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Extension of FSICR method for calculation of ship resistance in brash ice channel

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ABSTRACT

One of the contemporary issues of Arctic shipping is the navigation in ice channels. Due to the cold Arctic climate and regular ship passages, the thickness of brash ice and consolidated layer grows fast and significantly influences the ice resistance of a ship. At the same time, most of the existing studies devoted to the estimation of ice channel resistance refer to the Baltic region, where natural conditions are relatively mild. In this study, we develop the formulas to calculate ice resistance of a ship in the ice channel considering the peculiarities of the Arctic environment. Since a considerable practical experience of navigation in ice channels is concentrated in the Finnish-Swedish Ice Class Rules (FSICR), we used this methodology as the basis for further development. We extend the approach of FSICR (2012) and suggest a computational model to estimate ice resistance, which covers a number of aspects that are not taken into account for mild and moderate ice environment. In particular, the proposed model: a) considers significant thicknesses of brash ice (more than 1 m) and consolidated layer (more than 0.1 m); b) takes into account the influence of brash ice on the resistance due to the consolidated layer; c) considers the dependence of ship resistance from the flexural strength of consolidated layer. We made a sensitivity analysis to estimate the influence of main parameters of the ice channel and ship speed on ice resistance. The model is validated using the available fragmentary full-scale data on the operation of the LNG carrier *Christophe de Margerie* in the Ob Bay.

KEY WORDS: Ice resistance; Ice channel; Brash ice; Consolidated layer

INTRODUCTION

Navigation in ice channels filled with brash ice is one of the typical modes of icebreaking vessels operation. Brash ice is a mixture of water and small ice fragments typically sized less than 0.3 m across. The processes of brash ice formation and its accumulation in navigable ice channels have been described earlier (e.g. Ettema and Huang, 1990; Riska et al., 2014; Karulin et al., 2018). It is known that the layer of brash ice causes the increase in ship resistance compared to ice-free channels. The ship resistance is increased with the brash ice thickness, while the ship speed is reduced. When brash ice grows to reach certain thickness levels, shipping via channel is no longer possible and a new channel should be laid.

For addressing the issues of navigation through the brash ice channels, it is necessary to estimate the ship resistance under these sailing conditions. The Finnish-Swedish Ice Class Rules (Finnish-Swedish Ice Class Rules, FSICR 2010) prescribe a practical method for appraising ship's ice resistance in brash ice channels. The formulas of this method have been verified based on full-scale data obtained from operating track records of some vessels in the Baltic Sea, and, therefore, their scope of application is restricted in terms of ice channel characteristics and the ship's parameters and speeds. In particular, according to the FSICR assumptions, the thickness of brash ice in the middle of ice channel is limited to 1 m, while the consolidated layer grown from top layers of brash ice is not more than 0.1m. The geometry of ice channels and the intensity of shipping traffic are assumed as typical for the Baltic Sea operations (Veitch et al., 1991; Kujala and Sundell, 1992). In connection with newly emerging navigation routes in freezing Arctic waters (in particular, the Ob Bay), it is required to investigate the specific conditions of ship navigation via ice channels in the harsh environment. Studies regarding the evolution of navigable ice channels regularly used by ships, e.g. in the Ob Bay, indicate that brash ice may be as thick as 10 m, while its consolidated layer may reach up to 0.5 – 0.7 m, depending on temperatures and shipping frequency (Karulin et al., 2018). It precludes direct application of the FSICR formulas to the regions with harsh ice conditions.

This paper analyses the separate resistance components in FSICR formulas that describe various processes related to the ship motion in brash ice channels. Based on this study a computational model is suggested to go beyond the constraints of the FSICR formulas in ship resistance estimates. Apart from enhancing the range of ice channel parameters (thickness of brash ice and its consolidated layer), the formulas suggested in this paper include the functions of ship speed and consolidated layer strength.

Calculations by the above-said model were compared with FSICR calculations for the navigable channels in the Baltic Sea with good agreement between the results. At present, there is a lack of full-scale measurements taken in harsh weather regions. The available data on the operation of *Christophe de Margerie* LNG tanker in brash ice demonstrate good agreement with the results of calculations by the suggested formulas. Increasing shipping activities in the Ob Bay, in particular via navigable ice channels, should provide more information for verification of this model and, if necessary, updating of the same.

This paper considers pure ice resistance, assuming that the ice and water resistance are superimposed.

EVOLUTION OF CALCULATION METHODS

Scientific publications

Development of suitable calculation methods has been addressed in a limited number of papers. Mellor (1980) suggested a formula to calculate the resistance in brash ice based on its description as a loose medium characterized by internal friction angle φ and cohesion c. Brash ice behavior was described by the Mohr-Coulomb law. Mellor considered a cohesionless brash case ($c = 0$) and represented the resistance by the sum of three components: resistance due to passive pressure (internal friction) of the loose medium, friction resistance of ship bow and friction resistance of ship sides. The internal friction angle of brash ice of $\varphi = 50°$ was used. Mellor formulas are based on a simplified representation of ship hull form and ignore the dependence of resistance on ship speed. The formulas have not been validated by the measurements.

Further studies in this field also employed the methods of loose material mechanics and, essentially, attempted to extend the Mellor approach. For example, Kujala and Sundell (1992) give the formula of Malmberg (1983):

$$R_{CH} = \frac{1}{2}\mu_B \rho_\Delta g H^2 K_p \left(\frac{1}{2} + \frac{K_0}{2K_p}\right)^2 (B + 2H \tan\psi \cos\alpha)(\mu_H \cos\alpha + \sin\psi \sin\alpha) +$$
$$\mu_B \rho_\Delta g H^2 K_0 L_{PAR} \mu_H \qquad (1)$$

where R_{CH} is the ice brash resistance; μ_B, K_p, K_0 are the parameters related to the mechanical properties of the brash ice in the channel: $\mu_B = 1 - p$, where p is the porosity, K_p and K_0 are coefficients of the brash ice passive stress and lateral stress at rest accordingly; ρ_Δ is the difference between densities of water and ice; g is the gravity constant; H is the thickness of the brash ice; L_{PAR} is the length of the parallel middle body at the waterline; B is the ship width; α is the entrance angle of the waterline; ψ is the flare angle calculated as $\psi = \arctan(\tan\phi / \sin\alpha)$, ϕ is the rake of the stem at the centerline; μ_H is the friction coefficient between the ship hull and ice.

The first term of Eq.1 estimates the ice resistance due to the brash ice interaction with the ship bow and the second one represents resistance due to the friction of brash ice on the parallel middle body of the ship. Malmberg took a different value of the internal friction angle for brash ice $\varphi = 47°$. Like the original formula of Mellor (1980), the Malmberg formula does not relate the brash ice resistance to ship speed: the both approaches are based on the limiting equilibrium of the loose medium.

The influence of ship speed was examined in further studies. Riska et al. (1997) give a formula derived by modification of the formulas from Englung (1996) and Wilhelmson (1996):

$$R_{CH} = \frac{1}{2}\mu_B \rho_\Delta g H_F^2 K_p \left(\frac{1}{2} + \frac{H_M}{2H_F}\right)^2 \left[B + 2H_F\left(\cos\delta - \frac{1}{\tan\psi}\right)\right](\mu_H \cos\phi + \sin\psi \sin\alpha) +$$
$$\mu_B \rho_\Delta g H_F^2 K_0 L_{PAR} \mu_H + \rho_\Delta g \left(\frac{LT}{B^2}\right)^3 H_M A_{WF} Fn^2 \qquad (2)$$

where H_M and H_F are the thicknesses of the brash ice in the middle of the channel and on the ship side respectively; δ is the angle of repose of the brash ice (in the study, 22.6° is used); L and T are the length and the draft of the ship; A_{WF} is the waterline area of the foreship and $Fn = v/\sqrt{gL}$ is the Froude number, v is the ship speed.

The last term of Eq.2, containing the main parameters of the ship hull, is the dependence of some weighty medium resistance (brash ice resistance) on the ship speed. A non-linear speed dependency in the resistance was obtained both in full-scale observations and in model tests (Riska et al., 1997).

If a consolidated layer has been formed on top of the brash ice layer then additional resistance due to its action on the ship hull should be taken into account. According to Riska et al. (1997), the consolidated layer resistance is determined using the formulas derived for level ice of the same thickness. In general, the level ice resistance of the ship depends on several parameters and may be represented in the form:

$$R_i = f\left(h_i, \sigma_f, \rho_\Delta, \mu_H, \alpha, \phi, L, B, T, L_{bow}, L_{par}, L_{bow}, v\right) = C_1 + C_2 v \qquad (3)$$

where h_i is the level ice thickness; σ_f is the ice flexural strength; L_{bow} is the length of the ship bow. The coefficients C_1 and C_2 dependent on the ship particulars have been derived from modified formulations of Ionov (1988) and Lindqvist (1989).

The total ice channel resistance is determined as a sum of Eqs. 2 and 3. In the Eq. 3, instead of the level ice thickness, the consolidated layer thickness h_{con} is used, i.e. $h_i = h_{con}$.

The following assumptions were made in a calculation scheme developed by Riska et al. (1997):

- flexural strength of consolidated ice layer on top of the brash ice is assumed to be equal to the flexural strength of surrounding level ice;
- ship resistance due to the consolidated ice layer is calculated without considering the influence of brash ice.

Propulsion performance of ships in ice has been studied for some years in the Baltic Sea, including measurements of ice channel cross-sections and ship propulsion characteristics (Veitch et al., 1991; Kujala and Sundell, 1992). The formula of Riska et al. (1997) fitted well to the full-scale measurements in the environment and vessels specific to the Baltic. Therefore, this formula was used as a basis for the FSICR method to estimate ship resistance in brash ice channels. This procedure is described below.

Description and analysis of FSICR procedure

FSICR prescribe formulas for: a) newly built vessels, b) ships under design and existing vessels. The first group of formulas contains hull form parameters that are taken on average in the second group of formulas. Therefore, at certain values of hull form parameters, these formulas give the same results. In our further analysis, the formulas recommended for existing vessels are considered.

In accordance with FSICR, for a ship of ice class IA Super the resistance in ice channels filled with brash ice featuring a consolidated layer should be estimated as:

$$R_{CH} = C_1 + C_2 + C_3(H_F + H_M)^2(B + 0.658H_F) + C_4LH_F^2 + C_5\left(\frac{LT}{B^2}\right)^3\frac{B}{4} \quad (4)$$

where C_1 and C_2 for ships without a bulb shall be calculated as

$$C_1 = f_1\frac{BL}{2\frac{T}{B}+1} + 1.84(f_2B + f_3L + f_4BL) = f_1\frac{BL}{2\frac{T}{B}+1} + 1.84(f_2B + f_3L) + 1.84f_4BL \quad (5)$$

$$C_2 = 3.52(g_1 + g_2B) + g_3\left(1 + 1.2\frac{T}{B}\right)\frac{B^2}{\sqrt{L}} \quad (6)$$

Coefficients f_i, g_i ($i = 1,2,3$), C_i ($i = 3,4,5$) and f_d are obtained by substitution of the following parameters in formulas (2) and (3):

Brash ice thickness in channel H_{M0}	1.0 m
Consolidated layer thickness h_{con0}	0.1 m
Flexural strength of consolidated layer σ_{f0}	500 kPa
Water/ice density difference ρ_Δ	125 kg/m^3
Ice/hull friction coefficient μ_H	0.15
Ship speed v_0	5 knots (2.57 m/s)
Internal friction angle of brash ice φ	47°
Cohesion c	0 kPa
Porosity of brash ice p	0.2

$f_1 = 10.3$ N/m^2	$g_1 = 1530$ N	$C_3 = 460$ kg/(m^{2}s^2)
$f_2 = 45.8$ N/m	$g_2 = 170$ N/m	$C_4 = 18.7$ kg/(m^{2}s^2)
$f_1 = 2.94$ N/m	$g_1 = 400$ N/m$^{1.5}$	$C_5 = 825$ kg/s^2
$f_d = 5.8$ N/m^2		

$\left(\frac{LT}{B^2}\right)^3$ is not to be taken as less than 5 and not to be taken as more than 20.

The first two summands of the Eq. 4 (i.e. C_1 and C_2) give the resistance due to the consolidated layer. The other three summands represent the brash ice resistance: the bow resistance, the parallel midbody resistance and the speed dependent component.

Figure 1 shows the results of the calculated ice resistance of a sample ship moving through the ice channel according to the FSICR procedure (Eqs. 4 – 6). Contribution of various components into the total ice resistance can be assessed using the presented diagram. Parameters of the sample ship are given in Table 2.

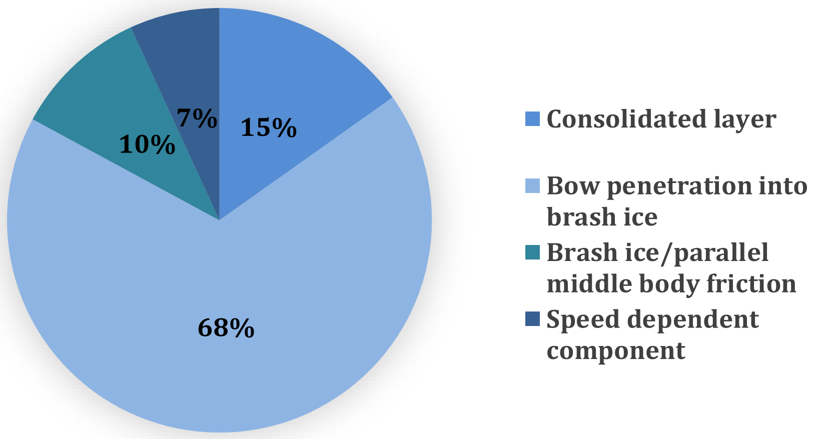


Figure 1. Contribution of various components into the ice channel resistance (the FSICR procedure, the sample ship)

MODIFICATION OF FSICR METHOD

Eqs (2) and (3) have to be modified if it is intended to extend the existing method to cover the cases when ships are sailing in channels filled with brash ice of significant thickness (>1m) whose consolidated layer is thicker than 0.1 m. Besides, it should be taken into consideration that principal dimensions of modern ice-going vessels may not fit the constraints of FSICR formulas, which have been verified for vessels with the maximum length of 250 m and the maximum beam of 40 m. For example, the LNG carriers of *Christophe de Margerie* type designed for LNG transportation in the Ob Bay are about 300 m long and 50 m wide.

Modification of formulas to calculate the consolidated layer resistance

The thicker is the consolidated layer on top of brash ice, the larger is its contribution to the total ice resistance of vessels. As mentioned in Riska et al. (1997), the resistance component due to consolidated layer is calculated by the formulas applied to estimate the resistance of level ice of the same thickness (Eqs. 5 and 6). The first term of Eq.5 represents the ice resistance of the ship parallel middle body, the second one is caused by the ice failure and depends on the ice flexural strength, the last term is the resistance component due to the turning and immersion of ice blocks. Coefficient C_2 in Eq. 6 represents the resistance component caused by pushing away the ice blocks: this component depends on the ship speed.

In order to take into account varying values of the consolidated layer thickness, its flexural strength and the ship speed, Eqs. (5) and (6) can be written as:

$$C_1 = f_1 \frac{BL}{2\frac{T}{B}+1}\left(\frac{h_{con}}{h_{con0}}\right) + 1.84(f_2 B + f_3 L)\left(\frac{h_{con}}{h_{con0}}\right)^2\left(\frac{\sigma_f}{\sigma_{f0}}\right) + 1.84 k_{br} f_4 BL\left(\frac{h_{con}}{h_{con0}}\right), \quad (7)$$

$$C_2 = 3.52\left(g_1\left(\frac{h_{con}}{h_{con0}}\right)^{1.5} + g_2 B\left(\frac{h_{con}}{h_{con0}}\right)\right)\left(\frac{v}{v_0}\right) + g_3\left(1 + 1.2\frac{T}{B}\right)\frac{B^2}{\sqrt{L}}\left(\frac{h_{con}}{h_{con0}}\right)\left(\frac{v}{v_0}\right) \quad (8)$$

where the suffix "0" refers to the values of the baseline FSICR model presented earlier.

Coefficient k_{br} in Eq.7 accounts for the influence of the brash ice on turning and immersion of ice blocks. This factor was assessed using the results of numerical simulations based on discrete element model (DEM) to investigate the turning of a consolidated layer block, taking into account the presence of ridge keel (Karulin, 2001). It was examined how the ridge keel influenced the component due to the ice block turning during first-year ridge interaction with an inverse cone structure with a slope angle of 35° (Fig. 2). The estimates were performed for various combinations of the internal friction angle and ice cohesion in the ridge keel represented as a loose medium: $c = 0$ kPa, $\varphi = 20°$; $c = 3$ kPa, $\varphi = 40°$; $c = 6$ kPa, $\varphi = 60°$ (full-scale). The thickness of consolidated layer was 1.0 m and keel depth 9.0 m. It was found that the ridge keel had a significant effect on the load component related to ice block turning, increasing it approximately 100 times as compared to that in open water at a relative ice/cone speed of 2 to 3 knots.

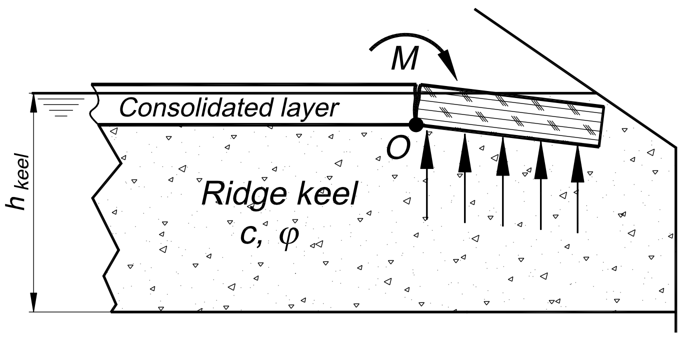


Figure 2. Turning of a consolidated layer block during first-year ridge interaction with a conical structure

Based on the modified Ionov's formula, Karulin and Karulina (2010) showed that the ship resistance component due to ice block turning also depends on the ship speed. For a sample ship of 100 m length sailing at a speed from 2 knots to 6 knots in level ice the resistance component due to ice turning and immersion varied in a range 5-20% of the total ice resistance, accordingly. In consideration of these results, it can be expected that Eq.5, which ignores brash ice effects, significantly underestimates the ship resistance component due to interaction with the consolidated layer. Our study introduces a coefficient to enhance the component related to turning of ice blocks in brash ice k_{br} (Eq. 7). Based on a comparison of the estimates performed for sample ships by the suggested method and by the FSICR procedure this parameter was set as $k_{br} = 5$. Test calculations were done for the ships listed in FSICR under the assumption that the flexural strength of the consolidated layer was the same as for the surrounding level ice, i.e. 500 kPa.

The subject of how the consolidated layer strength is related to the level ice strength should be primarily explored by analysis of full-scale measurements. It can be expected that the strength of consolidated layer is noticeably weaker than that of the surrounding level ice

Modification of formulas to calculate the brash ice resistance

From the comparison of Eq. 2 and Eq. 2, it is seen that in the modified Malmberg formula the first summand describing the load taken by ship's bow to overcome the brash ice resistance, the ratio between brash ice thickness at ship's bow (in the middle of the channel) and at ship's side $\frac{H_M}{H_F}$ (Eq. 2) is replaced by the ratio between the coefficient of lateral pressure at rest and the coefficient of passive pressure $\frac{K_0}{K_p}$ (Eq. 1).

The coefficient of passive pressure for the cohesionless medium with the internal friction angle φ is defined as $K_p = \frac{1+\sin\varphi}{1-\sin\varphi}$ and equals to 6.5 at the given internal friction angle of $\varphi = 47°$, while the coefficient of lateral pressure at rest is related to the Poisson ratio ν as $K_0 = \frac{\nu}{1-\nu}$ and equals 0.27 at the given $\nu = 0.21$ (Mellor, 1980).

The thickness of brash ice at the ship side is determined according to FSICR formula $H_F = 0.26 + (H_M B)^{0.5}$.

Coming back to the initial representation of resistance due to the passive brash ice pressure at ship's bow (first summand of Eq. 1), and using the coefficients introduced by FSICR (third summand of Eq. 4), we can write:

$$R_{bow} = C_3 {H_F}^2 \left(1 + \frac{K_0}{K_p}\right)^2 (B + 0.658 H_F) \quad (9)$$

The resistance due to the friction of brash ice against ship sides in way of parallel middle body is found from:

$$R_{par} = C_4 L H_F^2 \quad (10)$$

It should be noted that H_F in formulas (9), (10) cannot exceed the ship draft, otherwise H_F is assumed equal to T.

The speed-dependent component of ice resistance is found from:

$$R_{Fn} = C_5 \left(\frac{LT}{B^2}\right)^3 \frac{B}{4} \left(\frac{H_M}{H_{M0}}\right) \left(\frac{v}{v_0}\right)^2 \quad (11)$$

It is assumed that the thickness of brash ice in the middle of the channel (or ahead of the bow) H_M is less than the ship draft T. If this condition is not satisfied, then a brash ice layer will slide along the ship hull bottom, and one more resistance component will appear, which is friction between the brash ice and the bottom. In the described models, this case was not considered. Available data from the field observations in the Ob Bay showed that the ships were capable of going through the brash ice when its thickness was noticeably less than the ship draft.

Ship resistance in the brash ice channel

In accordance with the above-described approach, the ice resistance of a ship in brash ice of thickness H_M (in the middle of the channel) with a consolidated layer of thickness h_{con} can be estimated as:

$$R_{CH} = C_1 + C_2 + R_{bow} + R_{par} + R_{Fn} \quad (12)$$

where C_1 and C_2 are determined according to the formulas (7) and (8).

KEY PARAMETERS OF CALCULATION AND THEIR INFLUENCE ON ESTIMATED SHIP RESISTANCE

The ship resistance in brash ice channel was estimated by formula (12). Table 1 contains the variation range of key parameters.

Table 1. Variation range of key parameters

Parameter	Reference value	Range
Thickness of consolidated layer, m	0.1	0 – 0.7
Flexural strength of consolidated layer, MPa	0.5	0.3 – 0.7
Thickness of brash ice, m	1.0	1.0 – 5.0
Ship speed, knots	5.0	2.0 – 6.0

Calculations were performed for two vessels whose main particulars are given in Table 2. One ship had the same characteristics as the sample ship used for test calculations by FSICR formulas, and the other case was represented by the LNG carrier *Christophe de Margerie*.

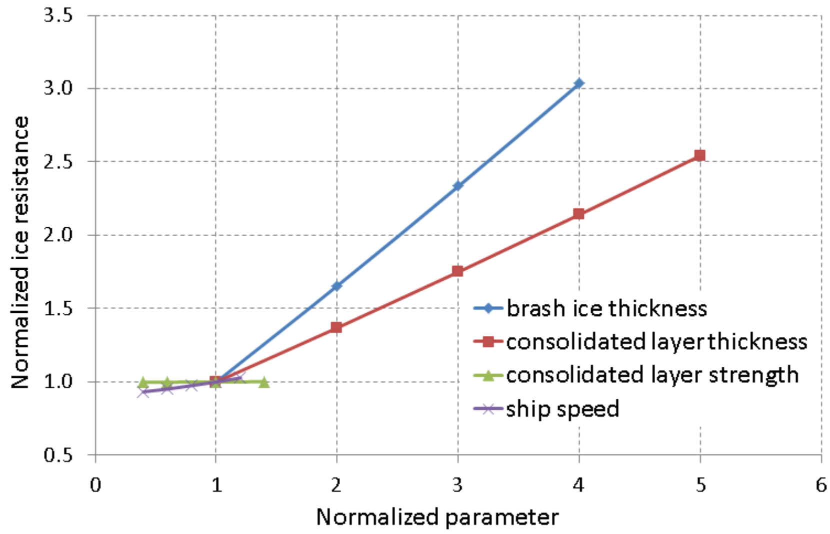
Table 2. Main particulars of ships

Parameter	Sample ship (FSICR)	*Christophe de Margerie*
Ice class	IA Super	IA Super
Design length, m	150	290
Beam, m	25	50
Design draft, m	9.0	11.8

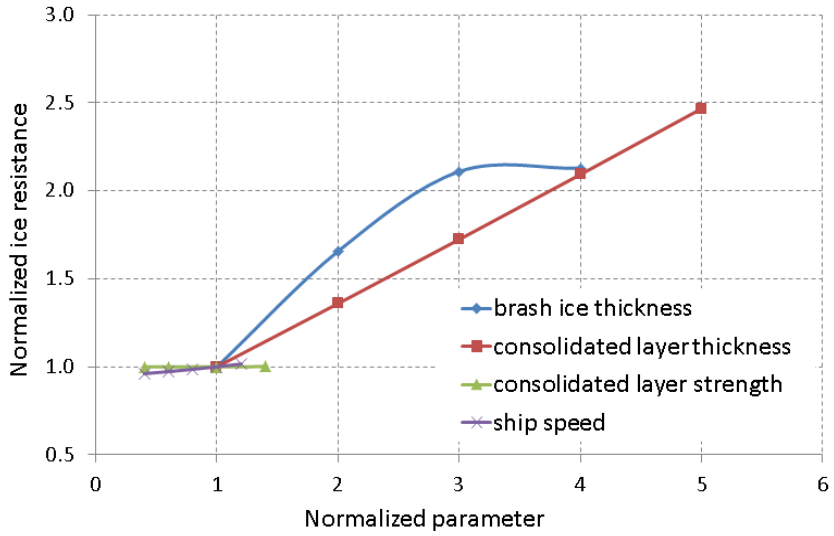
Figure 3 shows the results of calculations as dependencies of normalized ice channel resistance of the ships on normalized parameters. The normalized resistance is the ratio of the resistance R_{ch} at a specified value of some parameter to the resistance R_{ch0} at the reference value of this parameter, i.e. R_{ch}/R_{ch0}. When one of the parameters is varying, the others are set to their reference values. Similarly, the normalized parameter is the ratio of its specified value q to the reference value q_0 taken from the Table 1, i.e. q/q_0 where q is the one of the varying parameters.

The following outcomes can be made from the calculation using Eqs. 7 – 12:

- Strength of the consolidated layer has no noticeable effect on the results. The calculations have shown that at specified values of the consolidated layer thickness the ice breaking component is small, and the flexural strength variations within 0.3 – 0.7 MPa are negligible for the result (Fig. 3). Thus, even though the suggested calculation scheme includes the flexural strength of the consolidated layer (Eq. 7), it can be assumed equal to that of the level ice, if no other data is available
- Thickness of the consolidated layer has a significant effect by increasing the contribution of the resistance component due to the consolidated layer into the total load.
- Passive pressure component of resistance strongly depends on the brash ice thickness. This term gives the largest contribution to resistance, and, therefore, the total ice resistance is sensitive to brash ice thickness.
- When the ship speed is increased from 2 to 6 knots, the ship resistance is increased at 10% for the sample ship (FSICR) and at 6% for the *Christophe de Margerie*.



a) the sample ship (FSICR)

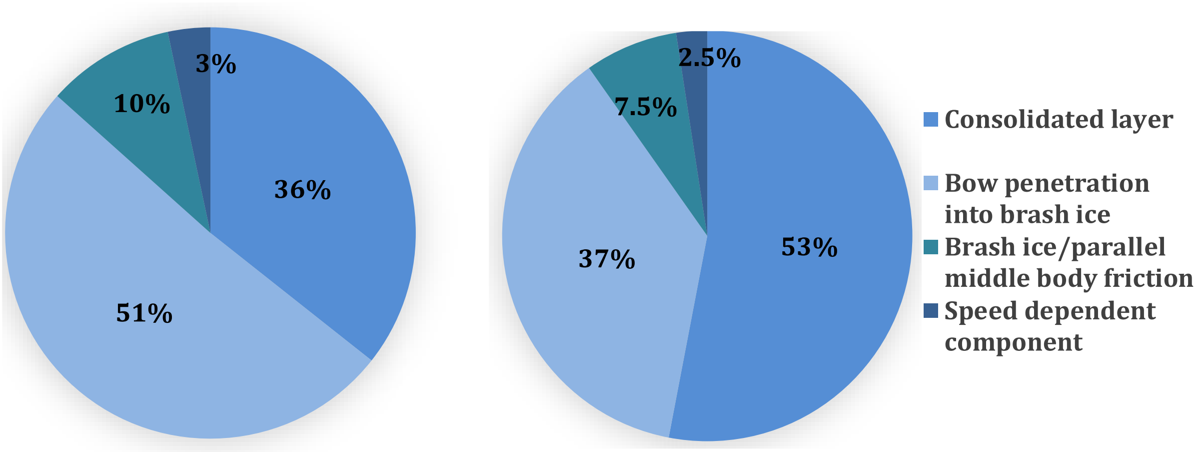


b) LNG carrier *Christophe de Margerie*

Figure 3. Influence of parameters variation on calculation results

Calculations of the ice channel resistance using the Eq. 12 suggested in this paper give 772 kN for the sample ship at the reference values of key parameters. This is in a good agreement with the value 758 kN obtained according to FSICR formulas. At the same time, the contribution of individual components to the total ice resistance has changed, which can be seen from the comparison of Figure 1 and Figure 4a. Figure 4b shows that an increase in the consolidated layer thickness from 0.1 m to 0.2 m at the constant brash ice thickness of 1.0 m leads to the dominant role of the consolidated layer resistance over the other components.

Test calculations for the *Christophe de Margerie* were done for the case of the ship movement ahead in 4m thick brash ice without consolidated layer. According to the track records of the *Christophe de Margerie* in the Ob Bay, the ship is able to sail at a speed of 4 knots under these conditions (personal communications with ship-owner). Eq. 12 estimates the ship ice resistance in this mode as 4900 kN at ship draft 11.8 m, 4650 kN at the draft 11.5 m and 4250 кН when the draft is 11.0 m. All these values are close to the bollard pull of this LNG carrier, which is approx. 4500 kN.



a) consolidated layer thickness=0.1 m   b) consolidated layer thickness=0.2 m

Figure 4. Contribution of various components into the ice channel resistance (proposed model, the sample ship, reference parameters from Table 1)

CONCLUSIONS AND DISCUSSION

This paper introduces a computational model that extends the scope of application of the FSICR formula to calculate ship resistance in brash ice channels. The calculation scheme is based on the general physical models and approaches developed earlier, such as the representation of brash ice as a cohesionless loose medium. Unlike the FSICR scheme, which is primarily focused on the Baltic ice conditions, the proposed model has the following modifications:

- The model supports ship resistance estimates for the significant thickness of brash ice (more than 1 m) and consolidated layer (more than 0.1 m);
- The model contains a coefficient to include the influence of brash ice on the resistance of the consolidated layer;
- Previously developed models are used to reconstruct the relationships for dependence of ship resistance on the flexural strength of consolidated layer and ship speed.

The estimates by the suggested method are in satisfactory agreement with the ship ice resistance estimates obtained according to FSICR for the Baltic ice conditions. Validation of the model for the case of thick brash ice that is typical for the Arctic navigation is restricted due to the lack of full-scale observations on ship resistance in such conditions. However, we used the available fragmentary data on the operation of LNG carrier *Christophe de Margerie* in the Ob Bay to verify the suggested formula.

Some issues identified in this paper are the subject to further discussion and study. In particular, the influence of brash ice on the ship resistance due to the interaction with consolidated layer has to be studied further for better understanding. The contribution of this component to total ice resistance increase with the growth of the consolidated layer thickness.

As it was mentioned earlier by Riska et al. (1997), the highest uncertainty is related to the parameters that describe brash ice as a loose medium: angle of internal friction, cohesion, porosity. There are various expert opinions about the specific values of these parameters that should be considered in calculations.

In the described calculation approach the thickness of the consolidated layer on top of the brash ice is included into the brash ice thickness. A thorough investigation is needed to support the correct specification of the brash ice thickness because the ship's resistance is very sensitive to this parameter.

Possibly, there is a need to consider an additional resistance component caused by sliding of the ship bottom over brash ice, which may be the case at a rather thick layer of brash ice in channel.

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