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NUMERICAL INVESTIGATION OF EFFECT OF CHANNEL CONDITION AGAINST SHIP RESISTANCE IN BRASH ICE CHANNELS

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ABSTRACT

Finnish-Swedish ice class rules require resistance estimation of ship navigation in a brash ice channel with a certain condition; channel width and thickness are specified in the rule. Some conditions such as size and shape distributions of ice pieces are not specified in the rule, but will affect a ship resistance; investigation of effect of these parameters is required to develop a more exact evaluation method of resistance values with experiments or with calculations. We investigate the effect of these conditions against ship resistance using a numerical estimation method we have developed based on physically-based modeling. We also develop a method to prepare a channel filled with ice pieces, which are placed randomly but do not penetrate each other. The channel resistance under irregular ice arrangements is compared with that under regular arrangements. Results of the numerical simulations show that arrangement of ice pieces and existence of a stopper block at the further end of the channel do not significantly affect the ship resistance. Effect of the number ratio of spherical and cubic ice pieces is also investigated; the more the spherical ice pieces are, the less the resistance is. This suggests that an appropriate ratio should be chosen, but the ratio is not obvious. Further investigations are required.

INTRODUCTION

Finnish–Swedish ice class rules (FSICR, Finnish Maritime Administration 2008) require estimation of a ship's resistance in brash ice channels. In FSICR, the resistance formula is defined, and evaluation of resistance "based on more exact calculations or values based on model tests may be approved." (Finnish Maritime Administration 2008) Because the FSICR approves resistance evaluation based on more exact calculations, it is desirable to develop a simulation method for ship navigation in brash ice channels that can evaluate more exact ship resistance. For this reason, a group in Kogakuin University, including the authors, has begun development of a numerical method to simulate ship navigation under conditions that many ice pieces surround the ship hull. Some results are described in Konno and Mizuki (2006a), Konno and Mizuki (2006b), Konno et al. (2007), Konno and Yoshimoto (2008), Konno (2009a) and Konno (2009b). Such research has not been reported by other researchers.

Some conditions such as size and shape distributions of ice pieces are not specified in the rule or in the guidelines of the rule (Finnish Maritime Administration, 2005), but will affect a ship resistance; investigation of effect of these parameters is required to develop a more exact evaluation method of resistance values with experiments or with calculations. Effect of these channel conditions against channel resistance is not extensively investigated.

In our previous study, Konno (2009b), the simulation procedure was applied to estimate ship resistance in FSICR brash ice condition. The estimated resistances were of the same order of magnitude, but around twice as much as that of FSICR rule formula. Arrangement of ice pieces in the channel and shape distribution of ice pieces were discussed, but were not investigated at that time.

In this study, we develop a numerical procedure to prepare virtual channels filled with irregularly-placed ice pieces. Generated ice channels are provided for numerical simulation of ice navigation in a brash ice channel. Effects of existence of a wall at the further end of the channel and shape of ice pieces are also discussed.

METHODS

Physically Based Modeling

To simulate ship navigation in an ice field, it is necessary to address collisions and other mutual interactions among ice pieces and the ship. We incorporate physically based modeling (Baraff, 1997a, b) into our simulation program to handle that situation.

Physically based modeling is a method to simulate motions of numerous, independent solids with collisions, friction, and other constraints among solids. It is used in computer games, computer graphics animation, and artificial reality to realize a physically reasonable motion of solids. A solid is often modeled as a rigid body, or a set of rigid bodies connected by some constraints such as joints. The motion of each solid is calculated by numerically integrating the momentum equation that is associated with the solid. Constraints such as boundary conditions, non-penetrating conditions and joints are not embedded into the momentum equation; forces or impulses that are attributable to the constraints are calculated explicitly.

Our simulator uses the Open Dynamics Engine (ODE) developed by R. Smith (Smith, 2006) to implement physically based simulations. The ODE is a library with capabilities of collision detection, calculation of mutual interaction forces, integration of momentum equations and simple animation.

An ice piece is modeled as a rigid body; breaking of ice is not considered. The ship is modeled as a rigid body. In simulation, the direction-of-movement component of forces affecting on the ship is measured as the channel resistance.

Simulation Condition

This study uses model scale simulations to investigate channel resistance under brash ice conditions.

A model ship (B-063; National Maritime Research Institute, Japan) was used for these simulations. Table 1 and Figure 1 respectively depict the ship's dimensions and shape. This ship has two bows, bow α and β, as presented in Figure 1; If the ship bow is bow α, then the stern is bow β, and vice versa. Bow α is used for this study. Although this model ship has no real ship corresponding to that, it is assumed that the model ship is 1/25 of actual scale (scale factor λ=25).

Table 1. Dimensions of model ship B-063

Variable	Symbol	Value
length of the ship between the perpendiculars [m]	L	3.040 m
length of the bow [m]	L_{BOW}	0.6062 m
length of the parallel midship body [m]	L_{PAR}	1.828 m
maximum breadth of the ship [m]	B	0.700 m
actual ice class draught of the ship [m]	T	0.440 m
area of the waterline of the bow [m^2]	A_{wf}	$BT/2$
angle of the waterline at $B/4$ [deg]	α	30 deg
rake of the stern at the centerline [deg]	ϕ_1	30 deg (bow α) 45 deg (bow β)
rake of the bow at $B/4$ [deg]	ϕ_2	30 deg (bow α) 45 deg. (bow β)

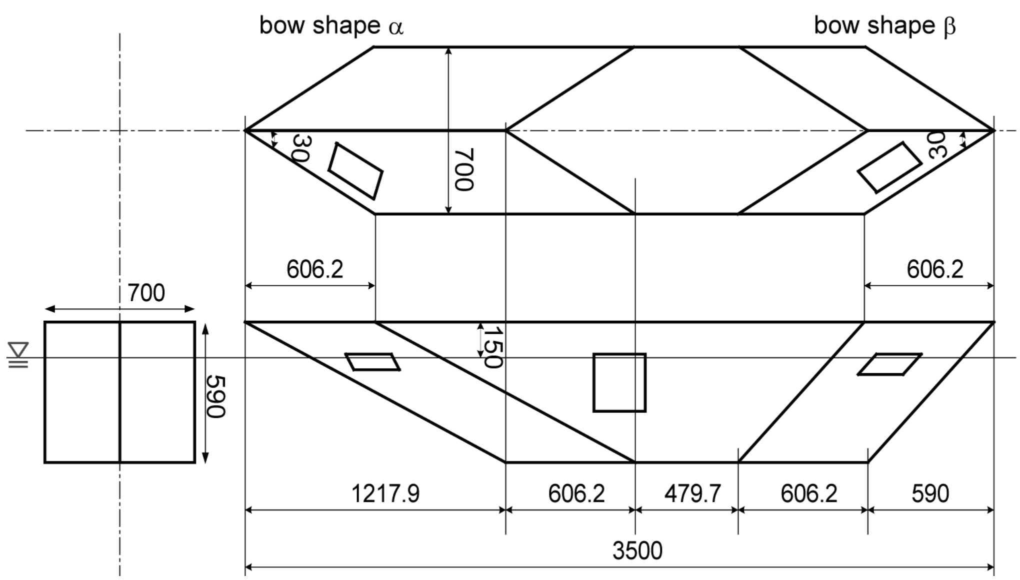


Figure 1. Model ship B-063

At the start of these simulations, ice pieces are placed between stationary ice sheets, as depicted in Figure 2. The model ship is forced to move with a given speed. The ship speed is 5 knots in real scale, and 1 knot=0.51444 m/s in the model scale, which is $1/\sqrt{\lambda}$ times that of the real scale. The time step is set to 0.01 s.

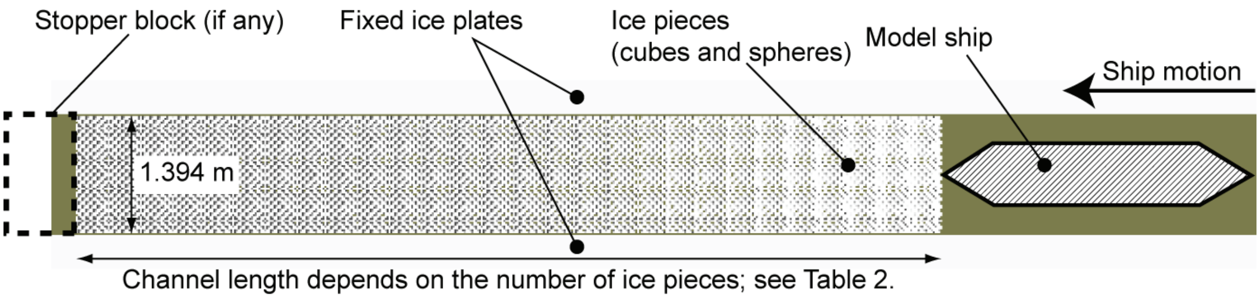


Figure 2. Initial arrangement of ice pieces. Top view

The fluid force affecting an ice piece is modeled as the following virtual force:

$$\vec{F} = -C_D A \cdot \frac{1}{2} \rho |\vec{v}| \vec{v} \,. \qquad (1)$$

Therein, C_D is the coefficient of drag, A denotes the projection area of the ice piece, ρ represents the water density, and v is the ice piece velocity. This equation represents that the ice motion is gradually enforced to stay still (although buoyancy on an ice piece is considered separately; it is explained later).

Fluid force on an ice piece is calculated with eq. (1) such that the drag coefficient C_D and projection area must be determined. Herein, C_D is set to 0.4, which is the drag coefficient of a sphere at Reynolds number of 10^3-10^5. The Reynolds number with the size of ice pieces (order of 1 m in real scale) and ship speed (5 knots in real scale) is around 10^6, and the motion of ice pieces is slower than that of the ship. Therefore, it is assumed that the coefficient described above is appropriate. This coefficient is applied to both spherical and cubic ice pieces. The projection area A of a spherical ice piece is set appropriately (area of a circle with the same diameter); that of a cubic ice is set to the square of its edge length, independent of the direction of motion.

In addition, buoyancy is considered separately. For a spherical ice piece, buoyancy is calculated according to the underwater depth of its center. For a cubic piece, static pressure around each ice piece is integrated numerically so that the buoyant force and moment are calculated. In both cases, pressure fluctuation in the flow field is not considered.

The coefficient of restitution between rigid bodies is set to zero. Densities of water and ice pieces are set, respectively, to 1000 kg/m^3 and 950 kg/m^3.

The friction coefficient between an ice piece and the ship hull is set to 0.1, as described in Finnish Maritime Administration (2005). The friction coefficient between ice objects (ice pieces or ice sheets) is set to 1.35, which is same as that of Konno (2009a,b) 1.35; this is determined based on two studies that examined the ridge keel friction: those of Karulin and Karulina (2002) and Matsuo et al. (2003)..

Preparation of numerical brash ice channel

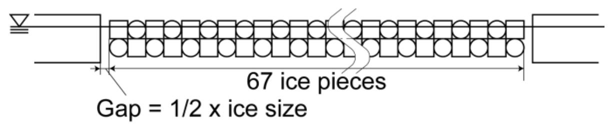
We prepare ten types of numerical ice channels with two methods of preparation and three average ice sizes: regular and irregular arrangements and large, middle and small ice pieces. Table 2 shows the main simulation cases.

Table 2. Main simulation cases

Case Name	Ice Size	Arrangement	Number of Ice Pieces	Channel Width	Channel Length
Case AR	Large	Regular	10000	1.394 m	12.095 m
Case AI	Large	Irregular	10000	1.394 m	12.069 m
Case BR	Medium	Regular	80000	1.394 m	12.095 m
Case BI	Medium	Irregular	80000	1.394 m	16.288 m
Case CR	Small	Regular	120000	1.394 m	5.644 m
Case CI	Small	Irregular	126000	1.394 m	5.251 m

In these cases, the numbers of spherical and cubic ice pieces are equal. Unequal cases correspondent to Cases AI and BI are also prepared.

Case AR (one layer)



Case BR (two layers)

Figure 3. Initial arrangements of ice pieces for regular arrangement. Sections normal to the direction of ship motion are shown.

The average channel thickness is calculated based on FSICR guidelines (Finnish Maritime Administration, 2005). In those guidelines, the average channel thickness in model tests, H_{av}, is specified as

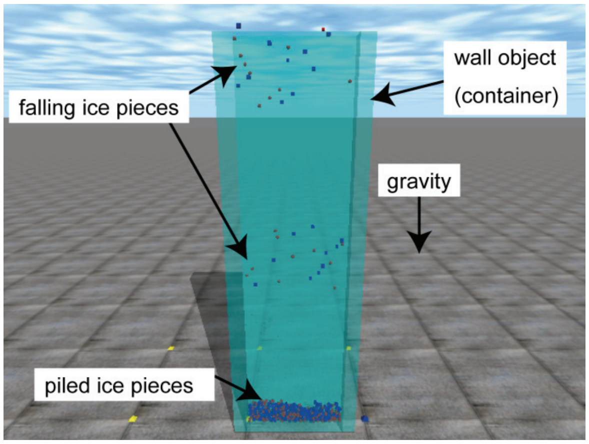
$$H_{av} = H_M + 1.40 \times 10^{-3} B\,. \qquad (2)$$

Therein, H_M is 1.0 m for Ice Class IA (real scale), and B is the maximum ship breadth. In the simulation described herein, because the scale is assumed 1/25 and the ship breadth B is 0.700 m in model scale, $H_{av} = 1.0\,\mathrm{m} \times 1/25 + 1.40 \times 10^{-3} \times 0.700\,\mathrm{m} = 0.04098\,\mathrm{m} \approx 41\,\mathrm{mm}$.

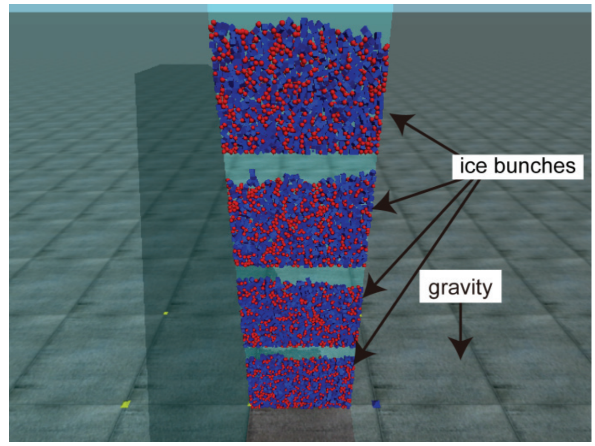
The ice piece size is defined based on the brash ice channel thickness. Figure 3 shows initial arrangements of ice pieces in two of six simulation cases, Cases AR and BR. In Case AR, 41 mm spherical and cubic ice pieces are placed in a chessboard manner. In Case BR, 20.5 mm spherical and cubic ice pieces are placed in a chessboard manner in the horizontal direction, and stacked to two layers in a vertical direction. In Case CR, 13.67 mm spherical and cubic ice pieces are placed in a chessboard manner in the horizontal direction, and stacked to three layers in a vertical direction. The channel width is set to 1.394 m, which is nearly twice as long as the ship breadth but which is adjusted to a multiple of the size of ice pieces. We call these arrangements *regular* arrangements.

In Cases BR and CR, simulations with a stopper block placed at the further end of the channel, as shown in Figure 2, are also conducted, and the results are compared with the results without the block.

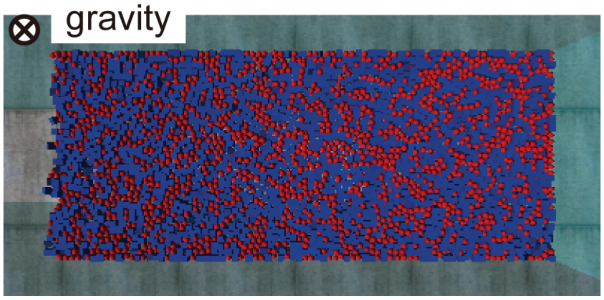
To prepare more natural ice arrangement with varied ice size, it is not appropriate to place ice pieces randomly; following conditions must be satisfied.



(a) Step 1: stack 500 spherical (red) and 500 cubic (blue) ice pieces into a container.



(b) Step 2: stack a few ice bunches generated in step 1.



(c) Step 3: rotate ice bunch and place it in a virtual channel, and wait a few ten seconds to let them drift to stable state.

(d) Generated initial ice condition. Top view

Figure 4. Procedure of *irregular* arrangement of ice pieces

1. Ice pieces must not intersect each other.
2. Ice pieces must be kinetically stable; they should not move before a ship collides against them.

To conform to the above conditions, we develop a set of computer programs that can perform a following procedure to prepare initial arrangement of brash ice pieces in a channel.

Step 1. We prepare a virtual container in simulation space. The inner footprint of the container is channel width times intended channel thickness, and the height should be high enough to hold ice pieces. We then throw randomly-generated ice pieces into it and pile them up. After this step, a bunch of ice pieces are generated. (Figure 4 (a))

Step 2. We then stack up a few of ice bunches generated by Step 1. (Figure 4 (b)) After this step, a large ice bunch is generated.

Step 3. We then rotate the generated large ice bunch to make it lie down so that a flatly placed ice bunch is generated. (Figure 4 (c))

Step 4. We place the above ice bunch in the water surface of a virtual channel, and wait a few ten seconds to let them drift to stable state.

All the above steps are virtually performed within a computer.

We prepare three virtual brash ice channels using the above procedure, Case AI, BI and CI. In Case AI, average ice size is same as that of Case AR (41 mm) but there is a 10% variation in size. In Case BI, average is same as that of Case BR (20.5 mm) with 10% variation. In Case CI, average ice size is same as that of Case CR (13.67 mm) with 10% variation. We call these arrangements *irregular* arrangements. In these cases, the numbers of spherical cubic ice pieces are equal.

We also prepare four conditions with different ratios of spherical and cubic ice pieces, 7:3 and 3:7, which correspond to 5:5 cases of Case AI and BI.

In all cases, consolidated layer is not considered.

RESULTS

Effect of ice arrangement and existence of stopper block on ship resistance

Figure 5 shows time series of the ship resistances in brash ice channels; results of Cases AR, AI, BR, BI, CR and CI are shown. In each case, the numbers of spherical and cubic ice pieces are equal to each other. A stopper block is not placed. In this figure, average ship resistance in Case AR between 10 s and 20 s is larger than that in Case AI. The resistance in Case BR is a little larger than that in Case BI, but the difference is not significant. The resistance in Case CR is a little smaller than that in Case CI, and the difference is also not significant.

The calculated channel resistances are nearly equal to the results described in the previous paper (Konno, 2009b). Because the resistances described in the previous work are around twice as much as those estimated by FSICR rule formula (Finnish Maritime Administration 2008), the results in the above simulations seem to also overestimate the resistance.

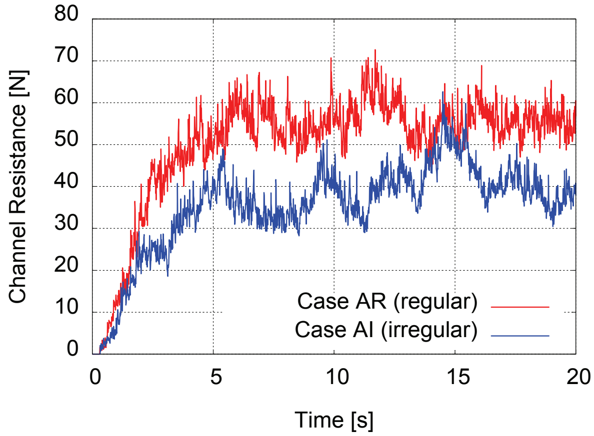
Figure 6 shows time series of channel resistance with and without a stopper block as described in Figure 2. Cases BR and CR with and without stopper blocks is compared. In each case, the numbers of spherical and cubic ice pieces are equal to each other. In Case BR, the ship does not reach the stopper block in 20 seconds so that the ship always navigates in the channel filled with ice pieces. The difference of the resistance between with and without the stopper block is insignificant. In Case CR, the ship hit the stopper block around 11 seconds. The resistance increases near that time, but before that, the difference of the resistances is also insignificant.

Effect of ratio of spherical and cubic ice pieces on ship resistance

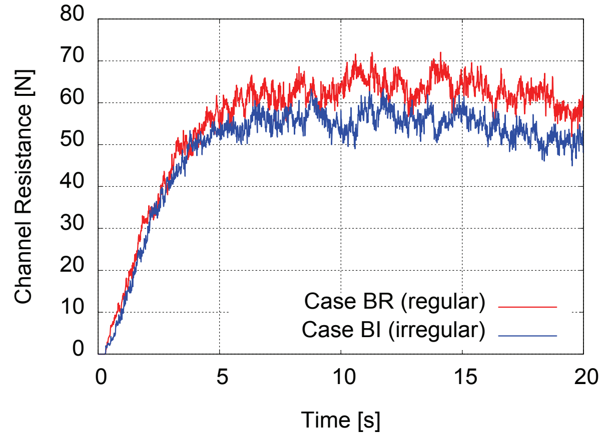
Figure 7 shows time series of channel resistances with different ratios of spherical and cubic ice pieces. Cases AI and BI, which are cases with irregular arrangements, are prepared with three different ratios; sphere to cube are 3:7, 5:5 and 7:3. Results of Cases AI and BI with ratio 5:5 are the same results of Cases AI and BI shown in Figure 5, respectively. In each case, the more the spherical ice pieces are, the less the resistance is.

DISCUSSION

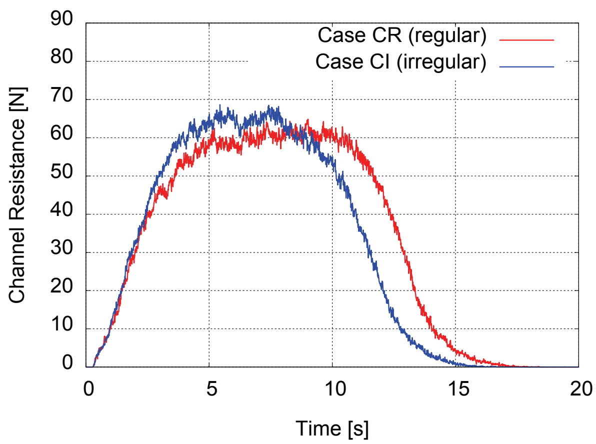
The results described in Figure 5 suggest that ice arrangement is not a dominant factor against ship resistance if rather smaller ice pieces are used. In the real brash ice channel situation, the size ratio of ice pieces against the ship size is smaller than that of our simulation so that the difference of arrangement of ice pieces might not be important. At this time, however, we cannot conduct simulations with more numbers of smaller ice pieces than the above simulations because of limitation of the computational resource so that we cannot investigate more *natural* situations.



With large ice pieces

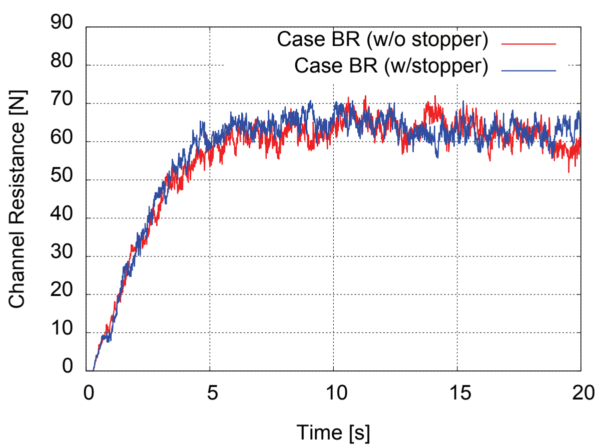


With medium ice pieces

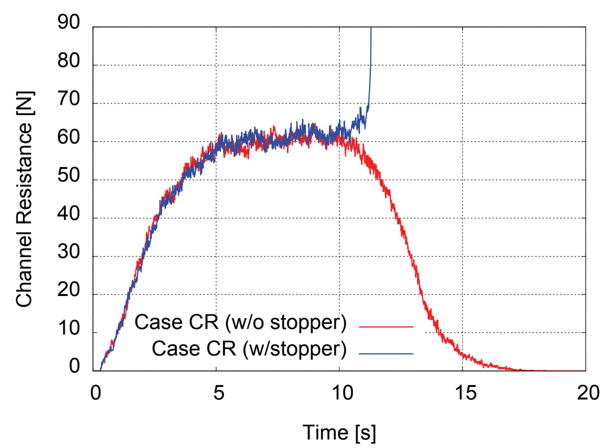


With small ice pieces

Figure 5. Time series of channel resistances with different channel arrangements

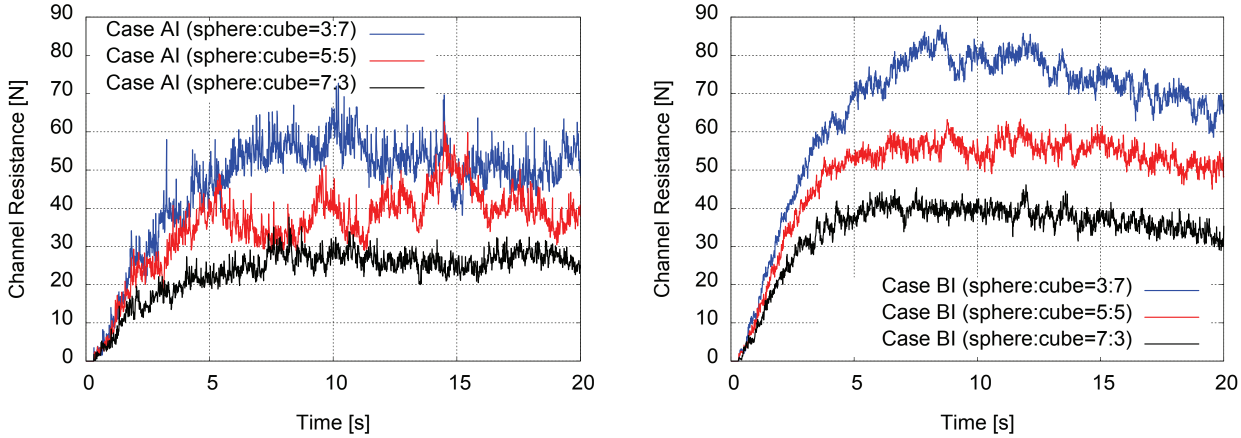


With medium ice pieces



With small ice pieces

Figure 6. Time series of channel resistance with and without stopper block. Cases with regular arrangements are used.



With large ice pieces　　　　With medium ice pieces

Figure 7. Time series of channel resistances with different number ratios of spherical and cubic ice pieces. Cases with irregular arrangements are used.

From the results described in Figure 6, it is observed that the existence of a stopper block does not affect channel resistance. As the stopper block imitates an infinite-length channel filled with ice pieces connected from the present brash ice channel, the above results suggest that the channel length deployed for our simulation for Case BR is long enough to estimate average channel resistance. The length is 12.095 m which is about four times as long as the length of the ship and is more than eight times as much as the channel width.

The results described in Figure 7 suggest that the ratio of spherical cubic ice pieces is a dominant factor against ship resistance. In the real situation, it seems that near-spherical ice pieces are comparatively more than cubic pieces. As is described in Konno (2009b), our simulation has a tendency to produce rather higher resistance in case of the same numbers of spherical and cubic ice pieces. Considering the above results, it seems that we should choose an appropriate number ratio of spherical and cubic ice pieces for preparation of virtual channel to obtain better simulation results. However, the appropriate ratio is not obvious, and further investigations are required.

The above simulations do not consider a consolidated layer of the brash ice but the FSICR requires consideration of that for ice class IA Super. The method to represent the consolidated layer in the simulation should also be investigated.

CONCLUSIONS

We develop a method to prepare irregularly-placed virtual brash ice channels that are more natural than that of regularly-placed ice conditions. Effects of ice arrangement and existence of a stopper block at the further end of the channel against ship resistance are investigated by using a numerical simulation method we have developed. As a result, channel conditions such as ice arrangement and existence of a stopper block do not affect on the ship resistance significantly. Effect of the number ratio of spherical and cubic ice pieces is also investigated. As a result, the more the spherical ice pieces are, the less the resistance is. This suggests that an appropriate ratio should be chosen, but the ratio is not obvious. Further investigations are required.

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A part of our simulations is processed with HA8000 Cluster System in Supercomputing Division, Information Technology Center, The University of Tokyo.

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