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Published in:
Cold Regions Science and Technology

DOI:
10.1016/j.coldregions.2022.103617

Published: 01/09/2022

Document Version
Publisher's PDF, also known as Version of record

Cold Regions Science and Technology 201 (2022) 103617

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Investigation of vessel resistance in model scale brash ice channels and comparison to full scale tests

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ARTICLE INFO

Keywords:
Brash ice channel
Brash ice properties
Finnish-Swedish Ice Class Rules
Model scale test
Full scale test
Brash ice channel resistance

ABSTRACT

The ice class-based rules and restrictions aim to ensure the safety and efficiency of the winter navigation system in the Baltic Sea. The vessel resistance prediction in a brash ice channel is a mid-term step in Finnish-Swedish Ice Class Rules ice class granting process that can be based on model scale tests. However, there are some limitations in the current model scale test guidelines. To improve the test procedures and to provide a better real-world correlation for all ship shapes, this paper explores the relationship between the brash ice properties and vessel resistance utilizing channel resistances measurements in model scale and full scale. The results indicate that the model scale results can be scattered and conservative, especially for modern, open-water-optimized bow shapes when model ice with a scaled-down strength is utilized. Model scale tests in brash ice channels with unscaled ice strength provided good correlation with full scale resistance tests and small variation in repeated tests. The results suggest that the correct modeling of ice fragment interaction would improve the prediction quality for all hull shapes.

1. Introduction

1.1. Background

The number of merchant vessels seafaring in ice-covered waters is increasing. Therefore, both ensuring the safety and optimizing the efficiency of vessels operating under these special conditions are important or even essential goals for both economic and environmental reasons. One of the sea areas with frequent winter navigation is the Baltic Sea, particularly the Gulf of Bothnia between Finland and Sweden.

The winter navigation system in the Baltic Sea consists of three components: (1) assisting icebreakers, (2) state authorities controlling the regulations and traffic restrictions, together with (3) an ice-strengthened merchant fleet. To secure the safety of the vessels and efficiency of the system, the Finnish-Swedish Ice Class Rules (FSICR) set requirements for ice classes considering both the vessel performance and hull strengthening. Whilst these ice class rules were originally created for the use in the Northern Baltic Sea, the principles of the rules have been accepted and adopted globally. The authorities set restrictions for the ice class and gross tonnage of the vessel based on the prevailing ice conditions. The restrictions determine whether a vessel is entitled to an icebreaker assistance. Thus, the correct ice class classification of vessels is very important.

As a consequence of the icebreaker assistance, merchant vessels typically operate in a brash ice channel in ice covered sea areas. Thus, FSICR defines performance requirements for ice classes in a brash ice channel (Trafi, 2017). A brash ice channel forms when multiple vessels are piloted through the same channel. As a result of repeated breaking and freezing cycles, ice accumulates in the channel, the broken ice pieces obtain a round shape and the mechanical properties change (Fig. 1) (Kannari, 1982).

The guidelines for the application of FSICR (Trafi, 2017) present in detail the determination of the engine power for a given ice class. The FSICR describe two alternative methods to determine the minimum engine power required for an ice class. The first method is based on a calculation formula which is defined in the rules. The second method is based on model scale testing in ice. The model scale testing in ice method described in the FSICR is designed to investigate whether the vessel meets the operational performance requirement with a lower engine power than determined based on the calculation formula. The required engine power determined based on the FSICR calculation formula can be conservative compared to the prediction based on model

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https://doi.org/10.1016/j.coldregions.2022.103617
Received 7 January 2022; Received in revised form 31 March 2022; Accepted 7 June 2022
Available online 13 June 2022

scale test results, as demonstrated by Jeong et al. (2017).

Currently, the FSICR guidelines are established as the generally applied method for model scale testing in a brash ice channel, and the guidelines attempt to define the target conditions for testing. The ongoing discussion on the vessel brash ice resistance is based on these guidelines (e.g. Konno et al., 2013; Matsuzawa et al., 2017; Karulina et al., 2019). The model scale test resistance predictions based on these guidelines are of interest, as they currently can be an important factor on ice class granting process. Thus, this article focuses on the performance requirements set out in the ice class regulations for brash ice conditions and investigates the vessel resistance in brash ice channel using model scale experiments.

1.2. Current method of model scale testing in brash ice

Experiments with physical models aim to mimic the examined phenomenon in controlled conditions in a different scale. Creating a functioning physical model in a reduced scale requires considerable understanding on the targeted condition and the studied phenomenon. Model scale testing in open water is an established method to predict the vessel performance in calm water. The first model scale tests in ice focused on determining the most extreme operating conditions, such as the limiting level ice thickness, under which a vessel could operate (Enkvist, 1972). Thus, the first types of model ice with scaled properties were developed to determine the level ice performance of traditional icebreakers in respect to both the resistance and vessel power (Schwarz, 1983). Several studies have concluded that the model scale tests in level ice provide a satisfactory correlation to the full scale vessel performance in ice (e.g. Vance, 1974; Nyman et al., 1999; Riska et al., 2001; Spencer and Jones, 2001; Lau, 2015). Thus, model scale testing in ice is the state-of-the art method to predict the vessel performance in ice in full scale prior to building the prototype (von Bock und Polach, 2016; Myland, 2019).

The correlation of level ice tests in full scale and in model scale have widely been utilized to develop the scaling methods, which are currently applied in model scale testing in ice. However, the global warming has universally decreased the sea ice thicknesses. As a thin ice sheet is more easily broken by wind and wave actions, the vessels are operating increasingly more in broken ice compared to level ice operations. Therefore, there is an increasing interest on the vessel performance in broken ice. However, there has been limited research and improvements on model scale testing procedures in broken ice, and therefore uncertainty exists in the validity of model scale tests conducted in broken ice conditions.

While FSICR are generally approved method for brash ice condition, there are some limitations in the guidelines. The current guidelines fail to consider some potentially important factors such as brash ice mechanical properties and fragment interaction as the guidelines only define the brash ice mass dimensions. Of a particular note and importance is the complete lack of the vessel resistance data in brash ice channels that would correlate the full scale tests to model scale tests and verify the method. It is notified that the diversity of broken ice complicates the use of correlation tests to develop methods specified for broken ice.

While several researchers have investigated brash ice in full scale (e.g. Kannari, 1982; Sandkvist, 1986; Veitch et al., 1991; Bonath et al., 2019), only few studies have investigated the association between brash ice mechanical properties (such as internal friction angle, angle of repose, and porosity), and the vessel resistance in brash ice (Wilhelmson, 1996; Riska et al., 1997). This gap in knowledge significantly complicates creating a reliable physical or numerical model of a vessel advancing in a brash ice channel. Both numerical and physical models need a high quality and validated set of input values for the modeled ice properties.

For these reasons, it is technically challenging to determine applicable guidelines for model scale tests in a brash ice channel. To ensure repeatable and harmonized model scale test results, it is necessary to understand the target condition and define the most important properties influencing the brash ice motion around a moving vessel hull, and the ice-ice and vessel-ice interactions affecting the vessel resistance. Furthermore, the model scale test results should be validated with full scale results.

1.3. Scope of work

This article explores the relationship between frequently-operated

Fig. 1. A typical channel in the Bay of Bothnia.

old brash ice channel properties, the design ice condition in FSICR, and vessel resistance, and reflects the resistance measured in model scale to full scale measurements. Our investigation is based on the results from our brash ice channel testing in model scale for three vessels, and the corresponding full scale test results for two of the vessels. As an addition to the vessel resistance tests, the investigation considers the extensive set of brash ice property measurements referred in our earlier research (Matala, 2021). Matala (2021) systemically reviews the influence of the initial flexural strength of the model scale brash ice fragments on brash ice porosity, angle of repose, internal friction angle, and piece size distribution. As an essential part of the research, the acquired model brash ice property measurements are reflected to representative values in nature, which were chosen to represent the brash ice in an old brash ice channel.

Our findings showed that the initial flexural strength of ice fragments influences all the studied properties (Matala, 2021). This indicates that the model ice types where the ice fragments have different strength and surface characteristics would behave and interact differently around a moving vessel hull, which would result in different hull resistances. It is notified that the FSICR guidelines require the reporting of the initial flexural strength but sets no target for it (Trafi, 2017). We also assessed the influence of the fragment shape on the brash ice response concluding that the fragment shape, angular in comparison to round, significantly influences the granular material overall properties. However, the observations from soft model ice during repeated testing showed no significant changes in the fragment shape (Matala and Gong, 2021).

In our earlier research, we concluded that to mimic brash ice in nature, the model brash ice should simulate the inter-particle interaction. In this study, we apply this insight to study the vessel resistance in brash ice. Taken together, our findings suggest that the scaling methods developed for level ice might not be directly applicable for broken ice conditions. The article puts forward the case that the current guidelines of FSICR may be suboptimal for producing harmonized resistance predictions using model scale testing in ice, therefore this paper seeks to study vessels in brash ice condition to enable further development of the scaling principles in broken ice.

The paper begins by introducing the methods applied for collecting the data. This is followed by the test results. In the discussion, we separately evaluate the effect of each studied brash ice property on the channel test outcome. The last section presents the findings of the research, focusing on the brash ice characteristics found to be central for the vessel resistance in a brash ice channel and thereby essential for brash ice channel testing. Finally, we propose targets for improvement on the current channel testing method aiming to provide standardized model testing conditions.

2. Methods

2.1. Modeling vessel and brash ice interaction

The vessel resistance in level ice is understood as the sum of resistance components. These components consist of resistance related to breaking the ice, displacing and submerging the broken ice pieces, and the friction and speed effect (e.g. Enkvist, 1972; Vance, 1974; Lindqvist, 1989; Kämäräinen, 2007). The proportion of each component depends on the vessel hull shape. In level ice the breaking component is generally considered predominating (Kujala and Riska, 2010). In contrast to the vessel resistance in level ice, there is no breaking component contributing to the vessel resistance in unconsolidated brash ice conditions. Brash ice in nature is an accumulation of round solid ice fragments with no significant inter-particle cohesion (Mellor, 1980). In this sense, the material can be considered as a floating granular material.

The vessel resistance in brash ice only consists of the bow resistance caused by transferring (or displacing) and submerging the brash ice mass, and the resistance aft of the bow, which is mainly caused by the friction (Mellor, 1980; Malmberg, 1983; Wilhelmson, 1996). Another important difference between the level ice and brash ice channel resistance is the nature of the ice fragments moving along the vessel surface: the ice fragments in a brash ice channel have a completely different form and associated friction properties compared to the freshly broken ice fragments from an intact ice sheet. In nature, the ice fragments in a brash ice channel are being exposed to multiple breaking-freezing cycles (see Fig. 1, Fig. 2, and Fig. 4). As a result, they become more solid, round, and smooth, and most likely induce less friction in the interaction with the vessel hull compared to the freshly broken level ice fragments (Kannari, 1982).

The model scale tests with vessels are traditionally performed considering the geometrical similitude. To attain the similarity between the open water test in full scale and model scale, Froude number (*Fn*) and Reynolds number (*Re*) should both be modeled accurately (Schwarz, 1977). However, the simultaneous modeling of these dimensionless numbers is not practically possible in model scale tests. As the Froude number ensures the correct scaling of the ratio between inertia and gravitational forces, it has been applied in the common practice (ITTC, 2017). In open water testing, the common practice is to correct for the error in viscous forces due to the incorrect Reynolds number by using established correction methods (ITTC, 2011).

In addition to the scaling principles applied in open water model testing, the ice failure process and the ice sheet behavior needs to be modeled and scaled in model scale testing in ice. This is accounted for in model scale testing in ice by considering the relationship of the ice elastic and inertia forces, i.e. maintaining the Cauchy number (*Ch*). In practice, this is determined by observing the relation of the elastic modulus E and flexural strength σ_f of ice (Schwarz, 1977). However, given the Froude scaling law is applied in model scale tests in ice, the scaled-down ice strength significantly influences the inter-particle interaction in broken ice condition affecting the test result. As the breaking component in brash ice is absent, the ice fragments interaction and loads related to the interaction – such as brash ice shearing, compressing movement, fragment rearrangement, friction from the inter-particle interaction and friction between ice particles and the vessel hull – become a significant factor in the vessel resistance compared to the level ice condition (Patil et al., 2021).

As the ice fragment interaction becomes a substantial factor in the vessel resistance, but the fragments having a scaled-down strength do not behave as a granular material (Matala, 2021), the traditionally applied scaling methods, i.e. maintaining the Froude and Cauchy similitudes might not be the best solution in tests conducted in broken ice. This raises a question, how ice having an unscaled strength would behave and model the resistance of a vessel in model scale brash ice tests with respect to traditionally scaled model ice. To answer this question

Fig. 2. Vessel 1 brash ice channel prior to full scale experiment in 2018.

model scale test results with differently scaled ice should be compared to the full scale results.

2.2. Vessel model scale tests in ice

The experiments presented in this paper were conducted following the procedures set out in the FSICR guidelines for the verification of a vessel performance through model scale tests for ice class 1A. All the tests were conducted in Aker Arctic model test laboratory in Helsinki, Finland. In the model scale tests in ice, the thickness profile typical to brash ice channels was modeled using an even equivalent thickness of brash ice H_{ave} that depends on the vessel beam B: $H_{ave} = H_m + 14 \bullet 10^{-3} \bullet B$. H_m is 1.0 m for ice class 1A (Trafi, 2017). This equivalent thickness is based on a channel profile typical to the Bay of Bothnia with the channel mid-part thickness equal to 1.0 m. The channel width was 2 • B in accordance with the FSICR guidelines.

The model test experiments were conducted as self-propulsion tests with a constant rate of the propeller revolution n. At the beginning of each test, the propeller revolution was set to the target rate, after which the model was let to accelerate to the constant advancing speed freely. Two different rates of revolution were tested in each channel. The model yaw and sway were restricted by guides to keep the model running straight.

The channel resistance was determined based on propeller revolutions and the obtained constant speed using open water calibrations. In open water calibrations, a constant propeller revolution is set to the propeller, and the model is pulled in open water at a constant speed. The model is held back with a force transducer, which measures the extra thrust available at this combination of propeller revolutions and speed. This extra thrust corresponds to the ice resistance in a model scale test in ice conducted with constant propeller revolutions, in which the model advances at the same speed. For analysis, the pulling force was measured at several propeller revolutions and speed combinations, which enables the interpolation of the test results according to any advance speed measured in the tests. The model scale resistance is scaled into full scale by multiplying the obtained model scale resistance by the third power of the scale factor (λ), λ^3.

In practice, the measured values in model scale rarely correspond perfectly the targeted values. To minimize the influence of the obtained deviation from the targeted condition, the test analysis includes three corrections that are applied to the direct measurements:

1. Channel thickness correction (Eq. 1), is utilized if the measured channel thickness ($h_{i,\ measured}$) deviates from the target ($h_{i,\ target}$) channel thickness

$$R_{CH,h\ corrected} = R_{CH,model} \bullet \left(\frac{h_{i,target}}{h_{i,measured}}\right)^x \tag{1}$$

where x is a constant depending on hull shape.

2. Correction considering model acceleration is applied if the vessel does not achieve a constant speed within the available test distance but there is acceleration or deceleration. The channel resistance is corrected based on the observed constant acceleration a. Resistance due to the vessel model acceleration is calculated by formula (Eq. 2), where m is the mass of the model, and added mass is evaluated to be approximately 10% of the mass of the model m based on Aker Arctic experience. $R_{acceleration}$ is subtracted from the non-corrected ice resistance of the model $R_{I,model}$

$$R_{acceleration} = (m + m_{added})a \tag{2}$$

3. Correction considering the model friction properties is utilized if the measured friction coefficient deviates from the target value (0.1 for a corroded hull). As the model surfaces are in general treated to correspond the surface properties of a freshly painted hull, the intention of the friction correction in FSICR is to ensure the vessel can meet the performance requirement also with a corroded surface. The friction correction is made to the test results in accordance to FSICR, Eq. (3)

$$R_{CH\ (with\ \mu_{target})} = \left[(0.6 + 4 \bullet \mu_{target}) / (0.6 + 4 \bullet \mu_{actual})\right] \bullet R_{I\ (with\ \mu_{actual})} \tag{3}$$

A similar model scale test series were conducted for three vessels. Table 1 lists the conducted model tests. The model test series compared three different model brash ice types, which were studied in Matala (2021):

1. Model brash ice made from fine-grained model ice with a parental ice flexural strength corresponding to 500 kPa,
2. Model brash ice made from fine-grained model ice with a parental ice flexural strength corresponding to 1000 kPa/1300 kPa
3. Model brash ice consisting of fresh-water ice cubes.

In addition, the influence of repeat testing on model ice properties was evaluated. The brash ice property measurements of Matala (2021) and Matala and Gong (2021), which are utilized in discussing the results, were conducted within the model scale testing campaign of Vessel 2.

Vessel 1 and Vessel 2 had a modern, open-water-optimized hull shape and Vessel 3 represents the more traditional shape optimized for ice conditions. The bow shape angles are presented in Table 2.

2.3. Vessel full scale tests

In addition to the model tests, we ran full scale tests on Vessel 1 and Vessel 3. It was not possible to obtain adequate full scale measurement from Vessel 2 due to the mild ice conditions which have occurred in recent years (Table 3).

Full scale measurements are the only source of information, which can take into account all the environmental factors. However, it must be acknowledged that the vessel channel resistance values obtained from full scale testing are subject to the measurement accuracy and tolerances. In practice, the brash ice channel profiles are most commonly irregular, and calculating an average channel thickness value is required. The average channel thickness is calculated from a series of ice thickness measurements that are influenced by the measurement locations, intervals and accuracy of the measurement method. In addition, the ice condition is constantly altering with time due to the temperature dependency of consolidated layer and ice strength. Thus, it is challenging to measure and describe the ice condition in nature in such an accuracy, which would confidently allow reproducing the same ice condition in the laboratory. Ice as such is a material with a rich range of

Table 1
List of conducted model tests.

Ice type	Test repeat/ Channel number	Vessel 1	Vessel 2	Vessel 3
FGX 500 kPa	1	2 power levels	2 power levels	2 power levels
FGX 500 kPa	2	2 power levels	2 power levels	2 power levels
FGX 500 kPa	3	2 power levels	2 power levels	2 power levels
FGX 1000 kPa/ 1300 kPa*	1	2 power levels*	2 power levels	2 power levels
FGX 1000 kPa/ 1300 kPa*	2	2 power levels*	2 power levels	2 power levels
FGX 1000 kPa/ 1300 kPa*	3	2 power levels*	2 power levels	2 power levels
Ice cubes	1	2 power levels	2 power levels	2 power levels
Ice cubes	2	2 power levels	2 power levels	2 power levels
Ice cubes	3	2 power levels	2 power levels	2 power levels
Ice cubes	4	–	2 power levels	–

Table 2
The bow forms of the tested hull shapes.

Vessel no	1	2	3
Vessel type	General cargo ship	General cargo ship	Product carrier
Scale factor λ	17.50	23.62	20
FGX-model ice target flexural strength 1 $\sigma_{f,1}$ f.sc./m.sc. [kPa]	500/29	500/21	500/25
FGX-model ice target flexural strength 2 $\sigma_{f,2}$ f.sc./m.sc. [kPa]	1300/74	1000/42	1000/50
Waterline angle α (B/4)	23	29	25
Stem angle ϕ (CL)	90	90	25
Stem angle ϕ (B/4)	46	88	30
Flare angle Ψ (B/4)	69	89	53
Overall length [m]	103	160	164

Table 3
Full scale references available.

	Vessel 1	Vessel 2	Vessel 3
Full scale reference	*Yes* (Matala, 2018)	*No*	*Yes* (Nortala-Hoikkanen, 1999)

forms and properties, and different ice conditions make the variety even wider and more difficult to capture.

Hence, the measured resistance of a vessel in nature, even in a documented condition only represents its resistance in the prevailing condition. Nevertheless, the ultimate goal of the model tests is to mimic a typical old channel, and the full scale tests were conducted with the best practices in an old channel, considering the channel thickness and the piece shape and size distribution. The vessel draught was the same in the corresponding correlation tests both in full scale and in model scale.

Vessel 1 full scale tests were conducted in the Bay of Bothnia in February 2018 (Matala, 2018). The channel thickness profile was measured from 8 locations within 2.7 km testing distance. The measurements in each profile were obtained by moving across the channel with a small skiff, and manually drilling through the brash ice in 2 m intervals as shown in Fig. 2. Fig. 3 provides the measured thickness profiles. The average thickness of the channel profiles center values was 1.03 m, which correlates well with the targeted channel defined in FSICR with a midpart thickness of 1.0 m. The channel had been in the same place and actively navigated long enough for the channel to develop, which was observed by the brash ice fragment shape and the channel thickness profiles (Fig. 2). The air temperature was close to 0 degrees and the channel was operated frequently enough to prevent any consolidation in the channel. During the tests, the vessel speed was varied by adjusting the propeller pitch level. Three different propeller pitch levels were tested. The vessel speed was let to adjust to a constant value during each test. The net thrust was determined as a function of speed based on the propeller thrust at the full power, the open water resistance, and the estimated thrust deduction. No corrections were made to the Vessel 1 full scale test results.

Vessel 3 full scale reference tests were measured in the Bay of Bothnia in March 1999 (Nortala-Hoikkanen, 1999). The channel thickness profile was measured at 6 different locations. The middle channel thickness varied between 0.65 m – 1.20 m. Similar to Vessel 1 full scale test conditions, this channel was also considered as a typical old channel due to the reported channel profiles and pictures confirming the fragment shape and size distribution (Fig. 4). By the day of the ice trials, 110 ships had passed along the channel. The average daily temperatures of the measurement days were −7.0 – −8.6 °C. The testing distance was 800 m. In the vessel resistance tests, the vessel speed was intended to be 4–5 m/s. Some acceleration and deceleration were observed during the tests although the propeller revolutions were kept constant. This was considered to be related to the force required to accelerate the mass consisting of the vessel displacement and the added mass of the brash ice (assumed to be 20% of the total mass; Nortala-Hoikkanen, 1999). However, no correction was applied to the measured values. The vessel resistance was determined afterwards utilizing the propeller K_T-curve.

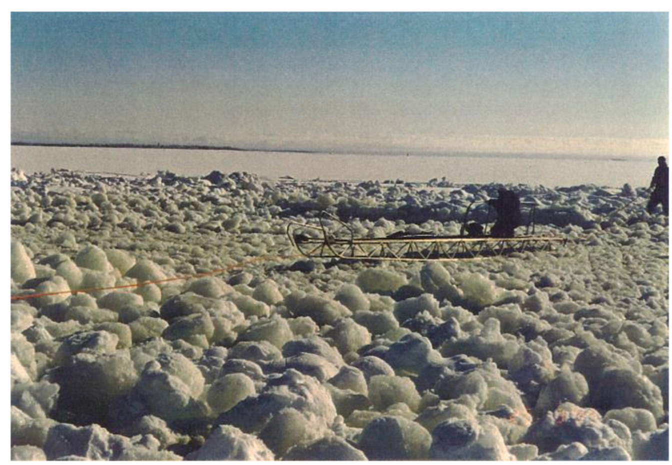

Fig. 4. The Vessel 3 brash ice channel prior to the full scale experiment in 1999.

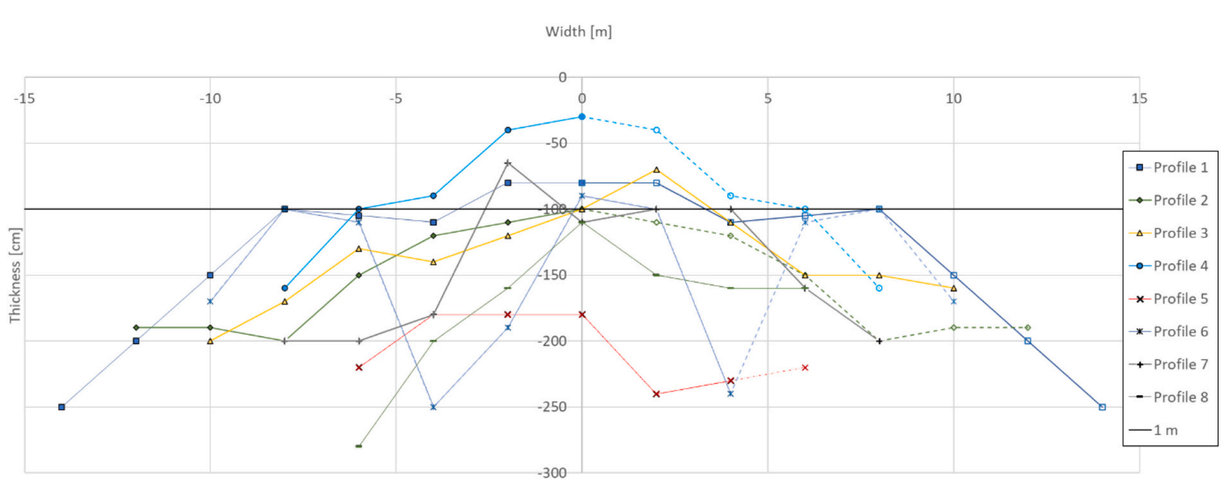

Fig. 3. Channel profile measurements prior to the Vessel 1 full scale experiment (Matala, 2018). According to FSICR, 1A vessel is to be able to advance with a certain speed in a channel, which is 1.0 m thick in the midpart.

3. Results

3.1. Model test results

This chapters present the model scale brash ice channel test results for all three vessels together with the corresponding correlation tests in full scale for Vessel 1 and Vessel 3. The results of each vessel follow the same notation, which is introduced in Fig. 5. Notations “FGX 500 kPa” and “FGX 1000 kPa” refer to FGX-model ice, with a corresponding flexural strength, which are scaled down using the Froude similarity law. Notation “Ice cubes” refers to the brash ice consisting of solid freshwater ice cubes with an unscaled flexural strength. The trendline style shown in Fig. 5 indicates the order of the test repeat. The brash ice in the channel was redistributed along the cross-section between the tests to have as uniform thickness through the channel as possible.

The corrections to the targeted ice thickness and the friction coefficient were made according to Chapter 2.2. Table 4 presents the measured thickness deviation from the target and measured friction coefficient to indicate the weight of the corrections. The target value corresponds to the equivalent channel thickness determined in FSICR guidelines for the verification of a vessel performance for the ice class 1A through model tests (Trafi, 2017).

3.2. Vessel 1

The Vessel 1 bow shape is optimized for open water conditions. Fig. 6 presents the vessel resistance in three different model ice types and in full scale. Fig. 6 clearly shows the wide variation in model test results. The test results also show that the first channel indicates a higher resistance than the following repeated tests in channels 2 and 3. When comparing the corresponding test repeats, there is no significant difference between the test results conducted in FGX 500 kPa and FGX 1000 kPa. What stands out in Fig. 6 is that the full scale correlation test corresponds significantly lower vessel resistance than what is predicted based on any model ice type. However, the ice cubes predict the lowest resistance from the applied model ice types, as an average, and are closest to the full scale values. Table 5 compares the ice resistance determined in each model channel to the ice resistance determined in the full scale test. The comparison is done regarding the predicted resistance at a speed of 5 knots, and it is based on the test result trendlines, which are assumed to remain linear within the considered area. The percentage in column “Resistance compared to full scale at 5 kn” indicates how much the model-test-based prediction exceeds the full scale value.

The model test results of Vessel 1 were analyzed according to the FSICR guidelines as presented in Chapter 2.2, with the exception of the friction correction: because the full scale reference was obtained with a relatively new vessel with a practically uncorroded surface, the model scale test results were corrected to correspond to a newly painted hull (the friction coefficient between ice and model is 0.05 according to Aker Arctic standards). The different model ice types had a slightly different friction coefficient with the model surface, and the friction correction was applied to equalize the different model test experiment results.

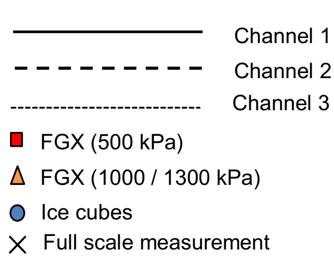

Fig. 5. Notations used for different ice types and the order of test repeat in the result figures.

3.3. Vessel 2

The Vessel 2 bow shape is optimized for open water conditions. Fig. 7 presents the vessel resistance based on model scale tests conducted in three different model brash ice types. From the data in Fig. 7, it is apparent that the results are scattered. The first test conducted in FGX-model ice indicates a clearly higher resistance compared to the repeated tests in the same ice field. Interestingly, the following two repeated test runs (channel 2 and channel 3) indicate a resistance similar to each other in the same ice fields. This trend between the repeat test results occurred with both FGX 500 kPa and FGX 1000 kPa model ice types. The weaker model ice FGX 500 kPa indicates a significantly higher resistance compared to the stronger model ice FGX 1000 kPa. The values from the tests conducted in the brash ice consisting of ice cubes remained relatively similar during the repeat testing and estimated smaller resistance as an average than other model ice types.

3.4. Vessel 3

The Vessel 3 bow shape is optimized for ice conditions. The measured resistances in the correlation tests are shown in Fig. 8. Similarly to the results from Vessel 1 and Vessel 2, the first test in FGX model ice indicates higher resistance when compared to the values measured on the repeat testing in the same ice field. The ice resistance determined in the FGX 1000 kPa ice was significantly higher when compared to any other ice. Overall, Vessel 3 results display less variation when compared to Vessel 1 and Vessel 2. The single most striking observation to emerge from the data comparison was that for Vessel 3 the correlation of the model scale tests with the full scale test seems accurate. The channel profile correlated well to the FSICR definition for an ice class 1A brash ice channel. Table 6 presents the comparison between the model scale and full scale test result. The comparison is done considering the speed of 5 kn. The percentage in column “Resistance compared to full scale at 5 kn” indicates how much the model-test-based prediction exceeds or undercuts the full-scale value. Because the full scale test results have no clear trend as a function of speed, the resistance at the lowest speed is assumed to represent the resistance at 5 knots speed. The trendlines of the model test results are assumed to remain linear and non-negative.

4. Discussion of the test results

The vessel resistance in a brash ice channel in full scale is a sum of a large variety of factors, including the vessel hull shape and interdependent brash ice properties. The vessel resistance in model tests is a sum of the same factors, in addition to which the model ice-related issues need to be considered carefully. Fig. 9 illustrates our current understanding of the factors influencing the vessel brash ice resistance. Fig. 9 categorizes the ice resistance components by their location on the vessel hull, origin of the force, force type, brash ice properties influencing each force, and finally summarizes which ice properties influence on the brash ice buoyancy and which on the fragment interaction.

The following chapters first consider how the separate factors presented in Fig. 9 might influence the model test results based on our experiments, and finally summarizes the observations to provide a more comprehensive understanding on the accumulative effect of all these forces when combined. As the test conditions were the same in all compared model tests and our focus is on comparing the model test results, the open water related factors and purely model scale technical factors are not discussed here.

4.1. Influence of model ice type and repeat testing on vessel resistance

Based on our findings presented in the Chapter 3, the model test results are scattered. A more detailed inspection of the model test results indicates that the vessel resistance measured in brash ice made of FGX-model ice is generally higher compared to the resistance in brash ice

Table 4
Measured channel thickness and friction coefficient between model and ice. The column "h channel deviation from target" represents the deviation of the average measured thickness from the targeted thickness.

		Vessel 1		Vessel 2		Vessel 3	
Ice type	Test repeat/ Channel number	$h_{channel}$ deviation from target [%]	Friction coefficient between model and ice μ_{meas} []	h $_{channel}$ deviation from target [%]	Friction coefficient between model and ice μ_{meas} []	h $_{channel}$ deviation from target [%]	Friction coefficient between model and ice μ_{meas} []
FGX 500 kPa	1	−1%		−4%		12%	
FGX 500 kPa	2	−4%	0.059	10%	0.044	4%	0.060
FGX 500 kPa	3	−8%		6%		6%	
FGX 1000 kPa/ 1300 kPa*	1	3%*		40%		3%	
FGX 1000 kPa/ 1300 kPa*	2	−2% *	0.0601*	24%	0.033	6%	0.059
FGX 1000 kPa/ 1300 kPa*	3	−4% *		20%		2%	
Ice cubes	1	5%		22%		5%	
Ice cubes	2	27%	0.052	11%	0.028	6%	0.051
Ice cubes	3	14%		1%		6%	
Ice cubes	4	–	–	31%		–	–

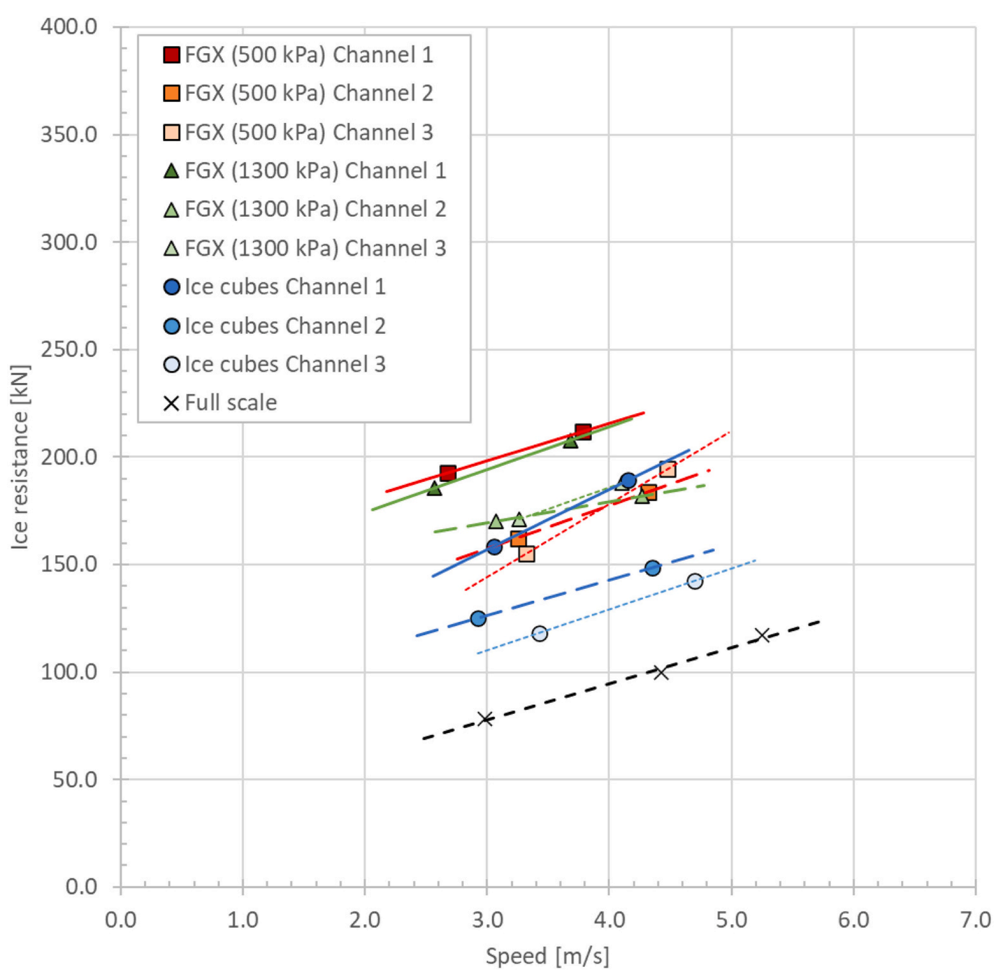

Fig. 6. Vessel 1 resistance in repeated model scale tests and in full scale.

Table 5
Comparison of the model scale test result to the full scale ice resistance at 5 kn.

Ice type	Test repeat/Channel number	Resistance compared to full scale at 5 kn [%]
FGX (500 kPa)	Channel 1	171%
FGX (500 kPa)	Channel 2	111%
FGX (500 kPa)	Channel 3	84%
FGX (1300 kPa)	Channel 1	163%
FGX (1300 kPa)	Channel 2	134%
FGX (1300 kPa)	Channel 3	122%
Ice cubes	Channel 1	105%
Ice cubes	Channel 2	69%
Ice cubes	Channel 3	44%

made of ice cubes. The model test results acquired from the tests conducted in brash ice consisting of ice cubes produce more consistent results in the repeat tests when compared to FGX-model ice tests.

Further analysis on the effect of the repeat testing on the vessel resistance is presented in Table 7 and Fig. 10. The vessel resistance was determined at the speed of 5 knots in each channel based on the ice resistance trendlines (Fig. 6, Fig. 7, and Fig. 8). The vessel resistance determined in the repeated tests are compared in Table 7 to the first channel test result. With some exceptions, the vessel channel resistance decreases with the repeat testing.

4.2. Influence of ice properties

The data on the change in the ice properties due to the test repeat is presented in our earlier research (Matala, 2021). In this section, we assess the influence of each property on the vessel resistance by combining the information drawn from the ice property measurements and the vessel resistance in the corresponding model brash ice. Two significant factors of inaccuracy need to be considered in the analysis. First, the model ice can easily undergo significant changes over time and as a result of sample handling. The time-based ice changes can be a factor even over the testing period. Therefore, to minimize the effect of time related changes to the ice properties, the ice property measurements must be taken efficiently focusing on the most relevant tests with minimal repeats. This easily results in a high variation in the measured values. Second, the ice properties studied in our research are related (Fig. 9) and influence each other. Therefore, the properties cannot be studied entirely independently. However, these measurements of brash ice properties and the vessel resistance help us to observe and measure relations between model ice types.

4.2.1. Porosity effect

The porosity is defined as the measure of void spaces in a material, i.e. for brash ice the volume of water or air compared to the total volume of a brash ice sample. The brash ice porosity influences the brash ice buoyancy force and consequently both the vessel parallel side frictional resistance, and the frictional component of the bow resistance. Porosity also affects the brash ice fragment interaction and thereby the displacing and submerging components of the bow resistance.

Our brash ice measurements indicate that each brash ice type has a different porosity and the porosity changes with repeat testing. Moreover, the measured average porosity is the smallest in the first test in

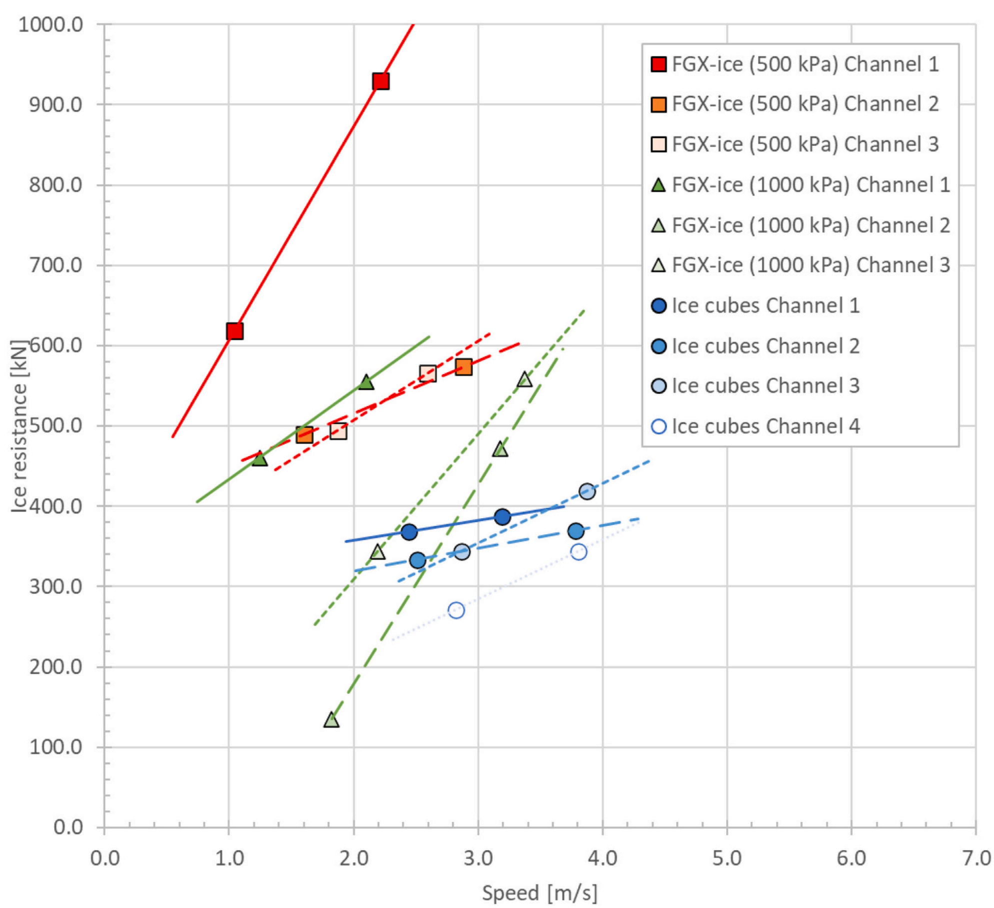

Fig. 7. Vessel 2 resistance in repeated model scale tests.

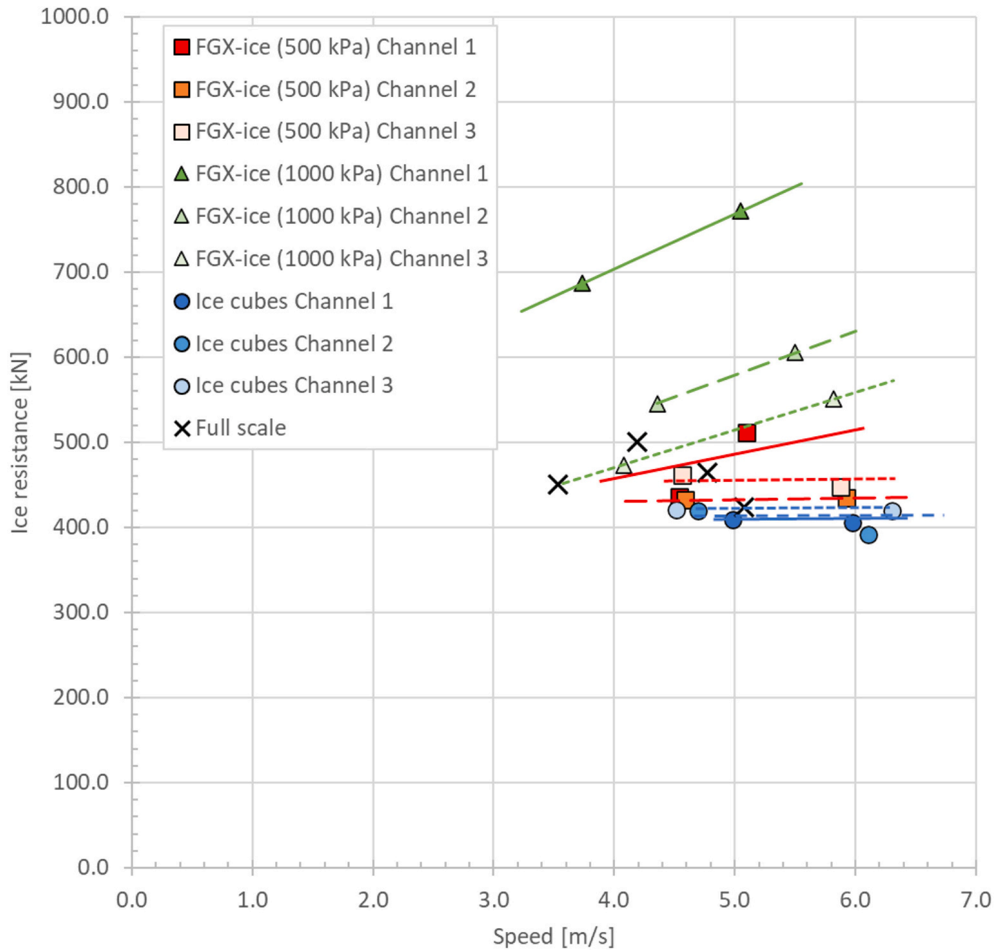

Fig. 8. Vessel 3 resistance in repeated model scale tests and in full scale.

Table 6
Comparison of the model scale test results to the full scale ice resistance at 5 kn.

Ice type	Test repeat/Channel number	Resistance compared to full scale at 5 kn [%]
FGX-ice (500 kPa)	Channel 1	−3%
FGX-ice (500 kPa)	Channel 2	−5%
FGX-ice (500 kPa)	Channel 3	3%
FGX-ice (1000 kPa)	Channel 1	36%
FGX-ice (1000 kPa)	Channel 2	1%
FGX-ice (1000 kPa)	Channel 3	−10%
Ice cubes	Channel 1	−9%
Ice cubes	Channel 2	−7%
Ice cubes	Channel 3	−7%

FGX-model ice (35.4% and 30.0%) and increase in repeated tests (37.8%–43.7%), indicating inversely similar trend with the measured vessel resistance. The porosity values measured from the brash ice consisting of ice cubes changes very little between the first and repeated tests (53.3%–55.1%), and the measured porosity values are higher compared to the values measured from FGX-model ice.

While we acknowledge that the small number of samples limits the generalization of this observation, we should also take into account that porosity correlates with the measured vessel resistance in model ice. This result is in line with the existing understanding, as the vessel resistance is assumed to relate to the volume of ice displaced by the vessel, and the ice volume decreases with increasing relative amount of void. The smaller resistance could also be accounted for the decreased particle interaction in a material with more void.

4.2.2. Piece size and shape effect

The brash ice piece size distribution influences the brash ice porosity. Previous research has indicated that the fragment shape influences the interaction of the fragments and consequently other studied properties of brash ice. In theory the fragment shape changing from angular to round could decrease the porosity up to 26% (Matala and Gong, 2021).

Our experiments indicated an insignificant change in the average shape characteristics of FGX model brash ice fragment in the channel test repeat. However, the brash ice fragments do undergo some changes when exposed to an additional stirring. Our observations from the model tests indicates that the structure of brash ice made from FGX-model ice easily alters to a non-granular material, while the brash ice consisting of separate ice cubes remains granular. Although the size of separate ice pieces does not change, the cohesion between the separate ice pieces alters the behavior and interaction of the ice pieces for non-granular materials.

Considering the size and shape, the cohesion may merge separate ice pieces together to behave and interact as a single larger ice block. The tendency of the model brash ice fragments to reformate likely relates to the model test repeatability: the model scale tests in the first channel in FGX-model ice appears to predict a different resistance compared to the repeated tests. Correspondingly, the resistance in ice cubes remains the same in the test repeats for Vessel 2 and Vessel 3. The reason why the Vessel 1 model scale resistance in brash ice made of ice cubes is

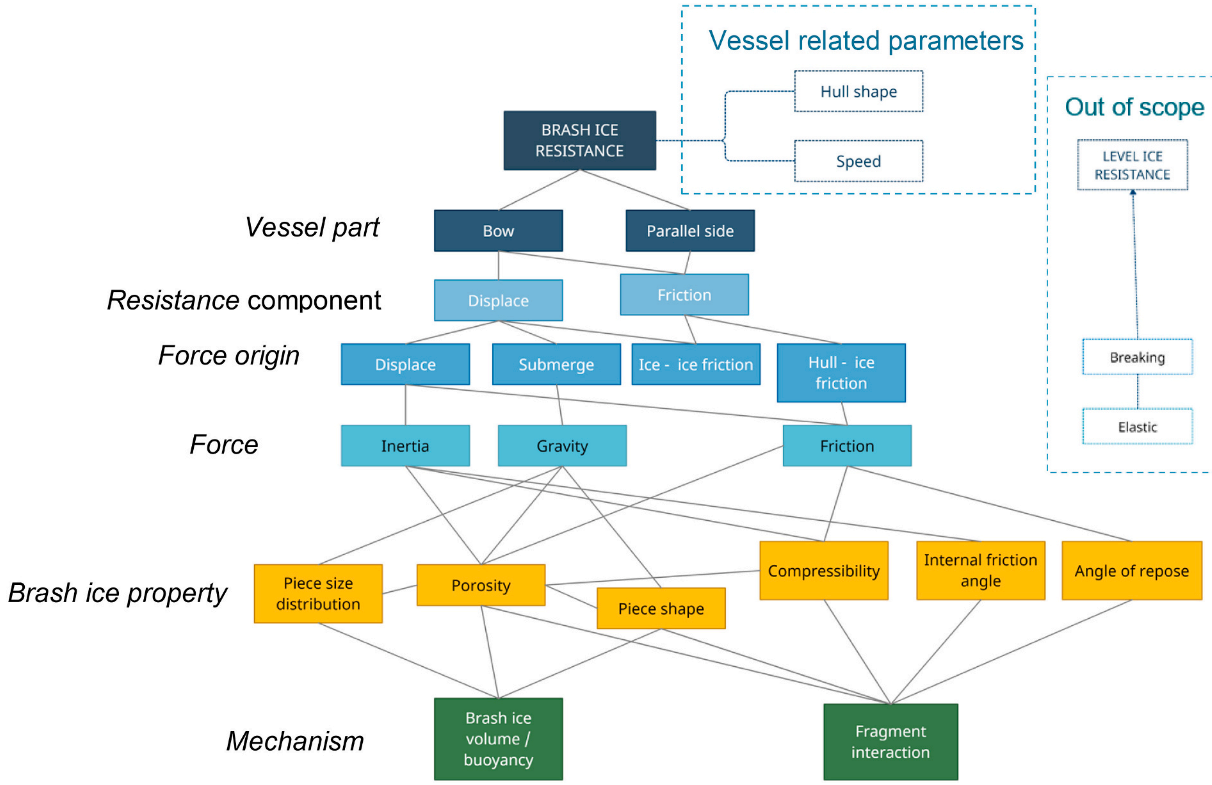

Fig. 9. Vessel resistance in a brash ice channel.

Table 7
The vessel resistance change in repeated tests at speed of 5 knots.

Ice type	Test repeat	Vessel 1	Vessel 2	Vessel 3
	Channel 1	100%	100%	100%
FGX 500 kPa	Channel 2	78%	54%	98%
	Channel 3	68%	55%	106%
	Channel 1	100%*	100%	100%
FGX 1000 kPa/1300 kPa*	Channel 2	89%*	53%	74%
	Channel 3	85%*	68%	66%
	Channel 1	100%	100%	100%
Ice cubes	Channel 2	82%	90%	102%
	Channel 3	70%	87%	103%

decreasing with the test repeat is possibly a consequence of the consolidation; as the Vessel 1 was the first model tested using ice cubes, the preparations required considerably time before starting the first test.

4.2.3. *Angle of repose effect*

The angle of repose influences the friction component of the vessel resistance in a brash ice channel. The angle of repose describes the slope the material can maintain without collapsing. Thus, it determines the maximum vertical height of a stable pile that can be formed from a volume of a certain material. The angle of repose below water adds the vessel resistance, because it influences the brash ice pile-up at the vessel side. According to the brash ice measurements, the angles of repose of the soft FGX-model ice (49 deg. / 71 deg) are higher when compared to the brash ice consisting of solid ice cubes (19 deg) already in the first test run. Moreover, the repeat testing in FGX-ice revealed that the angle of repose increased unrealistically close to vertical angles, while the angle of repose of ice cubes does not increase at all when repeating the model test (the angle of repose in the repeated tests with ice cubes were 16 deg./16 deg).

The high angle of repose was expected to increase the vessel frictional resistance because of the higher contact height between the vessel side and brash ice mass (see Fig. 11 b). The results from the model tests yielded evidence for the opposite relationship. The repeated model tests indicate a lower resistance in brash ice, where the higher angles of reposes are measured. One possible explanation is that while the forming vertical brash ice edge is higher when compared to a loose pile, it is also more solid and forms a small gap away from the vessel side. This leaves the vessel parallel side free from the vessel-ice friction, as illustrated in Fig. 11 c.

The ability of the brash ice to build and maintain slopes was visible in all vessel model tests, which were conducted in FGX-model ice. Fig. 12 shows closing of the channel after the model passage with both soft FGX model ice and brash ice consisting of ice cubes. Both picture sets are selected from the first repeated test of the test day, i.e. channel 2. For comparison, the channels are presented also before the model passage. Fig. 12 shows that the channel behind a vessel in soft model ice does not close realistically, but forms stable piles in the channel edges. The same effect can be seen in Fig. 13, which provides a comparison of channels immediately behind the vessel in model ice made of 42 kPa FGX model ice, model ice made of solid ice cubes and a channel behind a vessel in an old channel in full scale.

4.2.4. *Compressibility effect*

The compressibility evaluates the external loads required to displace a certain void volume from a brash ice sample. This water escape is related to the brash ice inter-particle mobility, which is influenced by factors such as particle surface characteristics and shape. The compressibility is assumed to have influence on the brash ice pile-up and eventually the vessel frictional resistance through ice piling up at the vessel side, and the bow resistance induced by submerging and displacing the brash ice. The compressibility index measurement results were around three times higher for the brash ice consisting of ice cubes when compared to brash ice made from FGX-model ice. This shows that less force was required for the same volume of water to escape from a sample of ice cube brash ice compared to the FGX-model ice sample.

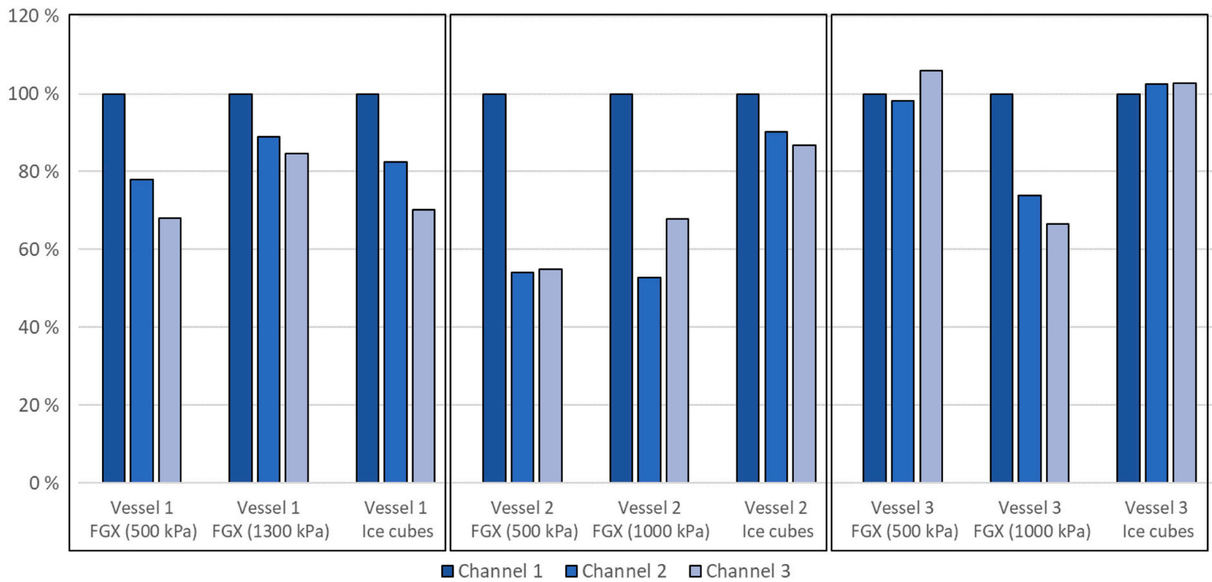

Fig. 10. The vessel resistance changes in repeated tests at the speed of 5 knots.

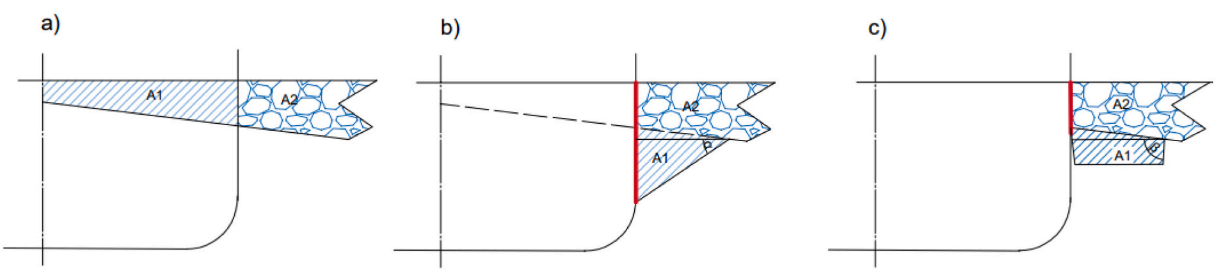

Fig. 11. Illustration of the possible effect of the angle of repose on the brash ice contact area in the vessel side. Picture a) shows the cross-sectional area of brash ice before being displaced by the vessel. Picture b) represents the idea, which is the basis of the FSICR channel equivalent thickness. Picture c) proposes how the displaced brash ice could locate, when the angle of repose is high, and the material is highly cohesive. The angle of repose is denoted as α and β; $\alpha < <\beta$; red line represents the contact height forming the frictional area between the vessel side and the surrounding brash ice. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

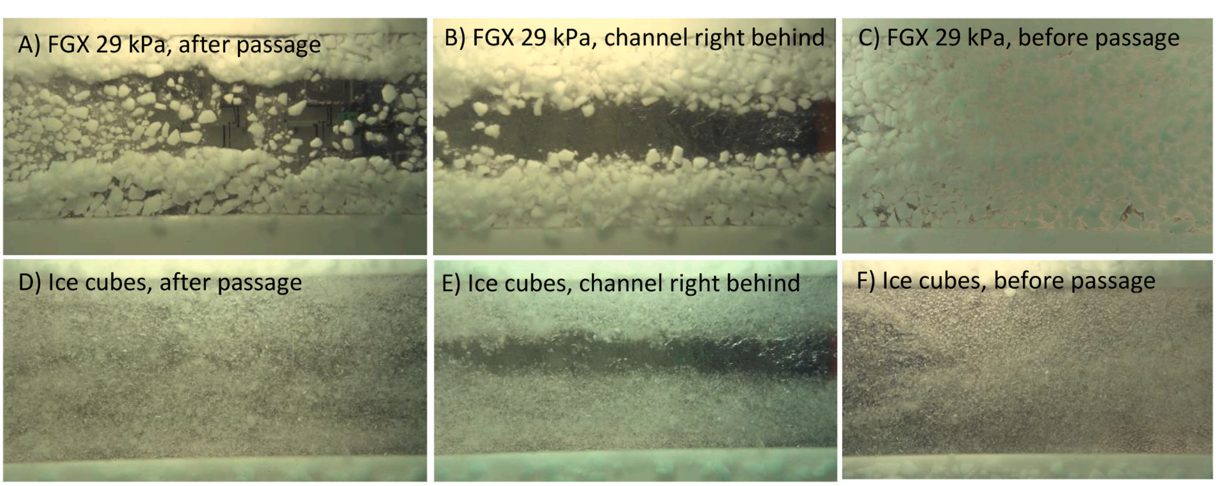

Fig. 12. Channel closing after the model (Vessel 1) passage with two different model brash ice.

This observation is consistent with the initial assumption on the effect of compressibility on the resistance. The resistance of a model in the brash ice consisting of ice cubes was found to be lower when compared to the corresponding tests conducted in FGX-model ice. This divergence seems to be most notable in vessel model tests which are conducted with open-water-optimized vessels, Vessel 1 and Vessel 2, and less determinative with ice-optimized Vessel 3. This difference between open-water-optimized and ice-optimized bow types is likely to be attributed to open-water-optimized bow type tendency to displace a higher volume of brash ice to the sides when compared to ice-optimized bow shapes.

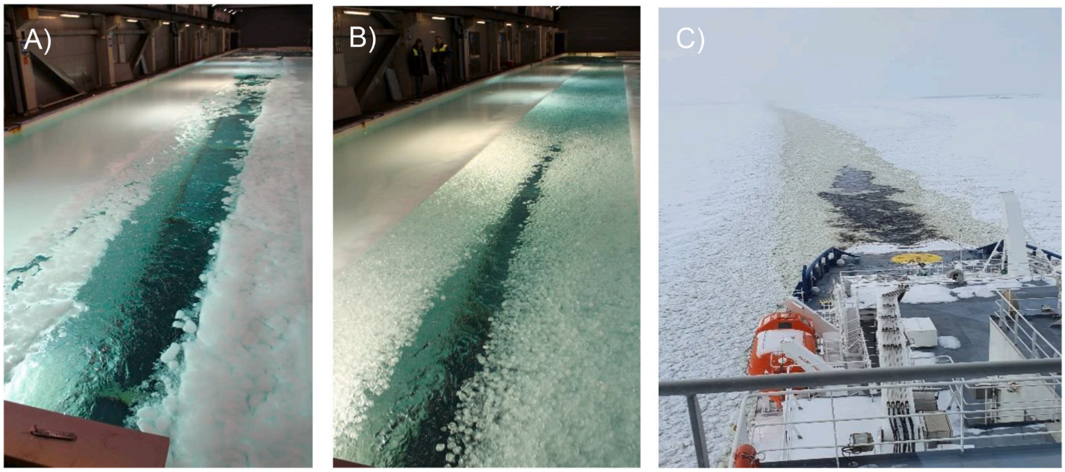

Fig. 13. A channel right behind a vessel in A) brash ice made of 42 kPa (m.sc.) FGX model ice B) brash ice made of ice cubes, and C) full scale.

4.2.5. Internal friction angle effect

The internal friction angle is assumed to affect the brash ice pile-up through the fragment interaction. Our earlier research (Matala, 2021) indicated the change in the material behavior by revealing the tendency of the FGX model ice to change the character from a granular material to a non-granular material, albeit the applied method failed to reliably measure the internal friction angle. All the model scale tests conducted in FGX-model ice showed a significant change in the measured resistance between the first and repeated test, which could be a consequence of this material change. However, as the first test is conducted in a granular material the test result should be expected to be more accurate when compared to tests conducted in non-granular material. Contrary to expectations, the resistance of the first test run was found to be furthest from the resistance indicated by the full scale correlation tests. This inconsistency may be attributed to the fact that the change from granular to non-granular material affects several brash ice properties. Simultaneously, the level of an effect varies between the different properties, and certain properties may have a determinative impact on the resistance. Thus, the combined effect may result in decrease in the measured resistance, although the effect of a certain property would increase the resistance.

4.3. Influence of vessel shape

The model test results of the open-water-optimized Vessel 1 and the ice-optimized Vessel 3 were compared to the resistance measured in full scale (Table 3). The correlation between the vessel resistance on full scale tests and model scale tests seems to be good for the ice-optimized vessel (3), while for the open-water-optimized vessel (1) the model tests overestimate the resistance. This could be a consequence of the different resistance component shares.

The hull shapes of Vessel 1 and Vessel 2 do not submerge ice pieces, but they rather move the brash ice to the sides and even in front of the bow. Consequently, the inter-particle interaction has a significant and increased influence on the resistance in model scale tests with models, where the total resistance mainly consists of the loads induced by ice piling and compacting on sides. Thus, it appears that the model scale testing of the open-water-optimized hull shapes in a brash ice channel requires more precise modeling of the brash ice inter-particle interaction.

For Vessel 3, the determined resistances between the different model brash ice types were less scattered compared to other vessels. This result may be explained by the Vessel 3 hull shape. The low stem angle of Vessel 3 enhances submerging of the ice fragments below the hull. Thus, the required submerging forces contribute more significantly to the measured resistance and reduces the share of other resistance components. As the densities of the different ice types were close to each other, see Table 8, the influence of model ice type to the pure buoyancy related submerging forces and behavior is considered negligible.

Furthermore, submerging of ice, i.e. a partly vertical displacement instead of a purely horizontal displacement of ice pieces, is considered to reduce the impact of the inter-particle interaction and piling up processes. These are supported by the qualitative evidence based on observations from the model brash ice moving around the ice-optimized vessel (Vessel 3) bow, see Fig. 14. Fig. 14 shows that the different model ice types are covering approximately the same areas of the model. This suggests that the ice submerging and piling up processes around this type of bow are not influenced by the different properties of model ice type.

4.4. Summary

The model test experiments conducted in different model brash ice produced scattered resistance results. This deviation was the smallest in the brash ice consisting of ice cubes, which also maintained the original properties better in the repeat testing when compared to the brash ice made of FGX-model ice, which evidently undergoes changes in the repeat model testing. The variation and test repeat-dependent changes in model brash ice were evidenced by the ice property measurements and qualitative assessment of the channel during a vessel model test.

With regards the correlation of the model scale test results to full scale results, the model scale tests seem to overestimate the resistance of Vessel 1, which represents a modern, open-water-optimized hull shape. The model scale tests conducted with ice cubes, i.e. the model scale brash ice with unscaled ice properties, predicted the lowest channel resistance, and the predictions were therefore closest to the real-world correlation value. The correlation of the results for Vessel 3, which represents a traditional ice-optimized bow shape, was better considering all applied ice types: different model ice types resulted in a smaller deviation with Vessel 3 when compared to other vessels. It is possible to hypothesize that the unrealistic ice pile-up, which occurs with FGX-model ice, is less likely to occur when testing the traditional hull

Table 8
Ice and water densities in the experiments. The column ρ_{ice} / ρ_w assesses the ice density influence on the buoyancy force.

Ice type	Density [kg/m^3]	ρ_{ice} / ρ_w [%]
FGX mode ice (25 kPa)	933	92%
FGX mode ice (50 kPa)	928	92%
Ice cubes	920	91%
Water	1011	–

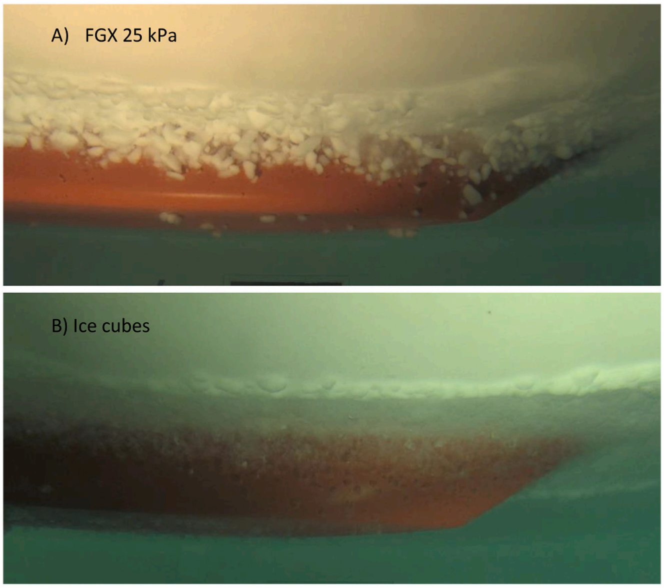

Fig. 14. Vessel 3 in two different model ice.

shapes, whereas the forces induced by ice pile-up are pronounced with the modern bow shapes.

While the model scale tests appear to make in general conservative predictions when compared to the full scale results, the FSICR calculation formula prediction of the vessel resistance in a brash ice channel was even more conservative for the modern bow types. For all three vessels investigated in this paper, the ice resistance determined using the FSICR formula was conservative with respect to the model scale test results. When comparing to the available full scale results, the resistance determined using the FSICR calculation formula was significantly higher for Vessel 1 (>> 10%) and marginally higher for Vessel 3 (<10%). While the observation is limited only to three vessels, the results are in accordance with earlier model scale measurements (Jeong et al., 2017). These results suggests that there is a need to reconsider the FSICR calculation formula regarding the hull shapes substantially different to the traditional shapes.

This paper focused on the physical model scale testing in ice. However, besides physical model scale tests, vessel performance in ice can be studied prior to building a prototype using numerical simulations (Xue et al., 2020). Numerical simulation of a vessel in a brash ice condition is often seen as a future alternative for model testing. Recently, several researchers have approached the brash ice channel using numerical simulations, such as Luo et al. (2020) and Koivurova (2020). Both simulations consider the interaction between ice particles based on physics, together with the qualitative assessment using physical experiments, this work at present suggests a promising correlation.

5. How to improve brash ice channel testing methods

The fundamental objective of the model scale testing in ice is to correctly predict the vessel resistance in the targeted ice condition to give an accurate estimation of the required engine power. Therefore, the ideal model brash ice should be well standardized to provide repeatable conditions for testing. The test conditions should also represent the natural conditions with such an accuracy that the vessel resistance determined in the model scale tests can be directly translated to the real-world vessel values.

Related to tests in a frequently-operated old brash ice channel, our observations indicate that the ice fragment interaction is a significant factor in the vessel brash ice channel resistance, especially when the modern open-water-optimized hull shapes are investigated. The currently used model ice underperforms in tests in modeling the brash ice fragment interaction. This is likely related to scaling down the ice flexural strength in accordance to the Froude similitude. When compared to the solid ice fragments, the soft FGX-type model ice fragments easily deform. As a result, the friction between the fragments increases, the separate ice fragments may merge and form a non-granular mass. This significantly alters the overall behavior of the ice mass passing around a moving vessel hull. These results suggest that the currently applied scaling methods, which include scaling down the strength of ice, might not be appropriate in model scale testing in brash ice. This could be supported by the fact that scaling down the flexural strength is principally applied to ensure correct modeling of the ice failure in bending. Since practically no breaking occurs in brash ice and in the other hand scaling down the flexural strength has a significant negative influence in correctly modeling the fragment interaction, we assume that – as the whole – the correct modeling of fragment interaction should be prioritized to correct modeling of a bending failure in brash ice tests.

This finding is supported by our earlier research on brash ice properties (Matala, 2021). The fragment interaction is assumed to be influenced at least by the ice fragment surface properties and solidity – or ability to keep form. In our research, the fragment interaction was systemically evaluated by measuring brash ice properties, such as angle of repose, compressibility, and porosity. Our research evaluated different model brash ice properties with the representative values in nature and concluded the brash ice consisting of solid ice cubes corresponds to nature brash ice better than the model brash ice made of FGX model ice with the scaled-down strength. The same research investigated the brash ice altering with the repeat testing, which also concluded the brash ice consisting of solid ice cubes to be the best option when compared to weak model ice, as the solid ice cubes produced the least changes in the repeat tests. A similar discussion has earlier been raised by other researchers, such as Palmer and Dempsey (2009), who discussed that simultaneous application of Froude and Cauchy similitude should be reconsidered for the tests where the forces related to these similitudes do not play a major role. It needs to be acknowledged that any type of ice is subjected to alterations with time, which is a notable aspect as itself.

While model ice is undoubtedly a major factor affecting the measured model resistance in brash ice, there are some other factors, which might also have varying degrees of influence in the vessel resistance.

The open water resistance is proportionally higher in brash ice channel than it is in level ice. Currently, the vessel resistance in ice is generally considered as a sum of the open water resistance and ice resistance. However, the surrounding ice field might influence the open water resistance, making the assumption of using the superposition principle invalid (Leiviskä et al., 2001; Kämäräinen, 2007). As the open water influence increases with the speed, it might be considered that the testing speed should be as close as possible to the FSICR performance requirement speed – 5 knots – in order to standardize the testing condition.

Based on the model test experiments, the test repeat significantly altered the measured vessel resistance in tests made of FGX model ice. Therefore, we would propose that the repeat testing should be avoided.

6. Conclusion

This research has explored the relationship between the model brash ice properties and the model scale test prediction of vessel resistance. The results indicate that the brash ice made of FGX model ice tends to predict a higher vessel resistance when compared to the brash ice made of solid ice cubes with unscaled strength. This was particularly highlighted with the modern open-water-optimized bow shapes. According to the comparison between the model scale and full scale tests, the tests conducted in the brash ice made of FGX-model ice tend to overestimate the vessel resistance. The prediction based on the tests conducted in the brash ice consisting of solid ice cubes were the closest to the full scale measurement. In general, the experiments results confirmed that the model test results conducted with the currently agreed procedures can be scattered and conservative.

This article contributes to the existing understanding by addressing the lack of the correlation test results of vessel channel tests in model scale and full scale. This study offers a new insight into the brash ice interaction process around a moving vessel hull. The findings of this study indicate that the realistic modeling of the brash ice particle interaction is of a high importance with respect to the modern hull shapes. This finding has important implications for developing further the brash ice model test procedures towards the next standard capable of modeling the relevant aspects in the currently changing environment. Continued efforts are needed to acquire more correlation data from the real-world measurements for the comparison and validation of the model scale test results of different hull shapes in brash ice channels to verify the findings and study further the influence of vessel hull shape. Further research on the model brash ice properties and the development of material property testing methods is also necessary both in full scale and model scale.

This research exploited unscaled ice and one traditional model scale ice, FGX-ice, which is a fine-grained model ice doped with salt. Some of the currently used model scale ice types utilize different dopants or mixture of dopants (such as ethanol, urea and ethylene glycol/aliphatic detergent/sugar) or have a different structure (such as columnar). It is unclear how the use of other model scale ice (the dopant and structure) would impact the results and challenges presented in this paper. Therefore, further experiments are needed to fully understand the implications of applying a different model scale ice.

It is notified that the ultimate goal of the FSICR calculation formulas is to define the minimum engine power requirement, and the resistance calculations are a mid-term step of these calculations. Thus, these results do not reflect the actual impact on the determined power requirement, as the propulsion design itself has an impact to the required engine power. Therefore, this study should be considered as an attempt to improve a part of the power requirement determination. The actual impact to the power requirement is left for future studies.

CRediT authorship contribution statement

Riikka Matala: Methodology, Formal analysis, Investigation, Writing – original draft. **Mikko Suominen:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was launched by Aker Arctic. The experimental part was funded by Aker Arctic and Winter Navigation Research Board projects W18-8 FSC channel resistance and W19-1 Channel resistance measurements in full scale and model scale. The model scale test experiments were done at Aker Arctic ice tank, Helsinki, Finland. The authors would like to thank professor Pentti Kujala for his kind guidance and supervision of the research. The research and paper writing were supported by K. Albin Johansson's Foundation.

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