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Further study on level ice resistance and channel resistance for an icebreaking vessel

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Abstract

In this paper, further research is carried out to investigate the resistance encountered by an icebreaking vessel travelling through level ice and channel ice at low speed range. The present paper focuses on experimental and calculated ice resistances by some empirical formulas in both level ice and channel ice. In order to achieve the research, extra model tests have been done in an ice basin. Based on the measurements from model test, it is found that there exists a relationship between ice resistance, minimum ice load, maximum ice load and the standard deviation of ice load for head on operation in level ice. In addition, both level ice resistance and channel ice resistance are calculated and compared with model test results.

Keywords: Level ice resistance; Channel ice resistance; Model test data; Icebreaking vessels

1. Introduction

Due to the increased hydrocarbon exploration and exploitation in ice-covered waters, ship transports and operations under ice impact are becoming more and more concerned. It is important to estimate ice loads acting on ice-going vessels under design conditions. For icebreaking vessels, there exist a large number of engineering tools for ice-class ship performance evaluation at the design stage. Lindqvist (1989) developed a formula to calculate ice resistance based on many full scale tests in the Bay of Bothnia. By modifying the formulations of Lindqvist (1989), Riska et al. (1997) proposed a level ice resistance formula with some empirical parameters. Keinonen et al. (1996) did research on resistance of icebreaking vessels in level ice and developed a formula based on results of a study of escort operations involving five icebreaking vessels. Moreover, Jeong et al. (2010) proposed new ice resistance prediction formula for standard icebreaker model using component method of ice resistance and also predicted the model test results to full-scale using calculated non-dimensional coefficients.

How to validate these tools based on model scale data remains an issue. Hu and Zhou (2015) compared model test data and numerical results calculated with several popular empirical and analytical formulas. They found that the empirical methods could predict ice resistance at different accuracy, but none of them could give a good estimation for all cases. In order to further study ice resistance, more model tests have been performed using the same ship model. The model test results with respect to ice resistance in both level ice and channel ice are presented in this paper. The relationships between mean, maximum, minimum and standard deviation regarding ice resistance are found and highlighted based on the model test results. In addition, the ice resistances in both level ice and channel ice are calculated are compared with model test data.

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2. Model test description

The icebreaking tanker MT Uikku is a double-hull icebreaking motor tanker that is owned by Neste Shipping and Kvaerner Masa-Yard's joint venture company, Nemarc. It is shown in Fig. 1. The ship model of MT Uikku was deployed in the model tests with a scaling factor of 1:31.56 (as shown in Fig. 2). The model ice was generated from ethanol (0.3%) doped water solution. The ambient temperature was lowered to approximately −10 °C. The carriage moved continuously from one end to the other of the basin in the spraying process where water-mist was emitted by nozzles. The freezing process continued until the target thickness of the ice was achieved. Then the ambient temperature was increased to around −2 °C and this process continued until the target strength (flexural strength) of the ice was achieved.

The ship model was trimmed to even keel without heel angle, so that the centre of buoyancy and the centre of gravity were in the same longitudinal and transverse location. The ship model was towed straightly through ice fields in all tests. The particulars of the full scale vessel are given in Table 1.

Test matrix with ice type, ice drifting speed and measured ice properties are presented in Table 2. It should be noted that tests with ice sheet I and II (shown in Zhou et al., 2013) are

Fig. 1. Icebreaking tanker MT Uikku.

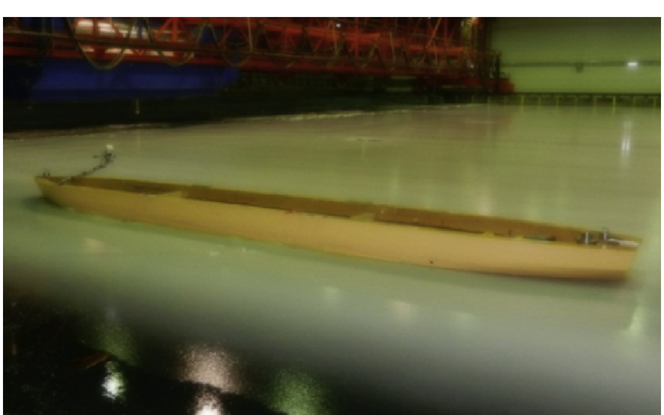

Fig. 2. Ship model of MT Uikku.

Table 1
Full-scale primary dimensions of MT Uikku.

Item	Notation	Unit	Value
Length	L	*m*	150.0
Length of bow	L_{bow}	*m*	39
Length of parallel	L_{par}	*m*	65
Breadth moulded	B	*m*	21.3
Tested draft	T	*m*	9.5
Bow waterline angle	α	*deg*	21
Bow stem angle	ϕ	*deg*	30
average flare angle	ψ	*deg*	58

also included here in order to have more measured data. Two extra ice sheets were made in the ice basin, where level ice and channel ice tests were carried out. Level ice tests means that the ship model was towed straightly in the intact ice sheet. After the ship model travelled through the ice field, a channel would form behind the ship model. The ship model would experience ice resistance from ice floes in the open channel, which is ice channel resistance. In total, three ice drifting speeds were set, namely 0.2, 0.5 and 1.0 m/s. When broken ice slides along the hull, there will be a friction force which is a function of relative speed between ice and hull. It is also proportional to the weight of ice in the water. The ratio of the friction force to the weight of ice is defined as ice-hull friction coefficient. The ice-hull friction coefficient was measured to be 0.04. The measured water density ρ_w is 989 kg/m^3 while ice density ρ_i is 906 kg/m^3.

3. Model test results and analysis

Ice resistance is defined as average value of all longitudinal forces invoked by ice acting on the structures in time domain. An example of a time history of measured longitudinal ice force is shown in Fig. 3, where the dot dash line denotes the mean ice force or ice resistance, the dot line denotes the minimum ice force and the dash line denotes the maximum ice force.

The dynamic fluctuations of ice force are mainly caused by ice breaking and ice submersion processes. When a structure transit in ice, its hull will break and displaces broken ice wedge. Crushing happens between hull and ice immediately after the ice sheet contacts the hull. The crushing force will keep growing as the contact area increases until its vertical component is large enough to cause a bending failure of ice. After the new ice floes are formed from the intact ice sheet, the advance of ship forces them to turn on edge until parallel with the hull. Then, the floes will become submerged and slide along the hull until they lose contact with the hull and clear away. During those processes, the ice force will fluctuate significantly.

3.1. Ice resistance

The results of all measurements with respect to the mean, standard deviation, maximum and minimum ice forces are given in Table 3.

Table 2
Test matrix and measured ice properties.

Ice sheet	Test No.	Ice type	Ice thickness h_i [*m*]	Bending strength σ_b [*kPa*]	Crushing strength σ_c [*kPa*]	Elastic Modulous E_i [*MPa*]	Ice speed V_i [*m/s*]
I	103	Level	0.77	724	1748	929	0.2
	104	Level	0.76	844	2192	984	0.5
II	205	Level	0.96	920	1840	1685	0.2
	206	Level	0.95	912	1862	1701	0.5
III	301	Level	1.04	540	2477	1474	0.2
	302	Level	1.04	669	2485	1273	0.5
	303	Level	1.04	592	2397	1390	1.0
	304	Channel	–	–	–	–	0.2
	305	Channel	–	–	–	–	0.5
	306	Channel	–	–	–	–	1.0
IV	401	Level	0.63	808	4040	1616	0.2
	402	Level	0.63	1029	5389	2058	0.5
	403	Level	0.63	903	4616	1805	1.0
	404	Channel	–	–	–	–	0.2
	405	Channel	–	–	–	–	0.5
	406	Channel	–	–	–	–	1.0

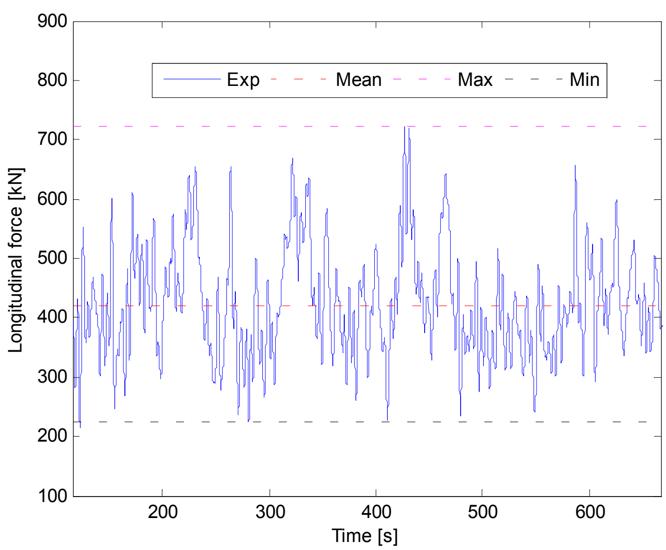

Fig. 3. Time history of measured longitudinal ice force.

In Table 3, the ratios of difference between maximum/minimum and mean force to the standard deviation of ice force are also included. It is interesting to find that the ratios are relatively concentrated from 2.8 to 3.6 for upper bound and 2.5 to 3.2 for low bound. Then the ratios could be written as

$$\begin{aligned} Kmax &= (Fmax - Fmea)/Std(F) \\ Kmin &= (Fmea - Fmin)/Std(F) \end{aligned} \quad (1)$$

Where *Fmax* is the maximum ice force, *Fmea* is the mean ice force or ice resistance, *Fmin* is the minimum ice force, *Std(F)* is the standard deviation of ice force.

Then least squares method is used to obtain the coefficient *Kmax* and *Kmin* based on the measured data given in Table 3. It is found that $Kmax = 3.26$ and $Kmin = 2.76$. The results of measured and fitted values are plotted in Fig. 4. Both maximum and minimum values are fitted very well with the correlation coefficients 0.998 and 0.986 respectively.

Compared to the measured resistances in level ice, the measured channel ice resistances are relatively small. This is as expected since the ship model needs more energy to break

Table 3
Measured ice forces for all cases (kN).

Case No.	Ice type	Mean	Std.	Max	Min	(Max − Mean)/Std.	(Mean − Min)/Std.
1 (Test 103)	Level	480	130	920	100	3.4	2.9
2 (Test 104)	Level	560	130	990	200	3.3	2.8
3 (Test 205)	Level	670	220	1410	100	3.3	2.6
4 (Test 206)	Level	720	193	1390	130	3.5	3.2
5 (Test 301)	Level	540	88	850	290	3.5	2.8
6 (Test 302)	Level	830	130	1200	450	2.8	2.9
7 (Test 303)	Level	780	160	1260	370	3.0	2.6
8 (Test 304)	Channel	220	65	420	60	3.1	2.5
9 (Test 305)	Channel	120	31	210	40	2.9	2.6
10 (Test 306)	Channel	210	65	430	40	3.4	2.6
11(Test 401)	Level	150	56	350	8	3.6	2.5
12 (Test 402)	Level	290	84	590	48	3.6	2.9
13 (Test 403)	Level	390	120	720	84	2.8	2.6
14 (Test 404)	Channel	98	22	175	30	3.5	3.1
15 (Test 405)	Channel	81	25	160	19	3.2	2.5
16 (Test 406)	Channel	69	25	140	5	2.8	2.6

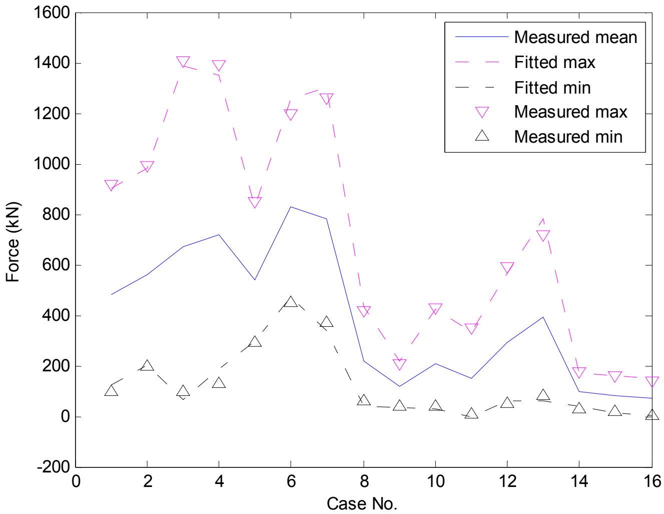

Fig. 4. Measured and fitted ice forces.

intact ice sheet and submerge the ice floes newly formed from ice wedge. The maximum channel ice resistance at the lowest ice drifting speed account 50% of maximum level ice resistance in case 8 and 14 as shown in Table 3. As the speed increases, the channel ice resistance tends to decrease due to shortened interaction time between incoming ice floes and the ship.

3.2. Level ice resistance

Level ice resistance could be taken as the summation of the force occurred during ice breaking process at the initial ice-hull interaction and the force due to submersion and sliding of broken ice from intact ice sheet. It is difficult to measure the global ice breaking force directly since the integration of ice submersion is inevitable. However, the breaking component can be determined by means of a test in pre-sawn ice indirectly. The intact ice sheet is cut into pieces in a similar pattern as observed in the level ice test. Then ice submersion force could be measured and subtracted from the total ice resistance to get the ice breaking force at the same ice drifting speed.

Unfortunately, the pre-sawn test was not included in the present model tests. Herein, one good reference highly related to the present research is introduced to study the ratio of ice breaking component to the total ice resistance. Heinonen (2014) carried out a series of experiments to study on the effect of speed on the ice resistance of a ship. The model of the icebreaker Kontio was used at a scale of 1:20. Both level ice tests and pre-sawn ice tests were performed at four model-scale speeds: 0.23 m/s; 0.69 m/s; 1.38 m/s and 1.84 m/s. The ice breaking forces were calculated as the difference between the resistances measured in level ice and in the pre-sawn ice. The measured percentages of ice breaking component to the total ice resistance as a function of Froude number are shown in Fig. 5. The relationship between the percentage and the Froude number is fitted with a second order polynomial curve based on the measured data. Then the fitted curve is used to calculate the percentages of ice breaking component for the MT Uikku ship model at different speeds. The calculated ice breaking and submersion components are given in Table 4.

The submersion ice resistance is defined as the resistance in pre-sawn ice. According to ITTC (2002), the submersion resistance coefficient C_v is written as

$$C_v = \frac{R_V}{\rho_i g B h^2} \tag{2}$$

where ρ_i is the ice density,g is the gravity acceleration, B is the ship breadth, h is the ice thickness.

The calculated coefficients are shown in Fig. 6. The coefficients range from 1.5 to 3.2, which are slightly lower than the range 2–4 suggested by ITTC.

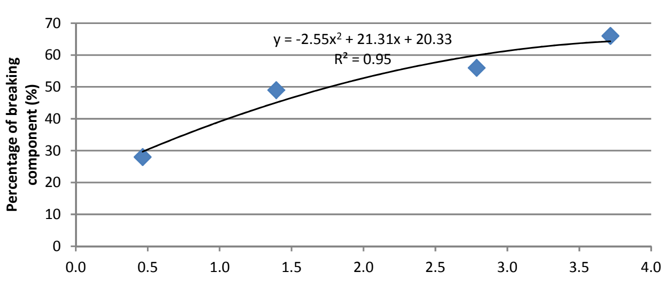

Fig. 5. Measured and fitted percentage of ice breaking component for the Kontio model.

Table 4
Calculated ice breaking and submersion components from measured resistance.

Case No.	Speed (m/s)	Froude Number	Breaking comp. (%)	Measured total resistance (kN)	Breaking comp. (kN)	Submersion comp. (kN)
1 (Test 103)	0.2	0.073	37	480	176	304
2 (Test 104)	0.5	0.183	36	560	204	356
3 (Test 205)	0.2	0.065	41	670	273	397
4 (Test 206)	0.5	0.164	41	720	292	428
5 (Test 301)	0.2	0.063	42	540	229	311
6 (Test 302)	0.5	0.157	42	830	352	478
7 (Test 303)	1.0	0.313	42	780	329	451
11 (Test 401)	0.2	0.080	34	150	51	99
12 (Test 402)	0.5	0.201	34	290	98	192
13 (Test 403)	1.0	0.402	33	390	130	260

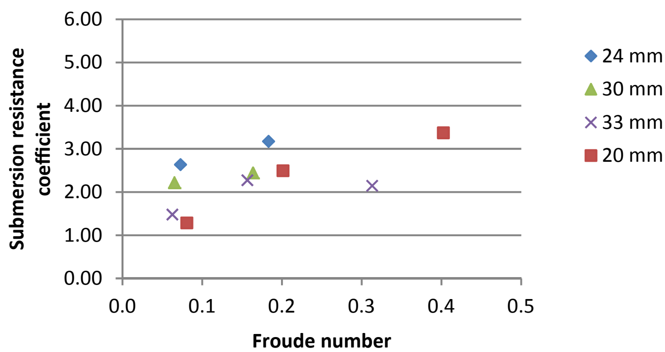

Fig. 6. Submersion resistance coefficient VS Froude number.

4. Empirical and analytical formulas

4.1. Level ice resistance formula

There are many empirical and analytical formulas available to estimate level ice resistance. Some of them are presented as follows.

a) Lindqvist formula

The Lindqvist formula was developed from research done on full scale tests in the Bay of Bothnia (Lindqvist, 1989). It is a rather simple way of estimating the ice resistance. In this model, the resistance is divided into crushing, bending-induced breaking and submergence. The formula gives resistance as a function of main dimensions, hull form, ice thickness, ice friction and strength. The formula is expressed as:

$$
\begin{aligned}
R_{ice} &= (R_c+R_b)\left(1+1.4\frac{V}{\sqrt{gh_i}}\right)+R_s\left(1+9.4\frac{V}{\sqrt{gL}}\right)\\
R_c &= 0.5\sigma_b h_i^2\frac{\tan\phi+\mu\cos\phi/\cos\psi}{1-\mu\sin\phi/\cos\psi}\\
R_b &= \frac{27}{64}\sigma_b B\frac{h_i^{1.5}}{\sqrt{\dfrac{E}{12(1-v^2)g\rho_w}}}\frac{\tan\psi+\mu\cos\phi}{\cos\psi\sin\alpha}\left(1+\frac{1}{\cos\psi}\right)\\
R_s &= (\rho_w-\rho_i)gh_iB\left(T\frac{B+T}{B+2T}+k\right)\\
k &= \mu\left(0.7L-\frac{T}{\tan\phi}-\frac{B}{4\tan\alpha}+T\cos\phi\cos\psi\sqrt{\frac{1}{\sin\phi^2}+\frac{1}{\tan\alpha^2}}\right)\\
\psi &= \arctan\left(\frac{\tan\phi}{\sin\alpha}\right)
\end{aligned}
\tag{3}
$$

where R_{ice}, R_c and R_b and R_s are total andice resistance, crushing resistance, bending resistance and resistance due to submersion;σ_b and h_i are respectively ice strength in bending and ice thickness; μ, ϕ, α and ψ are respectively the friction coefficient, stem angle, waterline entrance angle and flare angle; g is the gravity acceleration; ρ_w *and* ρ_i are water and ice density; E, and υ are Young's modulus and Poisson ratio of sea ice respectively. B, T, and L are ship's breadth, draught and waterline length; V is ship speed.

b) Keinonen formulas

Based on results of a study of escort operations involving five icebreaking vessels, Keinonen et al. (1996) did research on resistance of icebreaking vessels in level ice. In order to investigate low-velocity ice resistance, specific formulas were derived from full scale trials of icebreaker performance in ice at 1 m/s speeds. These prediction formulas include parametric influences for different vessel dimensions, hull forms, hull surface conditions, ice strengths and ambient temperatures. The speed-dependent resistance formula is written as:

$$
\begin{aligned}
&R = C_f\left(0.08+0.017C_sC_hB^{0.7}L^{0.2}T^{0.1}H^{1.25}k_1k_2\right)\\
&k_1 = (1-0.0083(t+30))\left(0.63+0.00074\sigma_f\right)\\
&k_2 = \left(1+0.0018(90-\psi)^{1.4}\right)\left(1+0.04(\varphi-5)^{1.5}\right)\\
&C_f = \frac{1+\dfrac{V}{\sqrt{gh_i}}}{1+\dfrac{V_1}{\sqrt{gh_i}}}
\end{aligned}
\tag{4}
$$

where R is total ice resistance in MN; C_s is water salinity coefficient (0 fresh, 1 saline); C_h is hull condition coefficient (1 inertia, 1.33 bare steel); B, T and L are ship beam at waterline, draft and waterline length in meter;ψ andφ are average flare angle and buttock angle in degree; t is air temperature; σ_f is flexural strength; H is ice thickness; C_f is the correction factor considering the effect of vessel speeds with reference speed $V_1 = 1$ *m/s*.

c) Riska formulas

Riska et al. (1997) proposed a level ice resistance formula by modifying the formulations of Lindqvist (1989). The formulation is based on a set of empirical coefficients, derived from full-scale tests of a number of ships in ice conditions in the Baltic Sea. The main resistance formula is given in Eq. (5), while constants are found in Table 5.

Table 5
Constants in Riska formulation for ice resistance in level ice.

Symbol	Value	Unit
f_1	0.23	kN/m^3
f_2	4.58	kN/m^3
f_3	1.47	kN/m^3
f_4	0.29	kN/m^3
g_1	18.9	$kN/(m/s*m^{1.5})$
g_2	0.67	$kN/(m/s*m^2)$
g_3	1.55	$kN/(m/s*m^{2.5})$

$$R_{ice} = C_1 + C_2 V$$
$$C_1 = f_1 \frac{1}{\frac{2T}{B}+1} BL_{par} h_i + (1+0.021\phi)$$
$$\left(f_2 B h_i^2 + f_3 L_{bow} h_i^2 + f_4 B L_{bow} h_i\right)$$
$$C_2 = (1+0.063\phi)\left(g_i h_i^{1.5} + g_2 B h_i\right) + g_3 h_i (1+1.2T/B) \frac{B^2}{\sqrt{L}} \quad (5)$$

where V, B, T and L are vessel speed, breadth, draught and length, h_i is ice thickness, ϕ is the stem angle in degrees and L_{bow} and L_{par} are the length of bow and parallel sides section, respectively.

d) Jeong formulas

Jeong et al. (2010) proposed new ice resistance prediction formula for standard icebreaker model using component method of ice resistance and also predicted the model test results to full-scale using calculated non-dimensional coefficients. The formulas are presented as follow:

$$R_I = 13.14V^2 + C_B \Delta\rho g h_i BT + C_c F_h^{-\alpha} \rho_i B h_i V^2 + C_{BR} S_N^{-\beta} \rho_i B h_i V^2$$
$$F_h = \frac{V}{\sqrt{g h_i}}$$
$$S_N = \frac{V}{\sqrt{\frac{\sigma_f h_i}{\rho_i B}}} \quad (6)$$

where R_I total ice resistance; C_B, C_C and C_{BR} are coefficient of ice buoyancy resistance, coefficient of ice clearing resistance and coefficient of ice breaking resistance; F_h and S_N are Froude number and strength number; α is index of Froude number; β is index of Strength number; ρ_i and ρ_w are ice and water density; $\Delta\rho$ is water density minus ice density; g is gravitational constant; h_i is ice thickness; B and T are beam and draft of the ship; V is ship speed; σ_f is the flexural strength of ice. The constants used are shown in Table 6.

4.2. Channel ice resistance formulas

When coming to the design point, the rule channel resistance for different ice classes should be taken into account.

Table 6
Constants in Jeong formulation for ice resistance in level ice.

Symbol	Value
C_B	0.5
C_C	1.11
C_{BR}	2.73
α	1.157
β	1.54

According to Juva and Riska (2002), the rule resistance equation is expressed in the following form:

$$R_{ch} = C_1 + C_2 + C_3 [H_F + H_M]^2 [B + C_\psi H_F] C_\mu$$
$$+ C_4 L_{par} H_F^2 + C_5 \left[\frac{LT}{B^2}\right]^3 \frac{A_{WF}}{L}$$
$$H_F = 0.26 + (H_M B)^{0.5}$$
$$C_\mu = 0.15\cos\phi_2 + \sin\psi \sin\alpha, \ \min 0.45$$
$$C_\psi = 0.047\psi - 2.115, \ \min 0.0 \quad (7)$$
$$\psi = \arctan\left[\frac{\tan\phi_2}{\sin\alpha}\right]$$
$$C_1 = f_1 \frac{BL_{par}}{\frac{2T}{B}+1} + [1+0.021\phi_1](f_2 B + f_3 L_{bow} + f_4 B L_{bow})$$
$$C_2 = [1+0.063\phi_1][g_1 + g_2 B] + g_3\left[1+1.2\frac{T}{B}\right]\frac{B^2}{\sqrt{L}}$$

where the term $[LT/B^2]^3$ is taken as 20 if it is above 20 and 5 if it is below 5; all other coefficients are shown in Table 7.

5. Comparisons

5.1. Level ice

Ice resistances by empirical and analytical formulas (Eqs. (5)−(7)) are calculated and compared with model test results. The calculated results and model test measurements are shown in Table 8, where the error between measured data and analytical data is also included. The corresponding results are plotted in Fig. 7 for comparison.

From Table 8, it shows that the Lindqvist formulas underpredicts ice resistances for most cases except cases 11 and 12. The average numerical error is −13% for all cases. Riska formulas give the largest predictions among all formulas, which overestimate the ice resistance up to 50% in average. Joeng formulas estimate ice resistance very well with the difference of 7%. Konenien formulas overestimate the ice resistance by 37% in average.

It should be noted that all formulas used in the present paper overestimate the ice resistance significantly for case 11.

Table 7
Coefficients for channel resistance formulas.

Symbol	Value	Unit
f_1	23	N/m^2
f_2	4.58	N/m
f_3	14.7	N/m
f_4	29	N/m^2
g_1	1537.3	N
g_2	172.3	N/m
g_3	398.7	$N/m^{1.5}$
C_3	845.576	$kg/(m^2 s^2)$
C_4	41.74	$kg/(m^2 s^2)$
C_5	825.6	kg/s

Table 8
Experimental and calculated level ice resistance.

Case No.	Experimental results	Calculated results (kN)				Numerical error (%)			
		Lindqvist	Riska	Jeong	Konenien	Lindqvist	Riska	Jeong	Konenien
1 (Test 103)	470	320	610	330	510	−32	30	−30	9
2 (Test 104)	560	380	630	520	600	−32	13	−7	7
3 (Test 205)	670	510	800	560	740	−24	19	−16	10
4 (Test 206)	720	560	840	800	810	−22	17	11	13
5 (Test 301)	539	426	892	459	663	−21	65	−15	23
6 (Test 302)	829	538	942	765	783	−35	14	−8	−6
7 (Test 303)	781	572	1025	961	847	−27	31	23	8
11 (Test 401)	152	251	473	259	425	65	211	70	180
12 (Test 402)	291	322	501	300	526	11	72	3	81
13 (Test 403)	391	351	548	542	579	−10	40	39	48

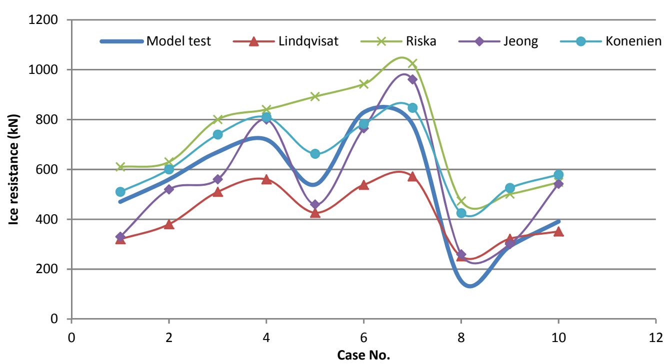

Fig. 7. Comparison of experimental and calculated ice resistance.

It is not hard to explain the difference. In case 11, ice is thin and towing speed is low, which may lead to elastic buckling rather than bending failure for the ship model. The resulting ice load is smaller than that occurred during bending process.

5.2. Channel ice

Ice channel resistances calculated with Eq. (7) are shown in Table 9, where the experimental data are also included. From Table 9, it is found that the rule channel ice resistance formula overestimates the resistance and is on the conservative side as expected. It should be noted that the channel ice resistance formula does not take the effect of ice drifting speed into account, but the effect of ice drifting speed may be significant according to the model test. In the model test, all ice channels were newly formed with different ice concentrations. For case 10, the ice concentration is very high, above 90% in average. For other channels, it is around 40%. If the case 10 is not considered due to very high concentration, the resistance decreases as the speed increases when comparing cases 8 and 9 or cases 14,15 and 16. This is mainly attributed to shortened time of ice-hull interaction and strong weak at high drifting speed.

Table 9
Experimental and calculated channel ice resistance.

Case No.	Model test (kN)	Calculation (kN)
8 (Test 304)	220	252
9 (Test 305)	120	
10 (Test 306)	210	
14 (Test 404)	98	204
15 (Test 405)	81	
16 (Test 406)	69	

6. Conclusions

This paper aims to study level and channel ice resistance exposed to an icebreaker in both numerical and experimental ways. Extra model tests have been carried to get more experimental data. There exists a clear relationship between ice resistance, standard deviation, maximum force and minimum force from the measurements. The maximum ice force is around 3.26 times standard deviation higher than mean ice force while the minimum ice force is around 2.76 times standard deviation lower than the mean ice force. The measured submersion resistance coefficient as a factor of Froude number is slightly lower than that recommended by ITTC. Some empirical and analytical formulas are used to calculate both level ice and channel ice resistance. The calculated results are compared against model test results. Empirical methods mentioned in the present paper predict ice resistance at different accuracy, but Jeong formula gives the best predictions in general. The ice channel resistance are also calculated and compared with experimental results. It shows that the rule ice channel resistance formula is relatively conservative. The measured channel ice resistance is also speed-dependent. This effect is suggested to be included in the ice channel resistance formula as well.

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