1992, the Finnish-Russian Offshore Technology Working Group initiated a research program to study the natural environment of the Pechora Sea. The objective is to acquire data on the physical environment and the ecological state of the sea area for the purpose of planning and implementing future oil and gas projects, offshore structures, vessels, infrastructure and transportation.

The ecological project aims at getting a good knowledge of the ecosystem of the Pechora Sea in its natural status. These baseline studies will be closely connected to environmental impact assessments and future monitoring programs. The ecological investigations have been carried out by the Finnish Institute of Marine Research (FIMR), Helsinki, Finland together with the Murmansk Marine Biological Institute (MMBI), Murmansk, Russia, during the period 1992-95. The separate research projects with a short description of the aim of that study and the materials and methods are described below.

Studies of pelagic plankton production, hydrography and water chemistry.

Phytoplankton production forms the basis for the marine ecosystem. The phytoplankton production is directly or indirectly affecting the fish, bird and mammal production in the sea area. The phytoplankton production is, however, also regulated by hydrographical and chemical conditions in the sea. The purpose of this baseline study is to estimate the phytoplankton production in the Pechora Sea and to measure the physical and chemical parameters affecting its production. A flow-through system with the ability of large scale mapping, was used to survey the spatial phytoplankton production in the sea area. This system also records surface temperature and salinity, which was used to detect the spatial distribution of temperature and salinity in the Pechora Sea. The results were complemented with satellite images.

The Pechora Sea is vertically highly stratified with varying hydrographic conditions affecting the plankton production. Vertical profiles of CTD measurements were therefore always done on fixed stations. The station net for these measurements were chosen with the intention of covering as much of the different parts of the Pechora Sea as possible. The most important parameters measured were, chlorophyll a, phytoplankton primary production, dissolved nutrients, phytoplankton and zooplankton species.

Quantitative macrozoobenthos studies

There are some widely accepted facts that have made zoobenthos studies suitable for monitoring purposes. The organisms are mostly sessile and must therefore tolerate the pollution or die. Benthic invertebrates are also usually long living and integrate effects of pollutants over time. The aim has been to build up a reliable background of quantitative data on the spatial distribution and structure of the zoobenthic communities in the Pechora Sea. In the future when oil production has started in the area, the possession of a reliable quantitative baseline, will prove to be a powerful tool in the monitoring of changes.

Quantitative zoobenthos samples were taken at 25 stations in 1992 and 38 stations in 1993. The station net for both years was planned to cover evenly the whole sea area. In 1992 the sampling sites were chosen based on a preliminary evaluation of the seismoacoustic and echosounding profiles from the same cruise. In 1993 the stations were chosen from a network of stations which have been earlier visited by Russian scientists. The distance between sampling sites was in general not more than 25
nautic miles. This distance is considered acceptable when trying to get a detailed picture of the spatial variations in the benthic communities.

**Biochemical composition of zoobenthos**

Bivalve molluscs are an important benthic group in arctic seas. Generally, they contribute up to 89% of the total benthic animal biomass. Moreover, they form a considerable proportion of the food source of a number of arctic predators, including demersal fish, sea stars and marine mammals. In this study, morphometric condition indices, levels of energy storage compounds (glycogen and lipid) and lipid class composition of eight bivalve species have been examined from populations collected from different areas in the Pechora Sea. The aim has been to yield information for comparative purposes in future monitoring programs, as barely any work of this kind has been accomplished in the Arctic sea areas.

**Petroleum hydrocarbons in sediments and bivalves**

The degree of oil contamination in the benthic environment of the Pechora Sea has been determined by analysing different petroleum hydrocarbon fractions, including both aliphatic and aromatic fractions, in bivalve molluscs and sediments from their living habitats. Aromatic and aliphatic components were separated with an HPLC system equipped with a silica column using an n-hexane eluent and analysed using a HP 5390 gas chromatograph (FID) with a SE-54 fused silica capillary column. Certified reference material from the National Research Council, Canada (NRC, HS-6) was used to check the repeatability and yield of the sediment extraction.

**Petroleum hydrocarbons in the water - the Komi oil disaster**

The aim of this general survey has been to get an overall picture of the oil pollution of the Pechora Sea. The degree of oil pollution in the water of the Pechora Sea was surveyed in 1993 using an ultraviolet fluorescence spectroscopy method, based on that adopted for the Global Ocean Station System project (IGOSS) which started worldwide oil monitoring in all sea areas already in 1975. The results have been compared with studies from other sea areas. The material was collected from 36 stations in the Pechora Sea in 1993 and has been reported in 1994. In 1994, about 60,000 tons of crude oil was spilled out near Usinsk in Komi. In the spring of 1995, after the break of the ices, it is assumed that the floods will transport considerable amounts of petroleum hydrocarbons via the Pechora River, first to the Pechora Bay and then diluted to the Pechora Sea. Within the frame of this project continuous monitoring of the PHC-concentrations with the flow-through system will be done in these areas for 2 weeks in June. The results will be compared with the baseline of 1993.
Submerged permafrost of Pechora and Kara seas, prospective in studies of frozen soils.

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Engineering-geological investigations in Arctic offshore have been carried out by SE "AMIGE" since the 1980's. One of the main object of the investigations is soil section to the depth of 150 meters. Soils with negative temperature have been found under seabed. These soils can contain water in solid phase, i.e. ice, as lenses, interbeds and cement. These phenomena are observed in central part of Kara sea and along of Yamal peninsula and in Pechora sea also.

Frozen soils were found under conditions of water depth from 15 to 115m on the depth of 10-30m under seabottom. The offshore investigations included boring with sampling, temperature sounding in-situ (CPT) and along core and multi-channel seismoacoustic profiling.

According to different evaluations [4] the continental shelf of the coastal part (to the depth 120-140m) has been found under water during Pleistocene transgression relatively recently, from 7-8 to 15-18 thousand years ago. Before this the area was developing rather long time in a subaerial arctic regime. Paleoclimatic reconstructions of the region [1] show that the thickness of permafrost formed in that time can reach up to 500 m. In accordance with estimation, in many cases (depending on the wide variety of factors) the time, passed from the last transgression is not enough for total melting of the submerged frozen massif. This way it is possible to expect wide occurrence of non-stable thawing zone almost everywhere on the region. "Quasi steady-state" thermoregime with storage of ice conclusions is possible to the depth of 50 m under bottom, at the seabed temperature of water T=1°C in central part of Kara sea.

2. Natural conditions necessary for the existence of submerged frozen soils.

The state of a non-lithified soil (frozen-thawed) is controlled by the freezing and melting temperatures of the pore liquid and thermal boundary conditions of the soil massif : the temperature of the sea water near the bottom (for subaqual-submerged state) and the amount of the deep heat flow.

However, as the conditions on the upper boundary of the layer are changing, quite often we have the non-stationary, transition state; changing history of them (last 10-20 thousand years) should be known to forecast recent conditions. Practically it means the necessity of knowledge of the last transgression time and the thickness of submerged frozen layer. The melting rate under given conditions is determined by ice-content of the soil.

2.1. Soil freezing and melting temperatures

The phase transition of free liquid takes place on the fixed temperature (Tc) and depends of its salinity, or actually on the amount of the total dissolved solids (TDS) only (on small pressure).

For the sea-water [3], freezing point is close to dependence: Tc=0.054 m, where Tc - in C-degrees, m - the TDS content, mineralization in promille. In the typical Pechora and southern part of Kara seas conditions the Tc is between -1.0 and -1.8°C.

In the soil (especially in the clayey soil) the freezing process begins at the Tc and is being continued in some temperature interval, so that the physical properties of soil change gradually with the temperature decrease as the pore volume is filled by ice, and finally when the ice-content reaches a characteristic value for the soil type, the soil transforms stepwise to be ice-bonded. Big ice inclusions (large lenses, stratified or oriented ice formations etc.) often are almost fresh (non-salted), that is the reason melting temperature goes to 0°C.

2.2. Near-bottom water temperature and the deep heat flow

The mean annual temperature of near-bottom water in Pechora sea is from roughly -1°C, near Novaya Zemlya upto +2°C on the SW sea part. In the western part of the Kara sea the mean annual sea water temperature is practically everywhere below zero, usually -1.0-1.5°C.

Heat flow data on the surrounding land are published [1,2] and according to this it varies from 0.038 W/m² on the Kola peninsula to 0.055 W/m² on down stream of Pechora-river.

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Temperature gradient in the upper 1 km section is evaluated from 28 degrees/km down stream of Pechora-river, up to 30-36 degrees/km on the Yamal peninsula.

2.3 Steady-state permafrost

The seabed temperature is negative over large areas of Barents and Kara seas. Layer thickness of negative temperature soils, i.e. steady-state permafrost, is determined by geothermal gradient value that in near-bed soils far exceeds the average because of the low heat conductivity.

The stable state of cooled soils in this zone is usually thawed for follow reasons:
- the freezing temperature of soil is equal or below the freezing temperature of the saline sea water;
- the temperature of the near-bed soils in steady-state is not below than mean-annual temperature of the near bottom sea water;
- pore liquid mineralization is not usually below than salinity of the near bottom sea water.

The thickness of this zone is not more 30-40 m.

On the other hand, sea bottom ice may be created at deep sea water temperature near to freezing point - the extent of this processes, however, unclear. We have known two cases of ice crystals formed in the shallow soils (collected by drop sampler) in central part of Barents sea at the depth of 220m and northern of Belj island at the water depth of 15m. It is clearly, that this generation of these has not stationary nature.

2.4 Unsteady-state permafrost

Stable condition of cold subsea soils is thawed at the water temperature below zero. Thickness of the zone is not more than 30-40m. More significant factor involved in occurrence of the wide spread permafrost below polar seas are the sea transgressions and regressions, which have taken place over last some ten thousands years. This causes, in subaenal conditions, the forming of frozen soil packets, which are submerged during next transgression.

So far as in many cases transgression rate was well above the thawing rate of frozen soils, this phenomenon has caused the forming of subaqual permafrost. In this case the estimation of degradation rate of frozen soils submerged under cool water is very important.

Evaluation calculations of the degradation of the frozen layer (one of the versions) are shown in Fig.1.

Fig 1: Evolution of subsea permafrost.
using the methods discussed in [5], which the initial thickness of 500 m, submerged by water 0°C, at the melting point of the soil -0.5°C, the heat flow of 0.05 W/m² and ice-content of 0.2. Despite the fact, that the model strongly highly roughen the natural process, it allows to evaluate the possible melting rate from the top and the bottom of the frozen layer, and the probability of the presence of permafrost at the given conditions.


Joint expedition to study of Pechora sea permafrost took place during autumn of 1993. Two boreholes were made on the Medynskaya structure (area) and near Matveev island to the depth of 104 and 101 meters, respectively. SE “AMIGE” and Technical Research centre of Finland (VTT) specialists executed the soil sampling and investigation on the vessel “Bavenit”. There were carried out the complex of laboratory researches of physical-mechanical properties and grain size determination of soils, as well as frozen ones, on the vessel and onshore laboratories including thermologging.

**Borehole 1 (Medynskaya).**

The soil section is presented by clayey-silty (loam) deposits with various texture (from massive to stratified) on the depth of 0-64m. Frozen soils were found on the depth of 36m. They had clear symptoms (signs) of frozen conditions: visible ice content and ice lenses, destruction of core at the temperature under zero, special shape of sandy soil samples - dense ice cemented core etc. The data about occurrence of ice contained soils were confirmed by changing of physical and chemical parameters: relative increase of moisture and high increase of resistivity; decrease of density, contents of ions and total salinity (water extraction results).

Water content and bulk density depend of state as well as composition and degree of deposit lithification. Moisture content (W) of frozen clayey-silt soils varies from 15 to 32%, bulk density (ρ) 2.0-2.2g/cm³; sands are characterized by W=22-33%, ρ=1.9-2.1g/cm³. Estimations of ice content based on the total moisture content and cement coil water content determinations showed that moisture values can reach 5-6%.

Strength properties of clayey soils can be over 1000 kPa at frozen state and put down a few times at thawed conditions. The temperature of frozen soils is about -1°C.

Boring to the depth of 101m and cone penetration testing (CPT) to the depth of 76m were executed in the hole 2, which is situated near to Matveev island. Complex of the offshore investigations showed that the soils aren’t frozen. Temperature tests were carried out in 15th points along of the hole. Minimum temperature was registered on the depths of 23-27m, and below this level the temperature increased with a gradient like normal geothermal one (30 deg/km).

4. Prospectives, methods of investigations.

Permafrost is special and problematic soils for building and foundation engineering. Clearly, this is one of important problem at the opening up of Arctic shelf and construct of oil and gas production platforms, pipelines and terminals there.

Main and, probably, the only reliable method of permafrost exploration is a strat observation and investigation of soils into a hole. The outstrip sampling by means of piston sampler “Shelby” like is the main way for the procedure. Using of rotary drill equipment with core barrel can melt soils and destroy natural state of those. This sampler can be used only on high ice contained deposits hard for the use of piston corer. Temperature in-situ tests should be executed with accuracy not worse than 0.1°C, transducer that have not heat influence of other sources, with respect of a small gradient value. The indicators of frozen soils can be absolute temperature values and significance of thermogradient (negative or near zero).

Physical-mechanical properties can be carried out either onboard or onshore laboratories, for the last case the storage of frozen soils at the natural temperature is very important, because refreezing and multi-time melting-freezing bring to destruction and changing actual properties. Probably, uniaxial compression test is optimal for strength parameters. It is enough simple, reliable and cheap.

CPT as one of the methods for strength parameters measurement may be use probably only on clayey, low ice contained soils.

Geophysical methods of subaqueous cryozone investigations are found to be difficult to apply for the next reasons:
- free gas extraction, that can accompany melting procedure, brings to a blocking of frozen soils impermeable for acoustic wave propagation,
- relict subaqueous frozen massif is melting, the part of liquid phase is significant in this case; resistivity of such frozen soils can not be differing much from the resistivity of thawed soils and interpretation of electrical sounding is problematic.

**Literature**

REFINED STORM WAVE MODEL

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In the usual wind wave mathematical model so called ideal wave generation conditions are used to calibrate, to test and to verify model. As a rule the most representative (from a author's model point of view) data of natural observation normalized by the wind speed at 10 meters level are used. One proposes that wind speed remains the same value along the fetch and the universality of normalized data remains valid for all wind speed value. In fact nonlinear effect of reverse influence of wave to wind is neglected. Without a proof the natural data given for mean wind speed value (7-15 m/s) are used for the case of strong wind speed (more than 20 m/sec).

In the present paper the misunderstanding of the approach is shown and new normalization of wave element by the friction velocity is offered. It gives the opportunity to take into account the nonlinear interaction between wind and wave.

The original spectral-parametric model based on the new normalization is presented in the article. It is shown that for the case of strong wind value the wave height becomes to be larger (received by the present model) than a value received by the model without friction velocity normalization.

The verification is carried out by using the model results and natural data received by special LOGIN expedition and the natural data given by the platforms at North, Greenland and Norwegian seas.

It is shown that our model allows to get more precise results for the wind wave computation in the strong storms.

1. Problem formulation

The energy balance equation we will used in the form of the WAM model [4]:

$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial \phi} (\psi \cos \phi S) + \frac{\partial}{\partial \theta} (\psi \cos \theta S) = G$$

where: $\phi$-latitude, $\theta$- longitude, t- time, S-angular -frequency, $\beta$- angle of wave propagation, G-source function.

The ray equation we will write in the following form:

$$\phi = \frac{C_s \sin \beta}{R}; \quad \theta = \frac{C_s \cos \beta}{R \cos \psi}; \quad \beta = -\frac{C_s}{R} \psi \cos \beta$$

where $C_s$-group speed, R-the earth radius

2. Spectral-parametric model

By applying the integral operator [1,2,3] to the equation (1) we derive the equation for spectrum parameters: zero momentum of spectrum $m$ and angle of wave propagation $\beta$: 
\[
\frac{\partial \phi}{\partial t} + \frac{1}{R} \frac{\partial}{\partial \phi} \left( CW \sin \beta \frac{\partial m}{\partial \phi} \right) + \frac{1}{R} \frac{\partial}{\partial \theta} \left( CW \cos \beta \frac{\partial m}{\partial \theta} \right) - \frac{G 18}{W m} = 0
\] (3)

\[
\frac{\partial \beta}{\partial t} + D \sin \beta \frac{\partial \beta}{\partial \phi} + D \cos \beta \frac{\partial \beta}{\partial \theta} = 5 \times 10^{-5} \left( \frac{\omega_m}{W g} \right)^{1.51} \times \omega_m \sin(\beta - \beta_w)
\] (4)

where, \( D = 0.45 g / \omega_m \), \( \omega_m \) - frequency maximum, \( W \) - friction speed.

The relation between the frequency maximum and zero momentum of spectrum is the following [5]

\[
\omega_m = 0.37(m_0) - 0.34
\] (5)

where

\[
C = \alpha \gamma \frac{\gamma - 1}{\gamma}
\]

\[
\alpha = 0.0075 \gamma^{2/3} \quad \gamma = 1.355
\]

\[
\alpha_1 = 0.000156
\]

\[
x_0 = \left( \frac{1}{\text{sech}(m_0/3450)^{0.5}} \right)^2
\]

To determine a dynamic speed the value of friction coefficient is used as

\[
\left( \frac{W_o}{W} \right)^2 = C_d
\] (7)

where \( C \) is defined by numerical solution of the equation [5]:

\[
\ln C_d + 0.267 / \sqrt{C_d} = 3.67 - 0.667 \ln m - 0.333 \ln W_{10}
\] (8)

where \( W \) - wind speed at 10 m level.

Spectral - parametric model includes three blocks: the parametric equations (5)-(8), a swell model and block of the interaction between wind sea and swell.

The swell model is based on the energy balance equation with zero source term. By substituting (2)-(4) into (1) we can write energy balance equation in the advective form:

\[
\frac{\partial S}{\partial t} + \frac{1}{R} \frac{\partial}{\partial \phi} \left( CW \sin \beta \frac{\partial S}{\partial \phi} \right) + \frac{1}{R} \frac{\partial}{\partial \theta} \left( CW \cos \beta \frac{\partial S}{\partial \theta} \right) = 0
\] (9)

The equation (9) is solved by utilization interpolation-ray method [6].

3. Some preliminary results.

At the begging the computation of wave elements for the case of ideal wave generation along the fetch was carried out by using the present model (SPMD) and the previous version
of spectral parametric LOGOIN [2,3] model (SPM). The previous version used wave elements normalization by wind value at 10 meters level.

The computation results of mean wave height along the fetch for different wind value are presented at table 1. The first line at table is fetch, second one - wave height for the SPM model, third one - wave height for SPMD model. As it can be seen from the table for the small wind value SPM wave heights are larger than its for SPMD model. On the other hand for the large wind value (more than 15 m/sec.) the reverse situation is presented. For the case of strong wind value the wave height becomes to be larger (received by the present model) than a value received by the model without friction velocity normalization.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Mean wave heights along the fetch X (km) for different wind speed U(m/sec) and for two models: h(m) - SPM model, hd(m) - SPDM model</th>
</tr>
</thead>
<tbody>
<tr>
<td>U=5m/sec</td>
<td>X 10 20 30 40 50 60 70 80 90 100 110 120</td>
</tr>
<tr>
<td></td>
<td>h 0.2 0.2 0.3 0.3 0.3 0.3 0.4 0.4 0.4 0.4 0.4 0.4</td>
</tr>
<tr>
<td></td>
<td>hd 0.1 0.2 0.2 0.2 0.2 0.2 0.3 0.3 0.3 0.3 0.3 0.3</td>
</tr>
<tr>
<td>U=10m/sec</td>
<td>X 50 100 150 200 250 300 350 400 450 500 550 600</td>
</tr>
<tr>
<td></td>
<td>h 0.6 0.9 1.0 1.2 1.3 1.4 1.5 1.6 1.6 1.6 1.6 1.6</td>
</tr>
<tr>
<td></td>
<td>hd 0.6 0.8 1.0 1.1 1.2 1.3 1.3 1.4 1.4 1.4 1.5 1.5</td>
</tr>
<tr>
<td>U=15m/sec</td>
<td>X 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500</td>
</tr>
<tr>
<td></td>
<td>h 1.4 1.9 2.2 2.5 2.8 3.0 3.2 3.4 3.6 3.5 3.5 3.5 3.5 3.5 3.5</td>
</tr>
<tr>
<td></td>
<td>hd 1.5 2.0 2.4 2.7 2.9 3.1 3.3 3.4 3.5 3.6 3.7 3.8 3.8 3.9 3.9</td>
</tr>
<tr>
<td>U=20m/sec</td>
<td>X 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500</td>
</tr>
<tr>
<td></td>
<td>h 1.9 2.6 3.2 3.6 4.0 4.3 4.6 4.9 5.1 5.4 5.6 5.8 6.0 6.2 6.3</td>
</tr>
<tr>
<td></td>
<td>hd 2.3 2.8 4.3 4.7 5.0 5.3 5.6 5.8 6.1 6.3 6.5 6.6 6.9 6.9</td>
</tr>
<tr>
<td>U=30m/sec</td>
<td>X 200 400 600 800 1000 1200 1400 1600 1800 2000 2400 2800 3200 3600 4000</td>
</tr>
<tr>
<td></td>
<td>h 4.1 5.7 6.8 7.7 8.5 9.2 9.8 10.4 11.0 11.5 12.4 13.3 14.0 14.2 14.2</td>
</tr>
<tr>
<td></td>
<td>hd 6.0 8.1 9.7 11.0 12.0 13.0 13.8 14.5 15.2 15.8 16.8 17.7 18.5 19.1 19.5</td>
</tr>
</tbody>
</table>

The model verification was carried out by using natural data received from the platforms at North, Greenland and Norwegian seas. The input pressure field for the wave model computation was used from ECMWF (GRID data). The verification was carried out twice a week for ten months for the period from July to April 1995. The example of such computation you can see at fig.1.
The number of simultaneously measured wave heights was near twenty five (from twenty to thirty). By using linear interpolation from the four nearest grid points to the point of real data measurements the accuracy of our computation was carried out. The picture presents the value of accuracy of our computations in relation to forecast period. The results shows that new version of our model reduced the computation error at 10% - 20%.

Conclusion

New version of spectral-parametric model is presented in the article. The model uses normalization by the friction velocity which approximation was offered by prof. Davidan. The verification of the model is carried out by using the model results and natural wave data received at the platforms at North, Greenland and Norwegian seas. The model utilization allows to reduce the error wave height hindcast and forecast at 10 - 20%.

It is shown that our model allows to get more precise results for the wind wave computation in the strong storms.

REFERENCES

The study of the Arctic environment always have been of high priority in connection with the tasks of navigation, industrial development, protection of biological resources. These works were carried out in the Russian sector of the Western Arctic for a long time. Some of the Russian institutions working in this region have been collecting data for more than sixty years. Nevertheless, the character and strategy of arctic activity underwent significant changes during last years. New scientific and practical requirements to the information supply stipulate the necessity of world standard oceanographic technology.

Barents sea is more exposed to the environmental impacts than any other part of the Arctic ocean. It is the traditional area of fishery and sea transport. Recent discoveries of oil and gas deposits on the Barents sea shelf started the new industrial activity which may become comparable with the same in the North and Norwegian seas. The radioactive pollution of this region caused by the military and industrial nuclear wastes is also the essential environmental problem.

The marine surveillance system for the southern part of the Barents sea was proposed by OCEANOR and designed as joint Norwegian-Russian project Seawatch - Barents sea. Its main
features are the following (fig.1):

- a sensor carrier which is an oceanographic buoy TOBIS moored with suitable mooring and equipped with sensors for measuring marine environmental parameters, data logging equipment and with onboard micro processors for data analysis control;

- a real time data transmission system and a land-based data control and analysis system including the necessary software (numerical simulation models, GIS and other means of data presentation);

- a user oriented menu driven information system tailored to the needs of identified user groups.

The set of parameters measured includes meteorological elements (wind speed and direction, air temperature and air pressure), wave height, current speed and direction, oxygen, phosphate (or nitrate), radioactivity, algae concentration (all these characteristics at 3m depth) and temperature/salinity profiles down to 50 m. Sensors for heavy metals, hydrocarbons and pH are developed also. The number of buoys required for the southern part of the Barents Sea is estimated from 6 (minimum) to 12 (optimum). The ARGOS satellite system is used for the data transmission in the real time scale. The data storage, analysis and presentation are performed by ORKAN software package developed by OCEANOR.

The implementation of the SEAWATCH project was supported by marine institutions and authorities of the Murmansk district: Arctic Marine Geological Expedition, Murmansk Marine Biological Institute, Polar Institute of Marine Fish Industry and Oceanography, Hydrometeorological Service, Arctic and Antarctic
Research Institute (Murmansk Branch) and Committee of Ecology. These participants and OCEANOR made the agreement in 1992 to organise Arcticmor Seawatch Group, which will coordinate the creation of the monitoring and the forecasting system.

During the following two years the SEAWATCH project was realised only partially. One buoy is exploited continuously in the observation point situated in the Stockman gas-condensate deposit area (73° N, 43° 50′ E). Two buoys, which provided time-series of several months, were situated respectively northward from Kanin and Waranger peninsulas. The data obtained as the result of these measurements may be valuable for environmental assessments and tracing of present and future anthropogenic impacts.

However, the main aim of the project is not achieved yet. The information system of the monitoring practically is absent. The most likely explanation is that the specialists and managers know too little about the project and its possibilities. The weakness of the communication infrastructure of the potential users also must be taken into account.

The further promotion of the SEAWATCH project will depend on the creation of diversified information service. The main ways of data presentation and transformation are briefly discussed below.

1. Direct data transmission to the users is the most obvious application and very important for the hydrometeorological service. The buoy data may cover remote sea areas rarely visited by ships. The presence of stationary observation points is useful not only as additional source of meteorological and sea
surface data, but also as the means for independent checking of sea forecasts. Updated information on the chemical and radioactive pollution, nutrients and phytoplankton content forms the valuable contribution to the ecological monitoring system of the Barents-region. The buoy observations may ensure the detection and tracing of pollutants immediately after their appearance in the corresponding area.

2. The probability estimations of the extremes fixed during the observations may be obtained using the available data on the climatological distributions of the hydrometeorological and chemical characteristics. At present the sea climatology is based almost totally on the shipborn observations, which are very inhomogeneous in time and space. Many important characteristics, e.g. wind and wave statistics, are calculated by indirect methods and need the verification. The estimations of wave height of rare occurrence are especially sensitive to the choice of distribution law and to the precision of determining of average values. Continuous time-series of wind and wave measurements are the indispensable source of the data required for the planning of installation and exploitation of stationary platforms (seasonal variations of the probability of the storms, duration of stormy or calm periods). The analysis of long time series, especially in comparison with the similar data of coastal hydrometeorological stations, aids to detect the natural and anthropogenic trends of the sea environment in proper time.

3. The forecasting of the sea state using the statistical methods and numerical models is the most prospective part of
marine hydrometeorological and environmental service. The technology developed by OCEANOR includes modelling of currents and storm surges (HYBOS), calculating drift, spread and seabed deposit of platform discharges (NOMAD), oil drift statistics and forecasting (DRIFTMAP, DOOSIM). This software package may be effectively supplemented by calculation and forecasting methods worked out in the marine institutions of Murmansk. Two of them were successfully tested and exploited in the Murmansk Hydrometeorological service: the numerical model of ice drift and ice-edge displacements, based on the method known as "particles in the cells", and method of wave parameters calculation and prediction based on the solution of energy balance equation for the components of two-dimensional spectrum. Previous versions of these methods were realised on the Soviet computers incompatible with IBM PC, but now this restriction is overcome.

There are some practical tasks which require not only the forecasting but also the retrospective analysis of the atmosphere and sea dynamics, e.g. detecting of the sources of radionuclide or chemical pollution. The buoy data permit to make necessary calculations, using time series for the corresponding period, or to verify the trajectories of water masses calculated with the use of synoptic charts.

Though the SEAWATCH system is self-sufficient regarding its main tasks, the needs of potential users will be satisfied better if the information system will be enriched by some additional kinds of information. The diversity of diagnostic and forecasted meteorological fields distributed by international
centres is essential for improving the methods of calculation and modelling. Remote sensing data showing the situation of ice-edge are important as the source of boundary conditions data for the numerical models of waves and currents. The monitoring system will be more effective, if supplemented by the observations of coastal hydrometeorological stations.

SEAWATCH project must be also considered in the wider context of such international programs as Arctic Monitoring and Assessment Program (AMAP), Global Ocean Observing System (GOOS), Global Resources Information Database (GRID) et al. Almost all of them depend on the observation data received from somewhere else and are focused on the coordination of the activity performed on the national level. On the contrary, SEAWATCH project is based on its own sources of information and so deserves more significant support from the central and local authorities. Taking into account the current economical situation in Russia, the most difficult stage of the project is to create and to trigger the information network, because for the present even the most interested users of environmental data are not ready to integrate themselves into the monitoring system.
The OCEANOR marine environmental, monitoring, forecasting and information systems

DATA ACQUISITION, PROCESSING AND CONTROL

OCEANOGRAPHIC BUOYS

SENSORS FOR:
- METEOROLOGY
- WAVES
- CURRENT
- TEMPERATURE
- SALINITY
- OXYGEN
- ALGAE
- NUTRIENTS
- BIONSENSORS
- RADIOACTIVITY (BEING DEVELOPED: HEAVY METALS, HYDROCARBONS, pH)

REAL TIME DATA TRANSMISSION

SATELLITE

READDOWN STATION

INFORMATION DISTRIBUTION

OTHER DATA SOURCES

PROCESSING CENTRAL

DATA CONTROL, ANALYSIS AND STORAGE
- HYDROGRAPHIC
- MODELLING
- FORECASTING

USERS
- PUBLIC AUTHORITIES
- AQUACULTURE/FISHERIES
- COMMERCIAL FISHING
- TOURIST INDUSTRY
- RESEARCH INSTITUTES
- NAVY COASTGUARD
- OFFSHORE INDUSTRY
- GRID
- OTHERS

Fig. 1 SEAWATCH System

OCEANOR
AN EXPERIENCE OF ECOLOGICAL IMPACT ASSESSMENT (EIA) OF LARGE-SCALE OFFSHORE OIL AND GAS PRODUCTION BASED ON THE STOCKMAN PROJECT

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Russian Academy of Science

Exploration of large deposits of hydrocarbon raw material in the Arctic region is a part of the state's strategy of economics development in Russia. There is a serious basis to suppose that at the beginning of the XXI century the centre of oil-gas exploitation will be shifted to these regions. Besides it is clearly seen that productive exploration of the shelf areas give specialists quite different as for their seriousness problems than earlier. It is especially important for the ecology as a well-known vulnerability of nature in the Arctic is known all over the world. Much has been said and written about Stockman gas-condensate deposit during last two years. And this is explainable as this deposit is unique as for its reserves. Perspectives of its explorations and exploitations are connected with the whole Murmansk region development.

It is natural that the questions of ecological security should be part and parcel of the Stockman project.

Stockman gas-condensate deposit is situated in the central part 290 km to the west of the Novaya Zemlya archipelago and 650 km away from Murmansk, depth in the area of drilling wells is 280-320 m. The deposit is unique as for its reserves - 3 trln cubic meters of gas and 22,5 mln t of gas-condensate.

To make it real it is necessary to develop a unique complex of equipment of very high complexity, as far as only 2 stationary deep-water platforms on the depths exceeding 300 meters are built but no one in the ice conditions now.

Gas transportation is supposed to carry out by under-water pipe-line. Stockman field Murman coast is chosen as the main, its length is 535 km. Further on the land the pipe-line will be laid along the route Murmansk Belomorsk-Petrozavodsk-Volkhov with an outlet to Vyborg (1838 km), (fig.1).

The area of exploitation and underwater transportation is characterized by severe natural climatic conditions: winds up
to 35 m/sec, negative air temperature from November to May (-2-4 °C), waves heights up to 19 m and 24,4 m, high probability of floating ice in the deposit area (to 166 days of extremely cold years, for instance in 1979). And what is more dangerous—icebergs with several hundred meters parameters by all dimensions and a large counted volume—500000 cubic meters.

Area of Stockman gas-condensate deposit and routes of the pipe-line are characterized by extremely uneven bottom relief depths overall, the largest one is Central Cavity.

Thus, construction and exploitation safety of the establishments and constructions is the determining factor of ecological security of the Stockman project.

Estimation procedure demands the answer to all the questions concerning environment impact. But it is necessary not only to study it well and to estimate its present state and to forecast what changes will take place in nature during implementation of the project.

Quite natural every specialist and even a very curious person should have his own opinion on the realization of the project, besides the very thought of the projects like this causes sometimes instinctive feelings of danger. Stockman project by all its range and dimensions helps to formulate a special public opinion, and to be more precise a very worried attitude to its ecological safety.

Thus, ecologists working at this problem had to prepare answers to all questions, which trouble people living in the Barents region.

A very important stage of EIA is the estimation of background (modern) state of environment including anthropogenic loads. The latter is necessary as a starting point in the estimation of ecological reserves of marine objects and its potential capability to further loads without ecosystem stability losses. Results of background environment descriptions in this presentation are not discussed in detail. We should mention only two important conclusions, necessary for further discussions: - modern level of chemical contamination in the open part of the Barents sea, including the area of Stockman gas condensate deposit, is low, that is in the frames of backgrounds standards.
Concerning oil hydrocarbons it does not exceed 0.04 mg/l, concerning other pollutants the situation is analogous, as the influence of economic activity in the open sea is not great; in the area of Stockman gas condensate deposit massive reserves of bioresources are absent, important ways of migration do not cross this area. Thus, peculiarities of geographical situation and modern ecological status of the region of potential influence turned out to be favourable from the point of view of possible ecological loss from the Stockman gas condensate deposit, first of all from the exploitation complex.

It is quite natural that arrangement and exploitation of the Stockman gas condensate deposit should have some negative influence on the Barents sea environment. The question is like this: will these influences be critical for marine ecosystems and fishery as a whole separately or together with existing. Our conclusion is quite simple: consequences forecast are in general supposed to be local. There are several points for it. First—remote ness, vast depths, non-coincidence of more important bioproductive zones and the area of fishing, low level of the open areas contamination—all these factors weaken possible negative consequences. Second—that is more important: type the raw material being exploited: at the Stockman gas condensate deposit not oil but gas with small content of condensate will be exploited; it will be methane without sulphur. This product is ecologically much safer than oil. Foreign experience that is Norway, USA testifies to the fact that accidental gas discharges do not produce serious negative influence on the environment and marine biota.

Even at the gas exploitation in the project technological operations lowering ecological risks are supposed. Refusal from the pipe-lines transportation to the coast is taken into consideration. In other words dry gas will be transported by pipe-lines from the platforms to the coast. In this case leakage, bursts and other accidental situations will take place without toxic hydrocarbons spills, that is locally and they will be short-term. This case (if it will take place) will not practically create the picture of a typical and a well-known situation of oil contamination, when birds, animals and fishes die, the
coast suffer from it—with all possible consequences.

Gas condensate will be separated from the exploited mixture at the platform and load into tankers and transported to the places of destination. Accidents are possible when condensate will enter the sea. Our specialists have carried out voluminous computer accounts of these spills behaviour depending on all situations possible. Duration of spill drifting, its evolution, length, changeability of stormy winds, currents, strength and many other factors are estimated.

As a result of probabilitiy calculations it turned out that gas condensate spilled in the area of a platform (maximal accumulated volume is 40000t) by no way can reach the Coast of Novaya Zemlya and Murman coast. It is a conclusion as this factor plays the main role. It may be said that if the area of exploitation were in the other place, the results would be have been worse for all of us.

It should be remembered that in Russia there exists a very strict law concerning nature protection which prohibits to discard drilling wastes, worked out drilling solutions, plastics, slams to the sea. More strict standards are being introduced abroad, in Russia they are already valid. For instance during investigation of the Sakhalin shelf deposits exploration of which is planned by the International consortium special attention has been paid to this factor.

Serious work is carried out to provide safety of construction establishments, development of the automatical system of control and blocking of ecologically dangerous situations. High potential of the Russian converting enterprises taking part in the feasibility study and foreign experience are directed to it. Foreign experience from the point of view of ecology is useful. We studied attentively series of generalizing materials—for instance, presentation of the independent group of foreign experts GESAMP (according to the order of UNESCO and others). These experts analyzed ecological consequences of marine oil-gas activity in different parts of the World Ocean that is in (Mexican gulf, North sea, Alaska shelf) and came to the following conclusions: This activity is noticeable but it yields to fishery, damping of the wastes contaminations, drainages from
the continent and atmosphere transfer.

As a result marine biota changes; mainly bottom populations are observed near platforms at the distance of 3-5 km, higher concentrations of hydrocarbons are as far as 8-12 km. Total area of the sea bottom under the influence is very small in comparison to the area of trawling at the bottom fish catching. The North sea may be considered an example of "coexisting of 2 main activities—fishery and oil-gas exploitation.

The second closer example is Norway. This state may be considered as one of the most advanced countries in the sphere. But besides, Norway is very serious to the questions of nature protection. Planned to the exploitation shelves deposits there are investigated as for their influence on the environment. Regions to the south-west of the Barents sea were examined in 1985-1989, and after additional introduction of several limitations this area was allowed to be exploited.

Thus, the problem is not can or cannot this shelf be exploited as it is rich in fish resources and trapping, the question is how to do it.

The problem of harmony between fishery and oil-gas exploitation is the most important in our region. To estimate strictly possible damages to fishery due to Stockman gas deposit exploitation is not easy. In the expertize much attention is paid to this problem.

Estimations of losses due to the loss to the fishery of some areas through which pipe-line will be laid are much clearer. Less evident are hypothetical losses owing to the accidents but there are variants. For instance, gas-condensate spills and methanol spills are not the same as methanol is more toxic. Much depends on the location of the possible accident, thus, we calculated safety distances of tankers routes. That is how far from the coast tankers could sail without a risk of reaching the liquid product while spilled of coastal zones.

But taking all available factors into considerations possible losses to the Barents sea fishery were estimated. It is supposed to be 1 per cent of yearly catch. As natural fluctuations and fishery intensity probably by an order as high, it is completely agreed with the general conclusion on low influence.
of gas exploitation on the ecology of the Barents sea.

This conclusion will be justified under strict following terms: avoidance of discharges into water toxical products, keeping to ecologically strict optimal time-table of carrying out construction work. This optimisation in the EIA of the Stockman gas condensate deposit was carried out considering seasonal cycles of animals and plants development as well as geographical peculiarities of pipe-line routes; providing construction safety with effective control systems security of all operations in the production cycle. The main aspect here is to prevent consequences of two main accidents: gas fountain and underwater pipe-line destruction; creation of protected zones to protect and save rare and disappearing marine mammals, bird species especially at the places of breeding and living.

One principal part of the work is the most important—that is biological monitoring. As there exists many unknown problems and the consequences of some of them especially long-term processes are difficult to forecast in the process of estimation of Stockman project, outstripping development of the monitoring system is regarded as an obligatory term of the project realization—from the building to liquidation of the deposit after 20-25 years of exploitation.

In the monitoring itself the main role must be played by hydrobiologists: only control of mussels, echinoderms and other bottom species populations state may give information on the anthropogenic influence. This is carried out all over the world the same must be done at the basin. Other types of observations are also important, in our case they are of secondary importance.

A reasonable question arises: do we know much enough on the hydrocarbonical contamination of marine biota and its consequences for marine environment in connection with shelf exploration. In general the answer must be negative and very cautious. Specialists point out several problems without a simple answer in the ecological grounds: these are: not always correct account of the spill dimensions of oil spill in the models. There are data of natural observations giving bigger estimates—to tens times; duration of oil hydrocarbons existence in na-
tural conditions. It is lowered very often; instead of several days, oil products stay in water without evaporation completely during weeks and months. The reason is slowing down of the processes of dissolution in water column, especially at low temperature; toxicity of oil products and sublethal effects. Many scientists criticize laboratory tests available for the survival used in exotoxicology. It is considered that wrong animal species are frequently used, besides population structure in reality and its systematic reaction to the contamination are not considered; effects of chronic contamination. In modern works more attention is paid to estimation of consequences from accidental spills, than to long-term exotoxicological effects. On the one hand locality of these effects is confirmed by long control in the places and on the other- what can happen with the affected ecosystem owing to the chronic intoxication, when point of return is overcome and the last cumulative effects of oil-gas exploitation on the the ecosystem level- we mean species substitution, population decrease.

All these problems are actively discussed in literature. Their listing must not refuse all that said about potentially weak negative influence of gas condensate deposit on the marine ecosystem in the Barents sea in the Stockman deposit project but should be a warning as in the Barents sea and the Kara sea tens of oil-gas deposits are discovered. Sooner or later they will be exploited, total influence on the environment will be increased. We should be ready for this to preserve the Barents sea with all biological life diversity.

Scientists on the international basis must continue steadily work not to face quite unexpectedly with problems of mutual trouble.
Evaluating J-Integrals For Ice-Substrate Interface Cracks Using Finite Element Analysis

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Abstract

Characterizing the ice-substrate interface as a bimaterial interface allows the behavior of cracks at the interface to be described using the interfacial energy release rate, $G_{\text{int}}$. The J-integral, used for characterizing energy release rates in homogeneous materials, is shown to be useful for characterizing interfacial energy release rates. Evaluating the J-integrals using finite element analysis, this analysis demonstrates that J-integrals are valid across a bimaterial interface and that basic properties of the J-integral hold for bimaterial interface. This paper demonstrates that the methods used in Whelan & Nixon (OMAE '95) are valid. Further, the use of standard SIF calibrations is investigated for the case of a bimaterial interface.

Introduction

Each winter in the northern hemisphere, land, sea, and air transportation vehicles and facilities may experience severe winter weather. This weather may include snow and freezing rain, either of which may give rise to a layer of ice or compacted snow which adheres strongly to the vehicle/structure. Clearing away this ice and snow is a high priority, since its presence may create safety problems. Ideally, a method could be developed to break the bond between the ice and the vehicle/structure, so that the ice could be "lifted" away in large sheets. However, the reality of current ice removal methods is that ice and compacted snow must first be pulverized and then swept or plowed off the vehicle/structure. Pulverizing the ice is clearly a much more energy intensive process than simply lifting a sheet of ice, because pulverization involves the creation of...
much larger fracture surface area. There is thus considerable incentive to investigate how the ice-substrate adhesive bond might be weakened considerably or broken.

A variety of techniques have been suggested for weakening the ice-substrate adhesive bond. These include anti-icing, in which chemicals are applied to the substrate just prior to the onset of precipitation, and other methods in which applied energy is focused on the ice-substrate interface (e.g. microwaves have been suggested as a source of such energy). A drawback for all these methods is that at present there is no reliable, consistent, and accurate way to measure the strength of the ice-substrate bond. If this adhesive strength cannot be measured, then the effectiveness of a given treatment cannot be evaluated in any meaningful way. The aim of this study is to continue the development of a method whereby the ice-substrate bond strength can be measured with accuracy, repeatability, and reliability.

In order to measure the efficacy of competing anti-icing surface treatments, an objective test is required, possibly based on a measure of the ice-substrate interfacial energy release rate. Assuming that one can induce a crack to grow along the interface between the sheet of ice and the substrate, one has to be able to relate the peak load at the onset of crack propagation to the interfacial energy release rate. The Eshelby-Rice J-integral [1,2] is quite popular for calibrating specimens which have a single homogeneous material, but when a two materials with differing stiffness are joined at an interface, the direct applicability of the J-integral is not so obvious.

The purpose of this paper is to demonstrate the applicability of the two-dimensional Eshelby-Rice J-integral for a bimaterial interface using the Parks[4] finite element evaluation technique, and to demonstrate that the two-dimensional Eshelby-Rice J-integral for a bimaterial interface can be used to investigate the interface in an ice-substrate system.

Single Material J-Integral

The J-integral is useful in the study of fracture mechanics because it can be used to calculate the change in total energy in a cracked body as the crack grows or the amount of energy required to
make that crack grow. Named by Rice[2] originally in a two-dimensional plane strain form, it paralleled work by Eshelby[1] on the three-dimensional energy-momentum tensor. It is especially useful in the study of cracks that may involve a "process zone", an area ahead of the crack that may not behave the same as the bulk of the material, since it allows the process zone to be treated as a black box.

Consider a linear elastic isotropic homogeneous body, \( \Pi \), Fig 1a (which is not a bimaterial body.) Let \( \Psi \) be an at least \( C^0 \) smooth contour in \( \Pi \) with an outward normal \( n \). Let \( T_i = \sigma_i n_i \) be the surface traction at a point on \( \Psi \). Since \( \Pi \) is homogeneous, the constitutive equations ensure that \( W_n \) and \( T_i u_i \) are integrable over all of \( \Pi \). The J-integral can then be expressed as (\( k = 1, 2, 3 \)) [5]:

\[
J_k = \int_{\Psi} (W_n - T_i u_i) \, ds
\]

(1)

When \( \Psi \) is a closed contour that encloses no singularities, \( J = 0 \) [5,6]. The J-integral is path independent [6], and when any \( \Psi \) encircles a crack, as in Fig. 1b, any two J-integrals are equivalent and non-zero [7].
Bimaterial Integral

A bimaterial interface consists of two bodies, \( ^1\Pi \) and \( ^2\Pi \), with possibly different \( G \) (shear moduli) and \( \nu \) (Poisson's ratios), which are joined along the \( x_1 - x_2 \) plane. For the purposes of this analysis, it can be assumed that \( ^1\Pi \) occupies the positive half-space and \( ^2\Pi \) occupies the negative half-space.

Consider two linear elastic isotropic homogeneous bodies, \( ^1\Pi \) and \( ^2\Pi \), joined along the \( x_1 - x_2 \) plane, Fig. 2a, where it can be assumed that the portion of the interface under consideration does not contain a singularity. Let \( ^1W \) and \( ^2W \) denote the strain energy of points in \( ^1\Pi \) and \( ^2\Pi \), respectively. Let \( u \) be the displacement of a point in either \( ^1\Pi \) or \( ^2\Pi \). Let \( \Psi = \Psi_1 + \Psi_2 \) be a smooth contour that crosses the interface, where \( \Psi_1 \) lies entirely within \( ^1\Pi \) and \( \Psi_2 \) lies entirely within \( ^2\Pi \). Let \( T_1 = \sigma_n \) and \( T_2 = \sigma_n \) be the surface traction at a point on \( \Psi_1 \) and \( \Psi_2 \), respectively.

![Figure 2. Two Linear Elastic Isotropic Homogeneous Bodies, \( \Psi_1 \) and \( \Psi_2 \).](image)

- a) With A Closed Smooth Contour \( \Psi \)
- b) With A Crack Approaching From The Left.
Smelser and Gurtin [3] presented a proof that for the plane strain case, the $J_1$-integral can be written as follows:

$$J_1^\gamma = J_1^\gamma_1 + J_1^\gamma_2 = \int_{\psi_1} (W n_{1-1} T \mu_{1,1}) \, ds + \int_{\psi_2} (W n_{1-2} T \mu_{1,1}) \, ds$$

(2)

The limitations that Smelser and Gurtin imposed on this $J_1$-integral were that the interface must be straight, and that the interface runs in the $x_1$ direction, Fig 2b. These conditions being satisfied, the $J_1$-integral should be path independent and zero when the contour does not enclose a singularity.

Given the above results, the $J_1$-integral given by (2) can be used to calculate the $J_1$-integral across a bimaterial interface.

**Potential Energy form of the $J_1$-integral**

G’oce [2] demonstrated that the $J_1$-integral can be evaluated using the change in potential energy for a change in crack length.

$$J_1 = -\frac{\partial P}{\partial a}$$

(3)

where $P$ is the potential energy, and $a$ is the crack length of a crack growing in the $x_1 - x_3$ plane.

This idea can be extended to a bimaterial interface in the following manner. For the two linear elastic isotropic homogeneous bodies, $^1\Pi$ and $^2\Pi$, jointed along the $x_1 - x_3$ plane:

$$J_1 = -\frac{\partial (1P)}{\partial a} - \frac{\partial (2P)}{\partial a} = -\frac{\partial (P+2P)}{\partial a}$$

(4)

This allows one to evaluate the $J_1$-integral for a bimaterial interface using the potential energy formulation. Since potential energy can be easily calculated using finite element analysis, this then leads to a means of calculating the $J_1$-integral for a bimaterial interface for a general geometry.
Numerical Analysis

The usefulness of describing the $J_1$-integral by calculating the rate of decrease of potential energy with respect to crack length was demonstrated by Parks [4] and Matos et al [8]. Using the technique of Parks, we have developed a simulation code, the basics of which are described in Whelan & Nixon [9], to calculate the $J_1$-integral in a pair of linear elastic homogeneous bodies.

Using the method described in [9], analyses were performed on cracked and uncracked coupons in uniaxial tension, Fig. 3. The coupons were 12 cm wide, 36 cm long, with 1 m thickness. The coupons had material properties of ice/ice, ice/aluminum, ice/Portland cement concrete (PCC), ice/asphaltic concrete (AC), and ice/polymethyl methacrylate (PMMA), Table 1.

Figure 3. Coupons with bimaterial interfaces: a) uncracked and b) cracked

In this analysis, $W = 12$ cm, $L = 18$ cm, $t = 1$ m, and $F = 100$ N.
Table 1. Material Properties of Substrates Used In Finite Element Models

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus</th>
<th>Poisson's Ratio</th>
<th>Ratio of Young’s Modulus with respect to that of Ice</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymethyl methacrylate (PMMA)</td>
<td>2.8</td>
<td>0.35</td>
<td>0.28</td>
<td>[14]</td>
</tr>
<tr>
<td>Ice</td>
<td>10</td>
<td>0.33</td>
<td>1</td>
<td>[10]</td>
</tr>
<tr>
<td>Asphalitic concrete (AC)</td>
<td>12</td>
<td>0.35</td>
<td>1.2</td>
<td>[13]</td>
</tr>
<tr>
<td>Portland Cement Concrete (PCC)</td>
<td>37</td>
<td>0.25</td>
<td>3.7</td>
<td>[12]</td>
</tr>
<tr>
<td>Aluminum</td>
<td>71</td>
<td>0.33</td>
<td>7.1</td>
<td>[11]</td>
</tr>
</tbody>
</table>

A finite element model was made of each coupon with a uniform mesh of square elements, 0.25 cm on each side. The model was analyzed using ANSYS 5.0, from Ansys Inc., with 8-noded parabolic plane strain elements.

In order to demonstrate that the $J_1$ integral for a bimaterial interface was in fact path independent and equal to zero in the absence of a singularity, a series of 11 contour rings were made about the site of the crack tip. The results of these analyses are given in Figs. 4 & 5.

As was expected, the $J_1$-integrals do not appear to be affected by the location of the contours, Fig. 4. In each curve, there is some variation in the magnitude of the $J_1$-integral, but this occurs in the 4th digit and beyond. The distribution of the magnitudes of the $J_1$-integrals in Fig. 4 appears to be based on the relative stiffnesses of the materials in question. The material with the highest $J$ integral has a substrate with the lowest stiffness with respect to ice (of those investigated), and conversely, the material with the lowest $J_1$-integral has the substrate with the highest stiffness with respect to ice (of those investigated).
Figure 5 shows that $J_1 = 0$ in the absence of a crack or singularity, regardless of contour or bimaterial combination. When examining Fig. 5, it is important to remember that it is essentially an enlarged view of Fig. 4 limited to $J_1$-integrals less than $J = 5 \times 10^{-6}$ N/m. The collection of curves at $J_1 = 0$ is in fact all five curves for the case in which there is no crack. As the contour number increases, the band of curves appears to thicken, with the largest value of $J_1$ being less than $J_1 = 5 \times 10^{-8}$ N/m.

For homogeneous specimens and mode I crack opening, standard $K_J$ calibrations have been developed either analytically or through numerical analyses. The standard $K_J$ calibrations are useful in calculating the energy release rate, $G$, or its more fundamental form, $J_1$, since the conversion from the $J_1$-integral for a homogeneous material is:

$$K_J = \sqrt{\frac{J_1 \cdot E}{1 - v^2}}$$  \hspace{1cm} (5)

It would be useful to use the standard $K_J$ calibrations for the case of bimaterials — with an appropriate factor, if required — so that $G_{\text{int}}$ could be found without requiring a numerical analysis.

---

**Figure 4.** $J_1$ integrals for the cracked coupon using ice on substrates of ice, aluminum, PMMA, asphaltic concrete, and Portland cement concrete. In order to give a sense of scale, the $J_1$ integral for ice on aluminum in the absence of a crack is included.
A relationship exists between the $J_1$-integral and the magnitude of the bimaterial stress intensity factors [15] (for plane strain):

$$J_1 = \frac{1}{H} \| K \|^2$$

(6a)

where

$$\frac{1}{H} = \frac{1}{2} \left( \frac{1 - (1')^2}{1' E} + \frac{1 - (2')^2}{2' E} \right) / \cosh^2(\pi \varepsilon)$$

(6b)

$$\varepsilon = \frac{1}{2 \pi} \ln \left[ \left( \frac{3 - 4(1')}{5'} + \frac{1}{5'} \right) / \left( \frac{3 - 4(2')}{5''} + \frac{1}{5''} \right) \right]$$

(6c)

We can rewrite (6a) in terms of the magnitude of the bimaterial stress intensity factors:

$$\| K \| = \sqrt{J_1 / H}$$

(7)

Figure 5. $J_1$ integrals for the uncracked coupon using ice on substrates of ice, aluminum, PMMA, asphaltic concrete, and Portland cement concrete. In order to give a sense of scale, the $J_1$ integral for ice on aluminum in the presence of a crack is included.

A relationship exists between the $J_1$-integral and the magnitude of the bimaterial stress intensity factors [15] (for plane strain):

$$J_1 = \frac{1}{H} \| K \|^2$$

(6a)

where

$$\frac{1}{H} = \frac{1}{2} \left( \frac{1 - (1')^2}{1' E} + \frac{1 - (2')^2}{2' E} \right) / \cosh^2(\pi \varepsilon)$$

(6b)

$$\varepsilon = \frac{1}{2 \pi} \ln \left[ \left( \frac{3 - 4(1')}{5'} + \frac{1}{5'} \right) / \left( \frac{3 - 4(2')}{5''} + \frac{1}{5''} \right) \right]$$

(6c)

We can rewrite (6a) in terms of the magnitude of the bimaterial stress intensity factors:

$$\| K \| = \sqrt{J_1 / H}$$

(7)
When the two materials in (6b) & (6c) are the same, (7) reduces to (5), allowing the use of a standard $K_t$ calibration of the specimen. Since (5) is actually a special case of (6a), one would expect a continuous relation as the two material became more dissimilar. To this end, analyses have been made of the double edged notch specimen (shown in Fig. 3b) with a distributed load, the single edged notch specimen (the symmetric half of Fig. 3b) with both a distributed load and an edge point load, and the asymmetric double cantilever beam (Fig. 6), each with a variety of crack lengths and the material pairs outlined in this study. The results of the analyses on the double edged notch specimen and the asymmetric double cantilever beam are presented in Figure 7. The results of the analyses on the single edged notch specimen with both uniform and point loads were very similar to that of the double edged notch specimen.

It appears, at first glance that for the double edged notched specimen, the magnitude of $K$ is independent of the quantity $H$, Fig 7a. Were this the case, it would mean that the standard $K_t$ calibration of the specimen could be used to calculate $G_{int}$. The slight variations in the values of the magnitude of $K$ with respect to $H$ suggests that a parameter similar to $H$ exists that could be used to make the magnitude of $K$ independent of the material combination.

![Figure 6. The asymmetric double cantilever beam.](image)
Figure 7. The relationship between values of $\|K\|$ and values of $H$ normalized with respect to $H$ for ice-on-ice: a) double edge notched beam with uniform load; and b) asymmetric double cantilever beam.
For the asymmetric double cantilever beam, Fig 7b, it appears that there is a simple relationship between \( \|K\| \) and \( H \), and this would imply that a simple mathematical surface relationship could be created to describe \( \|K\| \) as a function of crack length and of \( H \), allowing for the avoidance of further numerical analyses.

It should be noted at this point that \( \|K\| \) is the magnitude of the quantity \( K = K_1 + jK_2 \), where \( K_1 \) and \( K_2 \) are the normal and shear components of the interfacial stress intensity factor. The relative proportions of \( K_1 \) and \( K_2 \) cannot be deduced from \( \|K\| \), but \( K_2 \) should not be neglected since it is important in keeping the crack at the interface. Nevertheless, if one required a reasonable estimate for \( G_{int} \) for either the single or the double edge notched specimens, it would appear that the standard \( K_1 \) calibration of the specimen could be used without too great a penalty.

Conclusions

The \( J_I \)-integral is useful for the characterization of bimaterial interfaces since it allows for direct calculation of \( G_{int} \) for a particular specimen geometry and material combination. The foregoing work has demonstrated that two important properties of the \( J_I \)-integral for a homogeneous specimen also hold for a \( J_I \)-integral for a bimaterial specimen. The \( J_I \)-integral was calculated using Rice's potential energy formulation and showed that the \( J_I \)-integral for a bimaterial specimen is path independent and zero in the absence of a singularity.

Since the \( J_I \)-integral for a homogeneous specimen can be considered a special case of the \( J_I \)-integral for a bimaterial specimen, and since in those cases where \( K_1 \) calibrations exist of geometries they can be used to calculate the \( J_I \)-integral for a homogeneous specimen, it would be useful to be able to use the \( K_1 \) calibrations to calculate the \( J_I \)-integral for a bimaterial specimen. Three specimens were investigated and two were shown to be essentially independent of the material combination. The third specimen investigated showed a simple dependence on the material combination.
Acknowledgment

This material is based upon work supported by the U. S. Federal Aviation Administration under Grant No. 94-G-025. This support is gratefully acknowledged. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Federal Aviation Administration.

We thank Dr. Vladimir Vojislav Ogarevic for his help in reviewing this paper.

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Development of arctic shelf demands use of complex of the ships and the floating.

Composition of this complex is formed by:
- aspect function;
- natural-climatic condition of the region;
- construction peculiarity of main objects on the oilfield.

Aspect of function is formed by stages of life cycle oilfield:
1 - building of main objects on the oilfield;
2 - drilling of the wells;
3 - exploitation of the wells;
4 - destruction of the objects on the oilfield.

This stages covers oneself when the wells put into exploitations and because on some stages full complex of the ships and floating vehicles may be required.

Types of this ships are shown at the table 1.

<table>
<thead>
<tr>
<th>Problems of the service fleet</th>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>The problems</td>
</tr>
<tr>
<td>1</td>
<td>Preparing of ground for rig</td>
</tr>
<tr>
<td>2</td>
<td>Towing the floating blocks, building works</td>
</tr>
<tr>
<td>3</td>
<td>Delivery of the techn. materials, the pipes</td>
</tr>
<tr>
<td>4</td>
<td>Transport of personal</td>
</tr>
<tr>
<td>5</td>
<td>Laying the pipeline</td>
</tr>
<tr>
<td>6</td>
<td>Ensuring fire and ecological safety</td>
</tr>
<tr>
<td>7</td>
<td>Saving of the peoples</td>
</tr>
<tr>
<td>8</td>
<td>Repair and underwater works</td>
</tr>
<tr>
<td>9</td>
<td>Transport of oil</td>
</tr>
</tbody>
</table>

1. Building of main objects on the oilfield.

All types of the ships and the floating vehicles uses at that stage.

They fulfills next operations:
- preparation the foundations for drilling rigs;
- towing of floating blocks;
- installation - building works;
- carriage of technological materials, equipment, the pipes and so on;
- transport of rig personal;
- laying of the pipelines;
- ensuring an ecological and fire safety;
- repair and diver - technical works;
- list of the ships of technical fleet for 1-st stage and their main type-dimensions characteristics is shown at the table 2.

Types of the ships of technical fleet

<table>
<thead>
<tr>
<th>N</th>
<th>Type of the ship</th>
<th>Mine type-dimension parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Draggers</td>
<td>Productivity 1000 kub. m/h</td>
</tr>
<tr>
<td>2</td>
<td>Dragger barge</td>
<td>Carrying capacity 1000 t</td>
</tr>
<tr>
<td>3</td>
<td>Cargo ship</td>
<td>Carrying capacity 3000 t</td>
</tr>
<tr>
<td>4</td>
<td>Seagoing tug</td>
<td>Power 7 - 9 MW</td>
</tr>
<tr>
<td>5</td>
<td>Supplying ship</td>
<td>Cargo capacity 3000 t</td>
</tr>
<tr>
<td>6</td>
<td>Anchor handling vessel</td>
<td>Power 8 MW</td>
</tr>
<tr>
<td>7</td>
<td>Pipe-carrying ship</td>
<td>Cargo capacity 5000 t</td>
</tr>
<tr>
<td>8</td>
<td>Pipelaying ship</td>
<td>Displacement 30000 t</td>
</tr>
<tr>
<td>9</td>
<td>Crane ship</td>
<td>Cargo capacity 5000 t</td>
</tr>
<tr>
<td>10</td>
<td>Passenger ship</td>
<td>Passenger capacity 150 p.</td>
</tr>
<tr>
<td>11</td>
<td>Fire-fighting boat</td>
<td>Pump output 5000 kub. m/h</td>
</tr>
<tr>
<td>12</td>
<td>Sea oil-assembler</td>
<td>Productivity 100 kub. m/h</td>
</tr>
<tr>
<td>13</td>
<td>Ecological-control ship</td>
<td>Productivity 100 kub. m/h</td>
</tr>
<tr>
<td>14</td>
<td>Icebreaker</td>
<td>Power 12 - 20 MW</td>
</tr>
<tr>
<td>15</td>
<td>Diver boat</td>
<td>Displacement 1000 t</td>
</tr>
<tr>
<td>16</td>
<td>Tanker</td>
<td>Deadweight 15000 t</td>
</tr>
</tbody>
</table>

Most of this ships belongs to custom ships of technical fleet which are in structure of shipping companies and in that number in Murmansk shipping company (MSC). They may be leased for development of the oilfield at short time and with small capital expenditures. List of the ships of MSC have is shown at the table 3.

List of ships of MSC

<table>
<thead>
<tr>
<th>N</th>
<th>Name of the ships</th>
<th>Number</th>
<th>Type</th>
<th>Deadweight, t</th>
<th>Power, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dm. Donskoy</td>
<td>13</td>
<td>bulkier</td>
<td>19885</td>
<td>8200</td>
</tr>
<tr>
<td>2</td>
<td>M. Strekalovsky</td>
<td>5</td>
<td>bulkier</td>
<td>19250</td>
<td>8200</td>
</tr>
<tr>
<td>3</td>
<td>Kola</td>
<td>4</td>
<td>cargo</td>
<td>19940</td>
<td>15400</td>
</tr>
<tr>
<td>4</td>
<td>V.Kotik</td>
<td>3</td>
<td>cargo</td>
<td>4600</td>
<td>2390</td>
</tr>
<tr>
<td>5</td>
<td>Zvenigorod</td>
<td>2</td>
<td>bulkier</td>
<td>22900</td>
<td>7060</td>
</tr>
<tr>
<td>6</td>
<td>Fastov</td>
<td>2</td>
<td>cargo</td>
<td>7800</td>
<td>3970</td>
</tr>
<tr>
<td>7</td>
<td>I.Papanin</td>
<td>1</td>
<td>cargo</td>
<td>10500</td>
<td>13200</td>
</tr>
<tr>
<td>8</td>
<td>Sevmorput</td>
<td>1</td>
<td>a.lighter</td>
<td>332400</td>
<td>29400</td>
</tr>
<tr>
<td>9</td>
<td>A.Tarasova</td>
<td>2</td>
<td>c/pass.</td>
<td>1300</td>
<td>3880</td>
</tr>
<tr>
<td>10</td>
<td>Cap.Sorokin</td>
<td>3</td>
<td>icebreaker</td>
<td>5130</td>
<td>16240</td>
</tr>
<tr>
<td>11</td>
<td>Arctica</td>
<td>6</td>
<td>a.icebr.</td>
<td>4150</td>
<td>55200</td>
</tr>
<tr>
<td>12</td>
<td>Yamal</td>
<td>2</td>
<td>a.icebr.</td>
<td>3900</td>
<td>32500</td>
</tr>
</tbody>
</table>

2. Drilling and exploitation of the wells.

List of ships for this stage have decreased as compared with preceding stage almost two times at the expense of the tugboats, the pipelaying ships, the crane ships, the draggers and the dragger barges.

Possibilities of MSC have increased at this stage.

Practically all kind of works may be fulfill by ships of Shippin... Company. That time MSC are realizing the program of building of the 2000 t deadweight tankers. Another project are considering for building the tankers with greater deadweight.
MSC has the diesel-electrical icebreakers "Cap.Sorokin" -type with 16,2 MW horsepower installation and the atomic icebreakers "Taymir" -type with 33 MW horsepower installations which had built for exploitation on shallow water. There are the atomic icebreakers "Arctica" -type too.

The icebreakers "Cap.Sorokin" -type may be carry out icebreaking works of all kind in light and middle ice conditions.

More powerful icebreakers may be quickly attracts in necessity. They constantly works all year at Barents and Karskoe seas.

The lease of icebreaker "Cap.Sorokin" -type costs 25 thousands USD per day.

3. Destruction of the objects on the oilfield.

The tugs must be exploited on this stage of life cycle but the tankers will be take out. The strain of works will be reduced because quantity of the wells and so ecological dangerous operations as pumping of oil will be lower. Planning of quantitative composition of fleet and definition of possibility of exclude of the old ships without their rebuilding must been coordinated with availability at the region of MSC.

The shipping company is the complicated many functional enterprise which provides all vitality of its main elements - ships by repair, supply and so on.

The quality of work of fleet are formed by experience and qualification of the specialists. It is doubtful the creation of new shipping company since there is MSC. Many years and big capital expenditures are demanded for form the skilled workers and builds the necessity structure.

Problem of development of the oilfield on the arctic shelf may be solved in short time and with small capital expenditures by optimal combination of use the ships of MSC and creation of new special shipping company.
THE USE OF LOCAL-GENETIC METHODS FOR ICE DISTRIBUTION
FORECASTING IN SUMMER FOR PROVIDING SUPPORT TO SHIPPING
AND ENGINEERING ACTIVITIES IN THE KARA SEA

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the Russian Federation,
Arctic and Antarctic Research
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ABSTRACT

The possibilities of local-genetic approach for forecasting the ice concentration distribution in the Kara Sea are shown. On the base of ice-geographic subdivision into regions and natural stability of typical ice condition changes in homogeneous taxa the system of ice forecasts with preliminarity from 10 days to 3-4 months is elaborated for the purpose of providing support to shipping and engineering activities in the Kara Sea in summer period.

INTRODUCTION

Ice cover is the main natural phenomenon that limits shipping and presents a direct threat to engineering structures in the Kara Sea. The forecast of ice cover characteristics distribution at the main navigation routes and industrial assimilation zones is necessary for secure shipping and economically effective designing, construction and exploitation of engineering structures. As for the Kara Sea since 1990 such kind of forecasts are executed by means of local-genetic methods of ice conditions dividing into types.
METHOD

The local-genetic methods are based on natural stability of typical ice cover condition changes in the natural homogeneous regions of the sea area during summer period. This fact provides the possibility to forecast the peculiarities of distribution of close, open and very open ice and open water zones with preliminary from 10 days to 3-4 months using the form maximally comfortable for possible consumers of prognostic information.

As the ice processes in the Kara Sea take place on complicated interacting of hydrometeorological factors of different spatial-temporal scales, in order to take into account the real natural peculiarities of ice regime the whole sea area has been classified by the ice-geographic indicators (Yegorov, Spichkin, 1990). As a result of objective analysis and expert examinations, eight homogeneous regions were revealed in the Kara Sea: three of them in the south-western part of the sea and five in the north-eastern one (fig. 1). Within each natural ice-geographical taxon the homogeneous regime of ice indicators with typical variability of ice conditions in different scales - from synoptic to season - is displayed, and the typical ratio relations between different ice concentration zones are formed (fig. 2). The subdivision into types is a necessary preliminary stage for obtaining the representative information concerning the ice cover state and forecast executing.

The natural stability of ice processes development exists within each homogeneous region during summer period (Yegorov et al., 1989). The initial state of ice cover - thickness and age composition of ice of autumn origin, terms of melting beginning, presence of open water zones in the stationary polynyas - defines the typical peculiarity of ice conditions during June-September period, which can be partly corrected by the synchronic transports. For taking into account the synchronic atmospheric influence the special regional classification of surface atmospheric pressure field was elaborated; this classification reflects the distribution of main dominants of macrobaric relief (Yegorov, 1990). The combination of natural predictor anomalies defines the typical season course of interconnected parameters of ice and open water amount and distribution over the homogene-
Fig. 1. The homogeneous regions of the Kara Sea
Fig. 2. Ice cover extent (%) in the homogeneous regions of the Kara Sea.
ous region area. Every concrete year the typical variant of natural predictor anomalies combination is being formed which corresponds to the specific type of ice condition changes (Yegorov, Spichkin, 1994). From 5 to 9 stable season ice types are revealed for each region (fig. 3); their quantity and regime indicators are defined by ice-geographical specific features of concrete homogeneous region.

RESULTS

By means of local-genetic type-dividing the different forms of ice distribution forecasts in the Kara Sea are possible:

1. The forecast of close ice boundary (or edge) location for every 10-days period from June to September with preliminarity of several months (fig. 4). Such kind of forecasts is executed for the purpose of strategic navigation planning.

2. The forecast of close, open and very open ice and open water distribution with discreteness equal 10 days and preliminarity of 1 month (fig. 5). Such forecasts are made for tactic planning and sea operations conducting.

3. The forecast of ice concentration distribution with 10 days preliminarity for the purpose of operative navigation support.

Also since 1994 by means of local-genetic type-dividing the long-term forecast of stable ice formation isochrones in the Kara Sea with preliminarity from 1 to 3 months was being executed (fig. 6).

The ice forecasts based on local-genetic type-dividing are made in the AARI Ice Regime and Forecasts Department and widely utilized by research-operative groupes of Arctic Western sector for providing the profitable and ecologically secure navigation of Murmansk Shipping Company. The verification score of forecasts of ice concentration and open water zones distribution was equal 80-85 % for the period from 1990 till 1994.

By means of local-genetic approach an expert examination and correct calculation of regime characteristics are possible: also one is able to predict the possible changes of ice conditions both in the zones and in a direct proximity from the area of
Fig. 3. Mean typical values of the ice cover extent (%) in the Yamal-Yugorsky homogeneous region of the Kara Sea.
Fig. 4. Forecast of close ice boundary location with preliminarity 3-5 months
Fig. 5. Forecast of ice cover concentration distribution with preliminarity 1 month
Fig. 6. Forecast of terms of ice formation with preliminarity 1-3 months.
construction and maintenance of engineering structures. The utilization of spatial taxons of different scale allows to obtain the representative information on interannual variability of ice conditions, multiyear stable trends of anomalous ice cover state, occurrence frequency of especially dangerous ice phenomena and different regime indicators. During the period 1993-1994 such studies were carried out with regard to the ice conditions of the Baidaratskaya Gulf of the Kara Sea for providing support of designing and construction of the pipeline passage between the Yamal and Yugorsky coasts.

CONCLUSION

The five years experience of active utilization of local-genetic type-dividing for regime analysis and ice distribution forecasts in the Kara Sea may be considered successful that gives an opportunity to recommend confidently it's expansion to the other seas with ice cover.

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