The New Areas of the Ice Cover Modeling Using the Composite Model Ice “GP-ice”

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Abstract. To assess the vessels ice qualities in various ice experimental model basins, the active use of a large number of various methods of the ice cover modeling indicates that there is no single approach to this issue. In this work the fundamental contradiction underlying mentioned methods is pointed. And the new method of the model ice cover testing based on the consideration of the ice failure actual process is proposed. The method of using composite model ice “GP-ice” is proposed. It is also shown that the mechanical properties of the model ice field are in the range of values required to ensure the modeling conditions. The experimental investigation results are presented and the areas for further work are planned.

1. Introduction

The investigation of the resistance to the ships movement in the ice is the crucial and non-trivial task of great interest to researchers. For instance, in [6] 17 of the most well-known methods to estimate the ice resistance of the icebreakers are given. However, none of them can predict the ship speed in the ice of a given thickness with the adequate accuracy for the practice. The reasons of this are: the complex combination of the different part forces, acting when the ship’s interacts with the ice and the water; the ships surface shape is quite difficult to describe mathematically. But, apparently, the insufficient knowledge of the processes of ice cover failure as a special natural structure, as well as the properties of the ice as a specific material makes the greatest contribution. All this determines the crucial role of the model physical experiment in the problem of forecasting the ice propulsive quality of ship.

The modern ideas about the ice resistance of a ship [6] are based on the superposition hypothesis, i.e. the division of the total ship resistance in the ice into various components do not depending (or negligibly weakly dependent) on each other:

\begin{equation}
R = R_{icb} + R_{bi} + R_w ,
\end{equation}

here is $R_{icb}$ – the ice cover failure resistance; $R_{bi}$ – the resistance caused by the ship’s hull interaction with the ice fragments formed after the ice cover failure; $R_w$ – water resistance.

For instance, the original method for determining ice resistance is based on this principle [3]. In this work the ice failure resistance is determined by the model experiment in a solid natural ice. This ice has strength properties similar to the nature ice, but there is no similarity in the thickness. Then the model is run in the ice fragments obtained. Resistance in the resulting ice fragments (which are not
similar to natural ones) is subtracted from the found values. After this the additional experiment in the polyethylene blocks [3] in order to determine \( R_{bi} \) is performed. The resistance \( R_w \) is determined by the classical test in the pool without ice (“on the clear water”). This method has good convergence with full-scale data [10], and is also the most rigorously substantiated of the existing ones.

However, this method is very time-consuming, has a good few number of conditionalities and assumptions, does not have a sufficiently well-founded technology for testing the adequacy to the nature, and does not allow simultaneous modeling the resistance components (1). In order to overcome these disadvantages, the research consisting in the finding new areas in the ice cover modeling is conducted by the authors. One of these areas is the development of the ice model composite material (“GP-ice”).

2. Modeling of ice cover failure

The most significant disadvantages of the modern physical models of the interaction of the ice-technology objects with the ice cover is the sub-quality of the assurance of the processes similarity leading to the ice failure. One of the reasons for this is the insufficient knowledge of the natural ice failure, the small number of the experimental works carried out.

The most crucial investigations are [2, 9]. They give a sufficiently complete picture of the full-sized ice failure process, which was a continuation of the experiments of Russian scientists [7, 8, 9].

The main differences between the experiments presented in [5] and those mentioned above was the use of the ice loading kinematic method. Previously (the power method) the constant load increase up to break with the fixation of the break load [7, 8] was carried out by the deflection registration at the moment of the break [8]. Then under the kinematic loading the deflection under the load was set by its movement and the force response of the ice cover to the given moving was recorded. This made it possible to obtain a detailed and total characteristic of the process in the form of the failure diagrams, which shown the moments of load fall before and after reaching its maximum.

In addition, the mentioned early experiments were carried out according to the “central loading” scheme, i.e. a force is applied to the infinite ice cover. In the recent tests [5], the ice failure was carried out according to the schemes closest to the real impact of the technical vehicles and the installation on the ice cover – according to the laying channel scheme and widening its edges.

When a vertical force is applied to infinite ice cover, it is deformed. When the stress in the ice reaches the critical values, a cracks network is formed – first is the radial cracks, then – the circular. In that instant, the ice cover separated by cracks loses its continuity, but ice failure does not occur. With a further load increase, the ice is deformed as a structure consisting of the separate blocks. The ice cover failure occurs at the moment when the blocks supported on each other are broken along the edges from the interaction with each other; and the structure as a whole loses its load-carrying ability [2]. In that instant, a significant number of the cracks are formed, which are difficult to describe due to their large number.

Taking into account the described process of the ice cover failure, it becomes obvious that the methodology for testing the adequacy of the most modern physical models of the ice is unconvincing. This test is the break of the cantilever beam cut in the ice. As a result of this test, the maximum value of the load applied to the ice is fixed at the moment when the crack occurs and the beam separates from the rest of the ice, while the full-sized ice cover retains its load-carrying ability for a long time after the first crack appearance.

Attempts to mathematically describe the above-mentioned phenomenology of the ice cover failure process are met with grave difficulties. This made it difficult to draw up the strict physical simulation criteria based on both the mathematical equations and understanding or the physics of fracture due to the processes complexity occulting in the ice.

However, in the experimental investigations on the full-sized ice cover failure [7, 9], including [5], the fact of the proportionality of the maximum ice-breaking force to the square of the ice thickness was observed, which well approximates the test results according to the “central break” scheme:
\[
P = k_p \cdot h_{ic}^2
\]  

here is \( P \) the value of the concentrated force applied to the ice cover; \( k_p \) – the dimension factor (Pa), so-called “disturbance ratio”, connects the value of the force applied to the ice to the ice cover thickness.

The value of this coefficient turned out to be quite stable (the mean-squared departures from the mean were no more than 10\%) and for “central break” scheme was 1.96 MPa. This fact makes it possible to identify an empirical condition for modeling the ice cover strength, taking into account the complexity of ice failure process, based on the full-scale test data.

When carrying out experiments to determine the ice propulsive quality of ships \([6]\), the model geometry \( l_m \) are reduced by a factor of \( \lambda \) in comparison with the full-scale \( l_n \):

\[
\frac{l_n}{l_m} = \lambda
\]  

here is \( \lambda \) geometrical model-prototype relationship. The sizes of the ice cover \( (h) \) during modeling have also to obey the same rule:

\[
\frac{(h_{ic})_n}{(h_{ic})_m} = \lambda
\]  

The ships model tests are carried out in the sweet water, and the differences between the full-sized and the model density is ignored:

\[
\rho_m = \rho_n.
\]  

At the same time, for the simultaneous modeling of the water and the ice mass forces, the condition \((4)\) is strived also to fulfill for model and full-sized ice density.

Then, according to the modeling conditions, all forces associated with the acceleration of gravity (gravity force, buoyancy force, etc.) are decreased by a factor of \( \lambda^3 \), as \( g = \text{const} \) for full-sized and model. Taking into account \((3)\) and \((5)\), the result is obtained:

\[
\frac{G_n}{G_m} = \frac{\rho_n \cdot V_n \cdot g}{\rho_m \cdot V_m \cdot g} = \lambda^3.
\]  

The need for the simultaneous modeling of the mechanical and the bulk forces within the same system requires the maintenance with the same modeling scale for them \([11]\) (it is also called the object dynamic similarity condition):

\[
\frac{P_n}{P_m} = \frac{\rho_n \cdot V_n \cdot a_n}{\rho_m \cdot V_m \cdot a_m} = \lambda^3
\]  

When carrying out the vessels model tests, all mechanical forces associated with the ice resistance are reduced on this scale: the interaction forces of the ice fragments with the ship and among themselves; the flow forces associated with the ice and the ship; the force acting from the ship on the ice cover.

Thus, to simulate the process of the vessels interaction with the ice, it is necessary to select such ice model material so that the forces applied to the ice cover caused by the vessels movement destroy it at the moment when they reach a value by a factor of \( \lambda^3 \) less than the full-scale breaking force.

Evidently, the same rule have to be fulfilled for the model ice cover not only when interacting with the vessel, but also with any other mechanical force applied to it, and it will also be by a factor of \( \lambda^3 \) less than for the same full-scale loading scheme.

Thereby, the following proposition, which is fundamental for ice cover modeling, is put forward:

“The model ice cover testing for the model adequacy to the full-scale should be carried out on the on the test basis on the model ice failure according to the central loading scheme”.

\[\text{(2)}\]
Then, taking into account the formula (3) based on the data obtained during the tests on the full-scale ice failure according to the scheme “central break”, it is obtained:

\[ \lambda^3 = \frac{P_n}{P_m} = \frac{(k_p \cdot h_{ic}^2)_{n}}{(k_p \cdot h_{ic}^2)_{m}}. \]  

(8)

Taking into account (4), the requirement for the material of the ice cover model is obtained:

\[ (k_p)_m = \frac{(k_p)_n}{\lambda}. \]  

(9)

Similarly, to ensure the modeling condition of the deflection under the force at the moment of the break, it is necessary that the model ice modulus of elasticity is factor of \( \lambda \) lower than the full-scale:

\[ E_m = \frac{E_n}{\lambda}. \]  

(10)

3. The GP-ice composite ice model development

The material research areas according to the (9) and (10) were laid down in the NSTU n.a. R. E. Alekseev’s patent [1]. The ice cover model in which the polyethylene granules were frozen into the natural ice was proposed. As a result, it was named “composite”. The granules inclusion in the natural ice is led to a decrease in its strength due to the long and large intercrystalline disintegration and low ice adhesion to the polyethylene. In addition, polyethylene has a lower elastic modulus and its presence reduces the value of the ice cover total modulus of deformation. All of this was allowed to hope the methodology development that would satisfy conditions (9) and (10). At that time the works generalization devoted to this model is given in [3, 6].

The small tests number are caused by the tests laboriousness with the composite ice carried out in the experimental model basin in the natural cold conditions in the free air and the dependence on unstable weather conditions. It was not allowed to carry out a sufficiently extensive research of the composite ice and complete it in full. The small ice pool located in the heat chamber is changed the situation [4]. The independence from the environment and the decrease laboriousness made it possible to re-conduct the tests to study the composite ice properties and search the areas for carrying out the modeling conditions.

The tests were carried out in the ice pool with sizes of 1.1x2.5 m. The spherical granules with a diameter of 20 mm were used. The temperature in the chamber was maintained at -150…-180°C. The freezing time of the required layer is depended on the initial water temperature and was 1–5 hours. After the test the destroyed model ice together with the granules was melted in water, and a new granules portion, previously cooled in the chamber, was putted into the pool. As a result the time between the tests was shortened.

The model ice scheme is shown on figure 1a. These ice geometrics are given in figure 1b. The frozen layer thickness of the granules by the natural ice \( h_1 \) determines the reduced thickness of the modeling ice \( h \):

\[ h = \frac{V_D + V_{h1}}{S}. \]  

(11)

here is \( V_D \) – the volume of the spherical granules in the area \( S \), \( V_{h1} \) – the ice volume between granules in the area \( S \).
4. Experimental investigation results

During the tests on the model ice failure (see figure 2) the loading was carried out using the kinematic scheme, i.e. the force application device moved the stop block into the ice at a constant speed of 1mm/s. The resultant force was measured using a strain gauge and recorded using an A to D converter on a PC, the movement was recorded using a resistive-type sensor.

A typical view of the failure diagram is shown in figure 3. The two characteristic zones are shown in the diagrams. The first has the steep ascent and can be interpreted as a deformation with the radial cracks appearance. The second flat part is observed to be associated with the concentric cracks appearance and development.

Figure 2. The loading process of the ice cover with a subsequent failure.
Figure 3. The typical view of the failure diagram of the single-layer composite ice using the granules 20mm.

Two groups of the results were obtained by the experimental data processing. The first connects the power characteristic and the modulus of deformation value of the model ice cover with the reduced thickness of the simulated ice. Here, the modulus of elasticity is not meant. This modulus is difficult to determine due to the complex relationship between force and deflection at the initial part of the diagram. It is talked of the modulus of deformation, defined by the initial part of the diagram, in which it difficult to separate the beginning of the radial cracks formation. The approximate value of this module was determined, as for the case of an ideal ice cover, by the well-known Hertz formula [10]. These characteristics are shown in the diagrams in figure 4. The disturbance ratio was determined by the formula (2). The approximation formulas that allow using the experimental data in the numerical calculations are obtained.
Figure 4. The main force and deformation characteristics of the failure process of the modeling composite ice:

- the maximum breakdown force; b – the disturbance ratio; c – the modulus of deformation

• – depending on the granule freezing thickness; × – depending on the reduced thickness.

The second group of the results is associated with the possibility assessment of using the results obtained with granules with a diameter of 20 mm for modeling full-scale object. The formula (7) connecting the disturbance ratio of the natural and model ice cover with the geometrical model-prototype relationship is used. Based on the formula (7) and the tests on the failure of the simulated ice according to the “central break” scheme, it is possible to determine the modeling geometric scale corresponding to the given model ice thickness $h$. And also, using the formula (10), it is possible to determine the necessary characteristics of the model ice modulus of deformation for a more strictly correspond to the classical similarity theory. The curves for the required values are shown in figure 4c.
Figure 5. Parameters of the natural ice modeling using the “GP-ice” composite model of the ice cover: a – flexural rigidity; b – geometrical model-prototype relationship; c – natural ice thickness.
- depending on the granule freezing thickness; × – depending on the reduced thickness.

5. The results discussion and the conclusions
From the data obtained, it follows that when using granules with a diameter of 20 mm, it is possible to simulate the ice cover thickness up to 800 mm using the geometric scale \( l \) in the range of 20-70.

This limit \( l \) is insufficient for the most tasks associated with the interaction of the technical vehicles and the installation with full-scale ice cover. The modulus of deformation of the model ice turned out to be greater than it required according to the classical modeling theory. Despite the fact that the possibility of the total modeling the characteristic of the ice cover as a specific natural structure through the modulus of deformation concept is controversial, this factor should not be overlooked.

The resulting logarithmic type of the dependence of the disturbance ration on the composite ice thickness can be explained by the influence of the basin walls at thickness over 8 mm, as well as by a small number of the experiments over 10 mm. However, the general dependence, as well as the obtained values of the geometrical similarity coefficient \( l \) for the model ice thicknesses over 8 mm (figure 5c) makes it practically uninteresting to carry out further tests on the composite ice failure with a thickness of more than 8 mm with frozen granules 20 mm in diameter.
The carried out tests have shown a significant decrease in the strength of the model composite ice when polyethylene granules are frozen into it, which is sufficient to organize the tests to study the ice propulsive quality of ships. The obtained results show the correctness of the chosen approach to the use of the modeling composite ice on basis of the polyethylene granules and allow outlining the further research areas. These include:

1. The use of the different diameter granules, ranging from 3 to 25 mm.
2. The use of the granules multilayer freezing with a size of 3-10 mm.

6. References

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