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Babtsek V.A., Batskikh Y.M., Trjaskin V.N.

Damages of Icebreakers and Transport Vessels in Russian Arctic

Initial information on ship hulls damages and wrecks envelops period of 1954-1990. Total number of accidents and wrecks which have been considered exceeds 800.

Comparison of average number of damages and wrecks due to ice loads with corresponding number of vessels for typical with respect to ice conditions season¹ shows that this value is greater for eastern part of the Arctic as compared with analogous value for western area of the Arctic.

Table 1.

Average number of wrecks and damages due to ice loads for typical ice conditions (per cent of total number of vessels engaged in navigation in certain arctic areas)

<table>
<thead>
<tr>
<th>Navigation category with respect to ice conditions</th>
<th>Part of the Northern Sea Route</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Western</td>
<td>Eastern</td>
</tr>
<tr>
<td>Heavy</td>
<td>7,5-8,0</td>
<td>14,0-16,0</td>
</tr>
<tr>
<td>Medium</td>
<td>3,5-5,0</td>
<td>8,0-10,0</td>
</tr>
<tr>
<td>Light</td>
<td>1,0-1,5</td>
<td>2,0-3,0</td>
</tr>
</tbody>
</table>

For vessels following icebreakers and for self-dependent motion of transport vessels the main reasons of damages due to ice loads occur to be ship impacts against ice, nip in situation of strong wind, and ship masters mistakes in manoeuvring.

Unfavorable situation for manoeuvring may arise when a vessel overcomes young ice or ice cake after heavy snowfall so far as ice surface becomes monotonous and it is very difficult to find out hummocks and bits of old floes.

Weld connections may be destroyed, dents and longitudinal

¹Comparison is carried out for the summer navigation period only, so far as in the winter period there was no navigation in eastern part of the Arctic.
cracks in outer plating as well as framing deformations and holes may appear or yawing due to ship bow mid body or stern impact against ice in the process of manoeuvring or yawing.

Rudder, damage or rudder stock twist may occur when the ship turns sharply in thick ice or when the ship leans with her stern on ice floe.

Number of damages due to above mentioned reasons is big and it may be up to 40-50 per cent of total number of accidents, 40 per cent of damages being followed with water getting inside the hull through holes and cracks.

An accident may happen due to nip which is most intensive when drift ice meets some obstacles like islands, shallow waters.

Analysis results of ice damages correlation with ice concentration for vessels of various ice strengthening categories and for various modes of ship motion are given in Table 2.

<table>
<thead>
<tr>
<th>Ice class of the ship</th>
<th>Ice conditions (ice concentration)</th>
<th>Mode of motion</th>
<th>Western sector</th>
<th>Eastern sector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>9-10</td>
<td>7-8</td>
<td>3-5</td>
</tr>
<tr>
<td>ULA</td>
<td>11</td>
<td>56</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>UL</td>
<td>5</td>
<td>35</td>
<td>50</td>
<td>8</td>
</tr>
<tr>
<td>L1</td>
<td>3</td>
<td>7</td>
<td>55</td>
<td>20</td>
</tr>
<tr>
<td>ULA</td>
<td>15</td>
<td>28</td>
<td>52</td>
<td>5</td>
</tr>
<tr>
<td>UL</td>
<td>5</td>
<td>20</td>
<td>65</td>
<td>8</td>
</tr>
<tr>
<td>L1</td>
<td>-</td>
<td>7</td>
<td>22</td>
<td>15</td>
</tr>
</tbody>
</table>

Analysis of ice called damages and wrecks distribution for various routes along the Northern sea way (according to geographic principle) shows that their number is in good correlation with major ice massifs position and with their dynamics (see Table 3).

Analysis has been carried out for summer period of navigation only.
<table>
<thead>
<tr>
<th>Ship route operation</th>
<th>Specific part of the route</th>
<th>Per cent of ice damages and wrecks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novozemelsky straits-</td>
<td>a) Novozemelsky straits-meridian of island Biely</td>
<td>28</td>
</tr>
<tr>
<td>harbour on Enisey river</td>
<td>b) Meridian of island Biely-meridian of island Dikson</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>c) Meridian of island Dikson-Cape Sopotchnaya Carga</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>d) Cape Sopotchnaya Carga-Dudinka</td>
<td>9</td>
</tr>
<tr>
<td>Meridian of island</td>
<td>a) Meridian of is Dikson-western approach to Vil-kitcky strait</td>
<td>18</td>
</tr>
<tr>
<td>Dikson-meridian of</td>
<td>b) Vilkitsky strait</td>
<td>38</td>
</tr>
<tr>
<td>Ticksey</td>
<td>c) Eastern approach to Vil-kitcky strait-meridian of Ticksey</td>
<td>52</td>
</tr>
<tr>
<td>Meridian of</td>
<td>a) Meridian of Ticksey-meridian of Indigirka river (through</td>
<td>15</td>
</tr>
<tr>
<td>Ticksey-meridian of</td>
<td>D.Laptev strait</td>
<td></td>
</tr>
<tr>
<td>Peveck</td>
<td>b) Meridian of Ticksey-meridian of Indigirka river (through</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Sannikov strait</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c) Meridian of Indigirka river-meridian of Peveck</td>
<td>39</td>
</tr>
<tr>
<td>Meridian of</td>
<td>a) Meridian of Peveck-meridian of cape Billings</td>
<td>30</td>
</tr>
<tr>
<td>Peveck-Beringov strait</td>
<td>b) Meridian of cape Billings-meridian of cape Schmidt</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>c) Meridian of cape Schmidt-Beringov strait</td>
<td>17</td>
</tr>
</tbody>
</table>

The following distribution of accidents with vessels is true for the Arctic Seas: Kara Sea - 40 per cent (intensity of navigation is rather high in this area); Laptev's sea - 20 per cent; West-Siberian sea - 21 per cent; Chukotka sea - 14 per cent; Enisey river - 2 per cent.

One important peculiarity is to be noted with respect to frequency of accidents due to ice loads during summer navigation period (for each/month) (see Table 4). Accidents are especially often in the middle of summer navigation period (August-September). It is especially typical for navigation in the area of major ice
massifs like Taimyrsky and Ayonsky ones.

Table 4.

Ice damages and wrecks distribution for summer navigation period
(per cent of total number of accidents for the period)

<table>
<thead>
<tr>
<th>Month</th>
<th>Part of NSW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Western</td>
</tr>
<tr>
<td>June</td>
<td>5</td>
</tr>
<tr>
<td>July</td>
<td>16</td>
</tr>
<tr>
<td>August</td>
<td>25</td>
</tr>
<tr>
<td>September</td>
<td>35</td>
</tr>
<tr>
<td>October</td>
<td>19</td>
</tr>
</tbody>
</table>

Summer navigation in the Arctic in 1983 may be taken as good
illustration of ice damages number with ice condition category.
That year navigation was the heaviest for the period since 1954
till 1990 (see Table 5).
Table 5.
Transport vessels and icebreakers damages due to ice loads on the routes of NSW in 1983

<table>
<thead>
<tr>
<th>Section title</th>
<th>Section contents</th>
<th>Damaged vessels number</th>
<th>per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Region</td>
<td>Eastern</td>
<td>80</td>
<td>70.8</td>
</tr>
<tr>
<td></td>
<td>Western</td>
<td>33</td>
<td>29.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>113</td>
<td>100.0</td>
</tr>
<tr>
<td>2. Period of navigation</td>
<td>Winter-Spring</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Summer (traditional)</td>
<td>104</td>
<td>92.0</td>
</tr>
<tr>
<td></td>
<td>Autumn-Winter</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>113</td>
<td>100.0</td>
</tr>
<tr>
<td>3. Situation, when a vessel has been damaged</td>
<td>Following an icebreaker</td>
<td>64</td>
<td>56.6</td>
</tr>
<tr>
<td></td>
<td>&quot;Close&quot; towing</td>
<td>20</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>Leading on ice</td>
<td>17</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Self-dependent navigation</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Nip</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Release from nip</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>113</td>
<td>100.0</td>
</tr>
<tr>
<td>4. Character of damage</td>
<td>Propeller screws, blades</td>
<td>10</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>Dead woods, shafts</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Steering gear</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Dents, goffering</td>
<td>35</td>
<td>31.0</td>
</tr>
<tr>
<td></td>
<td>Dents with cracks</td>
<td>37</td>
<td>32.7</td>
</tr>
<tr>
<td></td>
<td>Holes</td>
<td>29</td>
<td>25.7</td>
</tr>
<tr>
<td></td>
<td>Loss of the ship</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>113</td>
<td>100.0</td>
</tr>
<tr>
<td>5. Vessels age</td>
<td>Less than 4 years</td>
<td>16</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>4 to 8</td>
<td>22</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>8 to 12</td>
<td>14</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>12 to 16</td>
<td>28</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>More than 16</td>
<td>33</td>
<td>29.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>113</td>
<td>100.0</td>
</tr>
<tr>
<td>6. Ice strengthening category</td>
<td>Icebreakers</td>
<td>15</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>ULA</td>
<td>9</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>UL</td>
<td>21</td>
<td>18.6</td>
</tr>
<tr>
<td></td>
<td>L1</td>
<td>62</td>
<td>54.8</td>
</tr>
<tr>
<td></td>
<td>L2 and L3</td>
<td>6</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>113</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Viewed as a whole arctic navigation at the Eastern sector of the Arctic in 1983 is similar to previous years. Transport vessels that are busy with cargo transportation in the Arctic received the most number of damages, viz. Li-class vessels – 43 accidents (54 per cent), UL-class vessels suffered less – 15 accidents (19 per cent).

The following distribution of damaged vessels takes into account their age:

- mean age more than 15 year – 40 per cent
- from 10 to 15 years – 26 per cent
- mean age less than 10 years – 35 per cent

Main reasons of large number of accidents due to ice loads with transport vessels and icebreakers during arctic navigation of 1983 were:

- extremely heavy ice conditions during all period of navigation;
- discrepancy of ice strengthening category (Li) and of hull structures wear (more that 12 years in exploitation) with external conditions;
- insufficient power output and low ability to overcome ice of diesel powered icebreakers such as "Moscow"-type and "Captain Sorokin"-type in the first turn, but sometimes "Krasin"-type icebreakers too. They could not insure safe navigation of transport vessels in extremely heavy ice conditions.

Analysis of ship hull structures damages of icebreakers and transport vessels leads to following conclusions and numerical estimates.

Arctic icebreaker are damaged at above the waterline parts of ship hull (38%), close to variable waterline and below this level (34%) including flat bottom (26%). Damages of structures located above the water level occur mainly due to the vessel leaning against an icebreaker in the process of towing, releasing from nip, etc. Icebreakers hull structure damages mostly occur in the form of dents or gapers (77%). Cracks and gaps (23%) appear sometimes in the ice belt plating of icebreakers (in the area of plating welded butts and seams) due to poor quality of welded joints.

It is usual nearly for all vessels with ice strengthenings
that 70 per cent of damages occur at the bow part, 20 per cent - at mid body, 10 per cent at stern. Predominant forms of transport vessels hull damages are dents and gofers. There are followed with cracks and ruptures.

Main part of damages were below cargo waterline, viz. 55 per cent; other were in the area of cargo waterline - 25 per cent, in the bottom - 15 per cent, above the waterline - 5 per cent.

Frequency of accidents analysis shows that more than 50 per cent of transport vessels hull damages coincided with situations when the transport vessels followed icebreakers. These damages were results of ship hull impacts against separately fües or against channel edges, when vessels speed was higher that allowable safe one.

Some results of statistical analyses of information on arctic icebreakers hulls damages are given in Figures 1 + 2.

It is necessary to note that icebreakers are mostly damaged only in the area of bilges and horizontal parts of their bottoms (plating and framing damages). "Moscow"-type icebreakers (class LL3) for example do not have any damages in the area of the ice belt after 30 years of intensive service in the arctic seas. (Figure 3).

More up-to-date and much more powerful icebreakers of "Ermack"-type (class LL2) ("Ermack", "Admiral Makarov", "Krasin") may be taken as examples of unsuccessful attempts of hull structures design (Figure 4).

Another character of damages is registered for ice going vessels. Generalized data on hull structures damages for "Samotlor" - type (UL) and "Amguema" - type (ULA) vessels are given in Figures 5, 6. Considerably greater value of structure damages in the bow part of ice belt proves that there were some shortcomings in the structures due to shipyard's (designer's) mistakes. Hull damages continued until all vessels' hulls have been strengthened in the areas between the stem and midship part of the vessels.

Damages of side, bilge, flat bottom structures of vessels for ice navigation in the form of dents are characterized with residual deformations of outer shell plating and with those of sections and webs used for framing. Analyses of information on damages of ship
hull structures in the process of ice navigation permit to pick out some principal forms of these damages:
- swells of web framing and plate structures (floors, bottom stringers, double sides platforms, bulkheads, etc.);
- buckling of stiffeners on the web framing and plate structures;
- tripping of ordinary frames;
- framing tear off outer shell along the welds;
- cracks and ruptures of welds at the places of framing intersections;
- cracks and ruptures of webs and plate structures in the areas of large plastic deformations;
- knees and brackets buckling and tear off girders;
- crumpling and swelling of ordinary framing’s webs at cross sections on supports;
- breast hooks buckling or ruptures;
- bilge keel tripping or tearing off the hull.
Some damages of ship hull structures are given in Figures 7-10.

Widespread form of structures damages is loss of buckling strength which is followed with web swell may happen with web frames, side stringers, floors, bottom stringers, double side platforms, etc. (Figures 8-9) due to compression loads of high intensity. Support moments which appear due to bending of outer shell promote to the loss of buckling strength of the web.

Buckling strength of plate structures panels and framing webs is ensured by means of arrangement of stiffeners being positioned either normally to the outer shell or “in parallels” to it. Effectiveness of strengthening scheme depends on a number of factors: on stiffeners positions and their orienting, on rigidity parameters of supporting elements, on thickness of the web to be supported, on the presence of cut in it, etc.

High level of damages during ice navigation is typical not only for web framing and panel structures but for ordinary framing as well. Frames, bottom longitudinals and supporting elements at their ends (knees, brackets) are damaged. Typical forms of damages are: residual deformation, tripping, crumpling, and swelling of
framing webs, cracks of welds and ruptures of basic material.

There is other widespread form of structures damages in Figure 10, viz. tripping of ordinary frames. The main reason of these damages is in the fact that framing maximum rigidity plane is positional at some angle to ice load direction, while girders rigidity in the direction of their minimal rigidity is insufficient.

Some recommendations to decrease the level of hull structure damages applied to some assemblies and elements of web frame and plate structure are formulated. Theoretical and experimental researches, experience of damaged structures repairs and supervision of strengthened structures during following vessel exploitation are the basis of these recommendation.

Information on the most often forms of structures damages presents considerable interest for elaboration/correction of Classification Societies Rules concerning to structures of ice going vessels and icebreakers.
Fig.1. Histogram of plating damages distribution for bilge and horizontal part of bottom areas (goffres) on the hull length of following icebreakers types "Moscow", "Ermack", "Cap.Sorokin".
Fig. 2. Histogram of bottom framing damages distribution along the hull length for "Moscow"-type (a) and "Ermack"-type (b) icebreakers.
Fig. 3. Icebreaker "Moscow" in docked position. There are no ice belt plating and framing residual deflections after 30 years of exploitation. There are goffers and swells in the bottom and bilge structures.
Fig. 4. Locations of structures damages of "Ermack"-type icebreakers that have been repaired during 10 years of exploitation (bottom longitudinals are not shown) 1 - side shaft bossing; 2 - repair work areas.
Figure 5. Frequency of damages appearance for "Samotlor"-type vessels

Figure 6a. Frequency of damages appearance for "Amguema"-type vessels (vessels of the Far East Shipping Company)

Figure 6b. Frequency of damages appearance for "Amguema"-type vessels (vessels of the Murmansk Shipping Company)
Fig. 7. Ice damages on ships hulls.  
a) dents in the area of ice belt of “Samotlor”-type tankers;  
b) dents of the bilge of “Captain Khlebnikov”-type icebreaker (LL3): 1 - deformation form (“incurvation”) of floor web lower part; 2 - undamaged hull's lines; damaged areas of ice-resistant coating "Inerta-760" are clearly visible.
Fig. 8. Floor web lower part swell in the hull structure of icebreaker "Captain Khlebnikov": 1 - swell on floor's web; 2 - vertical stiffener that had lost buckling strength; 3 - lower horizontal stiffener of the web.
Fig. 9. Buckling of floor's web (with rupture) and buckling of stiffener: 1 - stiffener tear off the web; 2 - rupture of the floor web; 3 - stiffener; 4 - framing element (bulb section).
Fig. 10. Ice belt framing damages of "Samotlor"-type tankers.
THE USE OF CLASSIFICATION OF ICE COVER DISTRIBUTION FOR HYDROMETEOROLOGICAL INFORMATION SUPPORT TO ENGINEERING ACTIVITIES ON THE SHELF OF THE BARENTS SEA

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ABSTRACT

It is shown that the classification method is one of the effective approaches to describing significant interannual and seasonal variability in ice conditions of the Barents Sea. The classification of ice conditions is made taking into account the intensity of their seasonal changes. Five classes of the ice cover distribution were identified. Mean and probabilistic characteristics of ice conditions for each class during a year are obtained. The types of ice conditions are identified for the suggested variants of the routes of underwater pipelines from the Shtockman gas-condensate field to the shore.

INTRODUCTION

The presence of ice cover is one of the most important natural features of the Barents Sea. Some sea regions are characterized by significant variability in ice conditions in space and with time (Mironov et al., 1993) that should be taken into account for designing, construction and use of engineering structures. The classification method is considered to be one of the effective approaches to describing significant interannual and seasonal variability in the distribution of ice cover.
METHOD

The present work uses a method of typological classification (Yeliseyeva, Rukavishnikov, 1977) where the choice of the indications for describing the objects does not have a formal substantiation, but is based on theoretical and professional knowledge of investigators. However, the identification of classes is performed by using objective criteria (a standard deviation). This method also allows "empty" classes (types), as compared with the classification on the basis of cluster analysis.

An important feature of the suggested approach is identification of classes (types) taking into account the intensity of seasonal changes in ice conditions. This allows estimating the ice season on the whole and then forecasting ice conditions and their changes during the annual cycle.

For identification of classes, ice area values which are an integral indicator of ice conditions, were used. However, ice areas were considered separately for uniform regions, rather than for the sea area on the whole. Traditionally, the Barents Sea is subdivided into three regions - Western, North-Eastern and South-Eastern (Viese, 1944). This regioning takes into account general physical-geographical features of the Barents Sea (bottom relief, system of currents, sea ice extent, etc.).

In order to estimate ice conditions during the entire annual cycle, two periods of their development can be arbitrarily identified - autumn-winter and spring-summer. An analysis of the correlation matrices of monthly ice areas showed February - one of the months of the maximum development of ice cover, to be best of all related to both the autumn-winter and spring-summer months.

For subdividing into classes, fractions of a standard deviation (\( \sigma \)) in ice area for each of the three regions in February were assumed to be a criterion. Five classes were identified: average (\( N \pm 0.46 \), where \( N \) - multiyear mean ice area in February), easy (-0.46 to -1.26), extremely easy (< -1.26), heavy (0.46 to 1.26), extremely heavy (> 1.26). The value 1.26 was assumed to be a criterion of a large positive or negative
anomaly (Spichkin, 1987). A long series of observation data on ice conditions from 1934 to 1994 was used. The distribution of ice areas in the Western region of the Barents Sea by the identified classes is shown in Table 1.

### Table 1

**Distribution of ice areas in the Western Barents Sea by classes**

<table>
<thead>
<tr>
<th>Class</th>
<th>Anomaly gradation, fraction, 6.</th>
<th>Sampling volume, %</th>
<th>Values of ice area, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&lt; -1.26</td>
<td>7</td>
<td>24 February 26 June</td>
</tr>
<tr>
<td>II</td>
<td>-0.46 ± -1.26</td>
<td>21</td>
<td>38 February 32 June</td>
</tr>
<tr>
<td>III</td>
<td>N ± 0.46</td>
<td>39</td>
<td>45 February 38 June</td>
</tr>
<tr>
<td>IV</td>
<td>0.46 - 1.26</td>
<td>25</td>
<td>52 February 41 June</td>
</tr>
<tr>
<td>V</td>
<td>&gt; 1.26</td>
<td>8</td>
<td>66 February 48 June</td>
</tr>
</tbody>
</table>

Large anomalies in ice conditions comprise 15% of the whole of the observation series. Ice areas in June, characterizing the spring-summer period, show the differences between the classes to be preserved. The success of the classification made is also confirmed by Fig.1 which shows changes in ice area for every class during the annual cycle. The largest differences are observed in winter (January-February), however, during the period from December to July, significant differences between the classes are preserved.

For a more detailed description of ice processes in spring-summer, two types are identified in each group. The first type characterizes an intensive development of the processes of ice melting and decay, and the second type - a delayed development. The identification of types was performed by analysing data on ice areas in the region in May and air temperature at the polar station Barentsburg during the period from April to June.

In each region of the Barents Sea there is a particular relationship between the values of the ice area and the distribution of ice cover (ice edge position, close ice
Fig.1 Changes in ice area in the Western region of the Barents Sea for the classes identified.

- 1 class  - 2 class  - 3 class
- 4 class  - 5 class
boundary). To find these relationships, the ice area values occupied by different isolines of the probability of open water and close ice were determined at the points of a regular grid with a spatial scale of 50 km. As a result, an empirical dependency was obtained for each region for the corresponding months (Fig. 2) allowing a transition from the ice area values to the distribution of ice cover.

Thus, mean charts of the distribution of ice cover with its development from month-to-month were obtained for each class. Also, it is possible to obtain probability characteristics of ice distribution both for the whole of the observation series and for the classes and types identified.

RESULTS

The use of the main principles of the typological classification enables identification of the types of ice conditions for applied purposes considering specific practical requirements.

In the course of the feasibility study for exploration of the Shtockman gas-condensate field, three variants of the routes of underwater pipelines were considered:

- Route 1 - to the Pechenga river (Liinakhamari),
- Route 2 - to the village Teriberka,
- Route 3 - to the Kanin Nos cape.

In connection with the fact that on Route 3 ice is observed basically every year and on Routes 1 and 2 ice is observed with an occurrence frequency of about 30%, the division into types was performed for more characteristic ice conditions on Route 1 and 2. The distribution of ice concentration and age categories on Route 3 was analysed in accordance with the types identified.

During the period from 1934 to 1993, eighteen years were identified when drifting ice was observed on Route 1 and 2. The following indicators were used as criteria for typification: duration of the ice presence on the route and the length of ice segments on the route. The analysis of the sampling under consideration (18 years) allowed identification of 3 types - heavy, average and easy (Table 2).
Fig. 2a An empirical dependency between the ice cover extent and the ice edge location of prescribed probability in the North-Eastern region of the Barents Sea.

- February - June - September

Fig. 2b An empirical dependency between the close ice area and the boundary of close ice of prescribed probability in the North-Eastern region of the Barents Sea.

- February - June - September
Table 2

Characteristic indicators of ice conditions on Routes 1 and 2 for different types of the development of ice processes

<table>
<thead>
<tr>
<th>Type</th>
<th>Mean duration of the ice presence, months</th>
<th>Mean length of the ice zones, km</th>
<th>Prevailing total concent., tenths</th>
<th>Prevailing ice age categories, its amount in arbitr.units</th>
<th>Occurrence frequency (%) at a different series length</th>
</tr>
</thead>
<tbody>
<tr>
<td>heavy</td>
<td>3-4</td>
<td>240</td>
<td>9-10</td>
<td>first-year, medium, 5</td>
<td>10 N=60, 35 N=18</td>
</tr>
<tr>
<td>average</td>
<td>1-2</td>
<td>80</td>
<td>7-10</td>
<td>first-year, thin, 5</td>
<td>7 N=60, 20 N=18</td>
</tr>
<tr>
<td>easy</td>
<td>&lt; 1</td>
<td>50</td>
<td>1-6</td>
<td>first-year, thin, 3</td>
<td>3 N=60, 45 N=18</td>
</tr>
</tbody>
</table>

The identified types significantly differ both in mean duration of the ice season, length of the ice zones on the route and the distribution of ice age categories and concentration. The occurrence frequency of heavy and easy types exceeds that of the average type which indicates once again insufficiency of mean values for describing the features of ice conditions in the area of the Shtockman gas-condensate field. That is why, a more detailed analysis of the ice distribution by age categories and concentration for each type was performed.

A heavy ice distribution type is characterized by the following features:

- ice edge is located much more to the south and west of the mean multiyear position;
- Route 3 is completely covered by drifting ice and Routes 1 and 2 - 50% on the average. In some years drifting ice can completely cover Route 2;
- ice on Routes 1 and 2 is present continuously for 3-4 months and on Route 3 - for 5-6 months;
- on all Routes first-year and thin ice prevails, also, 3 cases of the presence of first-year thick ice (1-3/10); were recorded;

- total ice concentration is, as a rule, 9-10/10, only in the marginal area near Routes 1 and 2 there are possible narrow zones of open and very open ice.

An average ice distribution type is characterized by the following features:

- mean multiyear ice edge position when Route 3 is basically completely ice-covered in the period of a maximum ice cover development and on Routes 1 and 2 ice covers only the northern segments 70-90 km long;

- ice on Routes 1 and 2 is present for 1-2 months, usually during March-April;

- first-year thin ice (3-5/10) prevails, separate zones of first-year medium ice (1-3/10) and zones of predominant young ice are possible;

- on Routes 1 and 2 total concentration of 7-10/10 prevails and on Route 3 quite extensive zones of open and very open ice are possible in the marginal zone.

An easy ice distribution type is characterized by the following features:

- ice on Routes 1 and 2 is possible only with the formation of an ice tongue along 40°E which can reach 71°30'N, the length of the ice zone on Route 1 is greater than on Route 2, on Route 3 ice is only in the southern zone;

- ice tongues in the area of Routes 1 and 2 can occur in February-May, however, shifting to warm water the ice quickly destroys, ice persists on the routes not more than for 30 days, on the average;

- an ice tongue on Routes 1 and 2 in March-May mainly consists of first-year thin ice, on Route 3 first-year thin ice prevails;

- on Routes 1 and 2 ice concentration of 1-6/10 prevails and on Route 3 concentration is 7-10/10.

Thus, in severe years the ice of total concentration of 9-10/10 was observed for 3-4 months on all routes of underwater pipelines, the prevailing age gradation - first-year medium ice.
In average years ice concentration of 7-10/10 prevails on the route segments covered by ice, and in marginal zones concentration is 1-6/10, prevailing age gradation - first-year thin ice, on Routes 1 and 2 ice is observed for 1-2 months.

In easy years an ice tongue is observed occasionally on Routes 1 and 2 with ice concentration mainly 3-4/10, and on Route 3 ice is found only in the southern zone, its concentration being 7-10/10.

CONCLUSION

Taking into account natural variability in ice conditions and specialization of information allows an effective use of the classification methods for different stages of exploring natural resources on the shelf of the Arctic Seas.

REFERENCES


The empiric model of vessel movement in the ice and generalization of the experience of the model usage in hydrometeorological support of shipping in the Arctic

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Abstract

The empiric model provides a basis for the method of quantitative assessment of the difficulty of vessel movement in the ice /2,4,12, etc./. There is a description of the model in the references /1,2,3,4, etc./. Unfortunately the conception used in developing the model as well as the efficiency and the reliability of the model usage in solving a wide range of practical problems are not covered enough. The authors decided to make up this deficiency. The principal features of the model, the results of its multi-year usage in hydrometeorological support of shipping in the Arctic are discussed in the report.

The description of the model

The model is intended and widely used in order to calculate the running parameters of vessel movement in the ice. These parameters are the following:

- speed (ice technical \( V_{1t} \) and ice running \( V_{10} \) /7/);
- time periods for the vessel overcoming of ice zones \( (\Sigma T_{1ce}) \);
- durations of vessel stops (idle time) caused by difficult ice conditions \( (\Sigma T_{c}) \).

The calculations \( (\Sigma T_{1ce}, \Sigma T_{c}) \) have some peculiarities but the vessel speed in the ice is the main factor. In this connection the approach to the calculations of \( V_{1t}, V_{10} \) is given below.

The basis of the empiric dependencies for calculating the running parameters is the results of the special AARI's expeditions which have been carried out for more than 2 decades during the trials of new icebreakers and ice-strengthened vessels as well as regular and non-standard (for example the expedition to the Pole) sea operations.

The results of the field observations obtained during the navigation in the compact level ice (fast ice, giant floe) and the ice cake (primarily during the navigation along the leads made in advance) of 10 tenth concentration are accepted as "benchmark" one. The requirements of stability of field experiments are performed exactly under these conditions.

Most representative data of the field observations on
icebreakers and vessels of various classes can be approximated:

a) compact ice

\[
V_{1t} \frac{s}{1} = V_0 - \Delta V_c = V_0 - \left[ FV_0 \frac{H_1}{H_1 + kH_1} + D \frac{H_1(H_1 + bH_1)}{e^{2H_1} + e^{-2H_1}} \right] - (1)
\]

\( V_0 \) - technical vessel speed in the ice free water;
\( H_1 \) - ice thickness outside hummocks (level ice);
\( H_1 \) - maximum thickness of the level ice overcome by the vessel with \( V_{1t} \frac{s}{1} \approx 1.5 \) knots (ice trafficability /8/). The values of \( H_1 \) for some icebreakers are given in Table 1.

When \( H_1 > H_1 \):

\[
V_{1t} \frac{s}{1} = 1.5 \left( \frac{H_1}{H_1} \right)^n - (2)
\]

\( F, k, D, b, n \) - empiric coefficients

b) ice cake (10 tenth concentration):

\[
V_{1t, \frac{1}{c}} = V_0 - \Delta V_{1/c} = V_0 - V_0 \frac{H_1}{N^2} - (3)
\]

\( L, B \) - length and width of the icebreaker, m;
\( N \) - power, thousand of h.p.;
\( M, z, d \) - empiric coefficients.

c) intermediate forms (ice cake) with 10 tenth concentration:

\[
V_{1t} = V_{1t} \frac{s}{1} \left( 1 - \frac{1}{e^{1/L}} \right) + V_{1t, \frac{1}{c}} \frac{1}{e^{1/L}} - (4)
\]

\( L \) - length of the vessel, m;
\( I \) - mean length of ice formations overcome by the vessel, m.

Table 1

Ice trafficability (\( H_1 \)) and speed in the ice free water (\( V_0 \)) for some icebreakers of various powers (\( N \))

<table>
<thead>
<tr>
<th>Icebreaker</th>
<th>( N )</th>
<th>( V )</th>
<th>Ice trafficability (( H_1 )), m</th>
<th>( L )</th>
<th>( B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Arktika&quot;</td>
<td>75</td>
<td>21,6</td>
<td>1,90</td>
<td>148</td>
<td>30</td>
</tr>
<tr>
<td>&quot;Ermak&quot;</td>
<td>41,4</td>
<td>19,0</td>
<td>1,55</td>
<td>135</td>
<td>26</td>
</tr>
<tr>
<td>&quot;Moskva&quot;</td>
<td>26</td>
<td>18,6</td>
<td>1,20</td>
<td>123</td>
<td>24,5</td>
</tr>
</tbody>
</table>

31
The empiric coefficients in the dependencies (1-4) are obtained for winter and summer separately. The dependence mentioned below is used in order to take into account the season changes of $V_{lt}$ during the whole year:

$$V_{lt} = V'_{lt} \Psi + V''_{lt}(1-\Psi)$$  \hspace{1cm} (5)

$V'_{lt}$ and $V''_{lt}$ - values of technical ice speed under given ice (5) conditions respectively in winter and in summer; 
$\Psi$ - season coefficient.

The technical ice speed $V_{lt}$ /7/ is an indicator of maximum technical vessel capabilities in operating in the ice. As to icebreakers the usage of the full power of a power plant is expected. In actual practice, according to the ice conditions mariners change a operating regime of the power-plant rather frequently. In this case the speed of vessel movement in the ice is named as ice running ($V_{l0}$) /7/.

The following dependencies are obtained to calculate ($V_{l0}$):

$$V_{l0} = (AV_{lt}+B)[1 - e^{k(5-V_{lt})}] + V_{lt}$$  \hspace{1cm} (6)

$A, B, k$ - empiric coefficients.

$V_{lt}, V_{l0}$ in level ice (fast ice and drifting ice of 10 tenth concentration) in any season can be determined on the basis of the above dependencies.

We mean the vessels used now for which the empiric coefficients have been obtained and the reliability of calculation have been also checked.

Operation of vessels in the level ice is scarcely carried out. In actual practice there is the ice cover the conditions of which are determined by some parameters /7/. Among them, concentration (C), thickness (H), snow depth (h), ridges and hummocks concentration (T), stages of melting (R), forms of ice (F) and compacting (Cg) make the most important impact on the vessel movement.

Ways of determining the above parameters along the vessel route and taking them into account in calculating ($V_{lt}, V_{l0}$) are stated in developing the model.

Investigations were to solve two problems:
- to work out the line of attack which will take into account the selective vessel movement in the ice, going round the most difficult regions. The zones favourable for the ice navigation are to be mostly used;
- to obtain the quantitative dependencies which allow to determine the values of the above ice cover characteristics along
the vessel route on the basis of observational data and materials of the regime generalizations. Necessity of solving this problem is caused by the fact that not all the characteristics of the ice cover are a subject of regular observations.

The statistical dependencies which relate the ice cover characteristics (concentration, ridges and hummocks concentration etc) immediately along the vessel route and their values in the whole region of navigation are the result of solving the first problem.

While solving the second problem the following empiric dependencies were obtained on the basis of the statistical processing of the rather representative observational data:

- stages of melting of ice of any age

\[ R_{T,c} = aR^d_{0T}; \quad R_{0T} = kR^b_{T,c}; \quad R_{WH} = 0.67R_{0T} \] (7)

\[ R_{T,c}, R_{0T}, R_{WH} \] - stages of melting of thin, medium and thick first-year ice as well as multi-year ice respectively.

\( a, d, k, b \) - empiric coefficients;

- thicknesses of ice of any age during melting:

\[ H_1 = \left[ 1 - e^{-R_{max}} \right] H_{max} \] (8)

when the stages of melting are not over 2 tenth;

\[ H_1 = H_{12} \left[ (0.022H_{max} - 0.25)R_1 - 0.048H_{max} + 1.47 \right] \] (9)

when the stages of melting is over 2 tenth:

\( H_1 \) - ice thickness calculated, m;

\( H_{max} \) - maximum (before melting) thickness of ice of certain age.

\( R \) - stages of melting, tenth;

- "additional" ice thickness (\( \Delta H \)) at the expense of ridges and hummocks concentration:

\[ \Delta H = (0.031T^2 + 0.125T - 0.156) H_1 \] (10)

\( \Delta H \) - increase of ice thickness at the expense of ridges and hummocks concentration /10/;

\( T \) - ridges and hummocks concentration, tenth;

\( H_1 \) - thickness of the level ice, m;

when \( T \leq 1 \) tenth, \( \Delta H = 0 \).

- compacting of various intensity (G.N.Sergeev, 1971):
\[ V_{lt} = \xi \cdot V_{lt} \]  

\[ V_{lt} \] - ice technical speed in the ice under pressure; 

\[ \xi \] - empiric coefficient calculated according to the following dependencies:

\[ \xi = 1 - 0.13 \left( 0.16H_{1r} + 0.92 \right) \]

\[ \Delta H_{cX} \]

\[ H_{1r} = 2.6 \left( H_{1} + \frac{\Delta H_{cX}}{H_{1}} \right) \]

\[ \Delta H_{cX} = 0.45; 0.70 \] when compacting is 1, 1-2, 2 tenth respectively. Determination of the empiric dependencies which take into account the ice concentration for various compositions of ice thickness (age) along the vessel route presents significant difficulties.

As it evident from the foregoing, rather reliable dependencies are obtained for the vessel movement in the ice free water and compacted ice of 10 tenth. On the basis of this approach, the vessel movement in the various compacted ice can be considered as two fictitious components: the first one - the movement in the ice free water, the other - in the ice of 10 tenth. This method of attack reduced the problem to the determination of the conventional (or relative) length of the route \( (S_{1cX}) \) passed by the vessel in the ice of 10 tenth when the concentration is given. Obviously that for the whole region:

\[ \sum_{i=1}^{n} S_{1cX} = 1 \]

Essentially all the data of the field observations obtained and generalized for 2 decades are used to calculate \( (S_{1cX}) \). When the drifting ice along the vessel route is of the same age the calculations are carried out:

\[ S_{1cX} = \frac{V_{lt \ 10} \ (V_{0} - V_{lt \ 1})}{V_{lt} \ (V_{0} - V_{lt \ 1})} \]  

\[ V_{lt \ 10} \] - technical ice speed in the ice of given thickness, the concentration is 10 tenth; 

\[ V_{lt \ 1} \] - technical ice speed in the ice of the same thickness but the concentration is different.
The calculation results for the whole spectrum of concentration and a wide range of thicknesses can be approximated:

\[
S_{\text{Ice} 1} = f(C_1, H_1, H_t)
\]

\(C_1\) - ice concentration, tenth. If the drifting ice of various concentration is of various age the relative route length in each age group should be calculated:

\[
S_{\text{Ice} 1} = (1 - \Sigma S_{\text{Ice} i-1}) S_{\text{Ice} 1} \quad i = 1 \ldots n-1
\]

\[
S_{\text{Ice} 1} = 1 - \Sigma S_{\text{Ice} i-1} \quad i = n
\]

\(S_{\text{Ice} 1}\) - relative route length in the ice of each age group; \(C_1\) - individual concentration of ice of each age; \(C_1\) - conventional individual concentration (put to 10 tenth); \(S_{\text{Ice} 1}\) - relative route length in the ice of the concentration of \(C_1\).

The calculation of \(S_{\text{Ice} 1}\) is carried out step by step for each age group. The calculation is started from the "oldest" age group /9,

Finally, having determined the relative (put to 10 tenth) route length and the ice technical speed in these ice the technical ice speed for the whole region the ice conditions of which is given is calculated:

\[
V_{\text{It}} = \frac{1}{S_{\text{Ice} 1} + S_{\text{Ice} 2} + \ldots + S_{\text{Ice} n}} \quad V_{\text{It} 1} + V_{\text{It} 2} + \ldots + V_{\text{It} n}
\]

The dependency (6) allows to change from the technical speed to the running speed. The accuracy of calculation for the running parameters of icebreakers of various classes has been checked for essentially all the spectrum of the ice conditions in the Arctic.

Clearly, the greater variability of the ice cover characteristics (thickness, concentration, ridges and hummocks concentration, compacting, etc.) the smaller accuracy of calculation (Fig. 1). Until the present time the calculations of the running parameters \((V_{10}, \Sigma T_{\text{Ice}}, \Sigma T_c)\) during the pilotage have been carried out according to the dependencies like:

\[
V_{10} c = f(V_{10}, H_1, \Psi)
\]

\(V_{10} c, V_{10}\) - ice running speed of the train and the
icebreaker (without the pilotage).

\[ H_1 \] - ice thickness;
\[ \Psi \] - season coefficient.

The empiric model has been recently adopted to calculate the running parameters of the ULA-class vessels (like "Amguema", "Norilsk").

It allowed to work out the calculation algorithm for the system "icebreaker-vessel". There is a wide range of compositions of the ice cover characteristics there.

The results of the empiric model usage in the interests of hydrometeorological support of shipping in the Arctic will be further considered. The areas of the model practical usage are quite various:

- zoning of the NSR according to the difficulty and security of the navigation /11/;
- background and development of the sea transportation along the new routes particularly from the Ob Bay /4/, Kharasavey Cape;
- to assess the possibility of increasing the duration of the navigable period by means of modern shipping facilities;
- to assess the reliability of the sea transportation along the part of the NSR which is given.

The empiric model is widely used in science-operative support of shipping in the western Arctic (N.Adamovich, 1987-95).

The comparison of the calculation results on the basis of the model and the real process of sea operations is of great interest. Some examples of such a comparison are given below (Tables 2.3, Fig.2). There is an evidence that accuracy of calculation depends on the ice conditions for which these calculations are made (Fig.1) and mainly on the reliability of the data on the ice cover characteristics.

Since the new instrumental methods of diagnostics of the ice cover real possibilities to adopt the empiric model to the new sources of information on the ice cover have been recently developed.

As a conclusion we state that the improvement of the empiric model is now underway towards considering the vessel work under the most difficult ice conditions (activity by impacts, movement in the ice under pressure, etc.).

The preliminary results of such investigations are promising.
Table 3

Comparison of the calculated ($T_c$) and actual ($T_a$) time period spent on waiting for the improvement of the ice conditions, the pilotage was carried out by the "Kola" motor vessel, May-June, 1987

| Region of Predominant Mean Durations Duration of the navigation ice speed of vessel compacting calculated actual (knots) (hours) $(T_c)$ $(T_a)$ |
|--------------------------------------------------|-----------------|-----------------|------------------|------------------|
| Laptev Sea Areas of thick first-year ice, ridges and hummocks concentration of 2-4 tenth. | 6,5 | 73 | 6 | 8 |
| Western East- Ice breccia of Siberian Sea multi-year ice including thick first-year ice, ridges and hummocks concentration of 3-4 tenth. | 1,7 | 183 | 83 | 91 |

REFERENCE

Table 2. Comparison of the calculation results of the operation indices (\(V_o\), \(ST\), \(s_v\)) for the atomic icebreaker of the "Arktika" type with the observation data during cruise in the arctic basin in the years 1987-1994 (july-august).

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<th>Characteristics of ice zone accounting for peculiarities of icebreaker movement</th>
<th>Observation data for multiyear ice concentration (arbitrary units)</th>
<th>Model calculation results data for multiyear ice concentration (arbitrary units)</th>
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\[ \sigma_v, \text{ knots} \]

\[ \text{max, mean, min} \]

\[ \bullet \text{observation data for the Arctic basin} \]

Fig. 1. Variation of the mean square deviation of the ship's velocity (\(\sigma_v, \text{knots}\)) relative to the ice age (and the ice thickness).

38
Fig. 2. Results of correlation of the $V_{lo}$ calculation (1) and the observation data for SA-15 ship navigation in the consolidated floating ice (fast ice) of the different thickness ($H$, cm) in the winter period.


The automated forecasting system for the scientific-operational support of the navigation in the Arctic.

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A. Yulin

Arctic and Antarctic research institute
St. Petersburg, Russia

ABSTRACT

The quite important way of improving the quality of long-range ice forecasts is to improve the methods of forecasting. The problems of searching and selecting the optimal informative predictors can be addressed in the framework of creating the Automated Forecasting System (AFS) on the basis of the linear combinations using the computer.

Utilization of the automated forecasting system "PEGAS" has shown its obvious effectiveness not only for forecasting, but for research as well. Using the AFS "PEGAS", one can successfully study data sets of large volume and single out optimal predictors from them, estimate a statistical dependency between predictors and predictants and construct linear regression models.

INTRODUCTION

The formation of ice conditions in the Arctic Seas is governed to a large extent by the character of atmospheric processes, on which the intensity of ice growth and melting and also its drift depend. That is why further development of long-range ice forecasts is closely connected with the solution of one of the most acute problems of present-day meteorology, that is: to find out physical causes for the occurrence of long-period anomalies of atmospheric circulation.

Another, equally important, way of improving the quality of long-range ice forecasts is to improve the methods of forecasting.

To resolve this problem on the basis of constructing the correlation dependencies results in a contradiction of some kind. On the one hand, the complexity of the investigated processes requires the inclusion of a large number of the arguments into the regression coefficients. On the other hand, at small observations series this leads to the instability of the calculated statistical parameters.

Removal of this contradiction is possible by means of the methods which allow one to identify highly informative characteristics from initial data. This task is resolved by the information transformation.

PROBLEM

Let us call a set of data on the state of the atmosphere and
the ocean the information system \( A \). Then under the system of the predictors \( (X) \) one should understand the results of the transformation \( (F) \) of the system \( A \), that is

\[
X = F(A).
\]

The information system \( (A) \) and the respective system of the predictors \( (X) \) is not something absolute and constant. They can vary depending on the task set. And the variation can be both due to the choice of system \( A \), and due to the transformer \( F \).

If the forecasted ice conditions are designated as \( L \), then the ratio between \( A, X \) and \( L \) can be represented in the form of the following scheme:

\[
A \rightarrow X \rightarrow L
\]

This scheme illustrates the fact that the data on the state of the atmosphere and the ocean, collected in \( A \), are used in the ice forecasts not directly, but through the system of the predictors \( X \).

And the case is possible, when \( X \), being comprehensive characteristics of the system \( A \) is not of large value for \( L \) forecasting. And vice versa, characterizing the system in rather a limiting way, the system \( X \) can turn out to be informative relative to the future ice conditions.

As has already been mentioned above the transition from the system \( A \) to the predictors \( X \) is connected with the \( F \) transformation. Such transformation usually results in a decrease of the volume of the initial information, its reduction.

The latter circumstance is of major importance since the total information volume in \( A \) is usually quite large and cannot be fully used during \( L \) forecasting.

One should distinguish between the structural and the relative compression methods.

The goal of the structural compression methods consists in finding out the transformation which leads to such a system of \( X \) predictors, on the basis of which one can reconstruct the initial information system \( A \) with a prescribed degree of accuracy. The relative methods of compression are aimed at delineating such part of the information which is directly relevant to the future ice conditions. Here, from a prognostic viewpoint the method of relative compression appears to be more effective. A general feature of the relative compression methods is the fact that the \( X = F(A) \) transformation is based on taking into account the properties of \( L \). This gives a possibility to extract from system \( A \) the required information, screened by the processes which do not have any relation to the forecast.

A multi-dimensional discriminant analysis can serve as an
example of a relative compression. The study made which is aimed to estimate the effectiveness of discriminant analysis during the forecasting of the ice cover extent of the Arctic Seas has shown that the predictors, identified by means of a discriminant analysis are sufficiently informative [3].

Quite important appears to be the fact that the relative methods of compression can be constructed in such a way that the information thus identified would be maximum relative to the criterion chosen. This allows one to make optimal the decisions, connected with the search and selection of the informative predictors. Since the entire procedure for the development of the forecasting method consists of the solutions of such kind, it appears to be possible to make this process automatic on the basis of a wide use of the relative compression methods.

AUTOMATED FORECASTING SYSTEM "PEGAS"

The problems of searching and selecting the optimal informative predictors can be addressed in the framework of creating the Automated Forecasting System (AFS) on the basis of the linear combinations using the computer [4]. The principal diagram of such system is shown in Fig. 1. The information system, which includes the archives of ice and hydrometeorological information is considered to be its obligatory component.

The most suitable form of presentation of the latter appears to be the fields of geopotentials, atmospheric pressure, water, air temperatures, etc., prescribed in the points of the grid overlapping the region under study (for example, part of the hemisphere to the north of the parallel $50^\circ$ N).

The next block of the AFS is the program for calculating the differences in the characteristic values between all grid points. Particularly informative appear to be the atmospheric pressure differences, characterizing the geostrophic flows in the atmosphere. For air temperature its direct values can turn out to be more informative in some regions.

From the large number of the obtained characteristics it is necessary to choose a restricted number of the most informative predictors, containing that part of the information, which has a direct relevance to the future ice conditions. For this the threshold values of quotient correlation coefficient for the given volume of sampling at a prescribed probability are used as a criterion during the selection of the predictors in the corresponding AFS block. The reduction of the volume of initial information is achieved by a more strict component at the
selection of significant coefficients.

Fig.1. Block-diagram of the automated search system for the optimum predictors and the construction of prognostic equations on the basis of linear combinations.

Taking into account that some anomaly or other of the ice characteristics is formed under the effect of non-uniform factors for a prolonged time interval, and the volume of the available samplings (the length of the observation series is usually small), the total number of the selected informative characteristics on all fields and time intervals, as a rule, exceeds the permissible number of the predictors to construct the regression equation. That is why for each group of the informative characteristics referring to a single field, there is one generalized predictor $P$, representing a sum of the effect coefficients $- K$:

$$ P = \sum K, $$

where the $K$ values are calculated by the formula:
$x = u \times r^2$, 
here $U$ - calculated value of the function by the regression equation; $r$ - square of the quotient correlation coefficient.

Similarly, the generalized predictors for several fields are obtained. In this case, the coefficient of the effect of the characteristics of all fields analyzed are summed up. The final prognostic equation has the form:

$$U = a \sum P + b$$

where $n$ - number of the information fields taken into account.

The suggested automated system envisages a possibility to conduct the analysis at any calculation stage, which is very important to account for the physical nature of the identified predictors, to prescribe different criteria to select the informative characteristics, to determine the errors of calculation (forecast) for the entire series of the forecasted phenomenon.

The program envisages the possibility to choose from the archive of multiyear data the length of the series, equal for all characteristics used in the calculation, as not all characteristics, entered into the archive can have the same observation series.

One more feature of this system is the possibility of its constant adjustment with the increase of the observation series and input of new hydrometeorological characteristics.

The automated system was preliminarily tested relative to the forecasts of the ice cover extent of the Arctic Seas and their regions. As initial data, the fields of mean monthly atmospheric pressure, expressed by its values in 189 grid points covering the Arctic region, were taken. Preliminarily, in order to reduce the information volume, these data were averaged over 21 regions. Also, the series of mean monthly air temperature values over the Arctic Seas were used.

The analysis of the results has confirmed the typical features known earlier, which characterize spatial and temporal dependencies of the ice cover extent of different regions on weather conditions [1].

The use of the above-mentioned archived data on air pressure and temperature has allowed for the construction of the prognostic schemes for the ice cover extent of the Arctic Seas 6-8 months in advance [2,5].

The testing of the verification score of the forecasts was made on independent data. For the analysis, the ice cover extent
series of the Barents, Kara, Laptev, East-Siberian and the Chukchi Seas for July-September was used. The assessment of the verification score of the January and March forecasts has shown their sufficiently high effectiveness, being 8-19% (with permissible error ±6 - for the January forecasts) and 16-33% (with permissible error ±0.8 6 - for the March forecasts).

In the final form the automated system yields the following characteristics:
- informative predictors, selected from the pressure fields and other hydrometeorological characteristics;
- regression equations between each informative characteristics and the forecasted characteristics;
- a generalized predictor for the entire series, used in the calculation;
- final regression equation between the generalized predictor and the forecasted characteristics;
- final result, containing the actual and prognostic series and the forecast error for each year which allows for the determination of the verification score of the forecast for the entire series used.

COMPUTER VERSION OF THE AFS "PEGAS"

The need for elaborating a computer version of the AFS "PEGAS" was caused by a wider range of problems whose solution requires the use of "PEGAS". Moreover, the development of local information grids has expanded the access of the AFS "PEGAS" to hydrometeorological databases of different spatial-temporal scales existing at the SSC AAK.

All service possibilities of the software were preserved when elaborating the computer variant. Using the AFS one can estimate a statistical relation between the predictor and predictant, select the predictors with the most statistically significant connection with predictants (by the criterion of the correlation coefficient critical value prescribed by the user). It also allows unification of the selected predictors into a general (generalized) one taking into account their significance (that is determined by a squared correlation coefficient value) and construction of forecasting schemes (linear regression equations) of a prescribed advance period.

Elaboration of the AFS "PEGAS" computer variant requires a significant revision of the procedure for the initial data preparation and grouping.

The initial data in the software computer variant are read from the files of electronic tables of the standard package.
"Paradox". This package of electronic tables has not been chosen by chance. Besides different advantages (vast system of database management) the "Paradox" has considerable possibilities to import and export data in the formats of some other packages of electronic tables such as "Lotos-1-2-3", "Windows", "Quattro Pro", etc. This extends the possibilities for using the AFS. The AFS can be applied to any data that are imported to the electronic tables of the "Paradox" package.

The basic working databases used for developing a long-term ice forecast - mean monthly surface atmospheric pressure fields for the Northern Polar area in the grid cells and mean monthly air temperature values over the regions were also formed in the "Paradox" package electronic tables.

The sets of predictors prepared for calculations are exported in the ASCII codes into the working file. Service information No. 1 describing general conditions of calculation is given in the special file. It includes: length of time-series used for calculations, quantity of the sets of predictors, quantity of the sets of predictants, initial date of calculation. The program is run by the executive file "pegas.exe". Calculation results are written into the file "res.dat". All files are collected in the "PEGAS" directory, occupying the memory of about 0.3 MB and require not more than 1 diskette 3.5' HD. The utilization of the AFS "PEGAS" is possible on any IBM-compatible PC.

APPLICATIONS AND CONCLUSIONS

Effectiveness of the elaborated computer software has been tested by the example of preparing a long-term forecast of the ice cover extent in the Arctic seas 6 months in advance.

The fields of mean monthly surface atmospheric pressure for July-December of the preceding year presented in 21 grid cells covering a vast zone of the Arctic for the period from 1955 to 1994 were used as initial data for calculations (Fig.10). The ice cover extent of one of the Kara sea regions in July- first half of August from 1955 to 1994 was taken as an element to be forecasted.

As a result of consecutive calculations made by means of the program, the final prognostic result for all years used for calculations is printed. An example of the calculation by "PEGAS-M" program is presented below.

The calculation results contain:

- quantity of sets used for the calculation (in this particular case they are 7: 6 sets contain the pressure field information
from July to December, the 7th contains ice cover extent; - the number of grid cells characterizing the pressure field (21 grid cells); the additional 22nd grid cell contains pressure values equal to zero (such method allows obtaining the informative characteristics directly from pressure values in one of the grid cells and also from pressure differences); - the following six lines contain the most informative selected differences of pressure (Arg 1, Arg 2) and regression equation of this difference with ice cover extent (where AQ is a free term, A1 is regression coefficient, R is correlation coefficient, R2 is squared correlation coefficient); - SR value is a generalized index for all pressure fields from 1955 to 1995; - regression equation between a generalized index (SR) and actual ice cover extent (Φ); - the following lines contain calculated (forecasted) values of ice cover extent (B) and their difference from actual ones (P = Φ - B).

Fig. 1. Grid area cells for characterizing the pressure field.

A comparison of the forecast errors with a value of ice cover extent (L) which is considered to be a criterion for testing the forecast verification gives an opportunity to estimate the probability of the forecast method.

In the given case at the value 6 = 16 % the probability of
ice cover extent forecast for a given series is equal to 90 \%, while the probability of the forecast based on the interannual mean value (L=49 \%) is equal to 58 \%.

Thus, the effectiveness of the forecast method when compared to the probability of the forecast based on normal values is quite high.

An example of the calculation using the "PEGAS-M" software

PEGAS-M software predictor sets set length of predictors crit.

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REFERENCES

INTRODUCTION

Exploration of oil and gas fields on the shelf of the Russian Arctic Seas and international use of the Northern Sea Route for shipping are connected with constant operations under complicated weather conditions of the Far North.

Hence, special hydrometeorological support, including ice forecasting, should be developed in advance or at least along with increasing activities on the shelf.

Calculations and forecasting of different characteristics of the sea ice state and its most probable change in time are an integral component of composite information on hydrometeorological conditions of the Arctic region. In some cases only calculation methods can compensate the absence of direct observations and reconstruct spatial-temporal variations in ice processes.

At the present time the AARI has methods for numerical forecasting of changes in sea ice state in the Pechora, Kara Laptev, East-Siberian and Chukchi Seas. These methods are based on the mathematical model of the evolution of ice cover under the effect of dynamic and thermal factors. This model was specially created for ice forecasting purposes. A spatial interval of the model is equal to 25 km, the calculation of changes in the ice edge position is made with an accuracy of 5 km.

It is necessary to note that sea ice models for operational hydrometeorological support have the following features distinguishing them from the models that are used for addressing research objectives:
- the description of physical processes in ice cover should take into account a real contribution of each of them to total variability in ice cover,
- a wide use of empirical parameters obtained when processing full-scale observations in a specific region for which calculations or forecasting were performed,
- a model is oriented to using really accessible hydrometeorological information, updated on a regular basis,
- a model has a friendly interface providing for a quick assimilation of initial data, calculations, conversion of the calculation results to the convenient form.

Methods using a prognostic model of ice cover evolution allow calculating seasonal (1-3 months) and synoptic variability in a spatial distribution of the most important sea ice characteristics:
- drift velocity,
- concentration,
- ice thickness,
- position of the drifting ice edge,
- position of pressure zones.

MODEL DESCRIPTION

Changes in ice conditions are governed by the influence on the ice cover of both the dynamic and thermal processes, that is why, the model includes corresponding calculation blocks.

The dynamic block of the model uses the prognostic fields of surface air pressure averaged over time intervals not less than one day, as initial data. This allows one to calculate the drift velocity on the basis of stationary momentum balance equations, since a typical time for the drift establishment does not exceed 3-4 hours. To find the ice cover characteristics, connected with the ice mass change it is necessary to use non-stationary equations. Ice mass changes for the model time interval (24 hours) insignificantly affect the drift velocity. That is why, the numerical solution is made by the splitting method, when one calculates the drift velocity, thermal change of the thickness and concentration of the ice cover, their kinematic distribution in succession.

The stationary momentum balance equation in the vector form is as follows:

$$\vec{\tau}_a + \vec{\tau}_w + \vec{F}_c + \vec{F}_b + \vec{F}_p = 0$$

- $\vec{\tau}_a$ - tangential stress at the upper ice surface,
- $\vec{\tau}_w$ - tangential stress at the lower ice surface,
- $\vec{F}_c$ - Coriolis force,
- $\vec{F}_b$ - internal interaction force inside the ice,
- $\vec{F}_p$ - projection of the gravity force on sea surface.

For calculating the tangential stress on the upper ice cover surface, the gradients of surface atmospheric pressure field are used.

$$\vec{\tau}_a = K_a (\cos \gamma_s \vec{k} \times \nabla \vec{P}_a + \sin \gamma_s \nabla \vec{P}_a)$$

- $\gamma_s$ - the angle of deviation of surface wind from isobar.
- $\nabla \vec{P}_a$ - the surface pressure gradient,
- $\vec{k}$ - a single vector perpendicular to the horizontal plane,
- $K_a$ - the coefficient of proportionality.
The tangential stress at the lower boundary is determined in a similar way:

\[ \tau_w = K_w (\cos \gamma_w (\bar{W} - \bar{U}_g) + \sin \gamma_w k \times (\bar{W} - \bar{U}_g)) \]

- \( \bar{W} \) - the drift velocity,
- \( \bar{U}_g \) - the speed of the current at the lower boundary of the friction layer,
- \( \gamma_w \) - the angle between the drift vector and the tangential stress,
- \( K_w \) - the coefficient of proportionality.

The Coriolis force and the projection of the gravity force on sea surface are expressed traditionally:

\[ \bar{F}_c = -2\rho_i H \bar{\omega}_z \times \bar{W} \]
\[ \bar{F}_p = -\rho_i H g \nabla \delta \]

- \( H \) - the ice thickness,
- \( \bar{\omega}_z \) - the angular speed of the Earth's rotation,
- \( g \) - the acceleration of the free fall,
- \( \rho_i \) - the ice density,
- \( \nabla \delta \) - the level surface tilt.

Let us note that the current speed at the lower boundary of the friction layer and the tilt of the level surface are not calculated directly inside the model. One uses in the forecasts mean fields of the current speed and level sea surface, obtained as a result of combining field observations and model calculations for the most frequent pressure situations.

To calculate the internal interaction force one uses a quasiviscous description of the rheology of the ice cover, at which the given force represents the divergence of the internal stress tensor \( \sigma_{ij} \)

\[ \bar{F}_b = \frac{\partial \sigma_{ij}}{\partial x_j} \]

To prescribe the boundary conditions on the shore appears to be an important part of the problem of determining the ice cover drift. And a different approach should be used depending on the fact whether the drift is off-shore or on-shore. The indicated choice is made in the model by the comparison of the direction of the coastline and the drift velocity.
For the on-shore drift it is permissible to assume only the velocity component normal to the shore to be equal to 0. When determining the component, parallel to the shore, in order to enhance the accuracy of approximating the derivatives on the grid area scale, it is suggested to take the velocity not near the shore, where the condition of the non-drift is fulfilled \( \bar{W} = 0 \), but rather at the external border of a narrow boundary layer of some hundred meters where the velocity gradients are maximum. In this layer, shear strains and tangential stresses play the largest role, and the viscosity coefficient is assumed to be dependent on the stress normal to the shore.

When the drift is outside the calculation area, at the liquid boundary, the derivative of the velocity is assumed to be equal to the neighboring value of the derivative in the internal calculation area.

In modelling the ice cover characteristics for the period of more than 3 days it is necessary to take into account a change of sea ice thickness and concentration as affected by thermal processes. Calculation of the heat flux through the underlying surface is carried out on the basis of the heatbalance equation:

\[
Q_R = Q_\Sigma (1 - \alpha) + Q_T + Q_C + E_A - E_S
\]

- \( Q_R \) - resulting heat flux through the surface,
- \( Q_\Sigma \) - incoming total solar radiation,
- \( \alpha \) - albedo of the underlying surface,
- \( E_S \) - long-wave radiation of the underlying surface,
- \( E_A \) - long-wave counterradiation of the atmosphere,
- \( Q_T \) - turbulent heat exchange with the atmosphere,
- \( Q_C \) - heat flux, connected with evaporation and condensation,

The features of the thermal block are: allowance for the air temperature transformation depending on the underlying surface state and the direction of air transports, as well as the effect of mesoscale inhomogeneity of ice and snow thickness on the melting processes by means of calculating the probability density changes in the ice thickness distribution. The latter allows one to define the time of the melt water appearance on the ice, which induces a sharp change in the ice cover albedo, differences in the melting of level and hummocked ice, change in the concentration due to the melt out of the most thin ice, formed in cold time in the cracks, leads and fractures of a dynamic origin.

For calculating a kinematic change in concentration and thickness of the ice cover, an original method has been developed which allows suppressing to a great extent the effect of the calculation viscosity related to the finite-difference representation of
differential equations. In this method ice concentration in the grid cell is governed not only by mean value, but also by the first instant of its spatial distribution.

RESULTS OF USING THE MODEL

For example, let us consider the forecast for ice concentration redistribution in the south-western Kara Sea.

Fig. 1 presents the actual distribution for July 12, 1992, that was used as initial one. Fig. 2 presents the forecast for July 19, 1992 issued 7 days in advance and Fig. 3 presents the actual distribution of concentration for the same date.

Fig. 1 Actual total ice concentration, 12 July 1992
Fig. 2 Total ice concentration calculated for 19 July 1992.

Fig. 3 Actual total ice concentration, 19 July 1994.
Changes in concentration of the ice cover for the calculation period are related to the effect of south, south-west winds and intensive melting under the influence of the outflow of warm air masses. The main features of the evolution in concentration as affected by the indicated processes, are seen on the calculated and the actual charts and in our opinion, they coincide.

Instead of the zone of 1-3/10 a strip of open water is formed to the north-east of the Bely island. The ice patch of 7-8/10 blocking the approaches to the western coast of the Yamal peninsula has disappeared, but directly along the coast there is still a strip of close ice of 9/10 formed by fast ice fragments and exported from the Baidaratskaya Gulf.

The zones of 7-8/10 and 9-10/10 off the southern shore of Novaya Zemlya are significantly reduced in size and the navigation conditions on the segment Kara Gate strait-Bely Island have become on the whole more favorable.

The differences in the position of the boundaries of the zones are connected both with calculation errors and with the inaccurate prescription of initial information (an increase in the number of zones small in area and a large irregularity of their boundaries on the actual chart of July 19, 1992 as compared to the initial chart of July 12, 1992, indicates not only changes in the ice cover, but improved observation conditions as well).

Operational ice forecasts calculated on the basis of this model are regularly issued at the AARI during the navigation period. The background seasonal forecast is 1-3 months in advance, operational forecast - 7-8 days corresponding to the advance period for forecasting surface atmospheric pressure and to the time for updating initial ice information collected over the area of the seas of the Russian Arctic.

The quality of forecasting the ice cover characteristics was verified by a number of model experiments whose results correspond to the actually observed behavior of ice cover. Quantitative estimates of the accuracy of calculating the ice drift velocity were performed using data on the coordinates of the drifting radiobuoys "Argos". On average, for calculating the ice drift velocity 5 days in advance, the velocity module error was 20% and the calculation probability of the drift direction at a 45 degrees allowance was 87%.

Concentration is the main characteristic, used for estimating the verification score of forecasts. The value 0.674 σ is used as a root-mean-square deviation of the concentration change for the advance period. At the same time since regular ice data are reported in the form of the charts at which the zones of standard concentration gradations are identified: 10-30%, 40-60%, 70-80%, 90-100%, an alternative scheme for the forecast verification is possible. And it is permissible that if actual and prognostic concentrations in the cell are in one gradation zone, then the verification...
score is 100%, if the indicated values are in adjacent gradations, then it is 50%, in other cases it is 0%.

Mean verification score of the prognostic fields of the concentration, calculated by both methods is 75-80%.

This model, as well as possible approaches to modelling of the processes in the ice cover are described in much detail in the monograph of Dr. Appel I.L. and Dr. Gudkovich Z.M., 1992.

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DESTRUCTION OF AN ICE BY EXPLOSIONS OF A GAS.

W. Tripolnikov (Arctic and antarctic research institute, S.-Petersburg)

An explosion is a radical mode for destruction of an ice in arctic off-shore building. It is self-evident that explosion must be realised without detracting for environment and building. To solve these problems we research structures of explosive substances and technologies of explosive work. Some developments on subject of destruction of ice cover near marine buildings by method of explosion of gas in the underice envelope cavity are covered by patents [1]. Figure 1 shows our experiment - it is explosion of some “CnHm + O2” gas mixes (GM) in

![Figure 1. - The explosion of gas in underice cavity](image1)

![Figure 2. - Destruction of ice by explosion of gas](image2)

underice cavity, figure 2 shows fragments of ice as the result of this explosion. It is well known [2] that with explosion of GM in air at the ground level produce peaks of shock waves pressure

\[ P^* = \left(0.08\gamma + 0.22\gamma^2 + 0.12\gamma^3\right), \text{ MPa} \]

\[ \gamma = \frac{3}{\sqrt{m/r}}, \]

where \( r \) - a distance from center of gas cartridge (meters), \( m \) - the mass of trotyl that is energy equivalent of mass GM in cartridge (Kilogrammes). According to this equation we have the pressure \(~2.5\ \text{MPa}\) in the boundary of GM with air. All aspects to control trotyl equivalent of GM are in the book [3].
When we exploded GM under ice cover and made the measurements of wave pressure in water the peak pressure also was turned to formula (1) near the cavity boundary. At the deep in water the shock wave pressure is governed by well known formula of P.Cole. Figure 3 demonstrates the impulse of pressure in water which provided by explosion of GM under ice cover (gas cavity). It is of interest to see the duration of the compression wave impulse which is result of shock wave reflection from boundary of ice and air. The shock wave impulse which strikes the contact surfaces of underwater construction is equal to $P^* \cdot 2h/c$, where $h$ - the thickness of ice, $c$ - the velocity of shock wave propagation. At the same time blowing-up under water solid or powder charges produce the shock wave strikes with much superior the foregoing quantity $P^*$.

![Figure 3. Pressure of compression wave in water](image)

At explosions of GM the shock wave performs reduction of the strength properties of ice, and the elevating force of gas cavity performs the destruction of ice cover if the gas burning is enough to create necessary pressure. We studied a possibility to realize the underice gas cavity free of the envelope and to determine the moment for detonation GM.

This problem can be solved in the theory. We consider the special case that the mass speed of gas generation is enough to perform the spherical expansion of gases under water. Let there air the uncompressable water and the speed of expansion is less than the speed of sound. In this case the potential of speed of liquid is (in spherical coordinates):

$$\varphi = R \frac{dR}{dt} + \text{const},$$

and Cauchy integrals is

$$R \left( \frac{d^2R}{dt^2} + g \right) + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 = - \frac{P(t)}{\rho}$$

$R$ - a radius or radial distance, $\rho$ - the density of liquid, $g$ - accelerate of gravity. This is the known equation of pulsed cavity in liquid. The equation of gas condition

$$P = \rho_0 \cdot GT$$

and balance equation [4] between mechanical energy and heat

![Diagram](image)
\[
\frac{d}{dt}(c, p, \rho_0 VT) = Jc_p T_0 - P \frac{dV}{dT},
\]

(5)

where \( V \) - the volume of cavity, \( \rho \) - the density of gas, \( G \) - the gas constant, \( T_0 \) - the initial temperature of gas, \( T \) - the temperature of gas, \( C_p, C_v \) - the specific heat capacity of gas, \( J \) - mass speed of gas. In this problem it is conceivable that temperature is

\[
\left\{ \frac{1}{T} \right\} = \frac{3}{R_0^3} \int_0^R \frac{r^2dr}{T(r)}
\]

(6)
i.e. we considered a homothermal approximation for temperature of gas [4]. We perform the calculations with initial condition: \( R_0 = 0.3 \text{ m}, P_0 = 0.1013 \text{ MPa}, c_p / c_v = 1.4, \rho_0 = 1.29 \text{ Kg/m}^3, \rho = 1000 \text{ Kg/m}^3 \), \( J \) - from 1 Kg/s to thousands Kg/s with some intervals of the gas generation.

The tables 1, 2 gives parameters and results of calculations: the time (\( t \)), a radius of sphere (\( R \)), the speed of expansion \( v = (dR/dt) \), the pressure in cavity (\( P \)), the acceleration of motion of gas-water boundary (\( a = \frac{d^2R}{dt^2} \)) with interval of the gas generation - 1 s and \( J = 1 \text{ Kg/s, 10 Kg/s} \).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The characteristics of dynamic process of expansion of gas cavity in water by ( J = 1 \text{ Kg/s} )</th>
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<td>( t (s) )</td>
<td>( R (m) )</td>
</tr>
<tr>
<td>0.00000</td>
<td>0.300</td>
</tr>
<tr>
<td>0.00298</td>
<td>0.300</td>
</tr>
<tr>
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<thead>
<tr>
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<th>The characteristics of dynamic process of expansion of gas cavity in water by ( J = 10 \text{ Kg/s} )</th>
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</thead>
<tbody>
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<td>( t (s) )</td>
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</tr>
<tr>
<td>0.00000</td>
<td>0.300</td>
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<tr>
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<td>0.365</td>
</tr>
<tr>
<td>0.02981</td>
<td>0.381</td>
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</table>
We performed also the experimental control work in-situ. Figure 4 shows two cavities under ice cover in one can be gas fuel and oxidative gas in another.

Now let us consider the question about the gas pressure in the cavity which is necessary for destruction of ice cover. The dynamic flexure of ice cover would be expressible as a function [5]

\[ w = \frac{1}{2\pi} \int_{0}^{\infty} \int_{0}^{\infty} F(t) k B_0(kr) \sin \left( \left( t - \tau \right) \sqrt{\frac{c}{cm}} \right) dk d\tau, \]  

where \( w \) - a flexure, \( B_0 \) - Bessel function, \( r \) - a radial distance in horizontal plate, \( k \) - a wave number, \( F(t) \) - the elevation force, \( D \) - the cylindrical stiffness of ice. But in this case the flexure is limited by fragile destruction of ice

\[ w^* h \beta^2 = 1.1 \frac{\sigma^*}{E} \]  

where \( \sigma^* \) - the limit of strength, \( E \) - Joung modulus of ice, \( \beta^2 = \left( \frac{\rho g}{D} \right)^{0.5} \)

At first we calculated (7) by variations \( t \) and \( F \), next calculated (8) by variations \( h, E \), \( \sigma^* \) that was interest. In addition we have the tables of solution of equations (2)-(6).

These dates by the uniting consideration are permits to choose one the ice destruction scenarios or to the contrary the ice to conserving.

The table 3 gives the sample of this type calculation with the conditions \( \sigma^* = 1.2 \) MPa (the limit strength of ice extending), \( E = 3000 \) MPa and with the above-listed initial parameters of gas cavity (spherical).

<table>
<thead>
<tr>
<th>Ice thickness, m</th>
<th>Gauge gas pressure, MPa</th>
<th>Massespeed Kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.11</td>
<td>70.3</td>
</tr>
<tr>
<td>1.0</td>
<td>0.26</td>
<td>368.4</td>
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<tr>
<td>2.0</td>
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<td>2626.6</td>
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<td>3.0</td>
<td>1.03</td>
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</tr>
<tr>
<td>5.0</td>
<td>1.96</td>
<td>39159.0</td>
</tr>
</tbody>
</table>

These dates are the approximation

\[ P \approx 0.26 \cdot h^{1.25} \]  

\[ J \approx 370 \cdot h^{2.83} \quad (1 \leq h \leq 5) \]  

\[ J \approx 370 \cdot h^{2.83} \cdot 2^{1-h} \quad (h \leq 1) \]
when \( h \) - meters, \( P \) - MPa, \( J \) - Kg/s.

A close look at the figure 4 will show another aspect of hydrodynamic in this problem among the stirring time interval and the homogeneity of mixture. It is some technical problem a way of detonation GM to perform in all volume of the gas cavity. The reflection of shok waves from ice and air boundary can quench detonation. It has been found [6] that the quenchless detonation is performed by define disposition of initiated charges. We determined experimentally the rule for this purpose: \( T'(r) > T^* \), where \( T' \) - temperature of gas at a front of initiated shok wave, \( T^* \) - the inflamm temperature of GM.

![Figure 4](image)

**Figure 4** Two gas cavities under ice.

It has been found experimentally that methane-air mixes detonation gives effective destruction of ice cover only at thickness of ice under 1 m. Experiments have shown for destruction of ice cover by thickness 2-2.2 m it is needs GM stoichiometric mixture with an oxygen to use and the burning in a mode detonation to realize. For destruction of ice cover by thickness more 2.2 m it is necessary in a mixture GM to added some powder. Doubtless for a solution these problems there are patents and "know-how".

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MODEL TESTS OF TOWED SEISMIC EQUIPMENT PROTECTION MEANS AGAINST ICE FLOES IN ICE MODEL BASIN

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ABSTRACT

The results of the model tests of two types of towed seismic equipment protection means against ice floes are represented. Dynamic forces acting on the towed equipment models were investigated during tests in the ice model basin. Recommendations based on the statistical analysis to improve the efficiency of towed seismic protection means against ice floes are given.

1. INTRODUCTION

The problem of protection of outboard geophysical equipment is actual during marine seismic surveys in an ice environment. The traditional seismic technology does not ensure safety of expensive towed equipment during investigations in an ice environment. The ice fragments sunk by the hull come to the sea surface behind the stern, interact with the seismic streamer, damage its constructional elements, and the largest ones can drag out the streamer on the surface of the ice edge. Therefore the probability of geophysical equipment loss is large during seismic surveys in an ice environment. That is why conducting seismic surveys in an ice environment demands to change traditional seismic technology. To solve this problem the comparative tests of two types of towed seismic equipment protection means against ice floes in different ice conditions were performed in the Ice Model Basin of Krylov Research Shipbuilding Institute.

2. TESTS METHOD

The first type of towed seismic equipment protection means against ice floes (the device N1) was elaborated by scientists of Research Institute of Marine Geophysics and St. Petersburg State Marine Technical University [1].
The main idea of the device N 1 was to remove the entrance of the streamer lead-in cable into the water near the stern of the ship by the use of the hydrodynamic depressor. Additionally the streamer lead-in cable was covered by the metallic fairings for protection against ice fragments. Thus, the entrance of the streamer lead-in cable into the water moves to the influence zone of propeller flows, therefore the probability of the mechanical interaction between the streamer lead-in cable and ice fragments reduces. The metallic fairings protect the streamer lead-in cable from the blows of ice fragments, too.

The second type of towed seismic equipment protection means against ice floes (the device N 2) is suggested by the COWI consult specialists and has the shape of cantilever construction pulled out from the vessel bottom to launch the streamer [2].

The tests of the aforesaid types of towed seismic equipment protection means against ice floes were performed in the ice model basin in a 0.45 m thickness flat solid ice, a broken ice 10/10 coverage and a hummocky ice. The model of the icebreaker "Mudjug" made to scale 1: 20 were chosen for tests in the ice model basin. The models of towed seismic protection means against ice floes were placed on the icebreaker model. During the tests the length of the streamer model was equal to the length of the icebreaker model. The cantilever construction pulled out from the vessel bottom on the length equaled 1.5 draft of the icebreaker model was located near the 12-th rib. The tests were conducted on the whole working part of the ice model basin 25 m in length with the speed of the carriage equaled 0.4 m/s. During these tests besides dynamic loadings measurements the visual observation on the interaction between the devices and sunk ice fragments were carried out.

The schemes of the models of towed seismic equipment protection means against ice floes and of the placement of the experimental equipment are represented in fig. 1.

3. TESTS RESULTS

The oscillograms of measured processes were obtained during tests in the ice model basin. The maximum force of the interaction between the device and ice fragments \( P_{1}^{\text{max}} \), the average force of the interaction between the device and ice fragments \( P_{1}^{\text{av}} \), a time interval of the interaction between the device ice fragments \( t_{i}^{\text{av}} \), and a time interval between the appearance of the maximum forces of the interaction between the device and ice fragments \( t_{i}^{\text{max}} \) were determined by the statistical data processing. For the most obviousness the values of the aforesaid forces were divided into the values of the forces arising
The schemes of the models of towed seismic equipment protection means against ice floes and of the placement of the experimental equipment.

- device N1;
- device N2;
- dynamometer; 
- streamer; 
- hydrodynamic depressor; 
- cantilever construction; 
- floating anchor; 
- icebreaker; 
- ice fragments.

Fig. 1
through the hydrodynamic flowing round the devices $P_{hid}$. The results of the statistical data processing are represented in the table.

Table.

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>The mean and the confidence interval of measured parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solid ice</td>
</tr>
<tr>
<td></td>
<td>Device N 1</td>
</tr>
<tr>
<td>$P^m / P_{hid}$</td>
<td>7.0 ± 0.13</td>
</tr>
<tr>
<td>$P'^m / P_{hid}$</td>
<td>14.0 ± 0.29</td>
</tr>
<tr>
<td>$t_{st}$</td>
<td>1.25 ± 0.03</td>
</tr>
</tbody>
</table>

The distribution functions of the forces acting on the devices from ice fragments and the ones of a time interval of the interaction between the devices and ice fragments were graphed according to experimental data obtained during the tests in a solid ice. These distribution functions are represented in fig. 2. These plots give the possibility to determine the probability of exceeding some set force, acting on the device. So the probabilities of exceeding the means for the device N1 are equal to $P^m / P_{hid} = 0.4$; $P'^m / P_{hid} = 0.48$; $t_{st} = 0.46$. The means for the device N2 are equal to $P^m / P_{hid} = 0.49$, $P'^m / P_{hid} = 0.45$, $t_{st} = 0.51$ accordingly. The probability deviation from the value 0.5 indicates some asymmetry of the investigated values distribution functions.

The results of traditional statistical processing of the forces acting on the seismic equipment protection means during the icebreaker model movement in a solid ice do not allow to make our choice in favour of the device N1 or the device N2 because the quantities of the mathematical expectation and the dispersion have similar values for the both devices. The main differences between the measured parameters (values) are a time interval and frequency of the interaction between the devices and ice fragments.
The distribution functions dependence on two dynamic parameters.

Fig. 2

I - distribution functions of the average loading;
II - distribution functions of the maximum loading;
III - distribution functions of a time interval of the interaction between the device and ice fragments;

ΔΔΔ  - device N 1;
***** - device N 2.
The relative interaction time were used as the measure of the interaction time between the device and ice fragments. It is determined by the formula:

\[ t_{\text{rel}} = \frac{\sum t_{i}}{t_{\text{rec}}} \]

where \( t_{i} \) - a time interval of the interaction between the device and ice fragments, \( t_{\text{rec}} \) - the recording total time. The following values of the relative interaction time were obtained in consequence of the data processing: \( t_{\text{rel}} = 0.46 \) (for the device N1), \( t_{\text{rel}} = 0.1 \) (for the device N2). The mean frequencies of the interaction between the devices and ice fragments are equal to \( f_{\text{rel}} = 0.38 \) Hz (for the device N1) and \( f_{\text{rel}} = 0.15 \) Hz (for the device N2).

The model tests of the devices were conducted in a broken ice 10/10 coverage because these conditions are the most dangerous and only in that case can one anticipate passing sunk ice fragments under the icebreaker model bottom. The individual interactions between the device N1 and ice fragments were observed during tests in a broken ice. In these ice conditions the device N2 had no contacts with ice fragments. Only one contact was practically registered. The differences of forms of the interaction between the devices and ice fragments can be explain by their disposition. The device N2 is located in the icebreaker model underwater part most protected against ice fragments passing. Both during the icebreaker model movement in a solid ice and its movement in a broken ice only the single ice fragments having the movement trajectory deviated from standard ones by the action of accidental factors can have contacts (or create the blows) with constructional elements of the device N2. While behind the stern, the device N1 is located in the zone of the coming to the surface of ice fragments sunk by the icebreaker hull and moved apart under the ice edge. In this zone the probability of the interaction between the device and ice fragments is sufficiently large. The tests results confirm this fact.

The high levels of ice loadings acting on the both devices were registered during tests in a hummocky ice. In these conditions the levels of ice loadings were 2-3 times higher as compared to the icebreaker model movement in a solid ice. During the icebreaker model movement in a hummocky ice the difference between the relative interaction time for the devices disappears. It is equal to 1 for the both devices. During the tests in a hummocky ice the hydrodynamic depressor estrangement from the streamer model was observed. The simultaneous contact of the device N2 with several ice fragments was noted in a hummocky ice. The analysis of the experimental data allows to draw a conclusion on impossibility of both devices exploitation in hummocky ice formations when their draught exceeds essentially the icebreaker one.
4. CONCLUSION

The tests in the ice model basin showed that ice loadings acting on the devices had the similar values for the both ones in a solid ice. During the tests in a flat solid ice the main differences of the devices were a time interval and frequency of the interaction between the devices and sunk ice fragments. In this case the aforesaid time interval for the device N 1 is two times more than for the device N 2.

The device N 2 practically does not interact with ice fragments during the tests in a broken ice 10/10 coverage. The device N 1 interacts with ice fragments less intensively as compared with the tests in a solid ice. The device N 2 interacts with sunk ice fragments in such a part of the cantilever which has no contacts with the seismic streamer. On the contrary the streamer lead-in cable of the device N 1 interacts with sunk ice fragments. It is the additional advantage of the device N 2.

The results of the carrying out investigations allow to recommend the device N 1 for the use during seismic surveys in a broken ice. It has a simple construction and can be used on the existing seismic research vessels with an icestrengthened hull. The device N 2 can be suggested for the use during seismic surveys performed on board the icebreakers in a solid thick ice. It can be recommended for new geophysical icebreakers projects, though both these types of towed seismic equipment protection means are not acceptable for seismic surveys in a thick hummocky ice.

REFERENCES


ICEBREAKING NOISE STUDY: TESTS IN ICE MODEL BASIN

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ABSTRACT

The results of the icebreaking noise measurements performed during the tests of a geophysical icebreaker model in the ice model basin are represented in this paper. The measurements were carried out with the use of towed and bottom hydrophones during the icebreaker model movement in different ice environments. The integral and spectral characteristics of the icebreaking noise were determined. The differences of the icebreaking noise levels were established during the model movement in a solid and broken ice with revolving and stopped propellers, with the bow and the stern ahead.

I. INTRODUCTION

During 1983-1995 Research Institute of Marine Geophysics (NLIMorgeophysica) carried out the cycle of geophysical investigations under different ice conditions. The results of these investigations showed that the high noise level recorded by the streamer was one of the hindrances for marine seismic surveys in an ice environment. It is obvious that during marine seismic surveys in an ice environment the towed streamer records additional icebreaking noise.

To study the spectral and integral characteristics of the icebreaking noise the special acoustic measurements were performed during the tests in the Ice Model Basin of Krylov Research Shipbuilding Institute.

2. MEASUREMENTS METHODS AND DATA PROCESSING

A two-shaft model of an icebreaker (L = 4.81 m, B = 1.2 m, T = 0.33 m) was chosen for acoustic tests in the ice model basin. This model was equipped with the electric engine and the reduction gear giving the rotation on the both shafts.

The icebreaker model tests were performed by the "rigid team" scheme. Such a scheme ensured a rigid tie between the towing carriage and the icebreaker model and therefore the constancy of hydrodynamic loading on the model propellers on the condition that the tow speed and the rotation frequency of the propeller shaft were constant.
The change of environment resistance (for example, a transition from a flat solid ice to a broken ice) is not accompanied by the change of loading on the propellers in case of the use of the "rigid team" scheme and is compensated at the expense of the change of pulling up effort acting on the model from the side of the towing carriage.

The tests of the icebreaker model were performed in open water, in a 0.3-0.5 m thick solid ice and a broken ice 9-10/10 coverage.

The tests programme included measurements of the ambient noise in the ice model basin and measurements of noise characteristics under different movement regimes of the icebreaker model.

The list of the measurements regimes is represented in the table.

<table>
<thead>
<tr>
<th>Model movement direction</th>
<th>Propellers rotation frequency, RPS</th>
<th>Open water</th>
<th>Broken ice</th>
<th>Solid ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow ahead</td>
<td>0</td>
<td>P1</td>
<td>P5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>P2</td>
<td>P6</td>
<td>P9</td>
</tr>
<tr>
<td>Stern ahead</td>
<td>0</td>
<td>P3</td>
<td>P7</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>P4</td>
<td>P8</td>
<td>P10</td>
</tr>
</tbody>
</table>

It should be noted, that the speed of the towing carriage was equal to 0.2 m/s during the tests pointed in the table.

The measurements of the noise arising from the movement of the icebreaker model in the ice model basin were performed with the use of both towed and bottom hydrophones.

The bottom hydrophones were located along the trajectory of the model movement in its diametrical plane. They were placed within 1 m distance from the basin bottom. The simultaneous noise measurements with four hydrophones allowed to raise the trust of received data.

The towing hydrophone was placed on the bow or on the stern of the model, on the bar. Bar length was equal to ~ 2.5 m. The bar was placed at a depth approximately corresponding to double model draught.

Acoustic electronics for measurements, recording and analysis of noises included, except aforesaid hydrophones, preliminary amplifiers, Brüel & Kjær tape drive N 7005, spectrum analyzer GIA-228 (Russia) used for data spectral analysis within the 1/3 octave-band.

The analysis of the noise measurements performed by the use of bottom hydrophones was carried out in the regime of memorizing the maximum value of the noise for a track.

For some movement regimes the obtained data were processed with the use of the narrow-band Brüel & Kjær spectrum analyzer N 2023.
3. MEASUREMENTS RESULTS

The analysis of the noise data received by the bottom hydrophones showed that the level of the ambient noise in the ice model basin is sufficiently low on the condition that the towing carriage and the icebreaker model are motionless. However the narrow-band spectral analysis allowed to distinguish intensive discrete components on the frequencies 25, 32, 50 and 100 Hz within the ambient noise spectrum. These discrete components are caused by the electric network noise, the noise of working mechanisms served the ice model basin and external acoustic sources.

The information about the subject of this investigation (the icebreaker noise) is represented in fig. 1. The graph shows, that the noise levels generated by the icebreaker model towed with revolving propellers have practically the same values within the 5-800 Hz band during the tests in open water, in a solid and broken ice. This regularity is caused by the predominance of the noises of the towing carriage, electric engine and propellers in the total noise registered by bottom hydrophones within the 5-800 Hz band. The measurements showed that the icebreaking noise predominated in the total noise field only within the 800-10000 Hz band. In this frequency range the icebreaking noise level was 15-20 dB higher during tests in a broken ice and 25-30 dB higher during tests in a solid ice as compared to the noise levels of other sources.

The analysis of the measurements performed by the use of a towed hydrophone showed that the icebreaking noise predominated in the total noise registered by a hydrophone within the 800-10000 Hz band, too. For example, the noise level registered by a towed hydrophone within the 800-10000 Hz band during the model movement with the stern ahead and stopped propellers in a broken ice was 12 dB higher as compared to its value under the stopped regime of the mooring of the icebreaker model. In the last case the total noise was completely determined by the electric engine and propellers work.

Spectra for the various regimes of the model movement are compared in the fig. 2. Both spectra have been obtained for the model movement with revolving propellers during the tests in a broken ice. The upper curve is corresponding to the model movement with the bow ahead, and the lower curve is corresponding to the model movement with the stern ahead. In the first case a towed hydrophone was put down into the water from the stern, and in the second case - from the bow. Both spectra have been obtained in conditions of the existence of the complete set of the noise sources such as towing carriage noise, electric engine noise, propellers noise and icebreaking noise.

The difference between the obtained results is very large within the whole frequencies range and reaches more than 30 dB for individual frequencies. So high levels of the noise measured by a towed hydrophone behind the stern of the model moving with the bow ahead can be caused by two reasons. Firstly, a towed hydrophone is located in the field of the intensive pulsations of hydrodynamic pressure generated by the propellers in their vicinities and within the model wake. Secondly, (this fact can be more essential) the level of the noise caused by the flowing round the hydrophone with the water stream is increased considerably under the hydrophone movement in the given area. The measured pressure pulsations have the pseudoacoustic nature and do not propagate in the far field.
The spectrum noise levels in the 1/3-octave band, measured by the bottom hydrophones under the geophysical icebreaker model movement in the ice model basin: movement with the bow ahead, propellers rotation frequency - 7 RPS.

![Graph 1](image1)

1- open water (regime P2); 2- broken ice (regime P8); 3- solid ice (regime P10).

Fig.1.

The spectrum noise levels in the 1/3-octave band, measured by the towed hydrophone under the geophysical icebreaker model movement in the ice model basin: a broken ice, propellers rotation frequency - 9 RPS.

![Graph 2](image2)

1 - movement with the bow ahead; 2- movement with the stern ahead.

Fig.2.
Thus, to reduce the streamer noise level the icebreaker movement with the stern ahead can be recommended for seismic surveys in an ice environment.

It should be noted, that the icebreaking noise formed during the movement of the geophysical icebreaker model in various ice environments was recorded within the 800-10000 Hz band. The linear scales of the icebreaker model and thickness of ice created in the ice model basin are equal to 1:30-1:40.

The investigated 800-10000 Hz band is transformed into the 20-250 Hz band by the help of the scale 1:40 owing to the equality of the model and icebreaker wave dimensions, model and natural ice wave thicknesses. This frequency range coincides practically with the seismic band.

It should be noted, too, that the results of the given investigations are compared with the data obtained under the measurements of the noise and vibration caused by the destruction with the hull of the nuclear-powered icebreaker "Arctica" during its cruise to the North Pole [1].

4. CONCLUSION

The icebreaking noise was recorded by bottom and towed hydrophones within the 800-10000 Hz band (corresponding the real 20-250 Hz band) under the model movement in various ice environments. In this frequency range the icebreaking noise predominates over other noise sources such as towing carriage noise, electric engine noise, propellers noise.

The spectrum of the icebreaking noise is continuous and has no discrete components. The integral icebreaking noise level measured by bottom hydrophones within the 800-10000 Hz band is equal to 110-130 dB relatively 1 μPa.

Under the icebreaker model movement with the bow ahead and revolving propellers (rotation frequency - 9 RPS) the noise level recorded by a towed hydrophone is 30 dB higher as compared to its movement with the stern ahead. Therefore to reduce the streamer noise level the icebreaker movement with the stern ahead can be recommended for seismic surveys in an ice environment.

Carried out acoustic measurements showed that in order to increase the truth of obtained results it would be necessary to test small self-propelled icebreaker models (scale 1:50) in the ice model basin. The use of such models will allow to exclude the influence of the towing carriage noise on tests results.

REFERENCE

SCALE EFFECTS IN ARCTIC ICE FRACTURE EVENTS - PART I

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Abstract: During ice break-up season, marinas, off-shore structures, and bridge piers are subjected to ice impact forces. The design of structures to resist floating ice sheet impact, the transport and traffic of vehicles on manmade or natural ice covers, and the promotion of ice penetration, ice breaking, or ice break-up have generated a broad spectrum of needs and questions into the mechanics and mechanisms of ice fracture. This requires the knowledge of ice behavior at large scale, bringing to light the important question: Can small scale tests be extrapolated to large scale (real world) situations? Unfortunately, linear elastic fracture mechanics is not generally applicable to ice. In other words, the size effect is unknown. Some have speculated what the size effect would be, but unless large scale tests are done, no size effect laws can be verified. To achieve this end, a set of large scale fracture and flexure tests have been conducted on freshwater lake ice and sea ice. Cyclic and creep recovery loadings were imposed on the plates to elucidate constitutive information necessary for modeling. Rate effects were investigated through a series of monotonic sweeps. These large scale in-situ field experiments were linked to laboratory testing through an extensive small scale testing program conducted at the site and in the laboratory. These experiments provide the information needed to verify existing lab-scale models and size effect laws. Acoustical signals from fracture tests on two of the field trips were recorded by Xie and Farmer (1994, 1995). The results are compared with the load/displacement records obtained to determine the correlation between the two methods. Also, Electromagnetic emissions from the first year sea ice was monitored and interpreted on two of the field trips to Barrow, AK (Petrenko et al., 1995). In Part II (Mulrane et al., 1995), the modeling of the small and large scale data currently in progress at Clarkson University is discussed. The modeling incorporates a cohesive zone model and in the future will be coupled with a viscoelastic component.

INTRODUCTION

The relevance of fracture mechanics to ice engineering is intuitively acceptable once one has witnessed ice impact on a structure, an ice jam, an icebreaker at work, or a bearing capacity failure. For instance, the indentation and penetration of an ice sheet by a structure is typically fracture-dominated. The different failure modes observed and studied are crushing, crushing with spalling, crushing with radial cracking, crushing with radial and circumferential cracking, and radial/circumferential cracking with bucking (Sodhi, 1986, Time o, 1987; Blanchet et al., 1989). The mechanism by which the above failure modes are established is tensile fracture. To reliably predict ice forces on structures, and to better understand the role of fracture, the dependencies of the opening mode (Mode I) fracture toughness on such factors as loading rate, loading direction, specimen geometry and sample size, as well as the ice properties need to be investigated.

Early investigations involving the fracture of ice (and other quasi-brittle materials such as concrete and rock) assumed the validity of linear-elastic fracture mechanics (LEFM) for the laboratory specimens employed, and LEFM toughness parameters such as Kc were determined. However, such parameters Kc and Gc as obtained from normal laboratory sized specimens have been found to be dependent on the specimen size (Dempsey,
Table 1: Summary of Large-Scale Experiments

<table>
<thead>
<tr>
<th>Date</th>
<th>Location...Phase</th>
<th>Ice Type</th>
<th>Ice Thickness h(m)</th>
<th>Test Geometries</th>
<th>Size L(m)</th>
<th>Scale</th>
<th># Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/15-29, 1992</td>
<td>Canmore, Alberta...I</td>
<td>S1 fresh water ice</td>
<td>0.50</td>
<td>3pt(^a) - FR(^a)</td>
<td>0.50</td>
<td>1.81</td>
<td>4</td>
</tr>
<tr>
<td>4/17 - 5/7</td>
<td>1993 Resolute, N.W.T. ...II</td>
<td>FY(^a) sea ice slightly aligned</td>
<td>1.8</td>
<td>3pt - FR SQ(^a) - FR SQ - FL (^a)</td>
<td>3.0</td>
<td>5/80</td>
<td>15</td>
</tr>
<tr>
<td>11/9-19, 1993</td>
<td>Barrow, Alaska(^a)...III</td>
<td>FY(^a) sea ice Strongly aligned</td>
<td>0.30</td>
<td>SQ(^a) R(^a) RT(^a) CORE (^a)</td>
<td>2.5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3/9-20, 1994</td>
<td>Barrow, Alaska(^a)...IV</td>
<td>FY sea ice Strongly aligned</td>
<td>1.5</td>
<td>SQ R SCB (^a)</td>
<td>0.3-0.5</td>
<td>180</td>
<td>5</td>
</tr>
<tr>
<td>1/1-10, 1994</td>
<td>SIMU Floating Camp, Beaufort Sea(^a)...V</td>
<td>FY sea ice slightly aligned</td>
<td>0.2-0.6</td>
<td>SQ MY Floe (^a)</td>
<td>2-15</td>
<td>1.75</td>
<td>5</td>
</tr>
<tr>
<td>5/8-19, 1994</td>
<td>Barrow Alaska(^a)...VI</td>
<td>FY sea ice Strongly aligned</td>
<td>1.7</td>
<td>SQ R</td>
<td>0.25-30</td>
<td>1120</td>
<td>N/A</td>
</tr>
</tbody>
</table>

1 Joint experiments with Cole, Petenko, Shapiro and Weeks
2MY floe fracture experiment joint with Coon, Farmer, Pritchard and Xie
33pt- Three point bend; 4FR-Fracture; 5RT-Reverse-tapered base-edge-cracked plates
6FY-First Year; 7SQ-Square Plate (L\times L); 8FL-Flexure; 9R-Rectangular Plate (L\times 2L)
10CORE - 0.2m diameter core, vertical, isothermal (small scale)
11SCB - Semi-Circular Bend Fracture/Flexure Geometry (small scale)
12MY Floe - Multi-Year floe

1991; Dempsey et al., 1992). There is reason to believe that much larger specimens than first expected are required to obtain the \(K_{\text{IC}}\) or \(G_{\text{IC}}\) values for ice. This necessitates the study of fracturing at larger scales.

Six field trips to the arctic have been completed over the last three years. These field trips were aimed at studying size and rate effects in sea ice. Large scale experiments coupled with small scale field and laboratory tests were completed to reach this goal. The experiments have yielded an abundance of information related to the fracture and constitutive behavior of sea ice. Table 1 summarizes the large-scale in-situ arctic experiments.

**DETAILED SUMMARY OF LARGE-SCALE FIELD EXPERIMENTS**

**Phase I: Canmore, Alberta**

A two-phase joint-industry-agency project (JIAP) was initiated in 1990 to calibrate a fracture theory for incorporation into probabilistic global ice load models. Phase I of the JIAP “Large-Scale Ice Fracture Experiments” was completed in January, 1992 near Calgary, Alberta (Kennedy et al., 1994). The primary goal of Phase I was to assess the feasibility of large-scale, full-thickness ice fracture measurements. Other objectives included:

1. Field experimentation of specimen cutting and scribing, loading systems, servo-control and instrumentation,
2. Determination of fracture toughness of full-thickness freshwater ice, global elastic modulus and scale effects.

The project began at the Bearspaw Reservoir near Calgary, Alberta. The Griffith tests and the first two beam tests were conducted there. Due to unreasonably warm temperatures, the test site was moved to Spray Lakes Reservoir in Canmore, Alberta. Ice conditions at the two sites were quite different in several respects. S2 freshwater ice existed at Bearspaw, whereas S1 columnar ice was found at Spray Lakes. Also, the ice at Bearspaw was highly fractured because of water level changes for hydropower needs. The ice at Spray Lakes had limited fractures and large areas with no visible cracks. The remaining experiments were conducted at the Spray Lakes site. Table 2 summarizes the experiments completed during Phase I of the project, at both Bearspaw and Spray Lakes.

**Griffith Tests:** Two Griffith experiments were performed at the Bearspaw Reservoir (Figure 1a). They consisted of simply cutting a notch in the ice sheet and inserting a flatjack. Displacement gauges were placed over
the flat jack and at each of the crack tips. The primary function of this experiment was to fine tune the testing apparatus. These experiments have not been analyzed because the ice sheet at Bears Paw was highly fractured with existing cracks interfering with the tests.

**Notched Bend Tests:** The three point (3pt) bend fracture geometry shown in Figure 1b was used with the aim of investigating size effects on in situ ice possessing a thermal gradient and a natural thermal crack density. Difficulties were encountered with the specimens freezing in place and with the sides melting - causing sloping sides unsuitable for use as loading faces. This behavior was evidenced especially in specimen B4 (Spray Lakes). Despite these problems, an initiated crack was arrested in the flat jack and at each of the crack tips. Some difficulties were experienced with multiple loadings and generally resulted in unstable propagation.

**Loop servo-controlled tests involved multiple loadings and stable crack propagation.**

**Cantilever Beam Experiments:** An additional evaluation of specimen size on the elastic modulus was made using three in situ cantilever beams as shown in Figure 1d. Several load/unload trials were performed on each experiment. Experiments CM1 and CM2 were successful. For CM3, the displacement gauges drifted due to the warm temperatures and wind; consequently, no useful data was obtained for this test.

**Small Scale Tests:** A set of small scale beam tests were completed by IMD of Canada at the site. These experiments help link the small scale lab tests with the large scale tests (Figure 1e).

**Characterization:** Due to the warm temperatures at the test site, no characterization could be done during the testing. A large block of the ice from Spray Lakes was shipped back to Clarkson University where detailed characterization of the ice was performed (Lazo, 1994).

**Phase II. Resolute Bay, N.W.T**

Based on the success of Phase 1, large-scale fracture tests in full-thickness sea ice were conducted on Phase 2 in April 1993 near Resolute, Northwest Territories (Kennedy et al., 1994). The tests in Resolute focused on the square plate geometry, with the successful completion of fifteen fracture and three flexure tests. Table 3 provides a summary of these experiments.

**Square Plate Experiments:** The square plates tested ranged from $(0.5 \times 0.5 \times 1.8 \text{m})$ to $(10 \times 10 \times 1.8 \text{m})$ cov-
Figure 1: Test geometries: a) Griffith crack, b) Three-point-bend fracture test, c) Reversed-taper geometry, d) Cantilever beam experiment

...er a size range of 1:160. The ice was 1.8m thick so a large Ditch Witch, shown in Figure 2a, was necessary to cut out the plates. The Ditch Witch made a 15 cm wide slot between the test piece and the parent ice sheet. This limited refreezing of the cut, providing the group time to clean the slash from the cut. A second smaller Ditch Witch was then used to cut the crack in the specimen. This machine cut a notch 1.6 cm wide, enough to insert the loading device, the flatjack. Because it was a narrow cut, it had to be constantly cleaned to prevent refreezing. The loading was achieved by means of a flatjack inserted into the precut crack in the specimen. On the surface of the specimen, the crack opening displacements were measured at three points: the crack mouth (CMOD), the crack tip (CTOD), and at a point in between (COD). At each point, two displacement gauges were used, an LVDT and a KAMAN non-contacting displacement gauge. The KAMAN gauge had a finer resolution, but went out of range much earlier. As the crack opened, the KAMAN gauge would go out of range while the LVDT would continue measuring, providing a continuous record of the crack opening deformation. By this method the unloading curve immediately following fracture could be captured. Figure 2b shows the test setup for a typical square plate fracture test. All gauges were connected to two different digital recording devices, two 486 computers. This method of two backups ensured that no data was lost. One 486 computer was used for real time viewing of the gauge responses and slow data acquisition. The other computer was devoted to high speed data acquisition. The flatjack was pressurized by either a gas or servo-controlled oil system. The pressure in the flatjack was proportional to the pressure applied to the ice, and was calculated through lab calibration of the flatjack. When using air, the load applied to the ice was controlled. Typically, these were longer tests, running for at least five minutes. This system was capable of introducing prescribed unloadings at various times in the loading. The hysteresis loops in the Load vs COD plots provide constitutive information as well as information necessary to calculate internal friction values. Servo controlled tests used displacement feedback for control. These were faster tests, usually taking less than one minute to fracture.

Flexure Experiments: The testing of in-situ flexure beams proved to be a difficult task in Phase I. One flexure beam was tested in Phase II. The test was successful, but required an excessive amount of preparation. It was found that test specimens using self-equilibrated loading (the RT on Phase I and the square plate on Phase II)
were inherently easier to setup, requiring minimal prepa-
ration. This provoked the use of the square plate keyhole
geometry (Figure 2c). This was a flexure test similar to
the square plate fracture tests, except that a 20cm hole
was bored at the crack tip. The displacement gauges
were placed at points on the crack, similar to the frac-
ture tests.

**High Speed Video:** Bob Gagnon of CNRC filmed the
clacking events in the large scale fracture tests.

**Acoustics:** The acoustic signals resulting from the
cracking events were recorded by Xie and Farmer from
the Institute of Ocean Sciences. They deployed two hy-
drophones with a sampling frequency of 44.1kHz. These
devices allowed acoustical measurements of propagation
speeds of developing ruptures and acoustic radiation lev-
eis due to micro-cracking as the tensile load was in-
creased. A detailed analysis of one of the experiments
follows this summary section.

**Small Scale Tests:** IMD/NRC of Canada carried out
experiments on the flexural strength of the ice for differ-
ent sizes, depths, and orientations (Figure 2d). A series
of small scale fracture toughness measurements with a
range of parameters similar to those of the strength tests
were also performed.

**Characterization:** A tent was set up at the site with
all the equipment necessary for the full characterization
of the ice. Characterization of the full thickness of the
ice sheet was completed as well as salinity and density
profiles. Details of this work are given in this paper as
well as in the paper by Wei et al (1995).

**Phases III, IV and VI: Barrow, AK**
In order to track the seasonal evolution of the mechani-
cal and physical properties of first year sea ice, three
Figure 3: a) Schematic of various load paths b) Core geometry; c) SCB fracture geometry; d) Four-point-bend flexure geometry
Figure 4: Large-scale ice-cutting machinery a) 30 ton Ditchwitch; b) Specially designed cutting machine
field trips were conducted at Barrow, Alaska: November 9–19, 1993, March 9–20 and May 8–19 of 1994. This was a joint field trip with members of the group from Clarkson University, CRREL, and the University of Alaska at Fairbanks (UAF). A total of thirty large scale tests were completed covering a wide range of sizes, temperature profiles, and loading paths. Each set involved a large scale in-situ (full ice thickness) matrix of experiments and a complementary small scale (partial thickness) matrix of experiments. The ice conditions encountered at Barrow were very interesting, that is, the sea ice was strongly aligned, and thus, in addition to the salinity, grain size and thermal profile there was this additional important microstructural feature to incorporate. Details regarding the microstructural work, logistics and site description are provided by Cole et al. (1995). In all these experiments, a computer-controlled flatjack loading system was employed to load the ice along preset load paths recording both load and deformation. Issues examined included the effects of size, rate, load path (monotonic, cyclic and creep recovery) and geometrical test orientation vs c-axis alignment. Figure 3a shows the schematics of the various load paths.

**November 9–19, 1993:** At this time, the ice was about 30 cm thick and showed a strong c-axis alignment. Because of the strong c-axis alignment, the test plan was modified and tests with the crack propagating parallel (hard fail, ||) and perpendicular (easy fail, ⊥) to the c-axis were conducted. Table 4 presents the large scale tests completed on the first trip to Barrow, AK. Due to the success of the square plate geometry in Phase II, it was used again. Unfortunately when testing SPF4, a square plate with the precut crack in the hard fail direction, the crack still chose to propagate in the easy fail direction, resulting in a strength failure. To overcome this problem, a rectangular geometry was chosen, with a length twice that of the width. This geometry was tested in SPF5 and proved to be successful. The fixture tests were accomplished by drilling a hole at the tip of the crack which was precut in the square or rectangular sample. The RT geometry used in Phase I was also tested. This geometry was able to overcome the crack's tendency to propagate in the easy fail direction when testing in the hard fail plane.

**Small Scale Tests:** Full depth cores were tested by cutting a crack from the side to the center of the core as shown in Figure 3b. A small flatjack was then put in the crack and the core was split in half. Each half was then used to make SCB specimens (Adamson et al., 1995) shown in Figure 3c. These tests show the variation in strength with respect to depth and orientation. Also, small plates subjected to four point bending were tested (Figure 3d). All small scale experiments were done under isothermal conditions. These tests provided the link between large scale tests and small scale laboratory experiments.

**Electromagnetics:** The electromagnetic emissions from both large and small scale experiments were recorded by Petrenko from Dartmouth (Petrenko et al., 1995). These results indicate crack initiation as well as track the cracking behavior, such as crack velocities through failure.

**March 9 to 20, 1994:** At this time, the ice sheet was approximately 1.7 m thick. The average air temperature was -25°C, creating a large temperature profile. Because of the ice thickness, the samples had to be cut with a ditchwitch (Figure 4a) and a specially designed saw (Figure 4b). To achieve similar aspect ratios (width to thickness).
### Table 4: Large Scale Ice Experiments @ Barrow, AK: November 9-19

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Geometry</th>
<th>Length (L) (m)</th>
<th>Crack Length (m)</th>
<th>Test Mode</th>
<th>Failure</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPF1</td>
<td>Square</td>
<td>2.5m</td>
<td>0.75</td>
<td>Fracture</td>
<td>Easy</td>
<td>Cyclic/Ramp</td>
</tr>
<tr>
<td>SPF2</td>
<td>Square</td>
<td>2.5m</td>
<td>0.75</td>
<td>Fracture</td>
<td>Easy</td>
<td>Cyclic/Ramp</td>
</tr>
<tr>
<td>SPF3</td>
<td>Square</td>
<td>2.5m</td>
<td>0.75</td>
<td>Fracture</td>
<td>Easy</td>
<td>Cyclic/Ramp</td>
</tr>
<tr>
<td>SPF4</td>
<td>Square</td>
<td>2.5m</td>
<td>0.75</td>
<td>Fracture</td>
<td>Hard</td>
<td>Cyclic/Ramp</td>
</tr>
<tr>
<td>SPF5</td>
<td>Rectangle</td>
<td>2.5m</td>
<td>1.25</td>
<td>Flexure</td>
<td>Hard</td>
<td>Cyclic/Ramp</td>
</tr>
<tr>
<td>SPF6</td>
<td>Square</td>
<td>2.5m</td>
<td>0.75</td>
<td>Flexure</td>
<td>Easy</td>
<td>Fast Ramp</td>
</tr>
<tr>
<td>SPF7</td>
<td>RT</td>
<td>1.0m</td>
<td>0.3</td>
<td>Fracture</td>
<td>Easy</td>
<td>Fast Ramp</td>
</tr>
<tr>
<td>SPF8</td>
<td>RT</td>
<td>1.0m</td>
<td>0.3</td>
<td>Fracture</td>
<td>Hard</td>
<td>Fast Ramp</td>
</tr>
<tr>
<td>CORE1</td>
<td>Core</td>
<td>0.2m(\phi)</td>
<td>0.1</td>
<td>Fracture</td>
<td>Easy</td>
<td>Fast Ramp</td>
</tr>
<tr>
<td>CORE2</td>
<td>Core</td>
<td>0.2m(\phi)</td>
<td>0.1</td>
<td>Fracture</td>
<td>Easy</td>
<td>Fast Ramp</td>
</tr>
<tr>
<td>CORE3</td>
<td>Core</td>
<td>0.2m(\phi)</td>
<td>0.1</td>
<td>Fracture</td>
<td>Hard</td>
<td>Fast Ramp</td>
</tr>
<tr>
<td>CORE4</td>
<td>Core</td>
<td>0.2m(\phi)</td>
<td>0.1</td>
<td>Fracture</td>
<td>Hard</td>
<td>Fast Ramp</td>
</tr>
</tbody>
</table>

### Table 5: Large Scale Ice Experiments @ Barrow, AK: March 9-20

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Geometry</th>
<th>Length (L) (m)</th>
<th>Crack Length (m)</th>
<th>Test Mode</th>
<th>Failure</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQPL1</td>
<td>Square</td>
<td>1.5m</td>
<td>0.45</td>
<td>Fract.</td>
<td>Easy</td>
<td>Ramp</td>
</tr>
<tr>
<td>SQPL2</td>
<td>Square</td>
<td>1.5m</td>
<td>0.45</td>
<td>Fract.</td>
<td>Easy</td>
<td>Ramp</td>
</tr>
<tr>
<td>SQPL3</td>
<td>Rect.</td>
<td>1.5m</td>
<td>0.45</td>
<td>Fract.</td>
<td>Hard</td>
<td>Ramp</td>
</tr>
<tr>
<td>SQPL4</td>
<td>Square</td>
<td>2.5m</td>
<td>0.75</td>
<td>Fract.</td>
<td>Easy</td>
<td>Mono/Ramp</td>
</tr>
<tr>
<td>SQPL5</td>
<td>Square</td>
<td>2.0m</td>
<td>0.6</td>
<td>Fract.</td>
<td>Easy</td>
<td>Ramp</td>
</tr>
<tr>
<td>SQPL6</td>
<td>Rect.</td>
<td>2.0m</td>
<td>0.6</td>
<td>Fract.</td>
<td>Hard</td>
<td>Ramp</td>
</tr>
<tr>
<td>SQPL9</td>
<td>Square</td>
<td>30.0m</td>
<td>9.0</td>
<td>Fract.</td>
<td>Easy</td>
<td>Cyc/CR/Ramp</td>
</tr>
<tr>
<td>SQPL10</td>
<td>Square</td>
<td>0.5m</td>
<td>0.25</td>
<td>Fract.</td>
<td>Easy</td>
<td>Cyclic</td>
</tr>
<tr>
<td>SCB</td>
<td>SCB</td>
<td>0.2m(\phi)</td>
<td>0.06</td>
<td>Fract.</td>
<td>II/E</td>
<td>Cyc/Ramp</td>
</tr>
</tbody>
</table>

### Table 6: Large Scale Ice Experiments @ Barrow, AK: May 8-19

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Geometry</th>
<th>Length (L) (m)</th>
<th>Crack Length (m)</th>
<th>Test Mode</th>
<th>Failure</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQ1</td>
<td>Square</td>
<td>16.0</td>
<td>4.8</td>
<td>Fracture</td>
<td>Easy</td>
<td>CR/Ramp</td>
</tr>
<tr>
<td>SQ2</td>
<td>Square</td>
<td>4.0</td>
<td>1.2</td>
<td>Fracture</td>
<td>Easy</td>
<td>Cyclic/Ramp</td>
</tr>
<tr>
<td>SQ3</td>
<td>Rect</td>
<td>8.0</td>
<td>2.4</td>
<td>Fracture</td>
<td>Hard</td>
<td>CR/Cyc/Ramp</td>
</tr>
<tr>
<td>SQ4</td>
<td>Rect</td>
<td>8.0</td>
<td>3.0</td>
<td>Fracture</td>
<td>Hard</td>
<td>CR</td>
</tr>
<tr>
<td>SQ5</td>
<td>Square</td>
<td>1.0</td>
<td>0.29</td>
<td>Fracture</td>
<td>Easy</td>
<td>CR/Ramp</td>
</tr>
<tr>
<td>SQ6</td>
<td>Square</td>
<td>0.25</td>
<td>0.13</td>
<td>Fracture</td>
<td>Easy</td>
<td>CR</td>
</tr>
<tr>
<td>SQ7</td>
<td>Square</td>
<td>30.0</td>
<td>9.0</td>
<td>Fracture</td>
<td>Easy</td>
<td>Cyc/CR/Ramp</td>
</tr>
</tbody>
</table>
ness) as compared to the first trip, larger samples were required. The tests conducted on the second trip are summarized in Table 5. A total of 10 tests were completed covering a size range of 1:30 with the largest being a 30m x 30m square plate.

**Small Scale Tests:** In addition to the large scale matrix, a set of small scale experiments were completed at the site. It consisted of sixteen semi-circular-bend (SCB), tests, 8 with the crack parallel to the c-axis (hard fail) and 8 with the crack parallel to the basal plane (easy fail). Each test was at a subsequently lower depth in the ice sheet, providing information on the strength relative to the depth. All of the SCB tests were conducted in a small field testing apparatus under isothermal conditions.

**Electromagnetics:** An electromagnetic monitoring system was again deployed by Petrenko (Petrenko et al. 1995). Electrodes were placed on either side of the crack path enabling the detection of initial microcracks as well as record crack velocities.

**Phase VI: Floating SIMI Camp, Beaufort Sea**

A total of six fracture tests were done at the SIMI floating camp in the Beaufort Sea. Table 7 has a summary of the experiments conducted at the camp.

**Square Plate Tests on Load Ice:** Five square plate geometry tests were completed on load ice with thickness ranging from six inches to two feet. Most of the square plates were subjected to an extensive set of cyclic and creep recovery sequences at relatively low loadings. A controlled monotonic load ramp was applied to fracture the plates. As with previous field trips, displacement gauges were placed at chosen locations on the ice surface to measure the crack opening displacements. Blocks of ice from several of the experiments were shipped back to Clarkson University for full characterization.

**Splitting of a Multi-Year Floe:** The most significant field achievement was the successful splitting of a 40m diameter multi-year ice floe shown in Figure 5. The surrounding lead ice was double cut with chainsaws and the pieces were removed. This created about a one foot gap around the floe to ensure it was not subject to any confining forces. A crack about 10m long was then cut in the floe. Due to the limitations of the saw, the crack was only cut partially through the thickness. Low level cyclic loading was first applied to force the crack to propagate down through the thickness. The floe was then loaded to failure. Acoustic signals were recorded by Xie and Farmer (1995) and the MIT/WHOI group. Results from Xie and Farmer show the cracking as a function of time, verifying the splitting. In addition, crack velocities and crack paths were determined.

**3. CHARACTERIZATION OF THE FIRST YEAR SEA ICE AT RESOLUTE**

The location of the testing site was approximately 700m from the shore on the west coast of Resolute in Alan Bay. During the period of study, the thickness of the ice sheet was about 1.8m, and the ambient temperature varied from -12 to -27°C. Most samples for salinity and density measurement, microstructure examination, and c-axis orientation analysis were taken from a 0.42x0.42x1.7Sm ice block. This block was cut out of the sheet on April 21, 1993. Since more than one transition ice zone was found in that ice block, additional vertical sections were taken from ice cores to verify the distribution of transition ice in the ice cover. Salinities were determined by measuring the conductivity of meltwater with a conductivity bridge. The densities were calculated from the measured volumes and weights of ice cubes. The temperatures at different depths of the ice cover were measured using a thermometer string buried in the ice sheet. Vertical and horizontal thin sections were prepared using a microtome and triple bagged to avoid sublimation. A universal stage was used to examine the textural features and to measure the c-axis orientations of the ice crystals. The microstructure of some interesting thin sections was further investigated under an Olympus stereo microscope. All of these measurements (except for the temperature measurements) were carried out in a test set up in the field. The grain size d of the ice crystals at different levels was measured based on the corresponding photographs available. In the columnar zones, grain size d refers to the crystal "diameter" of the columnar grains in a horizontal section, and is found through d = \sqrt{d1d2}, where d1 is the maximum length measured parallel to the (0001) plane of a grain and the maximum width measured parallel to the c-axis of the grain, as defined by Weeks and Arkley (1982).

**Salinity, Density, Temperature, and Grain Size Profiles:** The salinity, density, temperature, and grain size profiles are shown in Fig. 6. From Fig. 6a, the salinity takes the maximum value (7.8/o) near the top surface and the minimum value (3.0/o) near the bottom. The plot shows a trend of decreasing salinity with increasing depth. The slowest salinity gradient existed in the top 20-cm of the ice sheet. The salinity profile presented in
Figure 5: Multi-Year ice floe split at the SIMI Camp, Beaufort Sea
Table 7: Large Scale Ice Experiments @ the Floating SIMI Camp, Beaufort Sea

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Geometry</th>
<th>Length (L) (m)</th>
<th>Crack Length (m)</th>
<th>Test Mode</th>
<th>Thickness (m)</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQ1</td>
<td>Square</td>
<td>2.0</td>
<td>0.74</td>
<td>Fracture</td>
<td>0.20</td>
<td>Ramp</td>
</tr>
<tr>
<td>SQ2</td>
<td>Square</td>
<td>3.66</td>
<td>0.43</td>
<td>Fracture</td>
<td>0.20</td>
<td>Ramp</td>
</tr>
<tr>
<td>SQ3</td>
<td>Square</td>
<td>2.44</td>
<td>0.84</td>
<td>Fracture</td>
<td>0.60</td>
<td>Cyc/Ramp</td>
</tr>
<tr>
<td>SQ4</td>
<td>Square</td>
<td>4.88</td>
<td>0.84</td>
<td>Fracture</td>
<td>0.60</td>
<td>CR/Cyc/Ramp</td>
</tr>
<tr>
<td>SQ5</td>
<td>Square</td>
<td>15.0</td>
<td>3.29</td>
<td>Fracture</td>
<td>0.20</td>
<td>CR/Ramp</td>
</tr>
<tr>
<td>FLOE</td>
<td>80m dia.</td>
<td>9.0</td>
<td></td>
<td>Fracture</td>
<td>Easy</td>
<td>Cyc/Ramp</td>
</tr>
</tbody>
</table>

The c-axis orientations of the ice crystals were measured from the horizontal sections at 14 different levels through the depth of the ice sheet. Schmidt net plots were produced to determine the typical c-axis orientations at different depths. The Schmidt net plots indicated that the ice grains in the top layer of transition zone showed both near vertical and random or near random horizontal c-axis orientation. In the columnar zone, the c-axes of all ice crystals were horizontally or near horizontally oriented with a weak alignment at a depth of 15 m. This particular type of c-axis orientation did not significantly vary with depth until a slight deflection of the mean c-axis orientation from the original alignment was observed at a depth of 81 cm. At a depth of 106 cm, the c-axes of the columnar ice were found to be more or less randomly oriented in the horizontal plane. Slight alignment of crystal orientation similar to that found at 53 cm was observed again at a depth of 145 cm. More pronounced alignment, roughly in the North-South direction, was found near the bottom of the ice sheet. More details of the characterization and micrography can be found in the paper by Wei et al. (1995).

4. SIZE EFFECTS IN SEA ICE

Over the last 10 years an abundance of small scale laboratory tests have been conducted on columnar ice at various temperatures, rates and orientations. The Kc values were calculated assuming LEFM criteria. If the value obtained for the fracture toughness is to be regarded as a material property, then the stress intensity factor, KIc, at which a stationary microcrack extends in a material must be independent of the size and shape of the test specimen and the method of loading. Due to the uncertainty in these parameters, KIc was introduced (Dempsey, 1991) to represent the apparent fracture toughness at initiation. De Francesco et al. (1992) found that small-scale experiments exemplify an increasing resistance to fracture until a point at which unstable or catastrophic failure occurs. Considering this evidence, the fracture toughness is not describable by KIc.

Urabe et al. (1980) and Parsons (1986) examined the anisotropy of sea ice through a set of tests at different orientations. Parsons (1986) introduced the notation of VV, VH, and HI to define the orientation of the crack plane and crack front and to standardize...
future fracture testing. Timco and Frederking (1982) studied the effects of depth in the ice sheet on the fracture toughness finding an increase in toughness at lower depths. They also applied the method of adding the sub-grain size to the crack length to arrive at a corrected notch length developed by Urabe et al (1981). This was proposed to make the small scale results comparable to larger tests. Shen and Lin (1986) varied the loading rate to investigate the effects on the fracture toughness, noting no noticeable trend for the rates of 10 to 400 kPa√m/s. Tuhkuri (1987) conducted a set of in-situ 3pt bend experiments, larger than any previous three-point-bend fracture tests in an effort to overcome any size effect. He varied the loading rate and found the toughness decreased with increased loading rate. In addition, he investigated notch acuity effects by sharpening some of the crack fronts, but saw no affect on the fracture toughness. DeFranco et al (1994) observed stable cracking (crack jumping) in experiments on the RTCLWL geometry. An increasing resistance to fracture was seen in these experiments supporting the belief that KIC at crack initiation is not a true measure of the fracture toughness. Considerable scatter in the fracture toughness results is evident in the tests to date. This can be attributed to ice type, crack length, loading rate, specimen size, temperature, specimen geometry, crack orientation and specimen preparation. On the average, small scale VH tests typically yielded values between 56 and 90 kPa√m. Preliminary results from the large scale tests at Resolute show a significantly higher apparent fracture toughness. Smaller tests on the same ice (Williams et al, 1993) yielded values around 76 kPa√m, similar to other small scale results. These results tend to show a size effect is present in the

Figure 6: a) Salinity profile, b) density profile, c) Temperature profile, d) Grain size distribution
<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Test Geometry</th>
<th>Length (m)</th>
<th>$d_{av}$ (cm)</th>
<th>Crack Length (m)</th>
<th>Orientation</th>
<th>Temp. °C</th>
<th>$K_Q$ kPa$\sqrt{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vaudrey (1977)</td>
<td>4pt bend</td>
<td>0.05</td>
<td>1.0</td>
<td>0.013</td>
<td>??</td>
<td>-10</td>
<td>30-80</td>
</tr>
<tr>
<td></td>
<td>4pt bend</td>
<td>0.05</td>
<td>1.0</td>
<td>0.013</td>
<td>??</td>
<td>-20</td>
<td>25-115</td>
</tr>
<tr>
<td>Urabe et al. (1980)</td>
<td>3pt bend</td>
<td>0.36</td>
<td>0.3</td>
<td>0.07</td>
<td>VV(top)</td>
<td>-2</td>
<td>50</td>
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<tr>
<td></td>
<td>3pt bend</td>
<td>0.36</td>
<td>3.0</td>
<td>0.07</td>
<td>VV(bot)</td>
<td>-2</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>3pt bend</td>
<td>0.33</td>
<td>2.0</td>
<td>0.07</td>
<td>VH</td>
<td>-2</td>
<td>60</td>
</tr>
<tr>
<td>Shapiro (1981)</td>
<td>4pt bend</td>
<td>0.05</td>
<td>2.0</td>
<td>0.012</td>
<td>HH</td>
<td>-20</td>
<td>120</td>
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<tr>
<td>Urabe et al. (1981)</td>
<td>4pt bend</td>
<td>0.40</td>
<td>0.5</td>
<td>0.08</td>
<td>VV</td>
<td>-2</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.40</td>
<td>2.2</td>
<td>0.08</td>
<td>VV</td>
<td>-2</td>
<td>75</td>
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<tr>
<td></td>
<td></td>
<td>0.40</td>
<td>4.0</td>
<td>0.08</td>
<td>VV</td>
<td>-2</td>
<td>100</td>
</tr>
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<td>Timco and Frederking (1982)</td>
<td>4pt bend</td>
<td>0.065</td>
<td>1.5</td>
<td>0.012</td>
<td>HH</td>
<td>-20</td>
<td>100-140</td>
</tr>
<tr>
<td>Shen and Lin (1986)</td>
<td>3pt bend</td>
<td>0.16</td>
<td>??</td>
<td>0.08</td>
<td>VV</td>
<td>-20</td>
<td>80</td>
</tr>
<tr>
<td>Parsons et al. (1986)</td>
<td>DCB</td>
<td>0.4 - 1.0</td>
<td>5.0</td>
<td>0.25</td>
<td>VH</td>
<td>-10 to -20</td>
<td>67 - 281</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td></td>
<td></td>
<td>HH</td>
<td>-10 to -20</td>
<td>99 - 875</td>
</tr>
<tr>
<td>Urabe et al. (1986)</td>
<td>4pt bend</td>
<td>0.1</td>
<td>1-12</td>
<td>0.02</td>
<td>VH</td>
<td>-10</td>
<td>120</td>
</tr>
<tr>
<td>Tuukuri (1987)</td>
<td>3pt bend in-situ</td>
<td>0.45</td>
<td>??</td>
<td>0.2</td>
<td>VH</td>
<td>-0.4</td>
<td>136,119</td>
</tr>
<tr>
<td>Danilenko and Rogachko (1991)</td>
<td>4pt bend</td>
<td>0.1-0.2</td>
<td>1.5</td>
<td>??</td>
<td>VH</td>
<td>-2</td>
<td>60±20</td>
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<tr>
<td></td>
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<td>0.1</td>
<td>1-2</td>
<td>0.05</td>
<td>VV</td>
<td>-15 to -20</td>
<td>79</td>
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<td>-15</td>
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<td>0.8</td>
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fracture toughness of sea ice

5 CORRELATION OF FRACTURE RESULTS WITH ACOUSTICAL SIGNATURES

The fracture of sea ice creates acoustic signals that can be interpreted for determining the failure processes. It has been noticed that the acoustic signatures of ice fracturing are related to the rupture scale, velocity, orientations and other parameters of the fracture event. These events can be recorded in the field, but the results are difficult to model without knowledge of the forces creating the fracture. The fracture signals produced by the large scale tests provide the means of benchmarking the acoustical signatures with known load and displacement records.

On the Phase II trip, Xie and Farmer (1991) monitored the acoustical signals produced by several of the fracture tests by deploying an array of hydrophones. Limited by only two hydrophones, only a 1-D array could be deployed. With this arrangement, the approximate position of the crack tip was predicted as well as crack velocities. As described earlier, square plate geometries were tested in the large scale fracture experiments. The acoustical signatures from square plate 7, SQ-7, a 30m x 30m square plate fracture test, are investigated. A 9m precrack was cut in the test piece where the flatjack was placed (Figure 7a). Displacement measuring sensors were located at four points along the crack labeled as the CMOD, COD, NCTOD and the CTOD. Xie and Farmer (1991) deployed two hydrophones at 9.45 and 18.9 meters ahead of the crack tip. During the loading of the sample, several unloadings

Figure 7: Square Plate Test (SQ-7) a) Plan view of test, b) Load vs. time plot, c) Load vs. CMOD plot; d) Cracking predictions.
were incorporated to see the unloading compliance, as well as provide data for internal friction calculations. These unloadings can be seen in the plots in Figures 7b and 7c. It was a load controlled test which took approximately 650 seconds to fail. Records of the cracking events as defined by the hydrophone data were correlated with the load and displacement data. A good correlation was found. Initial and final fracture events correlated very well. During crack propagation, slight discrepancies were noted between the data sets. This can be attributed to cracking at the bottom of the test piece prior to surface cracking. The interpretations of the hydrophone records indicate the entire crack front propagated, whereas the displacement gauges on the surface indicated less crack advancement. As the crack propagated, the data sets correlated better. Figure 7d shows the crack length computed by acoustics and inferred from the displacement data. Once the crack propagated, the CTOD gauge was no longer at the crack tip, so any incremental cracking or crack jumping was not seen by the CTOD gauge. This resulted in a slightly smoother prediction of the cracking behavior. Comparison of fracture energies calculated from both load/displacement and acoustic records will be presented in future publications.

CONCLUSIONS

Six field trips to the arctic were completed where a series of large-scale freshwater and sea ice experiments were carried out. Small scale experiments were also done to link laboratory testing with large scale ice behavior. The problem of size effects is addressed, noting that the in-situ tests conducted provide the means for verifying existing size effect laws. A preliminary investigation of the relationship between fracture events and acoustical signatures was also done. The large scale testing enabled the benchmarking of acoustical records with known forces and displacements. The results of the large scale experiments are necessary for the modeling of large scale ice behavior. Modeling efforts are in progress at Clarkson University as described in Part II (Mulhule et al., 1995).

ACKNOWLEDGMENTS

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REFERENCES


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SCALE EFFECTS IN ARCTIC ICE FRACTURE EVENTS - PART II

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Potsdam, New York 13699-5710

Abstract: The objective is to evaluate the scale effect on the fracture toughness of sea ice over the range $10^{-1}$ m (laboratory) to 100 m (full thickness field experiments) employing a combination of on-site and laboratory experiments linked to theoretical fracture and constitutive models as well as theoretical ice property models. Nonlinear fracture models can then be used to predict the scale effect over the range $10^{-1}$ $\approx$ 1000m. The long term modeling objectives include: (a) Quantitatively validate the near-tip processes and relaxation processes. In this context, the effectiveness of the currently available size effect laws in terms of their predictions for fracture energy and process zone size must be established; (b) Quantitatively verify a process zone model for fracture in saline ice at any scale by linking the experimentally determined information with an analytical treatment of the process zone. Details of the modeling aspects of two large scale fracture test programs on ice are presented in this paper (see Part I, Dempsey et al, 1995). The tests were conducted on macrocrystalline SI freshwater ice (Phase I) and columnar S2 sea ice (Phase II) spanning size ranges of 1.81 and 1:160, respectively. The fictitious crack model used for much of the analysis is described. The importance of polycrystallinity, anisotropy as well as time dependent behavior on the fracture of ice is revealed. Various size effect laws are investigated. The above field data set is the most comprehensive in the world for any material; the size range in Phase II was five times larger than any other size range and physically larger by a factor of 40. The nature of the data gathered has important interdisciplinary ramifications. The size range is large enough to determine the applicable size effect theories. If they truly work, the fracture properties for ice can be predicted on the scale of kilometers.

INTRODUCTION

Six large-scale arctic in-situ ice fracture test programs have been completed over the last three years. These field trips were aimed at studying size, rate and seasonal effects on the fracture of sea ice. Large scale experiments coupled with small scale field and laboratory tests were completed to reach this goal. The experiments have yielded an abundance of information related to the fracture and constitutive behavior of sea ice and are fully described in the paper by Adamson et al (1995). The latter paper is Part I of this study and is hereafter referred to as Dempsey-Part I. The size range covered in these six test programs span sizes which range from lab sizes to very large sizes.

Fracture toughness testing of ice was intensively reviewed by Dempsey (1991). Because of the material anisotropy, nonhomogeneity of ice and very high homologous temperature at which fracture tests are usually carried out, Dempsey (1991) defined $K_Q$ as an apparent fracture toughness. At that time, concern was expressed about accepting the then reported fracture toughness values as the true material property. The use of larger sized specimens or nonlinear fracture mechanics was advocated.

The various influences on the fracture of ice are reiterated below.
- Rate of loading.
- Notch tip acuity.
- Material anisotropy.
- Grain size effects and inhomogeneities such as grain boundary sliding, brine drainage channels.
- Specimen size and notch sensitivity
- Inelasticity ahead of crack tip.

A full thickness ice sheet has both a temperature and salinity profile through the depth: the isolated effect of either parameter is not separately obtainable. For the analysis in this paper, these effects were essentially constant. The issue of crack tip acuity was maintained constant by sharpening and scribing the cracks with a special apparatus. The rates of loading were kept fairly constant except for a few tests. The length of the pre-cut crack was always such that the specimens were notch sensitive and failure occurred by fracture. Notch sensitivity for first year sea ice was experimentally investigated by Parsons et al. (1993). Dempsey (1991) and Dempsey et al. (1992) were able to obtain the R-curve for laboratory ice tests using the RT geometry. The crack growth stability is affected by material resistance, geometry of the specimen and the loading system. In experimental R-curve evaluations, the amount of stable crack growth needed to reach a plateau fracture resistance may be as much as 500a fractured. (Peck et al., 1985). If ice behaves similarly, an ice specimen having da ≈ 15 mm would need at least 7 meters of stable crack growth to reach its plateau resistance.

While the rate of loading and specimen geometry influence the actual criteria stated, there is clearly a need for large scale testing to resolve some of the issues alluded to above. Although many issues affect the fracture toughness of ice, only a few of them can be investigated if restricted to the testing laboratory sized specimens. Factors such as notch acuity, ice temperature, salinity and notch sensitivity can be studied independently. However, material anisotropy, specimen size effects, and the true nature of strain localization during fracture can only be addressed by testing large sized specimens. Other interesting aspects of large scale testing result from the possibility of obtaining R-curve information (DeFranco and Dempsey, 1992 & 1994). In-situ testing also incorporates the actual temperature, grain size and salinity profiles through the thickness. Furthermore, the testing of ice at ice temperatures above -5°C is really feasible in the field only.

**FICTITIOUS CRACK MODEL**

Quasi-brittle materials such as ice, rock and concrete exhibit strain softening. Strain softening is caused by distributed cracking ahead of the crack. The fracture under such circumstances can not be
Figure 1: Loading configurations
characterized by a single parameter. Parameters which become important include the tensile strength and the material's characteristic length in addition to the fracture energy. To take into account this zone of inelastic deformation, Hillerborg (1976) proposed the fictitious crack model. Another model which addresses the same problem is the crack band model proposed by Bazant and Oh (1983). The crack band model uses a strain softening constitutive relation and the crack band is assumed to have a certain characteristic width that is a material property. The fictitious crack model uses the concept of a stress-separation curve which is assumed to be a material property. The zone of inelasticity in front of the crack is called the process zone, which has now become a widely accepted term. Both these models have been shown to be equivalent. These models are nonlinear models and are usually implemented using the finite element method. The accuracy of the finite element calculations however is dependent on the relative size of the process zone compared to the specimen size. Planas and Elies (1991) advocate use of the finite element method for small to moderate sizes and asymptotic analysis for large sizes. The implementations of these approaches are rather involved and need considerable computing power.

The main effect of the inelasticity ahead of the crack tip is the size effect on the maximum nominal stress which is different from the predictions of linear elastic fracture mechanics. Bazant (1984) introduced a size effect law to characterize the fracture of quasi-brittle materials. The size effect law makes it possible to approximately compute nonlinear fracture properties (Bazant et al, 1986). Other approaches based on equivalent linear elastic fracture mechanics have been proposed with similar objectives in mind. The two parameter fracture model by Jeng and Shah (1985) uses $K_F$, the stress intensity factor at the tip of the effective crack and $C_{TOD}$, the critical crack tip opening displacement computed at the original crack tip, as the characterizing parameters. Karihaloo and Nallathambi (1987) proposed a model based on the effective crack by using the critical stress intensity factor and the critical energy release rate. All of the above approaches developed have been tested extensively for concrete.

One of the consequences of using nonlinear fracture mechanics is the additional information required about the failure process. Most often the critical crack tip opening displacement and tensile strength are sought. The rate of loading affects the fracture energy as well as the critical crack tip opening displacement. It affects the strength to a lesser degree (Richert-Menge and Jones, 1993). Ice has a tendency to creep under applied stress. This creeping induces additional crack opening displacements. The crack opening profile shifts away from that given by linear elastic fracture mechanics, moreover this shift is time dependent. The models which use an equivalent linear elastic fracture mechanics approach specify the rate of loading such that the specimen response remains essentially elastic. If the duration of testing is such that the time dependent deformations (creep) of the specimen contribute significantly then these deformations have to be considered in the analysis. The simplest way is to treat each rate separately; for example, Bazant (1993) specified separate size effect laws for fast, moderate, slow and very slow rates. A general approach must use proper constitutive models to incorporate creep. Much work has been done in this area and one may refer to Ashby and Duval (1985), Sinha (1983), Shyam Sundar and Wu (1990), Cole (1993), Schapery (1993) and references therein. Creep in the vicinity of crack tips in ice, following the approach used by Riedel and Rice (1980), was attempted by Shyam Sundar and Nanthikesan (1992) for a constant rate of load. They obtained the size of the transient creep zone ahead of the crack for time to failure based on an assumed loading rate and purely brittle fracture toughness values reported in the literature. Their analysis also requires linear elastic displacement fields to be valid away from creep zone.

In this paper, a much simpler approach is favored whereby the response of damaged material in front of the crack is modeled as a distribution of 'cohesive stresses' whose dependence on displacement is assumed to be a material property. The response of the bulk of the specimen is evaluated assuming linear viscoelastic behavior. Since the bulk of the specimen is not subjected to very large stresses, linear viscoelastic behavior seems a reasonable approximation. This concept for viscoelastic materials was proposed in a series of papers by Schapery (1975a, 1975b, 1975c). Using the fictitious crack model while also assuming that the stress-separation curve is rate dependent and while the bulk response is assumed to be linearly viscoelastic it should be possible to capture most of the important features of fracture of quasi-brittle materials. The work of Bazant and Beissel (1994) is a step in this direction.

**Method of Analysis:** For the analysis of the test results, the fictitious crack model was chosen because it can be generalized to include rate effects. Though the fictitious crack model itself is a nonlinear model its implementation requires the superposition of linear elastic fracture mechanics results. The weight function method introduced by Buckner (1970) and Rice (1972) is an accurate method for computing the stress intensity factors as well as the crack opening displacements. A thorough exposition of this method is given in a text by Wu and
Carlsson (1991). The weight function for the analysis of the process zone was used by DeFranco and Dempsey (1992) for ice. The latter approach did not use the stress-separation curve but instead used an ad-hoc stress distribution ahead of the crack.

An alternative formulation has been implemented and used to analyze fracture tests on ice at Clarkson University. The numerical accuracy has been checked by careful comparisons with the results of Li and Liang (1986). Complete details will be published in a forthcoming paper by Mulhule and Dempsey (1995).

Consider a crack-process zone configuration shown in Figure 2a. The X-axis is along the crack plane and loading is symmetric with respect to the plane of the crack. The physical or traction free crack has a length represented by \( A_p \) while the length of the fictitious crack is denoted by \( A \). The portion of the crack between the physical crack tip and the fictitious crack tip is named the process zone \( A_p \). Cohesive stresses \( \sigma_c \) act within the process zone. The external loading is represented by \( \sigma_c, b, \delta, \delta_c \) and \( \delta_{cr} \) represent the resultant crack opening displacement of the crack opening displacement due to external loading and crack opening displacement due to cohesive stresses, respectively. For convenience, all lengths are normalized by the specimen size length \( L \). The normalized coordinate is \( x \), the normalized lengths of the physical and fictitious cracks are \( a \) and \( a_c \). According to the spirit of the fictitious crack model, the growth of the process zone is obtained by combining the externally applied load and the cohesive stresses such that the resultant stress intensity factor vanishes at the fictitious crack tip. That is,

\[
K_\sigma(a, \delta) = K_c(a_c, x, \delta, a) = 0
\]  

(1)

\( K_c \) and \( K_\sigma \) represen stress intensity factors due to the external loading and the cohesive loading. Superposition of the loading cases require that the crack opening displacement be given by

\[
\delta(x, a) = \delta_c(\sigma_c, \delta, a) - \delta_c(\sigma_c(x, \delta), x, a)
\]  

(2)

In equation (1) and (2) the functional dependencies are explicitly shown to clarify the nonlinearity of the problem. The dependence of cohesive stresses on the crack opening displacement is the stress-separation curve given by

\[
\sigma_c(\delta) = f(\delta) \quad 0 \leq \delta \leq \delta_{cr}
\]  

\[
= 0 \quad \delta > \delta_{cr}
\]  

(3)

In equation (3), \( \delta_{cr} \) represents the critical crack opening displacement beyond which material is considered separated. Equations (1) through (3) describe the fictitious crack model. The weight function method is used to compute the stress intensity factors as well as the crack opening displacements. The system of equations is solved using the Newton-Raphson method to obtain the load vs crack opening displacement by using an algorithm similar to that developed by Li and Liang (1986). The same program can be used for a range of geometries simply by substituting for the appropriate weight functions. Unlike associated finite element analyses, only the process zone needs to be discretized. Solution accuracy is independent of the specimen size and computational time and memory requirements are reduced considerably. Currently efforts are under way to extend the model by incorporating the effects of rate dependency of the stress-separation curve and linear viscoelastic response.

Efforts to apply this method to the problem at hand are hampered because the stress-separation curve for ice is not known. Even if the stress-separation curve at lab-scale were known, this may not necessarily coincide with stress-separation curve which would correspond to the behavior for an ice sheet with a resident temperature, salinity, and grain size profile. Further, in the field, there is no direct test method to determine the desired stress-separation curve. The procedure being followed here is to back this information out of the in situ large-scale fracture experiments, using the load vs crack tip opening displacement and load vs crack mouth opening displacement data. Approximate stress-separation curves can thus be obtained by assuming various stress-separation curves and comparing the obtained load vs crack opening displacement plots with the

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</tr>
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<td>RT2</td>
</tr>
<tr>
<td>B3</td>
</tr>
<tr>
<td>B4</td>
</tr>
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</tr>
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</tr>
<tr>
<td>RT6</td>
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<td>RT9</td>
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Figure 2: Fictitious crack model: (a) process zone model and coordinates; (b) stress-separation laws; (c) experimental calibration on RT1.
experiments. If the experiment is under load control then only a part of the stress-separation curve can be obtained at the peak load. For stable tests, however, the complete stress-separation curve can be captured. Complete identification of the stress-separation curve for sea ice furnishes all of the required parameters which characterize fracture in sea ice.

ANALYSIS OF LARGE-SCALE EXPERIMENTS

Phase I: Canmore, Alberta

In Phase I both S1 and S2 freshwater ice were encountered. The Bears paw reservoir (near Calgary) ice was columnar S2 and the Spray Lakes ice (near Canmore, Alberta), on which most of the testing was performed, was S1 macrocrystalline ice. The approximate thickness of the Canmore ice was 0.57 m and had a slight snow cover. Characterization of the ice from Phase I was done by Lazo (1994). For the first 3 cm from the top, the grain size averaged about 0.75 cm. At about 20 cm from the top, the grain size had increased to 5 cm after which the number of grains reduced. The grain size at the bottom of the sheet reached at least 20 cm.

The fracture toughness values determined have an increasing trend with increasing size. For smaller specimens there is some scatter. To apply the nonlinear fracture approach developed and gain more insight requires elastic modulus and crack tip opening displacement data. Required data obtained from the tests is shown in Table 1.

The crack mouth and intermediate crack opening displacements, in addition to crack tip opening displacements, were measured. This makes it possible to obtain the values of elastic modulus based on the initial slope of the load-CMOD (E/CMOD) as well as the load-COD (E/COD) plots. Both values are shown in Table 1 for the RT and beam (BM) tests. For smaller sized specimens, the flat jack took up space at the crack mouth and not enough space was left to mount CMOD and COD gages. In the case of RT7, as well RT9, data from the gages not shown was spoiled due to slippage of the gages. It is seen from Table 1 that the values of modulus computed from CMOD and COD are very different for smaller specimens. The difference between them reduces as the size of the specimen becomes larger and larger. These results indicate that the crack opening profile is different from elastic isotropic predictions for smaller sizes. Ratios of crack length and ligament length to average grain size (da) are also presented in Table 1. The average grain size across the crack front was obtained by weighting the size of grain by approximately the length of crack front. For small sizes, this ratio is small. Another feature is seen by considering the effect of grain size on elastic modulus obtained from cantilever beam tests subjected to axial loads shown in Table 2. The magnitude of the elastic modulus increases with the size. A similar trend is seen in the fracture tests. The last three tests, namely RT3, RT6 and RT9 have an average elastic modulus of approximately 10 GPa and are almost constant. This transition occurs when the ligament as well as the crack is roughly 15 times the average grain size. Table 1 also shows the failure crack tip opening displacements. These are seen to increase with specimen size. Preliminary fracture energy estimates reveal a monotonic increase with size when computed based on COD values. The CMOD based values exhibit more scatter for the smaller specimens but are comparable with the COD based values for larger sizes.

Table 3: Phase II Data

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<th>TEST</th>
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<th>E (GPa)</th>
<th>CMOD GPa</th>
<th>COD GPa</th>
<th>K (MPa(\frac{m}{m}))</th>
<th>CTOD (\mu m)</th>
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<td>0.46</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>SQ11</td>
<td>30.0</td>
<td>-</td>
<td>2.0</td>
<td>1944</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>SQ14</td>
<td>30.0</td>
<td>-</td>
<td>-</td>
<td>8.33</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>SQ13</td>
<td>80.0</td>
<td>3.9</td>
<td>4.7</td>
<td>0.17</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Phase I In-Situ Uniaxial Moduli

<table>
<thead>
<tr>
<th>TEST</th>
<th>L (m)</th>
<th>E (GPa)</th>
<th>L/dₐ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1</td>
<td>0.09</td>
<td>2.84, 3.19</td>
<td>1</td>
</tr>
<tr>
<td>CM2</td>
<td>0.27</td>
<td>6.12, 6.35, 7.23, 6.44</td>
<td>3.3</td>
</tr>
</tbody>
</table>
The zone of inelastic deformations has a relatively large size for the smaller specimens. For analysis purposes it was easier to start from the smallest size. Since the stress-separation curve for ice is not known, various shapes were tried in order to obtain the best fit with experimental data. The requirements imposed in order that the stress-separation curve approximate the fracture behavior correctly were:

- The peak load must be predicted correctly. In other words, under load control the unstable propagation of the crack should occur at the test peak load.
- The load-CMOD curve must be predicted correctly. This ensures that the correct bulk response as well as the nonlinearity due to the process zone is being modeled correctly.
- The load-CTOD curve must be predicted correctly. This puts stringent requirements on the validity of the cohesive stress distribution as well as the size of process zone.

The smallest size for which the load-CMOD, load-COD and load-CTOD curves were available was RT1. The failure CTOD for RT1 was 7μm while from RT9 it was known that the critical CTOD would be greater than or equal to 25μm. Only part of the stress-separation can be obtained using RT1. In trying to match the load-CMOD and load-COD curves, a choice had to be made about the modulus of elasticity to be used for computing the crack opening profiles. After a few trials, it was realized that using \( E_{\text{COD}} \) resulted in very large values for the CMOD whereas using \( E_{\text{CMOD}} \) the COD values obtained were far below the experimental results. The COD gauge was closer to the crack tip hence it reflected the crack tip behavior better than the CMOD gage. For this reason, the intermediate modulus \( E_{\text{COD}} \) was used in carrying out trials aimed at determining the stress-separation curve Load-CTOD and load-COD plots were used for calibration. Good results were obtained by assuming the stress separation curve shown in Figure 2b. Figure 2c shows the comparison of the experimental load-COD curves with the constructed load-COD curves. The normalized process zone size obtained was 0.00057L which for RT1 was 0.8 mm. The load-CMOD curve, however, could not be matched and the disagreement was almost in the same ratio as \( E_{\text{COD}} \) to \( E_{\text{CMOD}} \). The tensile strength deduced from the stress separation curve was 2.5 MPa and the initial portion of the stress separation curve showed a pseudo-Dugdale type of behavior. The area enclosed under the stress-separation curve, the fracture energy, was 17 J/m² compared to 2.25 J/m² obtained from linear elastic fracture mechanics. The size of the process zone is very small and easily remains contained within a grain. The fracture is controlled by the grain in which the crack front lies.

A similar procedure was adopted for RT3. The modulus value used for RT3 was 8.0 GPa. The resulting stress-separation curve is shown in Figure 2b. The size of the process zone obtained was 0.0001L which for RT3 was 0.424 mm. The fracture energy obtained was approximately 31 J/m². There is a large discrepancy in the fracture energy values obtained using the fictitious crack model and the fracture energy computed from linear elastic fracture mechanics even though the size of process zone is small. In addition, the tensile strength values obtained seem rather high. The fictitious crack model assumes a homogenous response outside the process zone. Due to a small number of grains and rather warm temperatures this is unlikely to be correct; the fictitious crack model is not applicable here.

These two exercises demonstrate the importance of recognizing the basic parameters governing the response as well as the difficulties encountered in adapting approaches developed for other quasi-brittle materials to describe the fracture of macrocrystalline S1 freshwater ice. Due to the small size of the process zone further analysis was not attempted.

Though the process zone size is much less than the grain size, the failure CTOD is seen to increase with increasing specimen size. This indicates that the specimen size still exerts an influence, even at the largest size.

**Phase II: Resolute Bay, N.W.T.**

Table 3 summarizes the moduli, loading rate and failure CTOD for the tests at Resolute. For smaller specimens, the COD gage was not mounted due to space limitations. When both are available, the elastic moduli computed based on the load-COD and the load-CMOD plots are comparable to each other, indicating specimen homogeneity. However, the modulus values do not tend to a uniform asymptote with size. Based on observational details, such variation could well have been caused by changes in the proportion of frazil ice vs columnar ice from site to site.

Except for a few tests, the rate of loading was almost constant. The rate of loading was less than that used during Phase I. The failure CTOD values can be seen to have peaked at around 37μm for the larger specimens. This seems to be an indication of a critical crack tip opening displacement for the rate tested. However, the associated load-COD and load-CMOD plots were very nonlinear. The CMOD value at peak load ranged from 1.2 to 1.6 times the CMOD value obtained using the original crack length and assuming linear elastic behavior. Considering the fact the CTOD value has peaked, much of the additional increase in compliance can only be due to bulk
Figure 3: Comparison of various size effect laws: $L_0 \equiv 1 \text{ m}; \sigma_0 \equiv 1 \text{ MPa}.$
creep deformation. Bulk creep also seems probable because of the comparatively longer test durations.

For Phase I, the fictitious crack model was applied in an effort to accurately model inelastic deformations in the vicinity of the crack tip. The rate independent process zone model applied for the results of Phase I, albeit unsuccessfully, cannot be used here. The latter approach requires load vs crack opening displacement data measured under conditions of linear elastic material behavior outside the process zone. Such an approach is not possible due to extensive creep in the present case. In-plane creep data for a full thickness ice sheet is not available. The data obtained by Vaudrey (1975) was used in a preliminary study, by assuming small scale yielding conditions, to compute the crack opening displacements. The results were encouraging. The fictitious crack model is now being extended to include the bulk creep using linear viscoelasticity.

ANALYSIS OF SIZE EFFECT LAWS

The fracture experiments conducted on sea ice during Phase II were unique in testing the largest size range known for any material. This provided a rare opportunity to determine the size effect on the peak nominal stress due to fracture. The size effect predicted by linear fracture mechanics is too strong for quasi-brittle materials like ice because of inelastic deformations like microcracking ahead of the crack.

This fact has long been recognized. Bazant (1984) proposed a size-effect law (from hereon called the BZ law) which provides for a gradual transition from strength failures at small sizes to failures governed by linear elastic fracture mechanics at very large sizes. The size effect law so derived assumes that the relative size of the process zone at peak load does not depend on the size of specimen. The latter statement presumes that notched geometrically similar specimen sizes are being tested. La and Bazant (1993) have estimated that this size effect law will adequately, if based on a test size range of at least 1:5, predict fracture behavior over a size range of 1:20. The unknown parameters in the size effect law are derived from the fracture test data. Size effects caused by the development of the process zone can also be obtained using the fictitious crack model of Hillerborg (1976). The fictitious crack model is apparently valid for any size range and may be applied to notched as well as unnotched tests.

Size effects, however, are not caused solely by a process zone ahead of crack. Lack of polycrystalinity and material anisotropy are other factors which may cause a size effect. These size effects need special treatment.

In the case of concrete, to account for dissimilar initial cracks and a residual strength independent of size, modifications to the Bazant's size effect law were proposed by Kim et al (1983) — (from hereon called the KSL law). Carpentier et al (1993) proposed a multifractal scaling law (MFSL) for similar reasons. In spite of considerable experimental efforts in the general field of the fracture of quasi-brittle materials, the following questions remain unanswered:

- If the size effect in a particular size range is desired, what actual size range needs to be tested to determining the associated size effect parameters?
- How do the parameters of various size effect laws change due to changes in the absolute size of specimen? Phrased differently, if a 1:10 test size range spans 0.5 m to 5 m, as opposed to the test range 3 m to 30 m, how much do the size effect parameters differ?

The available size effect laws are now analyzed. The basic laws studied are the BZ, MFL and KSL size effect laws (\(\sigma_n\) represents the nominal maximum stress):

\[
\sigma_n = \frac{A}{(1 + L/B)^{1/2}} \quad \text{BZ (4)}
\]

\[
\sigma_n = D(1 + 10^B/L)^{1/2} \quad \text{MFSL (5)}
\]

\[
\sigma_n = \frac{A}{(1 + L/B)^{1/2} + D} \quad \text{KSL (6)}
\]

In this paper, to ascertain if the exponents that are equal to 1/2 in the BZ law (5) and in the KSL law (7) are truly optimal, slight modifications were proposed. That is, the exponent was left unspecified prior to obtaining the best fit with experimental data. With the exponent set equal to C, the latter two laws are renamed as the MBZ and the MKSL laws.

\[
\sigma_n = \frac{A}{(1 + L/B)^{1/2}} \quad \text{MBZ (7)}
\]

\[
\sigma_n = \frac{A}{(1 + L/B)^{1/2} + D} \quad \text{MKSL (8)}
\]

The undetermined constants in each of the above laws, A, B, C and D, were obtained via precise curve fitting of the original size effect data from Phase II using TableCurve (an automated non-linear curve fitting program that uses a 64-bit Levenburg-Marquardt algorithm). It should be noted that while carrying out the linear regression for the BZ law according to the procedure given in RILEM draft recommendations (1991) it was noticed that the coefficient of variation of the intercept exceeded the prescribed limit of 0.20. The non-linear Levenburg-Marquardt algorithm obtained optimum fits.

Note that the constant A represents a small-scale strength value and is closely related to the tensile strength. For the BZ, MBZ, KSL and MKSL laws,
Table 4: Size Effect Laws

<table>
<thead>
<tr>
<th>FIT</th>
<th>DATA (m)</th>
<th>LAW</th>
<th>A (MPa)</th>
<th>B (m)</th>
<th>C</th>
<th>D (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIT1</td>
<td>0.5-80</td>
<td>BZ</td>
<td>0.446</td>
<td>0.70</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBZ</td>
<td>0.417</td>
<td>1.18</td>
<td>0.5892</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MKSL</td>
<td>0.367</td>
<td>2.34</td>
<td>1.097</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MFSL</td>
<td>-</td>
<td>1.46</td>
<td>-</td>
<td>0.050</td>
</tr>
<tr>
<td>FIT2</td>
<td>0.5-3</td>
<td>BZ</td>
<td>0.450</td>
<td>0.68</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBZ</td>
<td>0.394</td>
<td>27957.13</td>
<td>7568.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KSL</td>
<td>-</td>
<td>-</td>
<td>0.57</td>
<td>-0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MFSL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.125</td>
</tr>
<tr>
<td>FIT3</td>
<td>3-80</td>
<td>BZ</td>
<td>0.241</td>
<td>2.71</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBZ</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KSL</td>
<td>0.261</td>
<td>2.26</td>
<td>0.5</td>
<td>-0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MFSL</td>
<td>-</td>
<td>1.78</td>
<td>-</td>
<td>0.038</td>
</tr>
<tr>
<td>FIT4</td>
<td>0.9-80</td>
<td>BZ</td>
<td>13.881</td>
<td>0.00055</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBZ</td>
<td>7.020</td>
<td>0.00208</td>
<td>0.497</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KSL</td>
<td>8.218</td>
<td>0.00151</td>
<td>0.5</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MFSL</td>
<td>-</td>
<td>2.26</td>
<td>-</td>
<td>0.024</td>
</tr>
<tr>
<td>FIT5</td>
<td>3-30</td>
<td>BZ</td>
<td>0.242</td>
<td>2.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KSL</td>
<td>0.252</td>
<td>3.35</td>
<td>0.5</td>
<td>-0.015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MFSL</td>
<td>-</td>
<td>1.67</td>
<td>-</td>
<td>0.042</td>
</tr>
</tbody>
</table>

B represents the ductile-brittle transition size, where this point lies at the intersection of the strength and LEFM asymptotes. The transitional size for the MFSL law is again given by B; however, this point now apparently separates the disordered regime from the ordered (homogeneous) regime asymptotes. In the MBZ and MKSL, C represents an arbitrary exponent, to be found by a best fit of the data. The constant D represents the residual or size independent strength asymptote for very large sizes.

The smallest specimen had a dimension of 0.5 m while the largest specimen had a dimension of 80 m. To study this size range the results are divided in five different cases, as shown in Table 4.

FIT1 covers the complete size range of the data. The associated comparison of the experimental data and size effect law fits are shown in Figure 3a. Note that all of the size effect laws span the data with similar accuracy. The MFSL law tends to infinity for smaller specimen sizes. Both the MFSL and KSL laws tend to a constant maximum nominal stress (given by the value of D) for very large sizes but they differ in the prediction of that value. The optimum value of the exponent for the MBZ law is slightly greater than 1/2 and the ductile to brittle transition size given by constant the constant B is slightly larger than 1 m.

FIT2 and FIT3 have been formulated to represent the sub-ranges of the data at the very low size range (spanning a 1:6 size range) and over the high size range (spanning a 1:27 size range), respectively. Attempts to find an optimum exponent for the MBZ law were not so successful. The KSL law could not be obtained for FIT2 and gave a negative constant stress for FIT3. The MFSL fit was good in FIT3.

Graphical comparisons with the experimental data for FIT2 and FIT3 is provided in Figure 3b & 3c, respectively. FIT4 tried to judge the importance of the small scale data by removing the smallest sized specimen. FIT5 spans the middle part of the size range by removing the data for both the small sizes as well as the largest size.

The MFSL law always overestimates the nominal maximum stress for small sizes because of its mathematical structure. Because of this inherent feature, removal of the data for smaller sizes has little effect as can be seen from FIT1, FIT3 and FIT5. The residual strength for the MFSL law is, however, very much affected by the cut off size chosen at the larger end. For FIT2, which has data provided up to sizes of 3 m, the residual strength predicted is much higher than the other fits for which either 30 m or 80 m is chosen as the data cut off. The difference in residual strength for 30 m and 80 m is very much less but it is still difficult to say if (i) an asymptotic limit has been reached, or (ii) whether the concept of a residual strength at very large sizes is tenable.

The KSL law tries to combine the features of the BZ law for small sizes and features of the MFSL law for large sizes. For this reason, the KSL law performs well only when the data for very small and very large sizes are both included, as in FIT1. Exclusion of the data from either extremity lessens the accuracy of the prediction at the corresponding extremity as is seen from FIT3 and FIT5. If the size range is too small, it is not possible to fit the KSL law, as is the case in FIT2.

Similar considerations explain the results for the BZ law. The constant A is governed by the smaller sized test data, as is apparent from comparing FIT1 & FIT2 with FIT3 & FIT5. Additionally, the smaller sized test data exerts a considerable influence on the predicted transition size as given by the constant B. Such results were anticipated by Li and Bazant.
Figure 4: Nominal Stress: Phase I Data

(1993). If test results near the transition size is included, then the size effect law accurately models the portion during which rapid changes occur and predictions for larger size ranges are good. Comparison of FIT1 and FIT2 where the input size range is reduced from 1:160 to 1:6 makes this point. However, if this 1:6 region is excluded, as has been done in FIT3 and FIT5, the effect on the parameters is considerable.

In FIT1, the optimum MBZ exponent for the complete size range is slightly different from 1/2 and the corresponding transition size is slightly larger. The optimum index, however may not always lead to correct behavior if tried on too small a size range as can be seen from MBZ in FIT2 as well as the fact that the MKSL law had to be abandoned in FIT3, FIT4 and FIT5. For materials like ice, where at the smaller sizes other effects like polycrystallinity become important, scatter in the data is expected. Since the size effect laws like the BZ and KSL laws factor in a size effect due solely to crack and process zone size vs (homogeneous) specimen size, they are very sensitive to this scatter as can be seen from FIT4 where the 0.5 m data was excluded. The latter observation indicates that a certain minimum size (relative to the average grain size) is necessary in order to obtain consistent results.

This discussion brings us back to the two questions initially posed:

- If the size effect in a particular size range is desired, what actual size range needs to be tested to determining the associated size effect parameters?
- How do the parameters of various size effect laws change due to changes in the absolute size of specimen?

In response to the first question it can be said that the range to be tested depends upon what part of the size effect curve is of interest. If the size range of interest is such that rapid changes occur in the size effect curve, then it may be advisable to carry out the size effect tests for as big a size range as can be done. The same logic applies to the second question. If both the size ranges in terms of absolute sizes lie on the portion of size effect curve where the changes are gradual, then the size effect law calibrated on one size range may be useful for size range with different absolute sizes. This point is difficult to state in quantitative terms because, depending on the data range tested, the transition size as well as the part of the size effect curve undergoing rapid changes is seen to change.

Phase I: Figure 4 shows the plot of log of maximum nominal stress vs the log of the size. Though there is a decreasing trend in maximum nominal stress with size, efforts to fit any sort of law proved fruitless. The most probable reason seems to be the presence of other size effects due to the very large grain size.

CONCLUSION

Preliminary analyses for the large-scale fracture tests from Phase I and Phase II are presented. The grain size has significant influence on the fracture


of S1 freshwater ice. Due to nonhomogeneous response, a nonlinear fracture mechanics model such as the fictitious crack model does not yield consistent results for Phase I. For Phase II (columnar S2 sea ice), the inclusion of bulk viscoelastic deformation has been found to be essential for proper numerical analysis. Various available size effect laws have been compared. The behavior of these laws over portions of the available size range was examined to study the effect of change in size range as well as change of the absolute sizes. The predictive capability of the size effect laws was shown to be rather fickle. By examining the various size effect laws in Figure 3 outside of the data range for which they were calibrated, a large difference is seen. This difference is imposed by the mathematical structure of the laws which have been constructed on the basis of specific beliefs. If a larger size range than what has been tested were to become available then all the size effect laws would again span this larger size range in the same fashion as Figure 3a with the same order of disagreement in the extrapolated region. Future research on this topic does not lie within the proposition of various curve fit or size effect laws such as those just examined. There is a clear need for a quantitative basis to the predicted size effects. The latter basis will reside with approaches reflective of the true material behavior.

ACKNOWLEDGEMENTS

Phases I & II of this study were supported in part by a joint-industry-agency project (JIAP) initiated and managed by Canadian Marine Drilling Limited (Canmar), a business unit of the Amoco Canada Petroleum Company specializing in arctic offshore drilling and marine activities. Funding for the JIAP was provided by Amoco, Canmar (Canada), Mobil, National Energy Board (Canada), Texaco (Phase I), Minerals Management Service and the Office of Naval Research under ONR’s Sea Ice Mechanics Accelerated Research Initiative [Grants N00014-90-J-1360 & N00014-93-1-0714].

REFERENCES


The State of Alaska asked the Corps of Engineers in February 1993 to investigate Alaskan port improvements related to the State's strategic position on the Northern Sea Route. The U.S. Congress appropriated $300,000 in November 1993 to begin the study and appropriated another $300,000 the next year to complete the 18-month investigation. The Corps study was administered by the Alaska District office in Anchorage, with technical assistance from the Corps' Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire.

The Corps mission requires a focus on port improvements, but this unique assignment called for an extensive information-gathering effort at the start. The Cold Regions Lab assisted the Alaska District with an overview of the history and present status of the Northern Sea Route and the state of the art in design of arctic ships. The University of Alaska assisted with a review of Russian capabilities to monitor and forecast arctic conditions, a summary of climatological factors which affect the cost of shipping, and a summary of international initiatives now under way, including the International Northern Sea Route Program.

Commercial port planning specialists were contracted to forecast commodity flows over the Northern Sea Route. A summary of historical world sea trade statistics was compiled and applied to forecast commodity flows which could be diverted from canal routes. Only non-liner services between regions geographically closer by the Arctic Ocean were considered in this analysis.

The Corps Cold Regions Lab inventoried the world fleet of ice-breakers and arctic cargo ships, with the assistance of a commercial specialist in Russian arctic ships. The laboratory also developed a computer simulation of the passage of selected cargo ships along the Northern Sea Route. This model applies the climatological and ship information gathered by the study to estimate the average transportation cost for various commodities by simulating many voyages in the full range of possible conditions. The simulation results were applied to adjust the forecast of commodity flows based on the competitiveness of the transportation cost.

Forecasts indicate that non-ferrous ores have the best prospects for Alaskan export to Europe via the Northern Sea Route. A State-owned ore terminal near the village of Kivalina on the Chukchi Sea has in recent years exported lead and zinc ore to Europe via the Panama Canal. The efficiency of the operation on the Chukchi Sea is constrained by the shallow approach to the terminal, the presence of ice, and concerns for whales' summer migration along this coast.

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specific feasibility analyses for channel and port improvements have begun as a result of these findings.

Forecasts for the entire Pacific rim indicate the possibility of a substantial increase in a broad range of commodity flows via the Northern Sea Route in future decades. The forecast throughput is large enough that shipments may extend well beyond the optimum climatic conditions of August and September. Shipment beyond this best season are certain to require ice-breaker escort along most of the route and thus to travel in convoys. Unalaska/Dutch Harbor, in the Aleutian Islands between the Pacific Ocean and Bering Sea, appears to be in a good position to serve Northern Sea Route convoys. A site-specific study of channel improvements, expansion of Unalaska/Dutch Harbor port facilities, and establishment of protected anchorages has begun.

The Corps published its Northern Sea Route Reconnaissance Report in June 1995. The report recommends site-specific feasibility studies by the Corps of Engineers of port improvements at both the ore terminal near Kivalina on the Chukchi Sea and at Unalaska/Dutch Harbor. The report also recommends efforts by others, including:

1. Augmentation of relations with trading partners in the Arctic and Europe by the Alaska Department of Commerce and Economic Development, the University of Alaska, and the Northern Forum;

2. Intermodal transportation projects by the Alaska Department of Transportation and Public Facilities and the U.S. Federal Highway Administration to bring Alaskan resources to tidewater,

3. Chart improvements by the U.S. National Oceanic and Atmospheric Administration,

4. Improved aids to navigation and safety measures in the Bering and Chukchi Seas by the U.S. Coast Guard; and

5. Applied research and development by the University of Alaska and others on climatological factors affecting shipping cost, the design of arctic cargo ships, and the design of shallow-draft supply vessels to serve rural Alaskan communities.
UNDERWATER TRANSPORT SYSTEM FOR THE ARCTIC

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ANNOTATION

The results of work of St. Petersburg Marine Engineering Bureau (SPMBM) "Malachite" jointly with other organizations on development of underwater transport system for the Arctic, which can and has to integrate in international transport trans-arctic system in the future, are stated in this report. Taking into account the great importance for the Russian economy of development of natural resources of Extreme North regions and Arctic Ocean shore, the forthcoming development of oil and gas condensate fields of arctic shelf, SPMBM "Malachite" as an engineering bureau having a large experience of underwater shipbuilding and being able to use up-to-date progressive technologies on creation of submarines, underwater vehicles and deep-diving technique is developing works on underwater transport means for the needs of national economy of Russia. Such a system will essentially increase an efficiency of shipments between the countries of the Pacific Ocean region and Europe. The base preconditions, general considerations on conception and tasks of underwater transport system, estimation of technical decisions and main performances of underwater tankers and container carrier, and preliminary results on its economic effectiveness are listed in the report. Authors rely upon a display of an international community interest in discussion of raised problems and interaction on their realization.

Redistribution of Russia's raw materials and energy supply resources significantly increased at present conditions the role of the north regions of the country and its arctic shelf, and accordingly the role of sea shipping, the necessity of increasing of their economic efficiency, speed and regularity.

The forthcoming exploitation of oil and gas fields in the Barents and the Kara Seas, in the coastal regions of Jamal, the necessity of the extreme north regions supply by fuel, manufactured goods and foodstuffs, possibility of use of the shortest sea route between an European and Asia ports (for example, the route Rotterdam - Yokohama is more than twice shorter through the Arctic Ocean than through the South routes), reveal the paramount importance of solution of the complex transportation problem for the Arctic, which have to solve three main tasks.

transportation of hydrocarbon raw materials from the Arctic to the Asia-Pacific Ocean and Atlantic regions;

transportation of the oil products, manufactured goods and foodstuffs for the whole Extreme North coast;

transit transportation of expensive and prompt cargoes by the Europe-Asia route through the Arctic routes of the high latitudes.

SPMBM "Malachite" during several years has been developed the possibility of creation of an underwater transportation means, which would solve the above mentioned tasks and will be a part of the complex transportation system in the Arctic.

These tasks of transportation system undoubtedly have international nature and have to be interesting for the countries of European Community as well as for Japan, as they will be able to intensify significantly a goods traffic on the above mentioned routes, and mainly to ensure their regularity and stability.

Social and economic necessity of the defence industry conversion, powerful scientific and technological basis of underwater shipbuilding, nuclear-powered submarines experience of navigation in the high latitudes, principle possibility of regular and all-the-year-
round cruises by means of nuclear-powered submarines are the preconditions for such a, in essence, new solution of transportation problem.

The most prospective oil and gas fields are located on the vast territory to the north from Arctic Circle and at the continental shelf of Barents and Kara Seas. Workable reserves are estimated for 1.5 milliard tons of oil, 250 millions tons of gas condensate and more than 15 billions m3 of gas. According to the preliminary data, the amount of oil and oil products export in the nearest 10-15 years from this region may be 20-25 millions tons per year.

Thus, for example, only from one "Prirazlomnoe" oil field, which is situated in the mouth of Pechora river (550 miles from Murmansk), the amount of oil transportation according to the most modest calculations may be from 330 thousands tons to 1 million tons of oil per year. (Here sea shipping is the only variant.) Kharasaveyskoe and Bovanenkovskoe gas fields can provide the amount of gas production no less than 180-200 milliards m3 per year. Shtokmanovskoe gas and condensate field in Barents Sea (400 miles from Murmansk) can provide the same amount.

Geographical position of the richest fields in the world makes favorable conditions for an export to the North Europe, to the USA, Canada, as well as to Japan and Korea after the development of transit transportation by the Arctic routes in comparison with the delivery from the fields of the South hemisphere - Persian gulf, Western Afica and South America.

At the end of 1980-s the real delivery of oil products to the regions of Extreme North was 9.75 millions tons, so it is entirely real to talk about 10 mln.tons per year as a minimum. In connection with that fact that Extreme North regions are difficult to access for a land transport, that river transportation is difficult because of shallow water, a delivery of a considerable part of cargoes is provided by ships through the North sea route.

At present the main direction of shipping development in Arctic is construction and operation of surface transport ships with increased icebreaking, with strengthened reinforcements of the hull, with increased power to weight ratio and powerful icebreakers.

However, the all-the-year-round navigation at the Arctic sea route has not been ensured till now, and the summer navigation is also unstable, almost every year it takes 2-3 months. Attempts to built icebreaking transport ships with nuclear power plant, for example, the lighter "Sevmorput", which mainly operates in warm latitudes, do not solve this problem. High cost of construction of ice ships and provided them icebreakers, seasonal prevalence of use of their ice qualities, decreasing of ice possibility during operation, considerable number of ice damages - all these demands consideration of ships, which have not ice resistance to the motion or reduce it to the minimum. Therefore, Bureau executed a number of design research works on creation of underwater transport ships, which at the normal operational conditions are independent form ice and hydrometeoro logical conditions at the surface, and which will provide regular supply of the Extreme North Russia's regions by oil products and export of hydrocarbons raw materials. Therefor Bureau executed several design research works on creation of underwater transport ships, due to advertisement some of them, such as tanker and container carrier, became widely known in the world and aroused a great interest. Underwater transport ships will be the basis for underwater transport arctic system, which will also include underwater water-development structures - reception terminals and pipeline systems for distribution of oil products to customers, as well as berths for tankers' mooring.

Regular and all-the-year-round underwater transportation of oil products will significantly influence on the strategy of cargoes delivery to the Extreme North regions, will exclude the necessity of creation of considerable oil products reserves in shipping ports before an opening of the navigation at Arctic sea route, will decrease tension on communications, by means of which oil products from processing enterprises are delivered to ports. In winter period by means of underwater tankers there is a possibility to deliver oil products to the shore oil tank farms from were they will be delivered to the customers by the rivers at an opening of the navigation.

Regular and all-the-year-round delivery is also important for general cargoes, which are also needed for the regions of the Extreme North.
Researches of the Norway Center on Study of International Economics and Shipping (The Fridtjof Nansen Institute) titled "Commercial aspects of creation of line transport service at the arctic sea route" (September 1993) considered the possibility of container transportation between Hamburg/Rotterdam and Yokogama through the arctic sea route. Obtained results allow to conclude, that the Arctic sea route is sufficiently interesting alternative for traditional routes during at least six months concerning the frequency of ships' running between and the time spent in the cruise.

Providing further development of satellite navigation, reliable and not expensive icebreaking support, development of superships with small draught and organization of cargo's completing, the line of container liner shipments working six months per year may provokes a strong competition for the companies, which transport cargoes by the South route.

These conclusions referred to the surface container fleet; speaking about underwater container shipments, they could function almost all-the-year-round and would provide one of the shipments' priorities - their regularity, especially for valuable cargoes, for which delivery time is a strict point.

With regard to the above mentioned, design developments and preliminary engineering and economic investigations of underwater tankers and container carriers for Arctic conditions were carried out during 1989-1994 by St.-Petersburg Marine Engineering Bureau "MALACHITE" jointly with the State Enterprise "ROSNEFT", Russian Academy of Science, Central Marine Research and Design Institute with the participation of the Research Institute of Arctic and Antarctic. Design solutions on selection of such ships' exterior were done with regard to the specificity of navigation region, operational safety requirements, ecological purity and other requirements placed upon the surface transport ships of the same purpose.

For transportation of hydrocarbon raw materials and oil products in the Russia's Extreme North regions it is proposed to use underwater tankers, equipped with nuclear power plant, which could ensure regular, all-the-year-round navigation independently of weather and ice conditions without icebreaking support at the expense of a possibility to move under ices. Two directions of underwater tankers creation were considered:

- re-equipment of inactivated submarines into underwater tankers at the expense of aboard attachment of two tank blocks or incision in a hull of tank compartments;
- creation of underwater tankers specially designed for Arctic conditions.

For the more complete realization of all advantages, which have underwater transport ships in the Arctic, it is necessary to create specialized underwater tankers which could navigate not only under ices, but also in ices.

A new structure of underwater tanker was proposed in carried-out design developments.

This hull structure worked through in ice basin in the Institute of Arctic and Antarctic ensures the possibility of icebreaking by means of the force applied to a bottom of ices. This gives underwater tanker the possibility to move in surface position as an icebreaker at coastal shallow-water parts of a route, and to come up closely to the places of loading and discharging, as well as to get over ice fields in Bering Strait at transit voyages by itself, without icebreaking support.

Underwater container carriers were developed for the transit cargo delivery on the regular shipment's line of Hamburg-Yokohama type.

Design decisions on an underwater container carrier are determined by the necessity of deployment of the possibly great number of containers, by the conditions of their loading, discharging and internal transportation, by the technological limits on building conditions.

Preliminary estimations show economic efficiency of underwater container carriers use.

Nuclear power plants of tankers and container carriers are fully correspond to the up-to-date requirements on radiation safety; they ensure ecological purity also due to the refusal from burning of hydrocarbon fuel.
### Shipbuilding Elements and Technical and Operational Characteristics of Underwater Vessels

<table>
<thead>
<tr>
<th>Name</th>
<th>Product Tanker</th>
<th>Tanker</th>
<th>Container Carries</th>
<th>Multipurpose supply vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal displacement, m³</td>
<td>33500</td>
<td>79000</td>
<td>78500</td>
<td>45200</td>
</tr>
<tr>
<td>Total submerged displacement, m³</td>
<td>58100</td>
<td>92000</td>
<td>92000</td>
<td>49400</td>
</tr>
<tr>
<td>Extreme length, m</td>
<td>174</td>
<td>238</td>
<td>238</td>
<td>207</td>
</tr>
<tr>
<td>Hull breadth, m</td>
<td>26.5</td>
<td>26.8</td>
<td>28.8</td>
<td>22.0</td>
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<tr>
<td>Height, m</td>
<td>19.4</td>
<td>20.2</td>
<td>20.2</td>
<td>17.3</td>
</tr>
<tr>
<td>Output of nuclear power-plant, horsepower</td>
<td>1x3000</td>
<td>1x5000</td>
<td>1x5000</td>
<td>2x2500</td>
</tr>
<tr>
<td>Service speed, knots</td>
<td>15</td>
<td>10-12</td>
<td>10-12</td>
<td>10-12</td>
</tr>
<tr>
<td>Ice-breaking capacity at speed of</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 knots, m</td>
<td>40</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum cargo-carrying capacity, t</td>
<td>12000</td>
<td>30000</td>
<td>30000</td>
<td>17500</td>
</tr>
<tr>
<td>The number of container (20 ft), unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean draught, m</td>
<td>9.0</td>
<td>16.0</td>
<td>12.8</td>
<td>11.0</td>
</tr>
<tr>
<td>The crew number, persons</td>
<td>35</td>
<td></td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Endurance, days</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>

Special design measures on safety, reliability and ecology, provided at creation of nuclear power plants for underwater transport ships and based on successful operational experience of submarines and atomic icebreakers, have to change some negative stereotypes of treatments to nuclear-powered ships and their calls into ordinary commercial ports.

Also it is necessary to mark some social aspects of underwater shipments realization in the Arctic:

- regularity and guarantee of oil products and other cargoes delivery to the Arctic can ensure better life and work conditions of people, better prospects of employment in the Russia's north regions;
- creation and use of underwater tankers and container carriers would allow to solve the conversion problem of the part of shipbuilding industry and social employment problems of retired high-qualified Navy specialists at the qualitatively new level.

Ashore infrastructure - loading-discharging complexes, terminals, storages, ashore transport communications, support systems: navigation, communication, power supply and etc. - is an important element of underwater transport system. However, it is equally necessary to develop all this at industrial exploitation of fields and at functioning of existing surface and icebreaking fleet.

Thus, creation and use of underwater tankers at export of hydrocarbon raw materials to the Europe, Canada and Asia countries, and at delivery of oil products to the Russia's Extreme North regions, as well as at transit shipment of general container cargoes at the route Europe-Asia through the Arctic Ocean is a prospective direction in improvement of the marine arctic transport system.

Technological problems on creation of underwater transport system, as well as development of loading-discharging systems and ashore re-loading sets, ensurance of safety, reliability and regularity of navigation, creation of necessary ashore infrastructure, to say nothing of shipbuilding tasks on creation of underwater transport ships are sufficiently complicated, but they all can be advantageously solved, provided a general progress of country’s economy and positive results of in-depth economic analysis.

Underwater transport system for the Arctic has all technological preconditions for its successful realization.

The task of such system creation is complex, large scale and long-term problem. Joint efforts of many countries, international investments are necessary here, and we offer cooperation to the participants of this symposium and to an industrial circles of Japan.
TEORETICHESKIY - SEKRET PODVODNOGO TANKERA - PRODUKTOWOZA VARIANT 2. LINES DRAWING OF UNDERWATER PRODUCT TANKER, VARIANT 2.
GENERAL ARRANGEMENT OF UNDERWATER PRODCT TANKER

1 - accommodation compartments
2 - primary control station
3 - auxiliary mechanisms compartment
4 - diesel-electric installation compartment
5 - cargo tanks
6 - pump room
7 - reactor compartment
8 - compartment with turbine-generator
9 - compartment with turbine-generator
10 - compartment with electric equipment
11 - steering compartment
12 - ballast-compensating tanks
13 - bow main ballast tanks
14 - stern main ballast tanks
15 - cr-habitation box
GENERAL ARRANGEMENT OF UNDERWATER TANKER

1 - compartment with electric equipment
2 - primary control post compartment
3 - accommodation compartment
4 - cargo tanks
5 - pump room
6 - diesel-electric installation compartment
7 - reactor compartment
8 - turbine compartment
9 - auxiliary mechanisms equipment compartment
10 - steering compartment
11 - rescue submersible
12 - ballast compensating tanks
13 - bow main ballast tanks
14 - stern main ballast tanks

1 - электромеханический отсек
2 - главный пост управления
3 - жилая посаженность
4 - воротные танки
5 - насосное отделение
6 - отсек главного-генераторной установки
7 - реакторный отсек
8 - грузовой отсек
9 - механический отсек
10 - рулевое отделение
11 - специальный подводный отсек
12 - воздушно-защитительное устройство
13 - насосные танки главного балласта
14 - балластные танки
GENERAL ARRANGEMENT OF UNDERWATER CONTAINERSHIP

1 - compartment with electric equipment
2 - primary control post compartment
3 - accommodation compartments
4 - cargo compartment
5 - reactor compartment
6 - turbine compartment
7 - auxiliary mechanisms equipment compartment
8 - steering compartment
9 - bow platform for cargo operation
10 - stern platform for cargo operation
11 - rescue submersible
12 - ballast compensating tanks
13 - bow main ballast tanks
14 - stern main ballast tanks
COMPRESSING OF SEA ICE AND LOCAL STRAIN OF ICE FIELD

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Russia, St.Petersburg

ABSTRACT
Measurements of strain in pack ice floes 4 meters thick were carried out on the drifting station "North-Pole-28". Quartz strainmeters and seismometers were used. In this report results of the observations of the active dynamic processes are presented. Principal strain increments and their directions, self-excited oscillations and the attendant meteorological parameters (such as air temperature and pressure, wind velocity) were analyzed. A hystogram of the strains in the 2-dimensional space was drawn (two coordinates were divergence and deviator of the strain tensor). The analysis has revealed two most typical states of the ice cover. The first one is the basic state; up to 90% of all the events belong to the first type. In this state, the magnitudes of divergence and deviator are small. The second one is the compression state; up to 10% of all the events belong to it. In this state, the stress magnitude increases. It was shown that the local strains can be indicators of the large-scale compression and ridging of the sea ice. Three events are interpreted according to the synoptical conditions. The compression processes are accompanied by the self-excited oscillations.

INTRODUCTION
The development of instrumental observation means allowed estimating the values of sea ice strains, their properties and some typical features. Studies (Legen'kov, 1992) were mainly conducted at ice camps of small- \(10^3\) m, medium- \(10^4\) m and large \(10^5\) m scales. The absence of objective methods for estimating the intensity of compression for the sites of such a size make difficult studies of the rheological properties of ice cover restraining thus progress in modelling and forecasting of dynamic processes. Such difficulties do not arise during
observations at local (100 m) measurement sites.

Composite local observations of the deformation processes of sea ice by means of a distributed system of strain-, stress-, tilt- and seismometers were used for studying the dynamic processes in the ice cover of the Arctic Basin (Smirnov, Shushlebin, 1980). Some typical features of local strains were found during the experiment in Fram strait (Manley et al., 1982). Local observations were also used for solving some applied objectives, in particular, when estimating ice loads on off-structures (Niemenlehto, 1986). On the whole, one may note that deformation of a separate ice floe reflects a wide range of oceanographic and atmospheric processes and can serve as an additional information source for their studies.

**Observation Means and Conditions**

Observations were performed during the drift of the "NP-28" station on an almost round ice floe with a mean diameter of 1500 m and a thickness of 4 m which was in a close ice massif and was separated from it by a belt of smoothed hummocks. Three quartz strainmeters were the main component of the measuring system (Smirnov, Shushlebin, 1983), deployed at a point by an equiangular scheme. Fig. 1 presents a scheme of a quartz strainmeter. Calibration of the instrument and regulation of its sensitivity were performed at the deployment site, with a maximum sensitivity of 10^-8. In addition, strain-, tilt- and seismometers were used. In general, the work program of the station included meteorological observations, hydrological measurements and satellite coordinate measurements. The analysis also uses the results of standard observations of the drifting station "NP-29" located at a distance of 800 km.

**Data and Their Analysis**

For the period of the drift of NP-28 in 1987-1989 a piecewise continuous data series on local strains was obtained. For resolving problems of the procession methods a small segment of the record for April 1988 was chosen when the station was in
the area of active dynamic processes. The obtained results allowed some preliminary conclusions which can be useful for planning further studies.

A two-dimensional tensor representation of the theory of elasticity of the mechanics of continuous media served as a basis of the mathematical model. Main ratios and the scheme of the deployment of strainmeters are given in Fig. 1. The strain tensor components, divergence and deviator, as well as main strains and their directions were calculated from the calibrated and detrend data. The calculation results, given in Fig. 2, show that at the background of a quasiharmonic deformation of a small amplitude (0..107h) the process of ice compression is pronounced (107..115h) and accompanied by intensive hummocking according to visual observation data. Compression is governed by the intrusion of a continental cyclone to the region of the Severnaya Zemlya Island. The influence of the cyclone on the drift trajectories of the stations "NP-28" and "NP-29", Fig. 2, is traced in the form of a significant increase in the drift velocity on April 20-21. The data of accompanying meteorological parameters, as well as the results of calculating drift velocity and direction are given in Fig. 2 and the surface atmospheric pressure map in Fig. 3.

It is known that the strain tensor can be split into a spherical and deviator tensor. Thus, any deformation can be represented in the form of superposition of a comprehensive compression strain and shear strain and any deformed state of the object under study in the form of a point in the strain space whose coordinates are divergence and deviator of the strain tensor (Nye, 1976). The results of observations in such presentation form are shown in Fig. 4. The main patch of points connected with the background quasiharmonic deformation includes more than 90% of all events. The points outside the patch belong to the process of compression and are grouped along the regression line close to zero, which coincides with theoretical estimates of the ratios of normal and tangential stresses (Kolesov, 1979). The statistical analysis of the diagram allows determining a confidence level of the amplitude of background strains and formulate a criterion for identifying the compression events. For investigating the nature of background deformation,
the length of the series under consideration is not enough, however, one should note the periodicity of the processes of ice cover divergence-convergence, a relatively constant strain amplitude and direction which may be governed by regional features of tidal processes.

**DISCUSSION**

A detailed analysis of the compression process - Fig. 5 allows determining its duration, increase and decrease rates, as well as duration of ice hummocking. The latter characteristics can be connected with a smooth decrease in the intensity of strains in the upper area of compression variation due to redistribution of strains at hummocking. The duration and intensity of compression suggest a possible development of plastic strains, however, their estimates on the basis of measurements in one point is difficult due to background strains.

An analysis of the synoptic situation shows that on April 18-21 a continental cyclone interacting with an extensive area of high pressure over Yakutiya, central Arctic and Greenland exited to the region of the Laptev Sea and then turned toward Severnaya Zemlya. The cyclone speed was about 500-700 km a day. The cyclone components are well-pronounced on a satellite image NOAA-10 (Fig. 3). Comparison of the obtained results allows stressing three facts.

1. The beginning of the compression process surpasses the cyclone front by about a day, if one assumes the front to be a moment of a maximum rate of the pressure drop, and basically coincides with the time of the advance of the cyclone front in the vicinity of "NP-29". This confirms the results of Smirnov (1988) and suggests that in close ice cover there is an additional mechanism for momentum transferring which is responsible for spreading of the compression process. A mechanism of elastic-kinematic interaction of separate ice floes can be such a mechanism. In this case the compression process can be presented in the form of the compression impulse or the frontal wave of compression emanating from a distant dynamic source. Let us note that the cyclone front coincides in our case with the
time of a maximum wind and drift speed.

2. A rapid shift of the station for 24 hours on April 21-22 after the cyclone front arrival is accompanied by an increase in the intensity of shear strains in the absence of compression strains. Such deformed state is characteristic of a longitudinal uniform and cross-non-uniform velocity field. The orientation of the shear strains indicates the presence of a cross gradient of the drift speed and allows estimating its sign.

3. Wind and drift speeds correlate quite well, however, their directions differ by about 45-60 degrees and this difference is preserved for 2-3 days. Comparison of the directions of surface pressure isobars, wind and drift speed direction, as well as the orientation of the compression axis shows the absence of direct relations between these two factors. However, the drift trajectory of the stations "NP-28" and "NP-29" can be considered as isobaric if the directions of isobars in the eastern sector of the central Arctic are averaged. Compression can also be considered to be isobaric if isobar directions are averaged for the Laptev Sea region. The mechanism for spatial correlation of the phenomena under consideration can be synoptic circulation in the boundary layer of the ocean in the first case and propagation of the compression impulse through ice cover in the second case.

CONCLUSIONS

1. Local deformation of ice floes as a result of the effect of synoptic-scale dynamic processes can be identified with a prescribed confidence level at the background of different strains related to thermodynamic processes in ice cover. An analysis of local strains allows an objective assessment of the main characteristics of the compression processes of sea ice - intensity and direction of compression, duration of compression and hummocking, rates of their increase and decrease. As a result, an instrumental method for monitoring the ice cover stress-strain state can be developed by measuring local strains in sea ice.

2. An analysis of the obtained results allowed identifying
two successive stages of the ice cover response to a synoptical process. The stage of intensive compression accompanied by sea ice hummocking surpasses by almost a day the stage of the maximum drift speed which is characterized basically by zero divergence and a significant value of shear strains. And spatial advancing of the area of the effect of compression process is 500-800 km relative to the area of the ice maximum drift localized over the cyclone front.

REFERENCES


Smirnov V.N., Shushlebin A.I. (1988). Results of observations of natural deformations of ice fields. Izvestiya AN SSSR, Physics of the Earth, No. 12, pp.75-78. (in Russian)


Fig. 1. Quartz strainmeter, delta strain rosette and basic equations.
1 - qurtz pupe
2, 3 - fundamentation
4 - termokompensator
5 - displacement sensor

\[ \tan2\alpha = \frac{\sqrt[3]{(e_{m1} - e_{m2})}}{2(e_{m1} - e_{m2} - e_{m3})} \]

\[ \frac{e_{max}}{e_{min}} = \frac{1}{3} \left( e_{m1} + e_{m2} + e_{m3} \right) \]

\[ \pm \frac{\sqrt{2}}{3} \sqrt{(e_{m1} - e_{m2})^2 + (e_{m2} - e_{m3})^2 + (e_{m1} - e_{m3})^2} \]
Fig. 2. Atmosphere temperature and pressure, wind velocity, drift speed, divergence and deviator of the strain tensor.
Fig. 3. Map of surface atmospheric pressure on April 21, 1994. TV-image (NOAA-10) on April 20 and drift trajectories of NP-28 and NP-29.
Fig. 4. Data in the strain space.

Fig. 5. Compression pulse.

\texttt{div/dev} - divergence/deviator of the strain tensor
INTERNAL STRESSES AT TYPICAL LOCAL INHOMOGENEITIES OF SEA ICE COVER

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The State Scientific Center of the Russian Federation the Arctic and Antarctic Research Institute

ABSTRACT

On the basis of representative full-scale studies performed in different conditions of the Arctic and the Antarctic the structure of normal internal stresses at typical inhomogeneities of ice cover (relief inhomogeneities, disturbance of isostatic equilibrium, temperature differences) was identified.

INTRODUCTION

The processes occurring in the zone of ice cover interaction with a structure, govern, in many respects, the level and character of ice loads. Ice destruction in the active zone is preceded by different preparatory processes related to the formation of a complex inhomogeneous stress state of the ice cover in the vicinity of the structure. Study of these processes is necessary for correct forecasting of extreme effects of the behavior of the ice in front of the structure.

At present there are no systematic data in literature that reveal variability in internal stresses on microscale inhomogeneities of the ice cover comparable to its thickness. Current full-scale studies of the ice cover stress state presented in (Tucker and Perovich, 1992, Niemelähto and Nordlund, 1986 and Templeton, 1979) do not give a clear and complete understanding that is up to the level of generalizations, although they manifest a strong relation of the measured stresses with the environmental parameters. In addition, the difficulties of interpreting the results of measuring stresses in the inhomogeneous ice field still remain. In view of the complexity of the task, new experimental studies are required.

The work is based on the results of experimental studies performed by the author in different expeditions under conditions of the ice cover of the Arctic (drifting station NP-30, 1990), the Antarctic (drifting station Weddell-1, 1992), as well as on
the ice of the shelf zone of the Sea of Okhotsk (1989) and the Kara Sea (1991).

EXPERIMENTAL PROCEDURES AND CONDITIONS

The main aim of full-scale studies was to measure components of normal internal stresses in different typical inhomogeneities of the ice cover. We shall assume internal inhomogeneities of the ice structure and physical properties not connected with the inhomogeneities of external force and hydrometeorological fields, to be ice cover inhomogeneities. A particular attention was given to the gradient zones with a sharp division of ice parameters and properties: relief inhomogeneities, disturbance of hydrostatic equilibrium, temperature differences.

For measuring normal stresses, small-size directed thermocompensated sensors were used whose construction and main characteristics are described by Smirnov and Sukhorukov (1993). When necessary, measurements of stresses were accompanied by the control of local strains and thermal regime of the ice cover zone under study.

In the course of these studies a stress-strain state of the ice, structural parameters of the ice cover, as well as the main background hydrometeorological conditions were controlled. For analysing the results of measurements there were used the observations of the periods when the adopted arrays of the stress sensors allowed recording the main components of internal stresses. Experiments were carried out in wintertime on the ice of variable thickness: from 0.1 to 3.0 m.

FIELD EXPERIMENTAL RESULTS

A microscale inhomogeneity of the ice cover stress state is primarily governed by the local disturbance of its homogeneous structure and the thermal regime. These local areas are characterized by significant gradients of the internal stress fields. Let us consider the most typical of them.

Areas of ice of variable thickness

In accordance with the work of Buzuyev and Dubovtsev (1971), a spatial correlation radius of the thickness distribution of the Arctic ice is 10-30 m on average for different age gradations.
This value corresponds to a horizontal scale of a transient zone, separating zones of ice cover of a different thickness $h$. While a cross-section of the ice plate sharply changes, the stress in the transient sections increases. The largest stress $6_m$ exceeds mean value $6$ in accordance with the formula: $6_m = K \cdot 6$, where $K$ - the stress concentration coefficient. It is more correct to determine the $K$ value experimentally under full-scale conditions. Since the effect of the stress concentration is governed to a great extent by the deformation form of the ice plate in the zone of thickness difference, the experiments were carried out separately for the case of a pure longitudinal ice compression (without flexure) and under conditions of the developing longitudinal flexure.

With regard to the conditions of a flat stress state of pure compression, Fig. 1, a presents a scheme of a measuring site set up on the Arctic ice cover near a fresh crack. With the growth of young ice in the crack, the concentration of stresses in the transient zone changes. Fig. 1, b presents an experimental curve of a relative distribution of the main maximum components of stresses depending on the ice thickness ratio at the contact boundary. As is seen from the diagram, the coefficient of the stress concentration is more than 1 in a wide range of ice thickness change $0 < h_1/h < 1$. The analysis of the distribution curve suggests that at $h_1 < 0.25 \, h$ the $K$ value tends to 2. Thus, it follows from the experiments that for the conditions of pure compression local stresses in transient zones of ice thickness difference may be twice as large as mean values.

In the case of the ice of variable thickness when a zone of relatively thin ice is between the adjacent areas of thicker ice cover, the development of the flexure strain is possible. The central zone of the surface layer of thin ice under load will experience flexural stresses that significantly exceed the level of external compression stresses. Fig. 1, d presents the results of the experiments performed under conditions of the Arctic Expedition NP-30 on different ice sites in accordance with the scheme in Fig. 1, c. These results are supported by the conclusions of the theoretical study of Takeuchi and Shapiro (1989), where the effects of the stress concentration in the ice of a non-regular thickness were modelled by means of the method.
of finite elements. As is seen, the concentration coefficient $K$ decreases exponentially with a decrease in the roughness of the ice cover boundaries. It is easy to see that in the case of the variable thickness of ice cover the level of flexural stresses in the zones of thin ice can exceed the mean level of compressive stresses of ambient ice by an order of magnitude at $h_1/h < 0.1$.

It is known that sea ice at flexure is freely deformed which is related to the structural features of the inhomogenous ice cover. In this case one can expect a complicated pattern of the localization of stresses even within a separate microinhomogeneity in its structure. Let us consider spatial variability of internal stresses in the ice plate fixed on the sides at longitudinal flexure. These conditions are quite typical at natural compression of ice cover of an irregular thickness.

With this purpose studies were performed on the Arctic ice cover by means of a physical half-full-scale modelling method. A hole of a rectangular form with dimensions $1.7 \times 1.0$ m was made in pack ice with a thickness $h = 2.6$ m where growth of ice with a thickness $h_1$ occurred naturally. A detailed one-dimensional structure of normal stresses in the surface layer of thin ice was determined by means of a horizontal chain of stress sensors frozen into ice with spacing of $0.1$ m. Simultaneously, the external stress state of the ambient multiyear ice was controlled. Fig. 2a schematically presents part of an ice plate with a thickness of $h_1 = 0.3$ m with SM sensors that are uniformly located along the loading axis from the thick ice boundary to the symmetry axis of the hole. Under the effect of natural quasistatic external forces, flexural strains were excited in the simulated ice plate governing a specific localization of internal stresses.

Let us estimate a relative local inhomogeneity of the stress state by the modulus of the parameter $\delta = \delta_1 / \delta - 1$, where $\delta_1$ - the stress $i$ of the same segment. The distribution of microinhomogenous stresses by the length of the ice plate is shown in Fig. 2,b where the parameter $\delta$ is along the ordinate axis and the distance from the plate edge to its center is along the abscissa axis. As follows from the diagram, a particularly sharp and stable in space localization of stresses is observed in the
central and marginal areas of the deformed ice plate. The magnitude of stress impulses on some segments exceeds mean level of external compressive stresses by 4-5 times which is in a good agreement with the experimental data in Fig. 1,d.

Areas of non-isostatic ice equilibrium

As shown by simultaneous measurements of ice thickness and its upper surface level marks, they are not always consistent which indicates a possible development of local displacements of ice cover due to horizontal inhomogeneity of the gravity field. For estimating the effect of initial shifts of the ice field on the development of inhomogeneous stress state, experimental studies of variability in internal stresses on the segment of the Antarctic ice cover of a mean thickness of 1.45 m restricted by a local curvature of the ice surface, were conducted. In accordance with the results of preliminary detailed measurements of the ice field 200 m long, a measuring site was arranged on the segment with a pronounced disturbance of the local and isostatic equilibrium of the ice floe. Fig. 3,a presents a sketch of the local ice surface structure with an indication of the location of measurement sensors SM frozen at a depth of 0.2 m from the upper ice surface. An analysis of variability in the stress state was performed on the basis of the statistical estimate of time series more than 1 month in duration.

A spatial inhomogeneity of internal stresses averaged over 5 days and expressed by the modulus of the variation coefficient ..., is given in Fig. 3, b for different mean levels of the stress state .. On the whole, there is a satisfactory agreement of spatial distributions of the ice surface stress and curvature. One can identify areas of the trough and ridge in the structural inhomogeneity where the location of stresses has a diametrically opposite character. With an increase in mean level of stresses, the parameter δ characterizing the extent of variability in the stress state increases. As is seen from Fig. 3, b in some cases the local stress value can exceed the mean level by a factor of 3.

It is interesting to note a stable, opposite in sign response of the stress state of separate areas of the structural
inhomogeneity. Records of instantaneous stress values measured by sensors SMK3 and SM5 presented in Fig. 3, c illustrate quite well the consistency in the stress state on concave and convex ice field segments at a distance up to 20 m from each other. A correlation analysis of the presented temporal dependencies has shown a good reverse correlation between them in a wide range of spectral components. For example, Fig. 3, d illustrates a character of the relationship between changes in stresses taken relative to a running mean value with an averaging interval of 5 days. The maximum correlation coefficient is negative in this case and equal to -0.77 at a zero lag 1. It can be concluded that under the effect of external forces a field of normal stresses non-uniform in space, is formed in the area of the non-isostatic equilibrium of the ice floe where zones of stress concentration are at a distance from each other approximately equal to 7 ice thicknesses.

Thermogradients of ice cover

For revealing the relationship between the processes of the temperature change in the ice and mechanical stresses, an experimental study of thermal stresses in the surface layer of the ice cover near the boundary of the sharp change in the heat exchange of adjacent zones was conducted. The methods used in the experiments are described in detail by Sukhorukov (1994).

Fig. 4, a, b depict a scheme of the experiment on modelling a horizontal local thermal inhomogeneity in the surface layer of the ice cover and the distribution of relative thermal stresses at various mean temperature gradients in the ice. An analysis of the results indicates that thermal stresses occur predominantly in surface zones with a maximum horizontal temperature gradient. The dimensions of the areas of concentration of surface thermal stresses coincide with the dimensions of thermal inhomogeneities and are comparable to the ice thickness. One may note a relatively high level of thermal stresses - more than 25% of the total absolute level of stresses in the local zone of the ice floe.

Fig. 4, c shows temporal variations in the surface ice temperature and in thermal stresses normal to the vertical site,
measured on the edge of a frozen fracture 0.6 m wide. This is an example, illustrating changes in the thermomechanical state in natural conditions of the Antarctic ice cover. As is seen, compressive stresses occur in the fracture with the increase in the ice temperature, at the decrease in the temperature, compressive stresses are reduced. An increment in thermal stresses in the surface ice layer was more than 50 kPa at a temperature change of 1 degree for several hours. A non-linear relation between the increment in the stress, a horizontal temperature gradient in the ice and the rate of its change is considered in (Sukhorukov, 1994).

CONCLUSION

A spatial coherence of the stress state inhomogeneities and local inhomogeneities of the ice cover has been investigated. Variability in internal stresses at most frequent local inhomogeneities of the structure and thermal regime of the ice cover has been found. The levels and scales of the localization of the stress state within separate ice inhomogeneities are established. The obtained results will serve as a necessary basis for developing methods for measuring the stress state of the ice in full-scale conditions. They will be actually useful for resolving different problems of ice cover dynamics, as well as for developing methods for calculating ice loads on off-shore structures.

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Sukhorukov K.K. A stress state of sea ice at a local change


Fig. 1. - Internal stresses at changes in the ice cover thickness.

a, c - idealized schemes of the experiments; b, d - experimental curves of the surface stress concentration for different ratios of the ice thickness (h1/h); a, b - the case of pure compression, h = 1.8 m; c, d - conditions for longitudinal flexure; 1 - h = 2.6 m, 1 = 1.7 m; 2 - h = 5 m, 1 = 20 m; 3 - calculation by means of the method of finite-elements at h = 6 m, 1 = 25 m (Takeuchi and Shapiro).
Fig. 2 — Variability in internal stresses on the segment of the cover of a non-uniform thickness at longitudinal flexure.

a — the scheme of the experiment at the longitudinal force loading of the ice plate, $h = 2.6\ \text{m}$, $h = 0.4\ \text{m}$; b — experimental curves of the spatial distribution of relative stresses in the surface layer of the loaded zone at different levels of the external stress $s$, $1 - s = 60\ \text{kPa},\ 2 - s = 15\ \text{kPa}$;
Fig. 3 - Variability in stresses on the segment of a non-isostatic equilibrium of the ice floe, a - a local relief of ice surface relative to sea level, BN - stress sensors; b - the distribution of relative locally non-uniform stresses for different levels of the stress state, 1 - s = 25 kPa, 2 - 50 kPa, 3 - 100 kPa; c - record of the components of internal stresses measured at the points (3) and (5), 4 - s3, 5 - s5; d - a function of mutual correlation between changes in relatively smoothed mean of surface stresses at the point (3) and (5).
Fig. 4 - Variability in thermal stresses.

a - a scheme of the experiment on modelling a typical local thermal inhomogeneity in the surface layer of the ice cover; b - the distribution of relative thermal stresses at different horizontal temperature gradients (dT/dR) in the ice, s = 0.1 MPa, 1 - dT/dR = 1 deg./m, 2 - 0.5 deg./m, 3 - 0.25 deg./m; c - temporal dependencies of surface ice temperatures (curve 4) and thermal stresses (5) at the edge of the frozen fracture 0.6 m thick and 25 m long.
INTRODUCTION

Drifting ice pressure ridges and grounded ice pressure ridges called "stamukhas" are very dangerous to offshore hydraulic structures: drifting ice pressure ridges are particularly dangerous to drilling rigs and production platforms, while stamukhas to subsea pipelines. Therefore, studying the above-mentioned ice features is essential for ensuring serviceability of offshore structures.

METHODS OF THE STUDY

The institute "SakhalinNIPImorneft" has been involved in studying ice pressure ridges and stamukhas offshore of Sakhalin since 1986. Studies with the radar stations located in Odoptu Bay resulted in obtaining drift directions and velocities for moving ice pressure ridges. Morphological parameters such as sail height, keel depth, etc. were studied in site by helicopter-delivered personnel.

Thermal drilling is an important method used for studying stamukhas. Morphological parameters for stamukhas upper parts were measured by visual methods, while stamukhas lower parts were studied based on thermal drilling. Prior to thermal drilling, a horizontal projection of stamukhas was covered by an assumed grid having a certain spacing. At nodal point stamukhas were drilled to the bottom or to exit points of a thermal drill from stamukhas. Based on thermal drilling, keel depths and penetration depths of stamukhas into the sea bottom were obtained.

To date, a considerable data bank has been accumulated for the above-mentioned ice features, which allows for application of statistical methods.
RESULTS

This paper gives measured maximum sail height, $H$ and maximum keel depth, $h$ for over 18 drifting ice pressure ridges and 52 stamukhas (Fig.1). Based on these data a very important parameter $k$ was obtained ($k = \frac{H}{h}$), which varies from 1:2 to 1:13 for ice pressure ridges and from 1:0.53 to 1:7.14 for stamukhas. Sufficient amount of data allowed to derive an average $k$ both for ice pressure ridges and stamukhas. It was found to be 1:4 for ice pressure ridges and 1:1.6 for stamukhas. Smaller value of $k$ for stamukhas accounts for the elevation of drifting ice pressure ridges above the sea level at the moment of their transformation into stamukhas. Also, it accounts for ice piling up on stamukhas during their life. Fig.1 gives a line representing parameter $k$ for the Beaufort Sea, for comparison (Sanderson T.J.O./).

The data analysis resulted in determining experimental areas, where stamukhas and ice pressure ridges occur. The area of occurrence for ice pressure ridges appeared to be nearly completely covered by that for stamukhas. Moreover, the area of occurrence for stamukhas turned out to be 7 times larger than that for ice pressure ridges. However, stamukhas density (i.e. the number of stamukhas per unit area) was only two times less. It suggests considerable scattering of data on stamukhas as compared to those on drifting ice pressure ridges. Such marked data scattering is attributed to probability factors. Parameter $k$ is probabilistic value for ice pressure ridges. The elevation of drifting ice pressure ridges penetrating into the sea bottom is also probabilistic value. It depends on bottom surface profile, mass and drift velocity of ice pressure ridges, physical and mechanical properties of soil and sea bottom slope. Height of ice piles on stamukhas is also probabilistic value. Since the distribution density function for $k$ is a composition of the above-mentioned factors, the scattering of $k$ for stamukhas is considerable.

The results of the studies given in the paper contribute to the better understanding of a mechanism for stamukhas development.

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Fig. 1. Relationship between sail height and keel depth
Abstract

During recent years, an ever increasing attention has been paid to gouges in the seabed created by icebergs. The reasons are the threats from gouging icebergs to subsea installations and pipelines. This paper briefly reviews models of the gouging process and presents information about gouging in Greenland waters, where gouge information is very sparse.

Gouging Processes

The gouging mechanism can occur in one of two ways: either an iceberg drifts into an area with decreasing water depth until its keel touches the seabed, or it may be in an initially freefloating metastable position while e.g. melting causes it to become unstable, and when it rolls its draft might increase bringing it into contact with the seabed. If the bearing capacity of the seabed soil is insufficient to support the weight of the iceberg the keel will become partially entrenched (the entrenchment depth depends on the weight of the iceberg and the seabed material). Once in this situation, if the environmental forces driving the iceberg (currents and winds) can overcome the frictional resistance between the entrenched keel and the seabed, the iceberg will continue forwards, dragging its keel through the seabed. In this way a characteristic linear to curvilinear trench is created in the seabed with corresponding embankments or berms on either side formed by material displaced from the trough. Such curvilinear features are commonly referred to as iceberg gouges.

In the eastern Canadian continental shelf from Baffin Bay to the Scotian Shelf iceberg gouge marks appear down to water depths greater than 700 m, and the marks vary markedly in size and morphology and can be up to 400 m wide, 10 m deep and over 10 km in length (cf. Harris, 1974, Chari & Barrie, 1987, and Lewis & Blasco, 1990). In West-Greenland waters gouge marks have been observed down to water depths of 340 m (cf. Brett & Zarudzki, 1979). It is in neither case, however, indicated if these gouges are ancient (e.g. from a period with smaller water depth/higher sea bed level and potentially different iceberg sizes) or created within more recent times.

In Figure 1 an example is shown of a sonograph revealing iceberg gouge marks on the seabed. The picture is sampled at a location northeast of Newfoundland, and reprinted from Harris & Jollymore (1974).
There is no general agreement about the terminology in the literature, and often one finds the expressions score, scour or furrow instead of gouging. However, the word gouging can not be misleading as e.g. the word scour, and therefore the process in which a drifting iceberg touches the seabed and creates trenches will be termed gouging in this paper.

There are two agents which are significant in the gouging process of the seabed - icebergs and sea ice pressure ridge keels. The latter originate from ridging of sheets of sea ice under pressure, and they rarely exceed 40 m in depth, thus only being responsible for gouges in shallow continental shelves and in nearshore waters. The effect of sea ice gouges is of paramount interest also for offshore operations in shallow arctic areas, but only the deep water gouges created by icebergs are considered here because of the large water depths around Greenland.

In order to evaluate the effects from gouges and the probability of their occurrence, several parameters must be considered. They are: iceberg mass and shape, current profile and wind velocities, water depth, iceberg density, seabed material, topography of seabed and sedimentation rates. The effects from waves are insignificant in the gouge formation process, but they may play a role in the degradation of gouges.

There are two independent, but complementary directions in the current research on iceberg gouges. One is the observation and analysis of gouge frequencies and morphology and the other is the mathematical and physical understanding of the mechanics of iceberg gouging and the associated soil deformations, especially below the gouge. These two directions will be treated in the following.
Measurements and Statistical Analysis

As a basis for a statistical analysis, measurements are required of gouge densities, depths, widths and lengths. The collection of data is performed from a vessel using a side scan sonar and a fathometer system. Both systems have been reported to be capable of resolving bottom relief of less than 10 cm on water depths up to 40 m (cf. Weeks et al, 1983). The side scan sonar records (sonographs) are sampled covering two bands; one on either side of the direction of the vessel's motion. The width of the bands depends on the water depth and the topography of the seabed. In most cases cited in literature the width of each band is about 3-5 times the water depth. An example of a sonar record showing iceberg gouge marks on the seabed is depicted in Figure 1, and in Figure 2 (taken from Weeks et al, 1983) an example of a fathogram of an ice gouged seabed is shown.

Figure 2  Fathogram of ice gouged seabed. Water depth is 36 m. From Harris & Jollymore (1974).

Figure 3  Schematic drawing of a gouge showing the locations of various measurements concerning iceberg gouges (From Weeks et al, 1983).
By analyzing the sonographs and fathograms, several parameters related to the gouges are derived. These are depicted in Figure 3, and described below.

1) **Dominant gouge orientation \( \theta \).**
   
   The dominant gouge orientation is determined from the sonographs by considering all gouges over a certain area (e.g., 1 km times 1 km).

2) **Spatial gouge frequency \( (N_i) \).**
   
   The expected number of gouges that would have been seen on a 1-km sampling line if the vessel's track was oriented normal to the dominant gouge trend is termed the spatial gouge frequency. \( N_i \) is determined by counting the number \( N \) of gouges per kilometre of sampled track from the fathogram, and dividing \( N \) with \( \sin \theta \) to the angle between the ship's track and the gouge orientation.

3) **Gouge depth (d).**
   
   The gouge depth is measured on the fathometer track as the vertical distance from the (presumably) undisturbed seabed to the lowest point in the gouge. It is important to notice that the measured gouge depth probably is smaller than the gouge depth when it was formed. This is due to the backfilling of sediments into the gouge. The backfilling consists of an initial backfilling just after the iceberg keel has passed, and of backfilled sediments during long time periods caused by currents and (eventually) waves. Furthermore, a large downwards pressure on the sediments will take place when the iceberg keel is passing, thus giving a compression of the sediments. This pressure is released after passage of the iceberg keel.

4) **Gouge width (w), and lateral embankment height (h).**
   
   The gouge width (w) and lateral embankment height (h) are determined from the fathometer track. These parameters can vary considerably along the length of a given gouge, and they are thus determined with a relatively large uncertainty.

5) **Gouge length (l).**
   
   The length (l) of a gouge can be estimated from the sonograph, when an appropriately large area is covered.

The statistical analysis of the measurements is primarily related to the gouge depths and their spatial frequency, since these two parameters are the most important when subsea installations and pipelines are designed.

Lewis (1977) used an exponential distribution to model the number of gouges versus the gouge depth, and found a high correlation coefficient between the data and the statistical distribution. Weeks et al. (1983) also used an exponential distribution for the gouge depths, but pointed out, that even though the correlation coefficient is high, chi-squared tests for goodness-of-fit are commonly failed, and in these cases a more satisfactory distribution function or a better rationalization of the deviations from exponentiality should be sought. They did, however, use an exponential distribution to model the gouge depths, and found a
relatively good agreement between measured data and the estimated distribution. Both studies were related to ridges in the open Beaufort Sea.

The exponential distribution has the following probability density function (pdf):

\[ f(x;\lambda) = \frac{1}{\lambda} e^{-\frac{x-x_0}{\lambda}}, \quad x > x_0 \]  

The variable \( x \) represents the gouge depth (measured positive), \( x_0 \) is a cut-off value (e.g. when gouge depths less than 0.2 m are excluded from the analysis, \( x_0 = 0.2 \)). The maximum likelihood estimate of the parameter \( \lambda \) is \( x_{\text{mean}} - x_0 \).

The cumulative distribution function (cdf) is given as:

\[ F(x;\lambda) = 1 - e^{-\frac{x-x_0}{\lambda}}, \quad x > x_0 \]  

As interest is normally paid to the probability of gouge depths greater than some specified value the complementary distribution function \( G(x;\lambda) \) is considered, i.e.

\[ G(x;\lambda) = 1 - F(x;\lambda) = e^{-\frac{x-x_0}{\lambda}}, \quad x > x_0 \]  

This function is simple to graph, since it is a straight line on a semi-log paper, and has a value of 1 at \( x = x_0 \).

It is noted that the nature of the gouge depth distribution is known to change with water depth, simply because the large icebergs are grounding before they can penetrate into shallow water.

The other parameter of interest is the spatial frequency of the gouges (i.e. the number of gouges per kilometre measured normal to the trend of the gouges). An analysis of the temporal frequency of the gouges (i.e. number of gouges per kilometre per year) would indeed also be interesting, but to provide data for such an analysis measurements are required at the same location during a number of years, and such data do not exist from Greenland waters, at least to the author's knowledge.

The spatial frequency of the gouges is a function of the water depth where the measurements are carried out. When the water depth variation over the measuring area is large compared to the mean water depth, the data must be subdivided into groups of different water depth ranges. Each group consists of a data sample to be analyzed (see e.g. Weeks et al. (1983) for an example of subdivision of water depths). In case of a small variation of the water depth over the measuring area, all measured data form one data sample. The importance of subdividing into water depth ranges is, however, dependent on the local conditions at the measuring site.

One data sample normally contains several kilometres of measurements, and as a basis for the statistical analysis the measuring length is broken down into smaller segments (e.g. 100 m), and the number \( N' \) of gouges is counted at each segment. The relative frequency of occurrence of the \( N' \) values is determined, and the results may be depicted as histograms.
Weeks et al. (1983) proposed to fit the data to a Poisson distribution function. The pdf of the Poisson distribution is given by:

\[ f(n; a) = \frac{(a^n e^{-a})}{n!}, \quad n = 0, 1, 2, \ldots, \quad a > 0 \]  \hspace{1cm} (4)

In (4) \( a \) is the sample mean, and \( n \) indicates the number of gouges over the segment length.

The analyses by Weeks et al. (1983) showed that the Poisson distribution underestimated the larger values of \( N^* \) compared to the measurements. They therefore considered an alternative distribution function to represent the variation of the measurements. The gamma distribution was chosen, and the pdf of this is given by:

\[ f(x; a, b) = \frac{(a^b x^{b-1} e^{-ax})}{\Gamma(b)}, \quad x > 0, \quad a > 0, \quad b > 0 \]  \hspace{1cm} (5)

In (5) \( \Gamma(b) \) is the gamma function, and the parameters \( a \) and \( b \) can be considered to be scale and shape parameters respectively.

An example application (taken from Weeks et al, 1983) of the relative frequency of \( N^* = N_t/10 \), measured in the Beaufort Sea at water depths ranging from 20 m to 38 m is depicted in Figure 4. The solid line bar graph represents the data, the discrete values indicate the fitted Poisson distribution, and the shaded area indicates the gamma distribution.

![Figure 4 Spatial gouge frequency distribution. Measurements in the water depth range 20 - 38 m, and fitted Poisson and gamma distributions. (After Weeks et al, 1983).](image)

It is seen that the gamma distribution is more successful in fitting the larger values of \( N^* \) than the Poisson distribution, which drops off too quickly for large \( N^* \) values.

A numerical model for simulating ice gouge depths associated with given return intervals for subsea structures of any geometric shape was developed by Wang (1990). The model
makes use of the exponential distribution for iceberg gouge depths (cf. eq. 1). One of the inputs to the model is the area gouge generation rate, which is the number of new gouges generated per unit area per year (i.e. the temporal gouge frequency). Since this parameter is rarely available, Wang (1990) developed a method to convert a linear gouge generation rate to an area gouge generation rate.

**Mathematical/physical Modelling of Iceberg Gouging**

The gouging process is rather complicated with many parameters involved. These parameters are related to the iceberg and the environmental conditions, and to the seabed bathymetry and material. The parameters related to the iceberg are: Iceberg mass, drift velocity, stability, hydrodynamic drag and underwater shape (area and draft). The parameters related to the seabed are: Bathymetry, composition (i.e. material) and sediment shear strength.

A mathematical model for an idealized concept of a "box-shaped" iceberg gouging a gently sloping seabed is depicted in Figure 5. The model, which was presented by Chari (1979), assumes that the seabed soil has an extremely low shear strength. The model thus should give estimates of the upper limits for iceberg gouge depths.

![Figure 5 Idealized theoretical concept of iceberg gouging. (From Chari, 1979).](image)

The model by Chari (1979) is based on an energy balance between the kinetic energy of the iceberg, the drag force on the iceberg, and the soil resistance. By assuming a linear decrease of all parameters as the iceberg penetrates through the seabed, mathematical expressions were derived involving the gouge length $L$ and maximum depth $D$ as follows:
\[ \frac{1}{2}M V_o^2 + (1/6)C_d \rho A L V_o^2 = (1/6) \gamma' (H+D)^2 BL + \tau D L \sqrt{2}/3 \]  

(6)

\[ D = L \tan(\beta) \]  

(7)

In (6) and (7) the following notation is used: \( M \) is the iceberg mass, \( V_o \) the initial steady state velocity (current), \( C_d \) the drag coefficient, \( \rho \) the density of sea water, \( A \) the iceberg area normal to the current, \( \gamma' \) the submerged unit weight of seabed soil, \( H \) the final height of soil in front of the iceberg, \( B \) the width of the iceberg at seabed level (also of gouge), \( \tau \) the shear strength (undrained) of seabed soil, and \( \beta \) the slope of the seabed. This early model does not account for wind forces.

Chari (1979) performed laboratory tests to verify the theoretical model, and observed a good agreement between the theoretical and measured forces. The iceberg gouge model was thus found satisfactory in so far as the mechanics of soil-iceberg interaction is concerned. The soil pressure on the sides of the model was found not to be significant, and the predominant resisting force was found to arise from the passive resistance of seabed material in front of the iceberg.

A somewhat similar mathematical model of a grounding iceberg (based on an equilibrium of forces on the iceberg) was presented by Lopez et al. (1981). They expressed the gouge length as a function of the iceberg mass, drag coefficient and soil resistance. The results of their analysis showed that under certain conditions, the hydrodynamic drag on grounding icebergs has a significant influence on the total gouge length.

To provide initial estimates of gouge depths at a given location the above mentioned models are recommendable due to their relative simplicity. However, a trenched pipeline can be severely damaged by a gouging iceberg even though the iceberg keel does not touch the pipeline. This is due to the large pressure and large strain on the soil beneath the keel of the iceberg. A mathematical approach to the complicated problem of determining how far below the ice the gouging deformation extends is given by Palmer et al. (1989), and a mathematical/numerical model that incorporates the vertical uplift of pipelines due to a gouging iceberg is given by Been et al. (1990).

**Iceberg gouging in Greenland waters**

Data material concerning iceberg gouging in Greenland waters are extremely sparse. Sampling of gouges have only been carried out during two projects; one involving the West Greenland shelf, and the other involving the East Greenland shelf.

In 1978 the "Project Westmar" geophysical survey was carried out. This survey covered the West Greenland shelf area between 64°N and 69°30'N as depicted in Figure 6. The study results are reported by Brett & Zarudzki (1979).

Among other surveys in Project Westmar, a total distance of 3894 km was covered by side-scan sonar records. Iceberg gouges were detected down to a depth of 340 m at which an abrupt cut-off occurs. One of the largest observed gouges was about 75 m wide and 4-5 km long. No data of gouge depths are given.
The spatial density of the gouges has been divided into three grades: intense, moderate and none. The intense grade applied to areas where the entire seabed is composed of gouge marks and associated marginal deposits. The moderate grade applies to areas where gouges are present up to an intermediate level. The distribution of iceberg gouges is shown in Figure 7. The distribution of the gouges in Figure 7 strongly suggests that the vast majority of the gouges arises from icebergs calved in Disko Bugt, and exiting from the bay via Egedesminde Dyb and Godhavn Rende. The gouges at depth 340 m were confined to an earlier period, since under the present glacial conditions icebergs with a draft larger than 300 m cannot exit from Disko Bugt, due to a basalt bar across the eastern end of Egedesminde Dyb at a depth of 300 m.
In 1979 a field survey program was carried out on the East Greenland shelf. The project DANA '79 provided data in the area from 65°N to 69°N. The results of the study have not been published in a format as the Project Westmar. However, based on an analysis carried out by Christensen and Jacobsen (1982) the gouge pattern has been depicted for the East Greenland shelf in the area mentioned above. A division into the following groups have been performed: few scours (gouges), some scours (gouges), and many scours (gouges). The result of this division is depicted in Figure 8.

The dominant current direction off East Greenland is southward because of the East Greenland Current. The limits of "many" gouges are found on the upstream (northern) side of the
Figure 8  Number of iceberg gouges (scour) in the east Greenland Area between 65°N to 69°N (based on analysis by Christensen and Jacobsen, 1982).

banks from 350 m and down, and "some" from 350 m to 450 m, and "few" gouges between 450 m and 600 m both on the upstream and on the lee side.

There is no information available at present regarding the frequency of gouging at the East Greenland shelf. Furthermore, the gouge depths have not been investigated thoroughly.

Summary

Iceberg gouging is known to take place in Greenland waters. In accordance with iceberg observations, gouging must be expected at least in water depths up to 180-200 metres West of Greenland and up to at least 300 m East of Greenland. Actual gouges have been observed, however, in water depths of 340 m West of Greenland and approximately 600 m East of Greenland. The differences between the two sets of limits can be due to:

- changes in extreme iceberg drafts over time (thousands of years), such that observed deeper gouges are relict features, or due to
failure to observe the maximum iceberg drafts. The limited number of icebergs measured and the limited season covered suggest that iceberg drafts in excess of the largest measured draft are likely to exist.

It will be of considerable interest to quantify the relative importance of each of these two sources of differences. The existing information about iceberg gouging in Greenland waters is very sparse, and further quantification will demand field campaigns.

The cost of burying subsea installations and pipelines in the seabed increases substantially with burial depth. For an entirely buried system the parameters of interest are the gouge depth distribution and the subsoil deformations, which depend on soil shear strength, gouge depth etc.

It might be necessary and/or acceptable to only partly bury an installation. Access to the wellhead will be necessary, and perhaps sufficiently low iceberg incursion probabilities can be documented in a given large water depth that an unburied pipeline becomes acceptable. For these system components, it will furthermore be of considerable interest to determine temporal and spatial gouging frequencies as a function of location.

Gouge depths and spatial gouging frequencies (without correction for relict gouges) can be determined fairly easily from recordings in a future survey. Perhaps existing surveys contain some of the wanted information already. No systematic search has ever been conducted. However, some extra uncertainty might result from using relatively old recordings, where the relevant personnel no longer remember the specific conditions and/or problems incurred during the survey. Knowledge of gouge depths is of paramount importance, as deep gouges might make the use of pipelines economically unfeasible.

The temporal gouging frequency will have to be determined in a dedicated programme. Since measurement techniques are based on relatively simple proven technology, and since a fair number of scientific cruises take place in Greenland waters, it should be uncomplicated and affordable to select e.g. two survey areas (one west and one east of Greenland) to be surveyed each summer for 3-5 consecutive years. This would constitute a major reduction in uncertainties relating to offshore development in Greenland waters.

Measurements carried out in Canadian waters are being stored in a data base (Geonautics Ltd., 1989). Statistical analyses based on large amounts of data in both space and time are thus made possible. Any measurement program in Greenland waters should also include storage of data in a data base, such that especially the temporal gouge density can be estimated with a fair accuracy.

Subsoil deformations have to be studied in a mathematical model. The purpose is to determine safe burial depths, and rough estimates will be of interest, albeit more accurate studies will have to be carried out before hydrocarbon development can proceed.
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ABSTRACT

In recent years there appeared a considerable number of experimental and theoretical investigations showing effectiveness of breaking up of ice cover, lengthening of navigation and pushing through ice using air cushion ships and platforms. Despite of experience gained in designing and performance of such ships many problems remain yet unsolved. Among these problems are: design methods of appropriate air cushion ships and platforms, forecasting in their seaworthiness, ice-breaking and operation qualities. It is these problems that are discussed in the report.

Information about air cushion ships (ACV) application for breaking up ice has appeared only recently but the effect produced by their application entertains a hope that such ships will take a noticeable place among other means in ice break up technologies.

Ice cover break up was first noticed, apparently, when such hovercrafts as "Raduga" and "Sormovich" were undergoing trials hovering over ice, but at that time this phenomenon wasn't paid much attention. The fact of ice breaking by a moving load was known earlier, for example, when different means of transportation were moving along the so-called "Way of life" across Ladoga lake. The undesired phenomenon of ice breaking by means of transportation moving upon ice can be considered at the same time as an effective means of lengthening navigation and fighting against ice jams using hovercrafts. In essence, ice breaking by hovercraft can be divided into two ways:

- the way of pressure (low-speed),
the way of resonance (high-speed).

Physical aspects of ice breaking using these two methods are well represented in literature [1, 2, etc.].

An analysis of the experience gained in hovercraft application to break up ice allows to determine advantages of these ships over traditional ice breaking means.

The way of pressure:
- low energy consumption during ice breaking,
- possibility of using ordinary non-propelled air cushion platforms coupled with (tied to) tugs or transport ships,
- relatively low capital investments and operation costs,
- good maneuverability in ice conditions,
- possibility to work in limited fairway depths,
- effective operation in snow-covered and in hummock ice,
- possibility to employ air cushion platforms as ferries and heavy weight cargo platforms in between navigation periods, etc.

The way of resonance:
- effective ice-cover break up in large areas with high speed,
- effective means of fighting against ice jams and, consequently, destructive floods,
- its employment as a means of transportation all year round,
- possibility to work in shoals in curved fairways effectively forcing both upon surface and underwater ice.

The above-mentioned advantages of ice breaking hovercraft allow to employ such ships most effectively in inland waterways, storage lakes and in sea coastal areas.

Effectiveness of new ways and technologies of ice cover break up was demonstrated during trials of ice breaking air cushion platforms (IBACP) and ice breaking air cushion ships (IBACS) such as LPVP-102LP, LPVP-105LP, LPVP-107P and others.

The way of pressure.

Air cushion platform movement is charactered by relatively low speeds (Fr < 0.25), and significant pressure ($P_{ac}$ up to 10 kPa) in air cushion. To evaluate effectiveness of the new ice breaking method, an ice breaking air cushion platform LPVP-102LP has been designed and built in Nizhny Novgorod State Technical University. It has successfully undergone trials
described in [3] and later one more platform of such kind LPVP-107P has been designed and built for experimental operation. This platform is designed for breaking up ice cover in rivers, storage lakes and in sea coastal areas and its main characteristics are the following:

- Length, o.a. (without akirt), m ................ 17.5
- Breadth, o.a. (without akirt), m ................ 20.0
- Depth, m ........................................ 2.7
- Height from supports to unremovable part, m .... 7.3
- Displacement full (with 50 per cent liquid ballast) at Tav. = 1.56 m, t .................. 260
- Displacement max. (with 100 per cent liquid ballast) at Tav. = 1.80 m, t .................. 307
- Material of hull and superstructure ............ steel
- Main engines rated output, kW .................. 2x635
- Crew ................................................. 2

This platform is equipped with diesel fan blower with two diesels M634A 630 kW power rating and two centrifugal fans VVN-18, their capacity being 30 m³/sec. For ship’s (electric) power supply there is a diesel generator with power rating of 50 kW.

Ice breaking air cushion platform is a non-propelled vessel of amphibian type which could be tied up to a tug, ice-breaker or any other ship.

The hull of the ship is of steel. Air cushion enclosure is made of removable, segment type flexible elements (parts) which, in case of damage, could be quickly replaced in field conditions. Ship’s operation is possible under temperatures up to 40°C.

Trials of the ship tied up to a tug of MB type (i.e. light tug) were carried out in clear water on the Volga river in the area as deep as 5.5-6.5 meters. Trials were carried out to control and to test operation of all units, devices and systems and eventually their reliability was confirmed. Tied up ships showed good sailing, operational and maneuvering qualities.

Ice trials of the ship were carried out coupled with ice-breaker "OKA" and small tug "MB". In the trials area ice was as thick as 40-70 cm and its break up scale from 0 to 1. In compact ice as thick as 35-40 cm the ice-breaker "OKA" was moving at a speed of 1-2 km/h, whereas tied up to a platform the
ships were moving in the same ice conditions at an average speed of 7 km/h, making a channel behind twice as wide as one ice-breaker.

At the place where the ice-breaker was to be tied up to the platform there was a ridge of telescoped, very close drift ice as thick as 120–130 cm. The ice-breaker had to work by way of ramming, employing heel-trimming system. It took the ice-breaker 5.5 hours to overcome the ridge, whereas tied up to the platform the ice-breaker broke through the ridge in 25 minutes.

Trials of the platform tied up to the small tug "MB" carried out later showed that it was possible to break up compact ice as thick as 40–60 cm at an average speed of 4–7 km/h.

Trials have shown that joint operation of the ice breaking air cushion platform and ordinary ice-breaker or a tug allows to increase greatly the effectiveness of ice breaking. Thus in ice as thick as 40 cm speed of the light ice-breaker "OKA" with the platform is twice as much as that of the heavy ice-breaker "Captain Chechkin", whose power is 2.5 times greater than total power of the "OKA" and the platform. Operation costs of the ice-breaker tied up to the platform are decreased 4 times and 3 times is the specific power consumption for breaking up of 1 m³ of ice. General layout of ice breaking air cushion platform (IBACP-107) is shown in fig.1.

In March-April 1994 as far as difficult ice conditions in the OKA river were observed, the platform was employed tied up to the ice-breaker "OKA" to break up ice cover to prevent high water and flooding.

Resonance way.

Experimental investigations of resonance way of ice breaking were carried out both in the ice pond of NSTU and in Gorky storage lake. The aim of the trials is to determine empirical characteristics of hovercraft/ice cover interaction.

Main dimensions of self-propelled air cushion ships are the following:

<table>
<thead>
<tr>
<th>Main particulars</th>
<th>ACS №1</th>
<th>ACS №2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LxBxH, m</td>
<td>5,1x1,6x0,2</td>
<td>7,4x3,6x0,5</td>
</tr>
<tr>
<td>Height of flexible skirt, m</td>
<td>0,5</td>
<td>0,7</td>
</tr>
<tr>
<td>Air cushion pressure, kPa</td>
<td>0,63</td>
<td>0,94</td>
</tr>
</tbody>
</table>
The trials have shown emergence of main cracks along with formation of a wide network of small ones during the ships movement. Broken ice channel width was 1.5-2 times as much as hull's beam. Flexible-gravitational waves emerging aft broke up the ice cover. Air cushion pressure in resonance ice breaking method are 2-2.5 times less than those emerging when pressure method is used.

Repeated hoverings of ACS over ice resulted in its fragmentation and partial clearing the channel from ice.

During trials it was noticed that in aquatoria whose width is commensurable with static bending flexure cup dimensions, it becomes difficult to break up ice using resonance method and if the width is 1.5-2 times less than \( r = \sqrt{\frac{4(Eh^3)}{12(1-\mu^2)p_0g}} \), resonance method is inexpedient.

This is explained by the fact that if ice thickness is increasing, the volume of the ice cover bending flexure cup influenced by the limited aquatorium diminishes. Thus development of flexible-gravitational waves is made difficult. In this case ice flexures under moving load are decreased by the inertia of water and ice and effectiveness of this method is lowered.

Fragments of ice breaking air cushion platform and air cushion ship trials are shown in fig.2 and 3.

Analytical aspects.

Despite of different physical principles of ice cover break up using hovercraft (by means of pressure and resonance methods) a mathematical model of their interaction with ice can be the same. In particular, ACS movement over ice cover can be represented as movement of pressure systems over deformable ice cover of a certain thickness resting on incompressible fluid of defined depth. Assigning the ice cover and fluid with a number of qualities and conditions one can solve a problem of the ice cover stressed-strained state, its resistance and breaking under the force of ACS movement. Parameters of hovercraft interaction with ice cover can be evaluated as well.
Waves' amplitudes emerging under stationary movement of the layer with excessive base pressure can be found in the first approximation from Laplacian equation for potential function $\varphi$ with linearized dynamic and kinematic boundary conditions on the surface and bottom of the storage lake.

Potential $\varphi$ can be represented in the integral form as

$$\varphi = \frac{i}{2\pi} \int_{-\infty}^{+\infty} \frac{v e^{i k x} c h(z + d + H) d k}{(D k^4 t h k H - m k^2 v^2 t h k H - \rho_w k v^2 + \rho_w g t h k H) c h k H} \int_{-\infty}^{+\infty} p(x) e^{-i k x} d x, \quad (1)$$

where $d$ - ice depth, $v$ - movement velocity, $H$ - storage lake depth, $m$ - surface ice density, $m = \rho_1 h$, $h$ - ice thickness, $\rho_w, \rho_1$ - water and ice density, $k = 2\pi/\lambda$ - wave number.

Integrand (1) special points are the poles found from equation

$$D k^4 t h k H - m k^2 v^2 t h k H - \rho_w k v^2 + \rho_w g t h k H = 0. \quad (2)$$

Number of poles found from (2) is infinite and their position in the complex area depends upon velocity $v$.

For analysis of movement and deformation of the ice cover being under a moving load it is necessary to consider the dispersion dependence binding wave number $k$ with frequency $\omega$ and derived from (2).

$$C = \frac{\omega}{k} = \left( \frac{D k^4 + \rho_w g}{\rho_1 h k^2 + \rho_w k / t h k H} \right)^{1/2}, \quad (3)$$

$$U = \frac{d \omega}{d k} = \frac{1}{2} \left( \frac{\rho_1 h + \rho_w / k t h k H}{D k^4 + \rho_w g} \right)^{1/2} \times$$

$$4 D k^3 (\rho_1 h + \rho_w / k t h k H) + \frac{\rho_w (D k^4 + \rho_w g)}{k^2 t h^2 k H} \left( t h k H + \frac{k H}{c h^2 k H} \right) \left( \rho_1 h + \rho_w / k t h k H \right)^2. \quad (4)$$

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where $D = \frac{Eh^3}{(1-\mu^2)}$.

$E, \mu$ - elastic modulus and Poisson's ratio for ice.

$C,U$ - phase and group wave velocity.

A similar result was obtained by D.E.Haysin [4] in the dynamic load application problem.

In real solution for $k$ the movement is accompanied by creation of waves propagating with phase velocity $C$ and having $\lambda$ length equal to $2\pi/k$. A set of other complex solutions of equation (1) describes a local roughness field attenuating exponentially with distance and equal in its properties to the lake rough surface with a stationary hovercraft.

Three cases of poles location are possible and, accordingly, three different regimes of movement:

a) movement velocity is less than the first critical velocity. In this case no real solution of equation (2) is possible. Progressive waves do not emerge and there is no energy transfer in the direction of movement.

b) movement velocity is greater than the first critical speed, but less than the second

$$v_{cr1} < v < v_{cr2}.$$  

Four real roots are possible with eq(2). In this case two progressive waves with different periods and group velocities are excited. The wave with a lesser period has a group velocity greater than phase speed and will propagate forward and the other wave will propagate aft.

c) with $v > v_{cr2}$ only two real solutions of eq(2) are possible. A progressive wave is excited here propagating forward in front of ACS. It should be noted that in deep water this type of movement is absent.

Critical speed is defined by mechanical characteristics of ice, water and depth of the storage lake

$$v \approx 1.33(Dg^3/\rho_w)^{1/8}$$  

- for deep water,

$$v = \sqrt{gh}$$  

- for shallow water.

The latter is satisfactorily confirmed by experimental investigations [7].

For ice breaking it's necessary to have such a load which allows to compensate energy losses inevitable when flexural-gravitational waves propagate in real conditions.
An analysis of calculation results allowed to define the following:
- when ship sails with resonance speed she is experiencing maximum wave resistance. With speeds exceeding the resonance one wave resistance decreases, oscillating, practically to zero;
- with certain parameters of hovercraft storage lake and ice cover a certain amount of relatively high resistance maxima could be observed at speeds greater than the resonance one and consequently, under these conditions wave excitement of quite high amplitude is also possible. However, ice break up in this case is not guaranteed;
- finiteness of storage lake depth causes increase of resistance under speeds less than $\sqrt{gH}$ and decrease of resistance under speeds greater than $\sqrt{gH}$ compared to the resistance in deep water;
- speed range under which resistance is significantly high is not large, consequently hovercraft movement in ice breaking regime may not be stable. A certain increase of the "resonance" speed range may be achieved by the optimal choice of ship's length.

A problem of ice breaking by means of pressure corresponds with the case of no energy transfer, corresponds to the quasistatic approach and may be significantly simplified. In particular, analytical and experimental analysis allowed to determine a dependence for the pressure required for ice breaking [5]

$$P_{ac} = lh^2 / r^2 [1 + r^2/S], \quad (5)$$

where $l$ - specific energy of ice breaking. Our experimental data have shown that $l = 1300 \pm 50$ kPa.

$S$ - air cushion area in plan.

Air consumption in the air cushion

$$Q = \frac{M_{ef}}{2} \sqrt{2P_{ac}/\rho_a} \quad (6)$$

where $M$ - air cushion perimeter.

$\rho_a$ - air density.

$h_{ef}$ - effective air clearance, $h_{ef} = 0.0075$ m.
When designing of ice breaking air cushion platform (IBACP) besides air cushion pressure and air consumption it is necessary to choose air cushion area and main dimensions ratio (length to breadth \(L/B\) ratio). Obviously \(S = \frac{Mg}{P_{ac}}\), where \(M\) is IBACP mass.

If in design project width of the ice channel is defined, then \(L = \frac{S}{B_c}\). At the same time it is meant that the channel width is close to the width of ice-breaking ACP. Otherwise main dimensions ratios can be defined from solution of the optimization problem proceeding from energy consumption minimum required for ice breaking.

Problem solution of infinite and semiinfinite ice plate bending with a channel form cut lying on elastic basis with rectangular distributed load. An analysis has shown that for each value of load width \(B\) there is value \(L/B\) leading to the minimum load value \(P_{ac}\) for ice breaking. These dependences may be represented as

\[
(L/B)_{opt} = (2.31/x_0) - 0.005
\]

and when load distribution area is given

\[
(L/B)_{opt} = (5.19/5) + 0.019.
\]

where \(x_0 = aB\), \(y_0 = aL\), \(S = x_0y_0\), \(a = 1/r\).

Choice of the aerodynamic scheme and flexible casing dimensions are described in [3].

One of the ways of comparing efficiency of different means of lengthening navigation and ice-fighting could be energy consumption for ice breaking per unit of volume. The energy consumption can be evaluated as

\[
K = \frac{N}{B_c v_t}.
\]

where \(N\) - vehicle power,
\(B_c\) - channel width,
\(v\) - movement velocity.

Calculations made for well-known ice-breaking means have shown significant decrease in specific power for ice-breaking air cushion technologies.
REFERENCES


Fig. 1 General Arrangement of IBACP-107P
Fig. 2 Fragment of testing of IBACP-107P
Fig. 3 Fragment of testing of ACV
PHYSICAL AND MATHEMATICAL MODELS OF
ICE-COVER BREAK UP

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ABSTRACT

Different stages of ice cover break up process are described. Theoretical solutions for elastic deformation and partly those for cracking stage have been obtained. Cracking and overcritical stages have been investigated experimentally. On the basis of experimental dependances obtained, semi-empirical calculation formulas are deducted. Dependances for evaluation of break up characteristic parameters are given for all stages. Ice cover break up energy have been evaluated in quantity and in quality both for the entire stage and for each separate stage as well.

The practical needs of prolonged shipping on the one hand and that of ice-borne facilities on the other hand, often imply quite contraversial stipulations when studying interaction between structures and ice floes. At times, easy ice destruction is required (e.g., for icebreakers) while at other times the greatest load-carrying capacity of ice is indispensable (e.g., for ice-laid roadways, utility platforms, ice-based airfields etc.). Therefore, the ice breaking concept per se is approached by branch experts depending on whether its easy destruction is desirable or not. At times, critical stresses and cracks in the ice field are to be helped but at other times it is to be breached thoroughly so that only its fragments should bear the external load. At assessing an ice plate load-carrying capacity, errors in ob-
taining the crack load are accounted for by a safety factor. While for shipping-extension cases it is ice-breaking energy that should be evaluated most faithfully.

In most practically essential cases, ice loading duration ranges from a fraction of a second to several minutes. Thus, the structure / ice interaction may be assumed as fast as ice creepage or relaxation might be neglected. On the other hand it is considered as permanent as both ice and water inertia may be ignored. So the ice sheet straining might be thought of as subjected to static and quasi-static loads.

Observations on breaking ice floes by vertical loads indicate that prior to ultimate breaching, the ice plate is being fractured by multiple cracks. The load-carrying capacity of such a plate assumed as an elastically-supported one, is maintained after its fracturing due to fragments interaction. Mathematical simulation of the pattern is rather an ingenious problem. One way to deal with is to study simplified models accounting for fewer breakage-promoting factors and then to make up integral models based on both the tendencies revealed and verification of adopted hypotheses and assumptions.

Before constructing a mathematical model, a basic physical model should be made up based on the results of observations and studies of photographs, films etc. test data.

As the ice plate is being loaded vertically, at first it deforms elastically. Then, as critical stresses are attained, several radial cracks arise running from the loaded spot. Further load increasing initiates concentric cracks surrounding the load spot. These cracks develop successively from afar to the load-applied spot and the ice plate is broken down over the innermost concentric crack. Thus the single plate is fragmented into a system of wedge-like pieces. Its equilibrium is explained as follows. Motion of an adjoining wedge being loaded axially at its apex may be thought of as turning around the axis passing near-by the lower edge of the wedge’s base. Therewith the wedge sides try to part its initial plane. As the other wedges turn in the same manner, their sides lower edges will contact and generate pushing forces offset to the wedge’s upper surface. A component of these stresses acting along the wedge axis, presses its
base against the rest of the ice but is offset to the wedge's bottom. Such force distribution on wedge sides balances the external load moment. The shearing force on the wedge is balanced by offset and friction forces of the pressed sides. As the external load increases, the compression stresses cause severe crushing of ice fragments.

In line with the physical model described, one should suggest that breakage results from the combined stress arising in ice structure components. Rigorous mathematical treatment of such a structure encounters a number of problems that are rather difficult to solve in the context of conventional approaches of continuous mechanics. Thus it is seemed reasonable to invoke approximative models that allow to get applicable theoretical results. Among these are well-known thin beams and thin plates theories. These are acceptable as a basis for further modifications due to their successful applications in a number of problems associated with ice straining.

As an example for further discussion, let us consider the experimentally based ice plate sagging relationship at a die contact (fig.).
The curve represents the ice plate's load-deflection relationship at kinematic (rigid) loading and provides a comprehensive data on ice plate straining under a load.

Ice breaking process might be treated as the succession of phases. The first phase features elastic behaviour of the ice plate: its response increases directly with the plate deflection. The second phase starts as soon as critical stresses are attained and a number of cracks generate that split the ice plate into fragments. The floe's response to deflection is slowing down. The greater the number of cracks, the weaker is the ice response to the load until a maximum ice response is attained at a certain deflection $W_p$. With further deflection increasing, the third phase takes place featuring in decreased ice response to deflection until diminishing at all (excluding buoyancy) at the ultimate breakage deflection $W_R$. The third stage takes place under kinematic loading only. At force loading, the ice's maximum response $Z_{\text{max}}$ equals to the breaching load.

A considerable amount of exact solutions has been obtained for both various load configurations and ice planforms [1,2,3,4,5,6]. Structurally, these are of the form

$$W = k_w Z/(D \alpha^2).$$

where $Z$ is the vertical load;

$D = Eh^3/12(1-\mu^2)$ is the ice plate's radial stiffness;

$h$ is the ice thickness;

$E$ and $\mu$ are the Young's modulus and the Poisson's ratio of ice, respectively;

$\alpha = \sqrt{\rho g/D}$ is the bending parameter for an elastically supported plate;

$\rho$ and $g$ are the water density and the gravity acceleration respectively;

Evaluations of the coefficient $k_w$ as a function of ice planform and load are available for most complicated shapes and do not present any difficulties at employing numerical methods [2,6,7,8]. For the second phase loading patterns exact solutions are available only for a limited number of specific cases [2,6,7,8], while for the third type they are seemingly unavailable.

The loading diagram $Z(W)$ as a whole (fig.) for many
essential cases can be presented quite soundly by the following quantitative data: deflection $W$ to response $Z$ ratio over the linear portion of the curve; the greatest response $Z_{\text{max}}$ with the corresponding deflection $W_p$; the deflection $W_R$ of ceasing ice resistance, and also strain energies:

$$A_p = \int Z dW$$

$$A_R = \int Z dW$$

needed to deflect the ice plate to $W_p$ and $W_R$ respectively.

As mentioned above, values of $Z_{\text{max}}, W_p, W_R, A_p$ and $A_R$ can not be obtained accurately enough by theory. Hence the authors have conducted sets of field experiments on various ice shapes [11,12]. An example of the experimental data for loading an infinite ice plate by flat dies of an $S$ area is cited in the table 1.

Table 1. The results of ice breaking field tests

<table>
<thead>
<tr>
<th>$h$, cm</th>
<th>$Z_{\text{max}}$, kN</th>
<th>$W_p$, cm</th>
<th>$W_R$, cm</th>
<th>$A_p$, kJ</th>
<th>$A_R$, kJ</th>
<th>$S$, m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>1.76</td>
<td>4.2</td>
<td>17.4</td>
<td>0.036</td>
<td>0.158</td>
<td>1.14</td>
</tr>
<tr>
<td>8.6</td>
<td>12.8</td>
<td>13.0</td>
<td>27.0</td>
<td>1.1</td>
<td>2.33</td>
<td>2.0</td>
</tr>
<tr>
<td>22.0</td>
<td>134</td>
<td>17.7</td>
<td>18.4</td>
<td>15.8</td>
<td>16.9</td>
<td>2.0</td>
</tr>
<tr>
<td>23.0</td>
<td>154</td>
<td>20.0</td>
<td>21.2</td>
<td>19.8</td>
<td>23.8</td>
<td>2.0</td>
</tr>
<tr>
<td>24.5</td>
<td>168</td>
<td>19.4</td>
<td>21.4</td>
<td>22.8</td>
<td>25.7</td>
<td>5.3</td>
</tr>
</tbody>
</table>

The ice-breaking test results for an infinite plate have been approximated by a relationship structurally alike the linear solutions [11,12]

$$Z_{\text{max}} = K_p (1 + 1.34 \alpha \sqrt{S}) h^2$$  \hspace{1cm} (2)

Here the coefficient $K_p$ has a physical meaning of ice breaking specific energy. Statistical analysis reveals that this might be taken $K_p = 1.9$ MPa with a root-mean-square deviation of 0.1 MPa at a fiducial probability of 0.98.

The linear relation (1) have been adopted as a state formula for $W_p$. However, the coefficient $K_w$ is over $1/8$ as derived from the elastic area solution due to cracks decreasing the floe stiffness. At 0.95 fiducial probability the coefficient might be taken $K_w = 0.28 \pm 0.04$. For proximate assessments, the following formula might be used:

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\[ W_p = K' \sqrt{h}, \quad K' = 0.42 \pm 0.05, \quad m^{1/2}. \quad (3) \]

For defining ice deflection at its ultimate breaking, no relevant state formula has been devised. Comparisons of ice breaking diagrams for various thicknesses (in dimensionless terms) reveal that the extent of the third (supercritical) breaking pattern depends essentially on ice thickness with deflection ratios \( W_R/W_p \) decreasing as ice thickness increases. Based on test results it may be expressed that

\[ W_R = W_p W_R. \quad (4) \]

The dimensionless coefficient \( W_R \) (thickness-dependent) may be approximated by the formula \( \frac{W_R}{h} = 0.1/h + 0.6 \) (\( h \) is assumed in metres).

To approximate energy \( A_p \), the following formula can do:

\[ A_p = \int_0^{w_p} ZdW = K_{AP} Z_{max} W_p. \quad (5) \]

where \( K_{AP} = 0.64 \pm 0.08 \) is an empirical dimensionless coefficient accounting for fullness of the diagram’s subcritical portion.

The relationship for the ultimate ice breaking energy may be presented as

\[ A_R = \int_0^{w_R} ZdW = \int_0^{w_p} ZdW + \int_0^{w_R} ZdW = A_p + h_{AR} Z_{max}(W_R-W_p) \]

or

\[ A_R = [K_{AP} + K_{AR} (W_R - 1)] Z_{max} W_p \quad (6) \]

where \( K_{AP} \) is an empirical dimensionless coefficient accounting for fullness and shape of the supercritical portion of the diagram. It might be approximated by the expression \( K_{AP} = 1.1 h + 0.7 \) (\( h \) is assumed in metres).

It should be pointed out that supercritical ice plate behaviour is less steady, thus the relations (4) and (6) are less reliable than (1), (2) and (5).
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MODELS OF INTERACTION OF ICE-BREAKERS WITH ICE COVER AT UNSTATIONARY CONDITIONS

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ABSTRACT

In thick ice, where the ice-breaker cannot move steadily its movement is exercised by ramming. It is shown that the average speed of ice-breaker per cycle, depending on the run length has its maximum. Recommendations for navigators on optimal run lengths, ice-breaker’s astern movement depending on ice thickness and its physico-mechanical properties are obtained. Calculations can be carried out and obtained for an ice-breaker of any displacement, main dimensions, hull form in contact with ice, power and propulsion complex.

In thick ice, where the ice-breaker cannot move steadily its movement is exercised by ramming [3,5].

Let’s consider ramming ice-breaking in an even compact ice field of \( h \) thickness and of \( \rho_1 \) density, floating upon water surface of \( \rho \) density. Ramming ice breaking process could be represented as a number of subsequent stages. When ice-breaker stops in compact ice its powerplant is reversed because ramming kinetic energy is exhausted. Powerplant reverse time \( t_{ra} \) depends upon powerplant potential and is considered known for any particular ship. Ship’s astern movement begins unless there is no hull jamming. Otherwise it takes some time to free the ship from jamming \( t_{rj} \). Astern movement in ship’s own channel by will of the navigator is exercised to a distance of \( t_{sr} \) necessary to gain entry speed for the next round of ramming in compact ice to be performed. For all this, larger part of the way is made by the ice-breaker under the influence of the astern traction force defined by propulsion / steering unit safety and enertial

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movement when reversed from astern to forward. It takes $t_{am} + t_{af}$ for astern movement. Speeding up forward in ship's own channel is accomplished exclusively to gain speed (kinetic energy) with positive acceleration. When speeding up it takes time $t_{sf}$ to cover the distance forward $l_{sf}$ equal to the astern movement distance; but forward movement of the ice-breaker having touched compact ice cover is gradually lowered up to the dead stop. During the time $t_d$ the ice-breaker covers the distance $l_d$ being the effective distance covered. Under ideal movement conditions in homogeneous ice field the process described is repeated cyclically. That's why ice-breaker's average speed as main performance parameter when ramming could be calculated according to the following formula

$$\nu = t_d / (t_{fa} + t_{rj} + t_{am} + t_{af} + t_{sf} + t_d).$$

Let's consider the main ramming stages. At ship's astern movement and then speeding up in her own channel accelerated movement is observed because traction force exceeds ice resistance under certain speeds (here and further on traction force of the ice-breaker going forward $P_e_{fa}$ and astern $P_e_{af}$ and ice resistance $R$ are found with deduction of water resistance from ice-breaker movement. i.e. "hook traction" and net ice resistance are considered).

Progressive movement equation is

$$(1 + k_{11'})d^2x' = P_e_{af} - R_{af} ,$$

where $k_{11'}$ - coefficient of apparent masses of water and ice;
$D$ - displacement;
$x'$ = $d^2x/dt^2$ - longitudinal acceleration;
$x$ - advancement;
$t$ - movement time;
$P_e_{af}$ - hook traction (astern and forward movement respectively);
$R_{af}$ - net ice resistance at astern and forward movement respectively.

At the stage when the ice breaker moves in compact ice after speeding up equation (2) can be used for movement forward, substituting net ice resistance in broken ice with net ice resistance in compact ice $R$.

As a result of ice-breaker's movement in her own channel filled with broken ice, net ice resistance constituents can be
represented as:

- impulse resistance \( R_1 \), caused by loss of kinetic energy by the ice-breaker colliding with ice;

- dissipative forces of resistance \( R_2 \) related to energy dissipation of a moving ship; they could be represented as a sum of two items: dissipative constituent emerging as a result of water resistance to the ship moving apart ice and dissipative constituent owing to ice friction itself;

- resistance \( R_3 \) owing to ice floe sinking and turning.

An analysis of ice spatial interaction \([6]\) allowed to represent net ice resistance when the ship moves in broken ice channel, as

\[
R_{net} = R_1 + R_2 + R_3 = k_{ld} \left[ c_1 \rho \eta B \frac{v^2}{2} \left( \Phi_1 + f \Phi_1' \right) \right] + c_h \rho v^2 h B \left( \Phi_h + f \Phi_h' \right) + k_t \left( \rho - \rho_1 \right) g h b B \left( \Phi_t + f \Phi_t' \right),
\]

where \( c_1 \) is non-dimensional coefficient regarding apparent masses of water and ice fragments;

\( B \) - breadth of ice-breaker;
\( v = \frac{dx}{dt} \) - movement speed;
\( f \) - ice to outer plating friction coefficient;
\( c_h \) - ice floes hydrodynamic resistance coefficient;
\( g \) - gravity acceleration;
\( b \) - average length of ice fragments, dependent on its thickness; observations have shown that it is determined by plates flexure on elastic basis and approximately can be taken from relation \( b \alpha = 0.312 \);

\[
\alpha = \sqrt{\rho g / d} \quad \text{plate curvature parameter on elastic basis;}
\]
\( d = Eh^3/(12(1-\nu^2)) \) - cylindrical rigidity of an ice plate;
\( E, \nu \) - elastic modulus and Poisson’s ratio;
\( k_{ld}, k_t \) - coefficients compensating theoretical model inaccuracies;

\( \Phi \) - non-dimensional integral functions given below describing ice-breaker’s hull form in contact with ice.

Functions \( \Phi \) are different for forward and astern movement because the forebody entrance form and afterbody differ. Movement analysis in compact ice allowed to find the main reasons for ice resistance \([2, 4, 6]\). Resistance to motion in even compact ice depends upon energy consumption for:

- braking up of ice cover;
- local destruction of ice edge in hull contact with ice.
turning round, sinking and moving ice fragments apart;
snow resistance [1];
ic friction against ship’s hull.

R expression for river ice-breakers is obtained in the form [2, 4]:

\[ R = R_{d} + R_{s} + R_{v} = \sum k r = \]
\[ = k_{d} r_{d} + k_{s} r_{s} + k_{v} r_{v}, \] (4)

where \( R_{d} \) - resistance static component to breaking;
\( R_{s}, R_{v} \) - static and speed-dependent resistance components of ice fragments;

\( k \) - empirical coefficients;
\( r \) - combination of factors defining ice resistance, connected with a certain physical process and having force dimensionality.

Let's write down the formula to find out resistance in compact ice cover as:

\[ R = \frac{k_{d} r_{d}}{h^4} \left[ (1+\gamma_{dfs}) + k_{s} \gamma_{rs} \sqrt{\frac{\sin \Phi_{2s}}{1+\tan^{2} \Phi_{2s}}} \right] \]
\[ + \frac{k_{b}}{d_{a}} + \frac{k_{r} \Phi_{b} d \alpha B}{h} \] (5)

\[ + 0.66(1+f_{\Phi_{bf}})B \alpha + \frac{k_{rb} \Phi_{b} d \alpha B}{h} \] (6)

where \( h_{s} \) - snow thickness on ice;
\( \Omega_{i} \) - area of ship covered around with ice fragments;
\( \gamma \) - non-dimensional functions characterising ice-breaker hull form in contact with ice (given below).

\( k_{v}, k_{d}, k_{s} \) - coefficients compensating for inaccuracy of theoretical model.

Analytical expressions for \( \Phi \) and \( \gamma \) are:

\[ \gamma_{dfs} = \frac{1}{\sqrt{n_{x}^2} + \sqrt{n_{z}^2}} ; \quad \Phi_{b} = \frac{2}{B} \left[ \sqrt{\frac{1}{n_{x}^2} - 1} \right] \]

\[ \gamma_{rs} = \sqrt{\frac{1}{n_{x}^2} - 1} ; \quad \Phi_{b} = \frac{2}{B} \left[ \sqrt{\frac{1}{n_{x}^2} + \sqrt{n_{z}^2}} \right] \]
\[ \Phi_t = \frac{1}{\Omega_1} \int n_x n_x d\Omega; \quad \Phi_{1f} = \frac{1}{\Omega_1} \int n_x \sqrt{1-n_x^2} d\Omega; \quad \Phi_h = \frac{1}{\Omega_1} \int n_x^3 d\Omega; \]

\[ \Phi_{1h} = \frac{1}{\Omega_1} \int n_x^2 \sqrt{1-n_x^2} d\Omega; \quad \Phi_{1hf} = \frac{2}{B} \int n_x^2 \sqrt{1-n_x^2} dL_{WL}; \]

\[ \Phi_h = \frac{2}{B} \int n_x^3 dL_{WL}; \quad \Phi_1 = \frac{2}{B} \int n_x dy; \quad \Phi_{1f} = \frac{2}{B} \int n_x \sqrt{1-n_x^2} dL_{WL}; \]

where

\[ n_x = \frac{\tan \varphi_2}{\sqrt{1+\tan^2 \varphi_2+\tan^2 \varphi_3}}; \quad n_z = \frac{\tan \varphi_3}{\sqrt{1+\tan^2 \varphi_2+\tan^2 \varphi_3}} \]

- direction cosines of external normal to ship's plating with longitudinal Ox and vertical Oz axes; \( n_{xs}, n_{zs} \) - direction cosines at the stem at the work waterline.

Let's put down expressions (3), (6) in the form more convenient for further investigations:

\[ R_a = k_1 \nu^2 + k_2, \]

\[ k_1 = k_{1d} \left[ c_1 \rho_1 \mu B (\Phi_1 + s\Phi_{1f})/2 + c_n \rho B (\Phi_h + s\Phi_{1hf})/2 \right], \]

\[ k_2 = k_t (\rho - \rho_1) g h b B (\Phi_t + s\Phi_{1f}); \]

\[ R = k_3 \nu^2 + k_4. \]

\[ k_3 = k_{t} \rho_1 \mu B \left[ c_1 (\Phi_1 + s\Phi_{1f}) + \frac{2 \rho \Omega_1}{\rho_1 B h} (\Phi_h + s\Phi_{1hf}) \right], \]

\[ k_4 = k_{dst} \frac{h^4}{d\alpha} \left[ (1+f\gamma_{br}) + k_{rs} \gamma_{rs} \sqrt{\frac{\tan \varphi_2}{1+\tan^2 \varphi_2}} \frac{d\alpha^2}{h} + 0.66(1+f\Phi_{br})B \alpha + \frac{k_{rb} \Phi_r d \alpha_3 B}{h} \right] + k_{frast} (\rho - \rho_1) g h \Omega_1 (\Phi_t + s\Phi_{1f}) + k_{ang} h_{ns} \Omega_1 (\Phi_t + s\Phi_{1f}). \]

Hook traction given in differential equation (2) is approximated by the following expression:

\[ Pe_{a,r} = P_{ma} \left[ 1 - 1.4(\nu/\nu_o)^2 \right], \]

where \( P_{ma} \) - ice-breaker traction on mooring lines moving as-
tern or forward;

\( \nu_0 \) - speed in clear water with given power.

With regard to (8), (9), (10) differential equation in more accurate form for each ramming stage is written as:

- for astern movement then speeding up in her own broken ice channel:

\[
\ddot{x} + A \dot{x}^2 = B ,
\]

\[
A = \frac{1.4Pm_{a.f} + k_{1a.f}\nu_0^2}{(1 + k_{11}')D\nu_0^2} , \quad B = \frac{Pm_{a.f} - k_{2a.f}}{(1 + k_{11}')D} .
\]

- movement in compact ice:

\[
\ddot{x} + L \dot{x}^2 = - M .
\]

\[
L = \frac{1.4Pm_r + k_3\nu_0^2}{(1 + k_{11}')D\nu_0^2} , \quad M = - \frac{Pm_r - k_4}{(1 + k_{11}')D}.
\]

In the expression for constant value \( M \) when \( Pm_r < k_4 \), \( M \) is positive. This corresponds to the ice-breaker's braking up to her full stop in ice with thickness exceeding maximum.

For the astern movement and speeding up stage solution is obtained in the form as:

\[
t = \frac{1}{\sqrt{AB}} \cdot \arctanh \sqrt{1 - e^{-2Ax}} ; \quad x(t) = - \frac{1}{2A} \ln \left[ 1 - \text{th}^2 \left(t \sqrt{AB} \right) \right] ;
\]

\[
\dot{x} = \sqrt{\frac{B}{A}} \cdot \text{th} \left(t \sqrt{AB} \right) ; \quad \ddot{x} = \frac{B}{\text{ch}^2 \left(t \sqrt{AB} \right)} .
\]

For movement in compact ice analytical dependence \( x(t) \) has the following form:

\[
x(t) = - \frac{1}{2L} \ln \left[ \frac{M}{C_5} \left(1 + \text{tg}^2 \left(\sqrt{LM} \cdot (C_6 - t) \right) \right) \right] . \quad (14)
\]

Respectively:

\[
\dot{x} = \sqrt{\frac{M}{L}} \cdot \text{tg} \left(\sqrt{LM} \cdot (C_6 - t) \right) ; \quad \ddot{x} = - \frac{M}{\cos^2 \left(\sqrt{LM} \cdot (C_6 - t) \right)} . \quad (15)
\]

With regard to initial conditions of ice-breaker's movement in compact ice we obtain:
Values of $\Phi$ и $\gamma$, calculated for four river ice-breaker projects are given in table 1. General characteristics of these ice-breakers are given in table 2.

Table 1

<table>
<thead>
<tr>
<th>Hull form characteristics of river ice-breakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function nomination</td>
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<tr>
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<tr>
<td>$tg \quad \varphi_{1s}$</td>
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<tr>
<td>$tg \quad \varphi_{2s}$</td>
</tr>
<tr>
<td>$\gamma_{bns}$</td>
</tr>
<tr>
<td>$\gamma_r$</td>
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<tr>
<td>$\gamma_s$</td>
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<td>$\gamma_{tst}$</td>
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<td>$\gamma_{rfr}$</td>
</tr>
</tbody>
</table>

Coefficients $k_{1d}$, $k_t$, $k_{fr}$, $k_{dst}$, $k_{fst}$, allowing to bring into conformity theoretical calculation with natural data, were defined using least-squares method on the basis on the results obtained during trials of river ice-breakers.

Coefficient calculation was made separately for each stage of ice-breaker movement. Their values are $k_{1d}$=1.91, $k_t$=1.83, $k_{dst}$=0.3·$10^6$ kPa², $k_{fst}$=4.7, $k_{fr}$=3.38.

The above-mentioned analysis of ice-breaker performance when ramming allows to put forward a problem of navigation tactics optimization and rational ice-breaker design aimed at such kind of work. Capabilities of ice-breaker are determined by her dimensions, hull form and main powerplant rating. For a certain
ice-breaker these parameters are fixed, that’s why for gaining maximum speed, navigation tactics comes to the foreground. Movement in compact ice where thickness exceeds maximum and could be overcome by ramming, speeding up in ship’s own channel and her forward movement is exercised at powerplant maximum rating. Astern movement is exercised at the propeller revolutions and power ensuring accident-free performance of propulsion / steering unit.

Table 2
Main characteristics of river ice-breakers

<table>
<thead>
<tr>
<th>Name of leading ship (project)</th>
<th>Portovy-1 (P-47)</th>
<th>Volga (16)</th>
<th>Captain Chechkin (1105)</th>
<th>Captain Evdokimov (1191)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year and county of construction</td>
<td>USSR</td>
<td>USSR</td>
<td>Finland</td>
<td>Finland</td>
</tr>
<tr>
<td>Length, m</td>
<td>1971</td>
<td>1950</td>
<td>1971</td>
<td>1993</td>
</tr>
<tr>
<td>Breadth, m</td>
<td>27.0</td>
<td>44.7</td>
<td>71.0</td>
<td>73.0</td>
</tr>
<tr>
<td>Depth, m</td>
<td>7.7</td>
<td>11.2</td>
<td>16.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Coefficient of general fullness, δ</td>
<td>0.51</td>
<td>0.536</td>
<td>0.61</td>
<td>0.753</td>
</tr>
<tr>
<td>Displacement, V, m³</td>
<td>182</td>
<td>655</td>
<td>2240</td>
<td>2200</td>
</tr>
<tr>
<td>Power, kWt</td>
<td>440</td>
<td>1325</td>
<td>4650</td>
<td>4815</td>
</tr>
<tr>
<td>- at engine flanges</td>
<td>362</td>
<td>960</td>
<td>3300</td>
<td>3800</td>
</tr>
<tr>
<td>- at propelling shafts</td>
<td>66.2</td>
<td>140</td>
<td>414</td>
<td>410</td>
</tr>
<tr>
<td>Traction on mooring line, kN</td>
<td>18.3</td>
<td>18.0</td>
<td>25.6</td>
<td>27.0</td>
</tr>
<tr>
<td>Speed in clear water, km/h</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Propellers:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- number</td>
<td>1.6</td>
<td>1.7</td>
<td>2.4</td>
<td>2.0</td>
</tr>
<tr>
<td>- pitch</td>
<td>0.86</td>
<td>1.89</td>
<td>1.31</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Movement in compact ice depends significantly upon entry speed (kinetic energy) into compact ice. However, for ice-breaker speed up it’s necessary to have a certain way defined by ship’s traction force and resistance to motion in the broken ice channel. The distance covered is defined only by movement in compact ice, and time necessary to cover the distance is the total time of all manoeuvres.

It’s worth mentioning that distance length covered by the ice-breaker in compact ice depends upon speeding up forward velocity $v_{sf}$, consequently from the length of speeding up way $t_{sf}$ and total time of the ramming cycle depends upon all manoeuvring stages. Thus, it seems natural to define optimal speed up
length depending on thickness of the ice-cover. Maximum average movement velocity \( v \), being the main index of ice cover ramming performance, could be taken as the aim function (1).

Let’s consider calculation algorithm of ice-breaker average ramming velocity \( v \) concerning length of the speeding up way \( t_{sf} \), using dependences taken for the main movement stages. In order to diminish influence of some separate elements of perfomance tactics upon the investigated function \( v(t_{sf}) \), the following assumptions not influencing upon generality of discussions are made: the ice-breaker comes to the edge of compact ice having a certain speed of \( v_{sf} \) and moves with the powerplant working at full rating as long as she comes to the dead stop; with reverse from forward to astern movement let’s assume that no jamming of the ice-breaker is observed \( t_{rj}=0 \), although introduction of jamming time doesn’t cause any methodological difficulties; the distance covered by the ice-breaker during reverse time from forward to astern movement is small and is neglected here; moving backward the ice-breaker increases her speed from zero to astern speed which she will gain covering the distance \( t_{am} \) equal to speeding up length \( t_{sf} \) at powerplant constant rating.

A stern time \( t_{am} \) and speed up forward time \( t_{sf} \) are determined by:

\[
\begin{align*}
t_{am} &= \frac{1}{\sqrt{A_a B_a}} \text{Arth} \sqrt{1 - e^{-2A_a t_{sf}}}, \\
t_{sf} &= \frac{1}{\sqrt{A_f B_f}} \text{Arth} \sqrt{1 - e^{-2A_f t_{sf}}}
\end{align*}
\]

Then speed up forward time at the moment of contact with ice-cover is determined by:

\[
\nu_{sf} = \sqrt{B_f / A_f} \text{th}(t_{sf} / A_f B_f).
\]

Time of movement in compact ice is found from ice-cover stop condition:

\[
t_d = \frac{1}{\sqrt{LM}} \text{Arctg} \sqrt{\frac{L v_{sf}^2}{M}}.
\]

Distance covered by the ice-breaker in compact ice is:

\[
t_d = -\frac{1}{2L} \ln \left[ \frac{M}{M + L v_{sf}^2} \right].
\]
Obtained values $t_d$, $t_{am}$, $t_{sf}$ together with total reverse time of the main powerplant $t_{rev} = t_{fa} + t_{ar}$ define average ramming speed.

As an example an illustration is given of average $v$ speed calculation depending on speed up length $l_{sf}$ for four designs of river ice-breakers working in different ice thickness conditions.

In accordance with calculations made by computers, graphs $v(l_{sf})$ are made. They are shown in fig. In the graphs there are curves allowing to find optimal speed up length $l_{sf}$ dependent on compact ice cover thickness. It's natural: when ice thickness increases, maximum average movement speed $v_{max}$ decreases (fig.).

![Graphs showing $v(l_{sf})$ for different ice cover thicknesses](image)

**Fig. 1** - P-47, **2** - 1105, **3** - 1191, **4** - 1191.
It's worth mentioning that change of $v$, when $l_{sf}$ is increasing, has a different character. If speed up length increases to optimal $l_{sf}^{opt}$, average speed $v$ increases significantly, but further increase of $l_{sf}$ results in gradual decrease of $v$ (fig.), i.e. with a certain increase of $l_{sf}$ over optimal $l_{sf}^{opt}$ average speed remains close to optimal. This gives freedom for navigator to choose speed up length and is confirmed by experimental data gained in ramming. With speed up length increase over optimal, forward movement per cycle increases, consequently frequency of cycles $n$ per unit of distance is decreased. This may have a positive effect on powerplant resource because number of reverses is decreased.

Obtained mathematical model could be recommended to define employment tactics of existing ice-breakers and to forecast ice navigability of such ships at the design stage.

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