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Investigation of relationship between brash ice conditions and ship resistance

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ABSTRACT

This study investigates the correlation between brash ice channel conditions including ice thickness, mean cross-sectional area and porosity, and ship resistance when navigating through brash ice channels. To determine the resistance of the brash ice channel, simulations are conducted using KISIS software, which was developed by the authors. Additionally, a Python program is created to measure the thickness of the numerically-generated brash ice channel geometrically. To conduct the numerical simulation of ship navigation, eight distinct types of brash ice channels are generated, comprising four conforming to a normal distribution and four conforming to a power distribution. These channels are used to conduct numerical simulations of ship navigation with three ship shapes. The results of the study indicate that ice thickness and cross-sectional area have a positive relationship with resistance, while porosity has a negative relationship. Furthermore, the relationship between mean cross-sectional area and hull resistance is linear and has the largest coefficient of determination. Therefore, mean cross-sectional area may be utilized to adjust the channel resistance to any channel condition.

KEY WORDS: Brash ice channels; Numerical simulation; Size distribution; Cross-sectional area; Porosity

INTRODUCTION

In accordance with the Finnish Swedish Ice Class Rules (Traficom, 2021), vessels must possess adequate thrust when traversing through brash ice channels. To obtain this value, it is necessary to determine the resistance of the channel when a ship navigates through a dense channel filled with small ice floes. Typically, this is achieved through model experiments conducted in an ice model basin. However, conducting such experiments is often difficult due to the considerable time and resources required. Consequently, the authors of this paper have developed a simulation software for ship navigation in ice-infested waters that can calculate the forces exerted on the vessel by the ice floes.

In model experiments, it is considerably challenging to arbitrarily select the channel thickness, size distribution, and ice fragment shape distribution. Consequently, the resistance values attained through such experiments may not necessarily be universal. To mitigate this limitation, it is worthwhile to explore the correlation between channel conditions and resistance through numerical analysis.

Hence, the aim of this study is to investigate the correlation between channel conditions such as ice thickness, mean cross-sectional area and porosity, and hull resistance. To accomplish this, the authors created a series of brash ice channels with varying size distributions through numerical techniques and utilized these channels to conduct simulations of ship navigation.

METHODS AND MATERIALS

Simulation of Ship Navigation using KISIS

In this study, the authors developed a simulation software called KISIS (K Ice Structure Interaction Simulator, Konno et al, 2008; Konno, 2009; Tokudome and Konno, 2023) using the Open Dynamics Engine (ODE, http://www.ode.org/). KISIS is capable of simulating a ship navigating through a channel filled with ice pieces. This simulation treats both the hull and the ice pieces as rigid bodies. Contacts are assumed to be non-smooth, or rigid, and frictional forces are determined via friction pyramids. The cohesion of ice pieces with each other, as well as with the ship hull or level ice sheets that construct the channel, has not been considered.

Equation (1) defines the hydrodynamic forces acting on an ice piece.

$$D = -C_D \cdot A \cdot \frac{1}{2}\rho|V_{\mathrm{flow}} - V_{\mathrm{ice}}|(V_{\mathrm{flow}} - V_{\mathrm{ice}}) \quad (1)$$

Here, D is the hydrodynamic drag, C_D is the drag coefficient, A is the projected area of the ice piece in the flow direction, ρ is the water density, and V_{flow} and V_{ice} are the fluid and ice velocities, respectively.

The hull resistance is determined exclusively based on the contact forces generated by the ice floes, without considering any hydrodynamic forces. Ice plates are positioned on the left, right, and front of the ice floes to construct the ice channel. The motion and deformation of the ice sheet are not taken into account in this simulation. The hull is towed at a constant speed.

Analysis conditions are summarized in Table 1. In the present study, a coefficient of friction value of 1.35 was selected for the interaction between ice pieces, as this value represents the mean friction coefficient obtained from ridge keel punch-through tests conducted by Karulin and Karulina (2002) and Matsuo et al. (2003). This choice is further supported by the discussion presented by Sato and Konno (2013).

The validity of the KISIS program used in this paper has been confirmed by Tokudome and Konno (2023) to show the same trend as the resistance calculation formula in the Finnish Swedish Ice Class Rules (Traficom, 2021).

Generation of Ice Conditions

In this study, we conduct numerical analyses of phenomena at the scale of model basin experiments. The analysis of hull resistance is conducted using eight distinct types of brash ice channels, comprising four conforming to a normal distribution of the size of ice pieces and four conforming to a power distribution (Bonath, Zhaka & Sand, 2019). In this context, 'size' refers to the diameter for spheres and the width and length for rectangular prisms. The former set of channels employed a fixed mean ice piece size of 0.03 m, accompanied by standard deviations of 0.003 m, 0.0045 m, 0.006 m, and 0.0075 m. Meanwhile, the latter set of channels involved four power distributions with expected piece size values of 0.025 m, 0.0265 m, 0.0275 m, and 0.03 m.

To improve the reliability of the calculation results, the authors prepared ten brash ice channels for each of the eight conditions. Alterations in the size distribution and associated parameters result in variations of ice thickness, average cross-sectional area and porosity.

The present study employs channels composed of both spheres and rectangular prisms, with the number ratio between these two shapes set at 1:1.

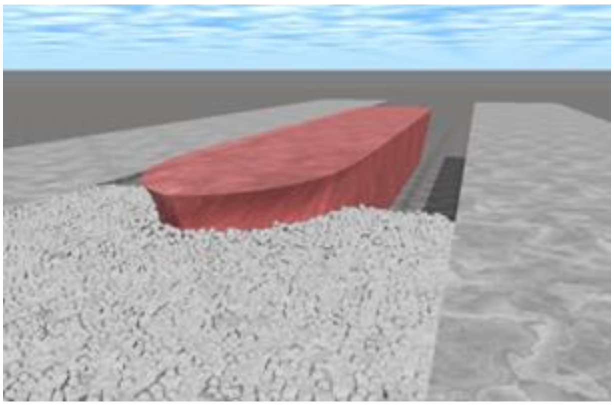

Figure 1. A snapshot of ship navigation simulation in a brash ice channel with JBC

Table 1. Simulation Conditions

Variable	**Value**
Density of water [kg/m^3]	1000
Density of ice [kg/m^3]	900
Coefficient of friction between ship full and ice pieces [-]	0.1
Coefficient of friction between ice pieces [-]	1.35
Ship velocity [m/s]	2.57
Length of the brash ice channel [m]	6
Width of the brash ice channel [m]	2.25

Assessment Method for Generated Brash Ice Channel Thickness

The authors developed a Python program to measure ice thickness geometrically. Specifically, ice thickness is calculated as the difference between the maximum and minimum values at the point of contact between the vertical line and the ice pieces. The inspection area is illustrated in Figure 2, while Figure 3 provides a schematic diagram of the inspection points.

The mean cross-sectional area and the porosity of the channel can be calculated using the following equations:

$$\bar{S} = \frac{\sum V_{\text{ice}}}{L} \tag{2}$$

$$\varphi = 1 - \frac{\sum V_{\text{ice}}}{LWT} \tag{3}$$

In these equations, $\bar{S}$ denotes the mean cross-sectional area, φ represents the porosity, V_{ice} refers to the volume of an ice piece, and L, W and T stand for the length, width and thickness of the channel, respectively.

The parameters of ice thickness, average cross-sectional area, and porosity exhibit interdependencies. Given a constant channel width, maintaining a consistent ice thickness results in an inverse relationship between porosity and mean cross-sectional area. In the context of a constant mean cross-sectional area, an increase in ice thickness corresponds to an increase in porosity. Lastly, when porosity remains constant, the mean cross-sectional area demonstrates a positive correlation with increasing ice thickness.

Ships

This study performs analysis on three hull forms and compares the results: one uses the Japan Bulk Carrier (JBC) provided at the Tokyo 2015 Workshop. The other two hull forms are adapted from those used in Tokudome and Konno (2023). These two hull forms have the same length, width and draft and differ only in the bow shape. The two hull forms are labeled Ship_15_30_30 and Ship_35_60_30 because of the difference in bow shape.

To conform to the FSICR guideline (Traficom, 2019), the hull models are scaled to achieve a hull width of 1.125 m. This corresponds to half of the channel width, which is 2.25 m. In this case, the length between perpendiculars of all the ships is about 7 m.

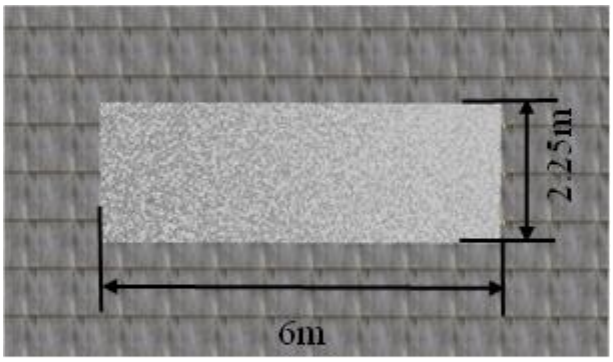

Figure 2. A brash ice channel used in the simulation

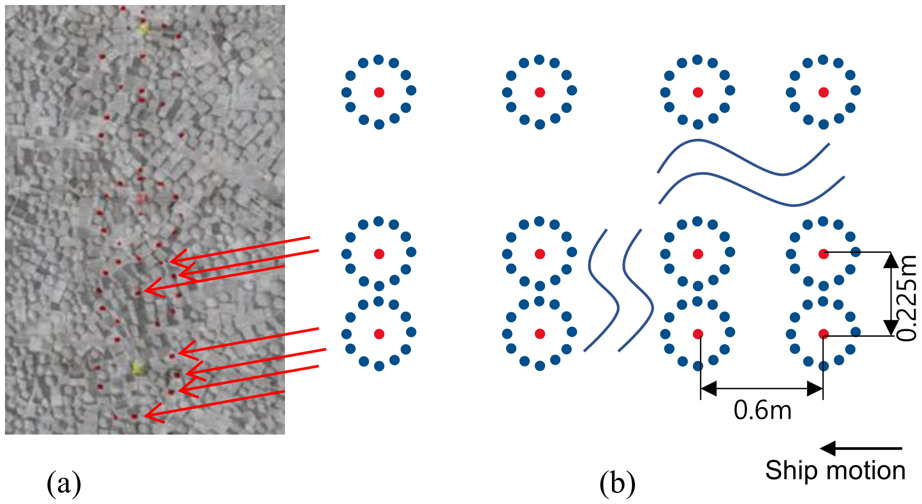

Figure 3. (a) Evaluation points for assessing ice thickness. Several points are highlighted with arrows. Some vertical lines do not intersect with ice and thus do not display evaluation points. (b) diagram illustrating evaluation points

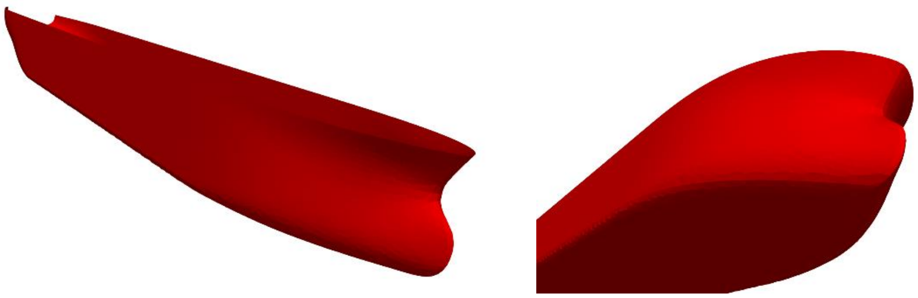

Figure 4. Ship model of Japan Bulk Carrier

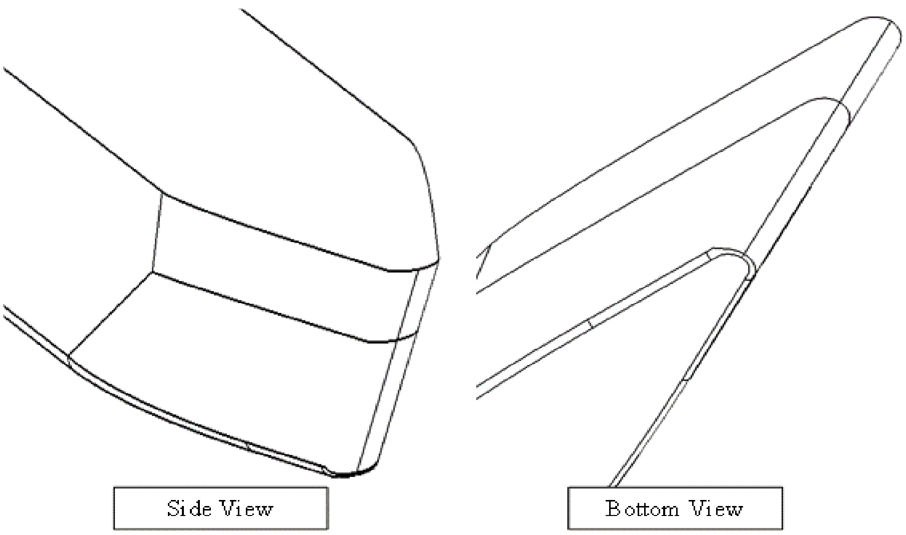

Figure 5. Bow shape of ship_15_30_30

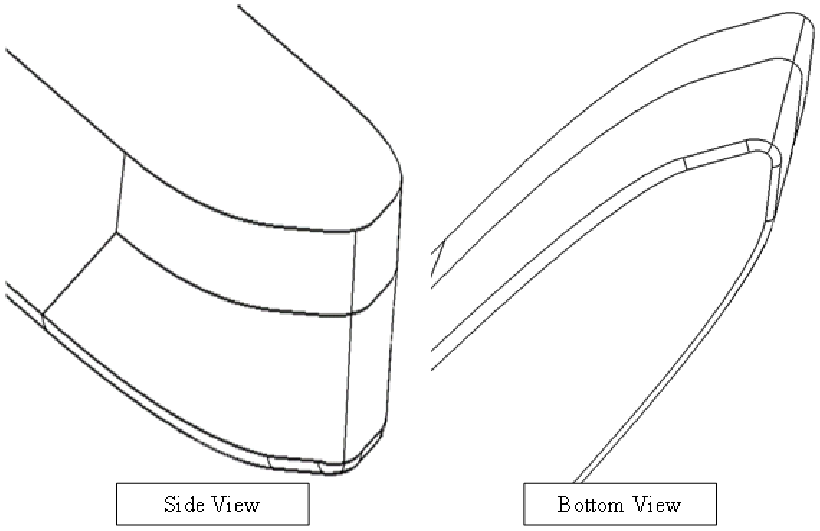

Figure 6. Bow shape of ship_35_60_60

RESULTS AND DISCUSSION

Figure 7 shows the time series values of water channel resistance obtained through numerical calculations. In the subsequent figures, the vertical axis represents the average resistance values taken from the time series data between 30 and 43 seconds for each respective condition.

Figure 8 displays the correlation between hull resistance and ice thickness, classified by hull shape. Figure 9 presents the correlation between hull resistance and mean cross-sectional area, also categorized by hull shape. Figure 10 illustrates the relationship between hull resistance and porosity, again by hull shape. The blue, gray, and orange plots correspond to JBC, Ship_15_30_30, and Ship_35_60_30, respectively.

Across all figures, JBC exhibits the highest hull resistance, followed by Ship_35_60_30, and then Ship_15_30_30, which has the lowest hull resistance.

The coefficient of determination of the regression line for the correlation between hull resistance and ice thickness ranges from 0.75 to 0.78. Figure 8 reveals a positive correlation between mean cross section and hull resistance, with the coefficient of determination of the regression line ranging from 0.93 to 0.95. Meanwhile, Figure 9 shows a negative correlation between porosity and hull resistance, with the coefficient of determination of the regression line ranging from 0.87 to 0.91.

The obtained results are deemed universal irrespective of the size distribution, as the results of both normal and power-law distributions of ice sizes yielded data points that are closely aligned on a single straight line.

The highest coefficients of determination for hull resistance and channel condition are observed for the mean cross-sectional area, indicating that hull resistance is most influenced by this variable. This may be because the mean cross-sectional area reflects the ice volume displaced by the ship.

Considering that the coefficient of determination of the regression line pertaining to the mean cross-sectional area is the highest, it is plausible to infer that hull resistance can be predicted for assumed channel conditions by adjusting the mean cross-sectional area even if the actual channel conditions used in the experiment deviate from the assumed conditions. A straightforward formula that expresses the estimation equation is presented below.

$$R_{\text{assumed}} = \frac{S_{\text{assumed}}}{S_{\text{examined}}} \times R_{\text{examined}} \quad (4)$$

The variable R denotes resistance, while S represents the mean cross-sectional area.

CONCLUSIONS

The aim of this study is to explore the relationship between channel conditions and hull resistance in ship navigation in brash ice channels. The results reveal that the thickness and mean cross-sectional area of the ice channel in the simulations display a positive linear correlation with hull resistance, while porosity and hull resistance exhibit a negative linear correlation. This correlation is valid for different hull shapes and ice size distributions. Moreover, the correlation between mean cross section and hull resistance is the strongest, irrespective of vessel shape or ice size distribution. Hence, the mean cross-sectional area can be used to adjust the channel resistance to any channel condition.

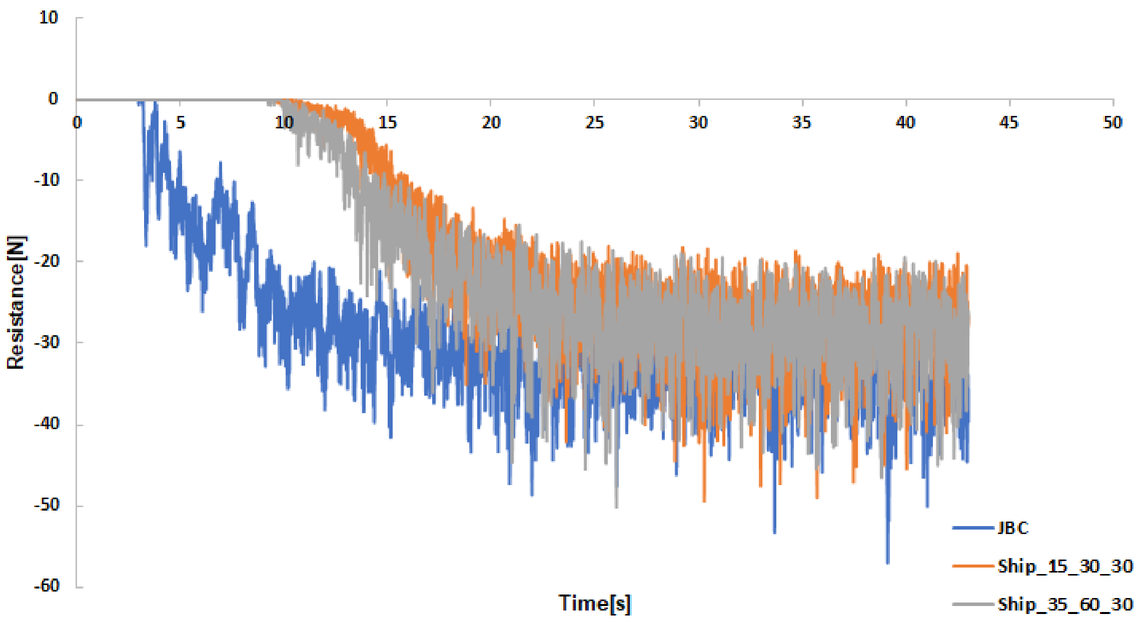

Figure 7. Examples of time series of calculated ship resistances for three different ships. Normal distribution, average 0.03 m, standard deviation 0.006 m.

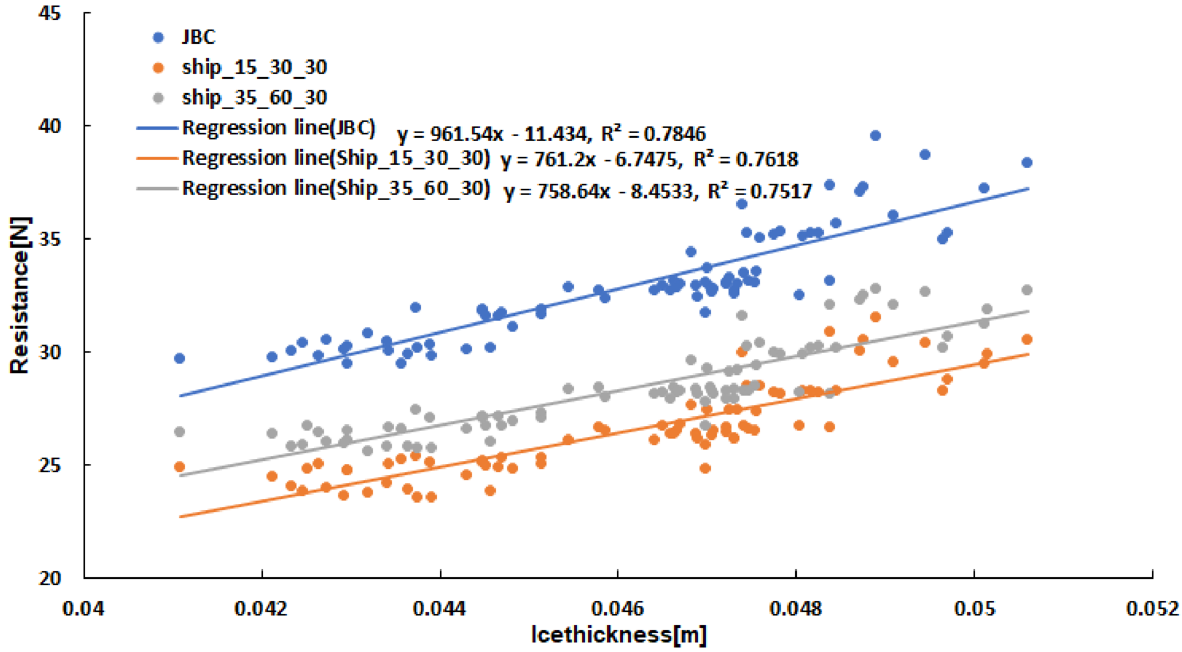

Figure 8. Correlation between ship resistance and ice thickness by ship shape

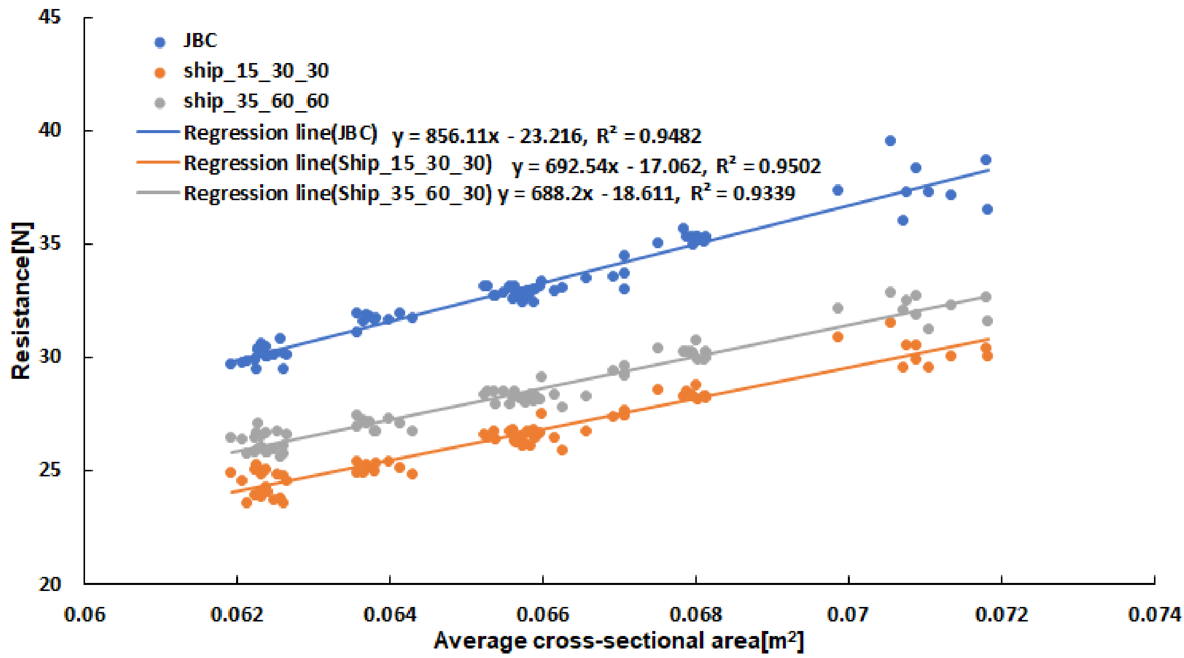

Figure 9. Correlation between ship resistance and mean cross-sectional area by ship shape

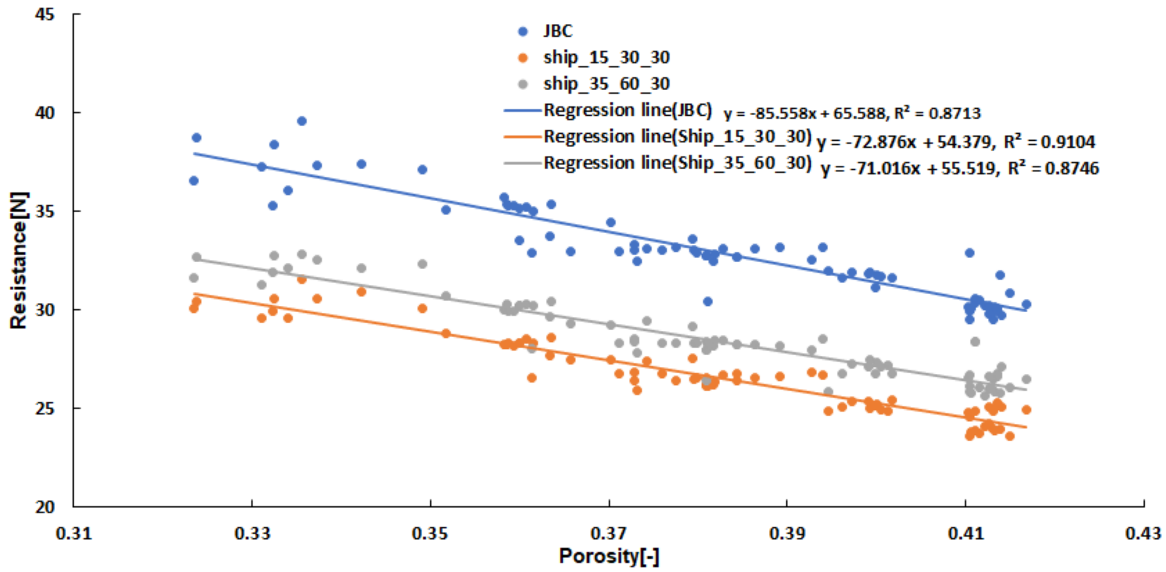

Figure 10. Correlation between ship resistance and porosity by ship shape

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