MODEL TESTS ON ICE-RUBBLE SIZE
AND SHIP RESISTANCE IN ICE RUBBLE

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R. Ettema, M. Matsuishi and T. Kitazawa

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ABSTRACT

Described here are the results of model tests on resistance to ship-hull motion through a thick layer of ice rubble; layer thickness was 45% of hull draft. The tests were aimed to elucidate the influences of ice-rubble size on ice-rubble resistance. It was found that as ice-rubble size increased so did the resistance encountered by the test hull. However, it was found also that a layer of mush ice produced a greater resistance than did layers comprised of ice blocks. A layer comprised of both mush ice and ice blocks produced a resistance intermediate to layers comprised of either mush ice or ice blocks.

Ship resistance generally increased with increasing ship speed. However, the relationships between component resistance terms, ship speed and ice-rubble size were found to be somewhat more complex. For example, the frictional resistance experienced by the parallel midbody of the test hull initially decreased with increasing ship speed, when the ice rubble was comprised of ice blocks which were small compared to layer thickness and hull size. The frictional resistance subsequently increased then decreased again with increasing ship speed. When the layer was comprised of relatively large ice blocks, frictional resistance increased to a maximum value then decreased with increasing ship speed. Generally, larger frictional resistance occurred for the layers comprised of larger ice rubble. In accordance with the relative sizes of ice rubble and ship hull, and with hull speed, the variations in frictional resistance can be explained in terms of a layer behaving as either a granular medium or as a viscous fluid.

An additional aim of the study was to verify the existence of a thrust due to the ascension of submerged ice at a hull's stern. The existence of a stern thrust had been postulated by Kitazawa and Ettema (1985). The present study indicated that a relatively weak stern thrust may occur, but its magnitude is negligibly small compared to other resistance forces.
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# TABLE OF CONTENTS

| LIST OF FIGURES ................................................................. | v |
| LIST OF TABLES ................................................................. | vi |
| I. INTRODUCTION ................................................................. | 1 |
| A. Scope of Study .............................................................. | 1 |
| B. Ice-Rubble Resistance to Ship-Hull Motion ....................... | 1 |
| C. Resistance Components .................................................. | 3 |
| D. Previous Model Tests on Ice-Rubble Resistance .................. | 4 |
| II. EXPERIMENTS ................................................................. | 5 |
| III. PRESENTATION OF RESULTS .............................................. | 7 |
| A. Resistance Curves .......................................................... | 7 |
| B. Time Histories and Observations on Ice Movement ............... | 7 |
| IV. DISCUSSION OF RESULTS ................................................ | 9 |
| A. Influences of Ice-Rubble Size on Total Resistance ............. | 9 |
| B. Influences of Ice-Rubble Size on Resistance Components .......... | 11 |
| C. Relative Magnitudes of Resistance Terms ......................... | 15 |
| V. CONCLUSIONS ...................................................................... | 16 |
| REFERENCES ........................................................................... | 17 |
| FIGURES ................................................................................. | 19 |
| TABLES ................................................................................. | 41 |
| APPENDIX 1: Time Histories of Measured Quantities .......... | 44 |
LIST OF FIGURES

Fig. 1. Test hull with the wedge and icebreaker bows........19
Fig. 2. Instrumentation for bow resistance measurement.......19
Fig. 3. The abbreviated lines of the test hull's midbody and stern........................................20
Fig. 4. Layout of the ice-rubble channel........................21
Fig. 5. Views of the test channel (a), and the icebreaker-bow hull moving through the test channel, (b).......22
Fig. 6. Views of the model ice rubble.............................23
Fig. 7. Resistance encountered by the icebreaker-bow hull in the ice-rubble channel.........................24
   (a) Total resistance..................................24
   (b) Bow resistance..................................24
   (c) Parallel-midbody resistance....................25
   (d) Stern resistance................................25
Fig. 8. Resistance encountered by the wedge-bow hull in the ice-rubble channel.............................26
   (a) Total resistance..................................26
   (b) Bow resistance..................................26
   (c) Parallel-midbody resistance....................27
   (d) Stern resistance................................27
Fig. 9. Comparison of total resistances encountered by the icebreaker-bow hull in rubble comprised of ice blocks, ice mush and a mixture of ice mush and blocks.................................28
Fig. 10. Movement of ice rubble around the icebreaker-and wedge-bow hulls.................................29
Fig. 11. Impact of individual ice rubble with the wedge bow...30
Fig. 12. Time histories of resistance forces (wedge bow, D = 91 mm, V = 0.62 m/s).........................31
Fig. 13. Time histories of resistance forces (wedge bow, D = 26 mm, V = 0.08 m/s)...........................31
Fig. 14. Time histories of resistance forces (icebreaker bow, D = 26 mm, V = 0.08 m/s)....................32
Fig. 15. Time histories of resistance forces (icebreaker bow, D = 12 mm, V = 0.08 m/s)....................32
Fig. 16. "Developed condition" of ice-rubble accumulation beneath an inclined bow (after Keinonen 1979)........33

Fig. 17. The lateral extent of yield zone/hull beam, \( \ell/B \), versus hull speed.................................34

Fig. 18. Influence of ice-rubble size on ice-rubble resistance.........................................................35

Fig. 19. Variation of bow-wave amplitude with hull speed and ice-rubble diameter..........................36

Fig. 20. Relative magnitude of resistance terms for the icebreaker-bow hull.................................37
   (a) \( D = 26 \text{ mm} \).........................................................37
   (b) \( D = 75 \text{ mm} \).........................................................37
   (c) \( D = 91 \text{ mm} \).........................................................38
   (d) \( D = 12 \text{ mm} \) (mush ice).................................38

Fig. 21. Relative magnitudes of resistance terms for the wedge-bow hull.........................................39
   (a) \( D = 26 \text{ mm} \).........................................................39
   (b) \( D = 75 \text{ mm} \).........................................................39
   (c) \( D = 91 \text{ mm} \).........................................................40

LIST OF TABLES

Table 1. Summary of Some Previous Model Tests on Ice-Rubble Resistance........................................41

Table 2. Principal Dimensions of the Test Hull.................................................................................42

Table 3. Characteristics of the Model Ice Rubble.................................................................43
MODEL TESTS ON ICE-RUBBLE SIZE
AND SHIP RESISTANCE IN ICE RUBBLE

I. INTRODUCTION

When a ship passes through a layer of floating ice rubble, the resistance that it encounters is influenced by a concert of parameters, including: hull form and speed, the roughness and lateral confinement of the layer, and the size, shape, strength and roughness of the ice fragments comprising the ice rubble.

A. Scope of Study. The primary aim of the laboratory study described here was to relate ice-rubble resistance to the size of the ice fragments comprising a relatively thick (45% of the draft of the test hull) layer of ice rubble. In particular, the study was directed to examine the influences of ice-rubble size on the component processes contributing to the resistance experienced by a ship hull moving through a layer of ice rubble. These processes involve the failure of the layer of ice rubble, submergence of ice, momentum exchange between ship and ice, friction between ship and ice, and water resistance.

The study is a continuation of an earlier study by Kitazawa and Ettema (1984a, b and 1985) who examined the resistance to ship-hull motion through layers of brash ice. During the course of their study, Kitazawa and Ettema postulated the existence of a stern thrust that is attributable to the contact of rising, buoyant ice rubble beneath the stern of a hull. A second aim of the present study was to verify the existence, and to document the magnitude, of stern thrust by attempting to measure it directly.

B. Ice-Rubble Resistance to Ship-Hull Motion. Ice rubble broadly denotes fragmented ice. As such, ice rubble occurs in many sizes and forms, although more strictly speaking it is categorized (e.g., see La Belle et al. 1983) as fragments whose major, linear dimension exceeds about 2 meters. Smaller ice fragments in the size range of 2 to 0.02 m are categorized as brash ice. Ice fragments that are yet finer usually
form mush ice. In this paper, for simplicity's sake, the term ice rubble is used to describe all sizes of fragmented ice, although a distinction is made between rubble comprised of ice blocks and rubble comprised of mush ice.

In order to understand the influences of ice-rubble size on ice-rubble resistance, it is useful to consider briefly the dynamics of a single fragment of ice floating amidst fellow fragments in the path of an on-coming ship, and then to consider the role of the fragment in the processes contributing to the resistance that the ship experiences while moving through the ice rubble.

While it is stationary, an ice fragment is acted on by its buoyancy and by the restraining forces at its contact points with adjoining ice fragments, to which it may be locally fused (freeze-bonded). In accordance with the relative magnitudes of the total restraining, freeze-bond force and the buoyancy force acting on each of its constituent ice fragments, a layer of ice rubble may behave either as a special type of granular material or as a skeletal framework of locally fused ice elements. For the former condition the ice fragment is relatively large and has a large volume to surface area ratio so that buoyancy force dominates, while for the latter condition the ice fragments are relatively small and have a small volume to surface area so that the net restraining, freeze-bond force is significant and causes the ice to be cohesive in character. Mush ice, as a cohesive porridge of relatively fine ice fragments, falls into this latter category.

When set in motion during the passage of a ship hull, an ice fragment will also experience inertia and hydrodynamic forces which are governed by the fragment's size and shape, among other factors. If the ice fragment is small compared to the scale of the boundary layer of water flow around a hull, it may move with about the same speed as water. Whereas if the ice fragment is relatively large, appreciable slippage may occur between it and the water flow, causing it to move more slowly than the water, and therefore be prone to impact the hull.
A relatively large slab of ice, perhaps more appropriately called a small ice floe, may additionally be broken when impacted by the hull.

C. Resistance Components. Consider now the resistance encountered by the ship hull. The total resistance, \( R_T \), can be divided conceptually into the following terms, each being related to a resistance process involving the displacement and movement of ice rubble around the hull:

\[
R_T = R_i + R_s + R_m + R_f + R_b + R_w - T_a
\]  

(1)

in which \( R_i \) = resistance associated with the shearing or compression of the layer; \( R_s \) = resistance attributable to the submergence of ice; \( R_m \) = resistance caused by momentum exchange between the hull and the ice rubble; \( R_f \) = resistance due to friction between ice rubble and hull; \( R_b \) = resistance associated with the breaking of ice rubble, which is significant if the layer is comprised of relatively large, platey ice pieces whose plan diameter approaches hull beam; and, \( R_w \) = water resistance. Included in (1) is \( T_a \), the thrust associated with the ascension of ice at the stern of a hull, as postulated by Kitazawa and Ettema. Although it is assumed that the resistance terms are independent of each other, it is likely that (1) is not exactly a linear relationship, and that some of the terms do indeed affect one another. For example, friction between ice rubble and the hull influences the movement of ice rubble in the vicinity of the bow, and thereby may influence \( R_i \). Some analyses of ice resistance implicitly include the effect of friction in their evaluation of \( R_i \) (e.g., Keinonen 1979), while others (e.g., Kotras et al. 1983, Naegle 1981) explicitly separate the effect of friction from the other resistance terms. Each component of resistance is, however, difficult to measure directly.

Segmenting a hull, as was done by Kitazawa and Ettema (1984a, b and 1985), may provide some insights on the relative magnitudes of the resistance terms given in (1), and enable assessment of their sensitivities to such parameters as, hull speed, thickness of rubble-ice layer and rubble-ice size. The present study involved a hull segmented into three parts as shown in figure 1: bow, parallel midbody and stern.
portions. Equation (1) can be modified for each hull portion in the following manner: Resistance experienced by the bow

\[ R_B = R_i + R_m + R_s + R_{bf} + R_{bw}. \]  

(2)

Resistance experienced by the parallel midbody

\[ R_p = R_{pf} + R_{pw}. \]  

(3)

Resistance experienced by the stern (without propeller),

\[ R_s = R_{sf} + R_{sw} - T_a. \]  

(4)

The subscripts B, P and S in (2) through (4) refer to the bow, parallel midbody and stern parts, respectively. In the present study, the test hull was instrumented so that \( R_B, R_p \) and \( R_S \) were directly measured. Additionally, two bow forms were selected such that either of the resistance terms \( R_i \) and \( R_s \) would dominate the other at low hull speeds when \( R_m \) is relatively small. In this manner, the test hull was designed so as to yield, after a certain amount of interpretation, information concerning the influences of ice-rubble size on resistance to hull motion through a thick layer of ice rubble.

D. Previous Model Tests on Ice-Rubble Resistance. Few laboratory studies have been conducted on the resistance encountered by vessels in relatively thick layers of rubble ice. Some of the studies that have come to the authors' attention are listed in table 1 which indicates the variety of ice-rubble sizes and materials as well as hull forms that have been used in model studies on ice-rubble resistance. There are several other studies (e.g., Enkvist 1983, Tatinclaux 1984) that have been conducted on ship resistance in a single layer of broken ice. These studies are not included in table 1.

It appears that only one study, that by Kostilainen and Hanirova (1982) has investigated the influence of ice-rubble size on ice-rubble resistance. Using plastic blocks to simulate ice rubble, they found that
resistance decreased with increasing size of ice rubble. Further, their data showed that a more nonuniform composition of ice rubble produced a greater resistance than that caused by each of the component ice-rubble sizes forming the mixture sizes.

II. EXPERIMENTS

Series of experiments were performed using the IIHR model-ice towing tank which is 20 m x 5 m x 1.3 m deep. Urea ice was used as the model-ice material.

The test hull, which is depicted in figure 1, was 3.0 m long and had a beam and draft of 0.44 m and 0.17 m, respectively. This same hull was used by Kitazawa and Ettema (1984a, b and 1985). In form, the hull is similar to a small oil tanker or bulk-cargo vessel with a single propeller. Two bow forms, a wedge and a simplified icebreaker bow, were used to investigate the influences of ice-rubble size on ice-rubble resistance for two, simple bow forms. The water-line angle of both bows was 30 degrees and the stem inclination angle of the icebreaker bow was 30 degrees. The hull was segmented into three parts: bow, parallel midbody and stern. The bow and the stern were each connected to the parallel midbody by way of a cantilever and load-cell mechanism for measuring the ice and water forces exerted against each part. The bow, separated at square station 7, was connected to the midbody by way of two moderately flexible plates and two cantilever beams, as shown in figure 2. An identical mechanism was used to connect the stern, which was separated at square station 2.5, to the midbody.

The abbreviated lines of the midbody and stern of the test hull and given in figure 3, and the principal dimensions of the hull are listed in table 2.

Total resistance, or towing force was measured using a dynamometer coupling between the hull and the ice tank's motorized carriage.

Details of the experimental ice-rubble layer are shown schematically in figure 4. Layer thickness H and lateral extent W were maintained
constant at 0.077 m (0.45 times the hull's draft) and 1.35 m (three times the hull's beam) respectively. The layer was bounded by two, parallel sidewalls supported from floating wooden panels which were used to simulate a bordering cover. The test channel and the icebreaker-bow hull moving through the test channel are depicted in figures 5a, b.

The ice rubble pieces were produced by fragmenting unseeded sheets of urea ice to a specified size range. The ice sheets were grown from a 0.5% concentration, by weight, urea solution.

The primary characteristics of the model ice rubble are summarized in table 3. Five sizes of moderately uniform ice fragments were used. Four layers were comprised of ice blocks with a thickness to average plan diameter ratio ranging from 0.21 to 0.33. One layer of mushy ice was comprised of crystal size fragments resulting from the disintegration of tempered, wet-seeded urea ice grown from a 1.0% concentration urea solution. In order to examine the affect of mixed ice-rubble sizes on ice-rubble resistance, one layer was formed of a mixture of mush ice and ice blocks. Figures 6a, b and c illustrate the layers comprised of 91- and 46-mm ice blocks, and mush ice, respectively.

The porosity of the layers of ice rubble varied with the size of the ice rubble, generally decreasing with increasing ice fragment size. It was noticed that the larger ice pieces tended to align themselves horizontally in the layer and thereby reduce interstitial void volume, whereas the smaller pieces tended to be more randomly oriented. The porosity of each layer of rubble ice was measured by removing a portion of each layer with a perforated canister of known volume and measured weight.

For each series of experiments, several transits of the test layer were made with the hull moving with constant model speed in the range of 0.08 to 1.20 m/s. After each hull transit, the characteristics of the track left by the hull were noted. The layer of ice rubble was then regroomed and levelled to its original condition. Usually, for each test series, about two tests were repeated in order to determine the variation in the experimental data.
III. PRESENTATION OF RESULTS

A. Resistance Curves. The temporal mean values of the resistance forces acting against the test hull, its bow, parallel midbody and stern are plotted versus hull speed for the following categories of fragmented ice:

1. Rubble ice: see figures 5a-d and 8a-d, for icebreaker- and wedge-bow hulls, respectively;
2. Mush ice: see figure 7a-d;
3. Mixed mush and block ice: see figure 9.

The wedge- and icebreaker-bows were used for the rubble-ice tests, while only the icebreaker bow was used for the mush-ice and mixed-ice tests.

Figures 7 through 9 illustrate that ice-rubble resistance is influenced by hull speed and bow form as well as by the size and form of ice rubble. For the icebreaker-bow hull moving through a layer of ice rubble, resistance increased with increasing hull speed and ice-rubble size. However, the model hull experienced its greatest resistance for the layer comprised of mush ice. For the larger sizes of ice rubble, resistance slightly decreased at first with increasing speed of the wedge-bow hull, then increased with increasing hull speed. The resistance caused by a layer composed of mush ice and ice blocks was intermediate to the resistances associated with either mush or block ice (figure 9). These results differ significantly from those reported by Kostilainen and Hanrova (1982).

B. Time-Histories of Resistance and Observations on Ice Movement. The time history of resistance experienced by the test hull with each bow can be related to observations on the movement and displacement of ice rubble around the test hull. For example, it was observed that ice passed directly beneath the icebreaker-bow hull with little lateral displacement as schematically indicated in figure 10a. However, for the wedge-bow hull moving slowly, ice was displaced laterally and moved
through a cuspsate shear zone flanking each side of the wedge bow (see figure 10b). At higher speeds (in excess of 0.4 m/sec) the ice rubble flowed as a viscous fluid around the wedge-bow hull (figure 10c). In addition to the formation of shear zones, a characteristic feature of ice-rubble displacement by the wedge-bow hull was collision between individual pieces of ice rubble and the bow, especially for the larger ice rubble pieces. The photograph figure 11 illustrates the collision of ice rubble with the bow of the wedge-bow hull. Time histories of the total, bow and stern resistances are contained in Appendix 1.

The overlap of the processes of formation and ice-piece collision led to a fairly irregular time history of resistance for the wedge-bow hull, as shown in figure 12, for D = 91 mm and hull speed = 0.62 m/s. The resistance fluctuations are somewhat less for the smaller ice rubble, D = 26 mm and hull speed = 0.08 m/s, as shown in figure 13.

Time histories of the resistance experienced by the icebreaker-bow moving slowly through the rubble ice indicate some relatively long-period cycles of resistance; e.g., see figure 14 for D = 26 mm and hull speed = 0.08 m/s; also figure 16, for D = 12 mm (ice mush) and hull speed = 0.08 m/s. The cycles can be attributed to adjustments in hull trim which in turn can be associated with the unsteady accumulation and collapse of ice rubble submerged beneath the inclined icebreaker bow. Keinonen (1979) describes the steady-state, "developed condition" of ice-rubble accumulation beneath an inclined bow. He suggested that the accumulation of ice rubble occurs as shown in figure 16. The relatively long-period resistance cycle, which is most apparent in the resistance experienced by the icebreaker-bow hull moving through the layer of mush ice, figure 15, indicates that the "developed condition" is unsteady. Commensurately, as is evident from figures 12 through 15, resistance due to ice rubble can at times be unsteady.

The maximum width (see figure 10b), \( l \), of the cuspsate shear, or yield, zones adjoining the wedge bow was estimated, from a video film of each vessel transit, and plotted normalized with hull beam B, as shown in figure 16. The shear zones were observed to dilate, or swell and collapse, nonsynchronously each side of the wedge bow. The unsteadiness
of the shear-zone formation is reflected in the longer-period oscillations of resistance shown in figure 12 for the wedge-bow hull. The width, \( l \), increased with increasing size of ice rubble, and decreased with increasing hull speed. For all tests except one, \( l/B \) was less than unity (channel width = 3B), and decreased with increasing hull speed as is indicated in figure 17. The shear zone was broader than half the width of test channel for the test involving the 91-mm diameter ice rubble and the wedge-bow hull moving with a speed of 0.08 m/s. Incidentally, the foregoing observations suggest that the definition of confined channel must take into account the size of the ice rubble comprising the channel and the speeds at which a vessel transits the channel.

IV. DISCUSSION OF RESULTS

The resistances encountered by the test hulls transiting the test layers of ice rubble were significantly affected by the size of the ice rubble comprising the layers. The influence of ice-rubble size on ice-rubble resistance can be summarized graphically as shown in figure 18 which is discussed below under the following headings:

1. Influences of ice-rubble size on total resistance;
2. Influences of ice-rubble size on resistance components;

A. Influences of Ice-Rubble Size on Total Resistance. It is evident from figures 7a and 8a, that the total resistance encountered by the test hulls generally increased with increasing size of ice rubble pieces. The layer comprised of mush ice exerted a greater resistance against the test hull with the icebreaker bow than did the layers comprised of discrete ice blocks.

Total resistance attributable to rubble ice and mush ice, \( R_R \), can be evaluated as being the total resistance \( R_T \) minus openwater resistance \( R_{ow} \). Ice-rubble resistance, \( R_R \), nondimensionalized with the mean resistance associated with submerging ice rubble beneath a hull, \( R_s \), is
plotted in figure 18 versus the approximate number, $N$, of ice fragments in a characteristic volume of ice-rubble layer. A logarithmic scale is used for plotting $N$ so that the broad range of ice fragment sizes can be encompassed. Here, $R_s$ and $N$ are determined as

$$R_s = (1-p)(1-\rho_I/\rho_w)\rho_w gHBd$$

and

$$N = \frac{B^2H}{D^2h} .$$

It is assumed for (6) that characteristic volumes of ice-rubble layer and ice rubble fragments can be defined as $B^2H$ and $D^2h$, respectively. The volume $B^2H$ is appropriate for characterizing the layer of rubble ice ahead of the hull's bow because the plan area of the bow and the area of ice that it loads are proportional to $B^2$. Note that $N$ is intended only to indicate approximately the number of ice pieces per unit volume of rubble layer.

In order to outline zones of distinctive ice behavior, figure 18 is divided into three regions in accordance with the following classes of ice sizes: layers comprised of mush ice; layers comprised of rubble (including brash) ice; and fields of small ice floes.

Consider first the central, or rubble ice, region of figure 18. In this region, rubble ice behaves as if it were comprised essentially of a granular material and ice-rubble resistance increases with increasing ice-rubble size and hull speed. As is discussed later in this paper, this trend reflects largely an increase in resistance due to the impact of individual pieces of ice rubble with the hull's bow.

The increasing resistance indicated in figure 18 for the mush ice region can be attributed to the fabric-like behavior of the layers of mush ice. A possible further cause for this increased resistance is the lack of scaling of the freeze-bond forces between ice pieces. This effect is of significance for fine ice pieces, and is a short-coming presently plaguing laboratory testing of fragmented ice. It remains to be seen if such an increase in resistance occurs for full-scale vessels transiting fragmented ice.
At the other end of the size range, vessels transiting a field of ice floes, whose diameters, $D$, approach vessel beam, $B$, ice-breaking would introduce an additional resistance component due to ice-breaking $R_b$ (see (1)) which would likely lead to an increase in resistance. Because no tests were conducted by the authors using ice rubble in this size range, the form of the resistance curves in this region are not defined.

**B. Influences of Ice-Rubble Size on Resistance Components.** Having stated above that ice-rubble size influences ice-rubble resistance, it is of interest to examine now the manner by which ice-rubble size affects the component resistance terms in (1): strength of ice-rubble layer; submergence of ice rubble; momentum exchange between hull and ice rubble; and friction between hull and ice rubble.

The resistance forces measured for each segment of the test hulls can be used to interpret the affects of ice-rubble size on the resistance terms. Equations (2) through (4) indicate the approximate relationship between the measured forces and the resistance terms. Insofar that the resistance terms are difficult to separate exactly, and may indeed be somewhat interactive, a certain amount of interpretive error is involved.

Resistance due to internal resistance of layer, $R_i$: For a layer comprised of ice rubble acting as discrete ice blocks, $R_i$ increases with increasing size of ice rubble. This is evident in Fig. 8b in which the resistance measured for the wedge bow moving with very low speed can be attributed primarily to $R_i$. Although the wedge-bow hull was not tested in a layer of mush ice, it can be surmised using the data from the experiments conducted by Kitazawa and Ettema (1984a,b and 1985) that the internal resistance of the mush ice exceeded that for the rubble ice tested.

Resistance due to submergence, $R_s$: It is apparent from figure 7b that $R_s$ increases with increasing size of ice rubble. For low speeds, resistance due to momentum exchange, $R_m$, between the hull and ice pieces is relatively small compared to $R_s$ so that the resistance experienced by the icebreaker bow is attributable largely to $R_s$. (Whereas for the
wedge-bow, resistance was largely attributable to \( R_1 \). When the icebreaker-bow hull moved through the layer of mush ice, the layer was deflected downwards, locally disrupted and passed beneath the icebreaker bow.

Resistance due to momentum exchange between hull and ice, \( R_m \): It is evident from figures 7b and 8b that \( R_m \) increased with increasing size of ice-rubble pieces. For relatively large values of hull speed, the resistance force experienced by the bow is due largely to the impact of ice rubble against the bow. Because \( R_8 \) is independent of hull speed and \( R_1 \) is much decreased due to shear thinning, \( R_8 \) and \( R_1 \) are relatively small compared to \( R_m \).

Resistance due to friction between hull and ice, \( R_f \): The ice-rubble resistance encountered by the parallel midbody of the test hull were influenced by hull speed and by ice-rubble size. If it is assumed that midbody resistance was mainly due to friction between hull and ice, it can then be shown that \( R_f \) is dependent on hull speed and is affected by ice-rubble size. However, on the basis of results from the present tests, it is somewhat premature to conclude definitively the manner whereby hull speed and rubble size influence \( R_f \). For example, although it is evident from figures 7c and 8c that the larger ice rubble generally produced greater frictional resistance, the relationship between frictional resistance and hull speed is less clear. For the largest ice rubble, (\( D = 91 \) mm), frictional resistance due to ice rubble (\( R_{pf} - R_{pw} \)) initially increased with increasing hull speed then decreased with increasing hull speed. Whereas, for the smaller ice rubble (\( D = 26 \) mm), frictional resistance initially decreased, then increased and subsequently decreased with increasing hull speed.

Although more confirming tests are needed, and data points are relatively few, it can be conjectured that the initial decrease in frictional resistance for the 26-mm diameter ice blocks was due to a reduction in layer pressure against the hull's midbody. Mellor (1980) offers a plausible explanation for the decrease in layer pressure along the hull aft of the bow. Treating ice rubble as a granular material, he uses Rankine yield theory to argue that the normal force, or pressure,
exerted against the midbody should be less than that produced with the layer in a passive Rankine state. With increasing hull speed, the pressure should decrease even further because less time is available for the layer to compact and thicken and develop a greater pressure. Eventually, for still larger hull speeds, the layer became fluidized and could not be treated as a granular medium. When this occurred, frictional resistance increased with increasing speed. The increase with hull speed is similar to the increasing resistance encountered by a body moving through a viscous fluid. For flat plate moving through a viscous fluid, drag increases with the three-halves power of the velocity of the plate (Schlichting 1979). Associated with increasing hull speed is, of course, the formation of ship waves.

It was noted during the experiments that, for increasing amplitude of bow wave, the rubble layer dilated to become more porous, and a pocket of openwater formed at the hull's shoulder, which was coincident with the trough of the bow wave. With increasing amplitude of bow wave, water was flushed along the hull's midbody. For the very high test speeds, ice contact with the hull's midbody was greatly reduced and consequently, the frictional resistance \( R_{pf} \) decreased for both the icebreaker and the wedge bows.

The Rankine yield theory for a granular material likely does not hold for the layer comprised of the 91-mm diameter ice blocks, because the blocks were too large compared to layer thickness and hull size. It is possible, therefore, that significant pressure reduction did not occur in the layer along the hull's midbody, and that frictional resistance simply increased with increasing hull speed. This would imply that the value of friction coefficient between ice rubble and ship hull increased with increasing hull speed. Data produced by Forland and Tatinclaux (1984) on friction between a pressurized ice block and a metal surface show this effect. For the larger hull speeds, bow-wave formation influenced the flow of water and ice around the hull causing a reduction of ice contact with the hull, as occurred for the finer ice rubble.

Stern thrust due to ice ascension, \( T_s \): The existence of a significant stern thrust attributable to the ascension of ice submerged
beneath the hull, as postulated by Kitazawa and Ettema (1984a,b, and 1985), was not fully supported by the results from the present study. As can be seen from figures 7d and 8d, even in openwater the stern of the test hull experienced a thrust that can be ascribed to the flow of water around the stern and the formation of a stern wave. The magnitude of the stern thrust in openwater increased with increasing hull speed and, thereby, with increasing amplitude of stern wave. The presence of ice rubble led to a mild increase in stern thrust for slow speeds, but resulted in a decrease in stern thrust for relatively high speeds because the rubble ice dampened the amplitude of the stern wave. The layer of mush ice produced a resistance, against the stern portion of the icebreaker-bow hull, which steadily increased with increasing hull speed. This is quite a different result from that obtained for the layers comprised of ice blocks. One explanation for the resistance imposed by the layer of mush ice is the fabric-like, cohesive behavior of a layer of mush ice. The effect of cohesiveness of mush ice can be seen by comparing the tracks left by the test hull, with icebreaker bow, moving through a layer of ice blocks (figure 6a) and through a layer of mush ice (figure 6b). The center of the layer of ice blocks is considerably thinned after hull passage; not so for the layer of mush ice.

Resistance attributable to water flow, \( R_w \): Insofar that \( R_w \) usually is negligibly small in comparison with the other resistance terms in (1), it is customary to either neglect it or to assign it a value equivalent to the hull's openwater resistance at the same speed. However, when bow and stern waves develop around a hull \( R_w \) may not be negligibly small compared to the other terms in (1). The present study has shown that a layer of ice rubble acts to reduce the amplitude of ship waves and thereby influence \( R_w \). The influence is indicated in figure 19 in which are plotted measured amplitudes of bow wave versus hull speed for the wedge-bow hull moving through openwater and a layer of ice rubble. It can be surmised from figure 19, that because the presence of a layer of ice rubble reduces the amplitude of a bow wave, the water resistance, \( R_w \), may be somewhat less than openwater resistance \( R_{ow} \). This is illustrated
in the following section in which the relative magnitudes of resistance terms are plotted.

C. Relative Magnitudes of Resistance Terms. By matching the measured resistance forces (total, bow and stern), minus their openwater values, to the resistance terms in (1), it is possible to obtain estimates of the relative magnitudes of these resistance terms for the test hull. This is done in figures 20a-d and 21a-c for the test hull fitted with the icebreaker- and wedge-bows, respectively.

Although the matching process admits a certain amount of interpretive error, particularly in the division of the ice resistance measured against each bow form, the overall trends do illuminate the influences of ice rubble size on resistance terms. It is assumed in figure 20 that \( R_b \) is negligibly small compared to \( R_j \) for the wedge-bow hull, and in figure 20 that the reverse is true for the icebreaker-bow hull. Further, it is assumed that \( R_m \) is zero when the hull is not moving but increases proportionately with speed to the power 1.5 to 2.

The friction of ice rubble against each bow was estimated using the method proposed by Mellor (1980) with the friction coefficient between hull and ice rubble of 0.14. This average value of friction coefficient was determined from the resistance experienced by the hull's parallel midbody with the wedge-bow hull moving at the slowest test speed.

It is evident from figures 20a-d and 21a-c that with increasing speed of the test hulls the proportion of ice-rubble resistance to total resistance decreased. This is because openwater resistance increased more sharply than did ice-rubble resistance. For the test hull fitted with the icebreaker and wedge bows, the ratios \( (R_b + R_m)/R_T \) and \( (R_i + R_m)/R_T \), respectively, initially decrease with increasing speed of hull, until becoming more-or-less constants whose values depended on ice-rubble size and bow form.

When the test hull was moving with creeping speed through the layer of rubble ice, frictional resistance between ice and hull accounted for about 30 to 45% of total resistance encountered by the hull. At the highest test speed, frictional resistance contributed about 10 to 20% of
the total resistance. Between these two velocities, frictional resistance varied in a fairly complex manner with increasing hull speed. Explanations for the variation of frictional resistance with hull speed are proposed in the preceding section of this paper.

Thrust attributable to the ascension of ice at the stern of the hull was negligibly small for both bow forms and all sizes of ice rubble.

V. CONCLUSIONS

The following conclusions were drawn from the laboratory study on the influence of ice rubble size on rubble ice resistance encountered by vessels.

1. The resistance encountered by the test hull moving steadily through a layer of ice blocks, or discrete ice-rubble pieces, increased with increasing ice-rubble size and generally with increasing hull speed.

2. The test hull moving through a layer of mush ice encountered a greater resistance than it did when moving through a layer of identical thickness but comprised of ice blocks.

3. The resistance exerted by a layer comprised of ice blocks and mush ice was intermediate to the resistances exerted by a layer comprised of either ice blocks and mush ice.

4. The proportion of ice-rubble resistance to total resistance encountered by the test hull decreased with increasing speed of hull motion through an ice-rubble layer because openwater resistance increased more sharply than did ice-rubble resistance.

5. The frictional resistance encountered by the test hull's parallel midbody was dependent on hull speed and the relative sizes of ice rubble, ship hull and layer thickness.
REFERENCES


Greisman, P. (1981), "Brash ice behavior." Report No. CGRDC-9/81, U.S. Coast Guard Research and Development Center, Groton, CT.


Fig. 1. Test hull with the wedge and icebreaker bows (hull length at LWL = 3.0 m, beam = 0.44 m, draft = 0.17 m).

Fig. 2. Instrumentation for bow resistance measurements.
Fig. 3. The abbreviated lines for the test hull's midbody and stern.
Fig. 4. Layout of the ice-rubble channel.
(a) the test channel

(b) the icebreaker-bow hull moving through the test channel

Fig. 5. Views of the test channel.
(a) Ice Blocks

(b) Mush Ice

Fig. 6. The model ice rubble.
Fig. 7. Resistance encountered by the icebreaker bow hull in the rubble-ice channel; (a) total resistance; (b) bow resistance; (c) stern resistance; (d) midbody resistance.
Fig. 7. Continued.
Fig. 8. Resistance encountered by the wedge-bow hull in the rubble-ice channel; (a) total resistance; (b) bow resistance; (c) stern resistance; (d) midbody resistance.
Fig. 8. Continued.
Fig. 9. Comparison of total resistances encountered by the icebreaker hull in layers of rubble comprised of ice blocks, ice mush, and a mixture of ice mush and ice blocks.
Fig. 10. Movement of ice rubble around the icebreaker-bow hull (a), and the wedge-bow hull (b) and (c).
Fig. 11. Impact of individual ice rubble with the wedge-bow.
Fig. 12. Time histories of resistance forces: wedge-bow hull, \( D = 91 \) mm, \( V = 0.62 \) m/s.

Fig. 13. Time histories of resistance forces: wedge-bow hull, \( D = 26 \) mm, \( V = 0.08 \) m/s.
Fig. 14. Time histories of resistance forces: icebreaker-bow hull, \( D = 26 \text{ mm} \), \( V = 0.08 \text{ m/s} \).

Fig. 15. Time histories of resistance forces: icebreaker-bow hull in mush ice, \( D = 12 \text{ mm} \), \( V = 0.08 \text{ m/s} \).
Fig. 16. "Developed condition" of ice-rubble accumulation beneath an inclined bow (after Keinonen 1979).
Fig. 17. The lateral extent of the yield zone divided by hull beam, $\lambda/B$, versus hull speed.
Fig. 18. Influence of ice-rubble size on ice-rubble resistance.
Fig. 19. Variation of bow wave amplitude with hull speed and ice-rubble diameter.
Fig. 20. Relative magnitudes of resistance terms for the icebreaker-bow hull.
Fig. 20. Continued.
Fig. 21. Relative magnitudes of resistance terms for the wedge-bow hull.
Fig. 21. Continued.
<table>
<thead>
<tr>
<th>Study</th>
<th>Type of Ship</th>
<th>Beam (m)</th>
<th>Draft (m)</th>
<th>Length (m)</th>
<th>Speed Range (m/s)</th>
<th>Model Ice Material</th>
<th>Plan Dia. (mm)</th>
<th>Thickness (mm)</th>
<th>Layer Thickness (m)</th>
<th>Channel Width/Hull Beam</th>
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<tbody>
<tr>
<td>Voelker and Levine, 1972</td>
<td>a</td>
<td>0.318</td>
<td>0.165</td>
<td>3.087</td>
<td>0.3 1.2</td>
<td>mushy saline</td>
<td>25</td>
<td>10</td>
<td>0.023 ~ 0.047</td>
<td>0.2 ~ 2.0</td>
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<td>Greisman, 1981</td>
<td>b</td>
<td>1.14</td>
<td>0.366</td>
<td>4.27</td>
<td>0.15 2.1</td>
<td>hard urea</td>
<td>25 ~ 250</td>
<td>12</td>
<td>0.09</td>
<td>3.0</td>
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<td>Kostilainen and Hanirova, 1982</td>
<td>c</td>
<td>0.69</td>
<td>0.321</td>
<td>7.91</td>
<td>0.15 2.0</td>
<td>plastic</td>
<td>15 ~ 53</td>
<td>12</td>
<td>0.026 ~ 0.13</td>
<td>1.2 ~ 2.0</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15 ~ 24</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30 ~ 53</td>
<td></td>
<td></td>
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<tr>
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<td>0.39</td>
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<td>plastic</td>
<td>15 ~ 53</td>
<td>12</td>
<td>0.075 ~ 0.15</td>
<td>1.3 ~ 2.0</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30 ~ 53</td>
<td></td>
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<tr>
<td>Eskola, 1983</td>
<td>d</td>
<td>1.075</td>
<td>0.475</td>
<td>7.22</td>
<td>0.60 1.8</td>
<td>plastic</td>
<td>20 ~ 54</td>
<td>12</td>
<td>0.075 ~ 0.104</td>
<td>1.2 ~ 2.0</td>
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<td>Hanirova, 1983</td>
<td>d</td>
<td>1.333</td>
<td>0.347</td>
<td>7.5</td>
<td>0.25 1.5</td>
<td>plastic</td>
<td>20 ~ 54</td>
<td>12</td>
<td>0.075 ~ 0.15</td>
<td>1.2 ~ 2.0</td>
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<td>Kitazawa and Ettema, 1985</td>
<td>d</td>
<td>0.44</td>
<td>0.17</td>
<td>3.0</td>
<td>0.15 1.2</td>
<td>tempered urea*</td>
<td>10 ~ 50</td>
<td>30</td>
<td>0.075 ~ 0.24</td>
<td>1.2 ~ 3.0</td>
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</table>

* flexural strength = 18 kPa
a Great Lakes bulk carrier, Edward L. Ryerson
b Icebreaking tug, Katmai Bay
c Passenger ferry
d Sea-going bulk-carrier
Table 2. Principal Dimensions of the Test Hull

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Wedge-Bow Hull</th>
<th>Icebreaker-Bow Hull</th>
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<tbody>
<tr>
<td>Length between perpendiculare</td>
<td>Lpp (m)</td>
<td>2.900</td>
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<tr>
<td>Water line length</td>
<td>LwL (m)</td>
<td>3.000</td>
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<tr>
<td>Breadth</td>
<td>B (m)</td>
<td>0.442</td>
</tr>
<tr>
<td>Draught</td>
<td>d (m)</td>
<td>0.170</td>
</tr>
<tr>
<td>Displacement</td>
<td>ψ (m³)</td>
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<tr>
<td>Block coefficient</td>
<td>Cb</td>
<td>0.81</td>
</tr>
<tr>
<td>Level ice thickness</td>
<td>hi (m)</td>
<td>0.03</td>
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Table 3: Characteristics of Model Ice

<table>
<thead>
<tr>
<th>Mean Diameter (mm)</th>
<th>Standard Deviation of Diameter (mm)</th>
<th>Mean Thickness (mm)</th>
<th>Layer Porosity</th>
<th>Form of Ice Rubble</th>
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<tr>
<td>12</td>
<td>3</td>
<td>2</td>
<td>0.46</td>
<td>Mush</td>
</tr>
<tr>
<td>26</td>
<td>8</td>
<td>6</td>
<td>0.46</td>
<td>Blocks</td>
</tr>
<tr>
<td>41</td>
<td>12</td>
<td>15</td>
<td>0.44</td>
<td>Blocks</td>
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<tr>
<td>74</td>
<td>20</td>
<td>21</td>
<td>0.38</td>
<td>Blocks</td>
</tr>
<tr>
<td>91</td>
<td>20</td>
<td>30</td>
<td>0.34</td>
<td>Blocks</td>
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</table>
APPENDIX 1: TIME HISTORIES OF MEASURED QUANTITIES

TABLE A-1-1: CALIBRATION COEFFICIENTS FOR RESISTANCE FORCES

<table>
<thead>
<tr>
<th>Experiment No. (File No.)</th>
<th>Date</th>
<th>Total Force (N/volts)</th>
<th>Bow Force (N/volts)</th>
<th>Stern Force (N/volts)</th>
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<tr>
<td>DO25A-F</td>
<td>Oct. 25</td>
<td>33.70</td>
<td>39.97</td>
<td>-10.10</td>
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<tr>
<td>DNO5A-G</td>
<td>Nov. 5</td>
<td>37.38</td>
<td>34.70</td>
<td>-5.08</td>
</tr>
<tr>
<td>DNO7A-J</td>
<td>Nov. 7</td>
<td>35.39</td>
<td>33.93</td>
<td>-5.83</td>
</tr>
<tr>
<td>DN12A-G</td>
<td>Nov. 12</td>
<td>36.13</td>
<td>7.82</td>
<td>-5.40</td>
</tr>
<tr>
<td>DN16A-G</td>
<td>Nov. 16</td>
<td>35.05</td>
<td>7.72</td>
<td>-5.28</td>
</tr>
<tr>
<td>DN16H-P</td>
<td>Nov. 16</td>
<td>37.04</td>
<td>7.73</td>
<td>-5.38</td>
</tr>
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<td>DN21A-J</td>
<td>Nov. 21</td>
<td>34.89</td>
<td>7.78</td>
<td>-5.70</td>
</tr>
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<td>DN22A-H</td>
<td>Nov. 22</td>
<td>37.00</td>
<td>7.78</td>
<td>-5.60</td>
</tr>
<tr>
<td>DN26A-I</td>
<td>Nov. 26</td>
<td>35.64</td>
<td>7.74</td>
<td>-5.52</td>
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<td>DN26J-Q</td>
<td>Nov. 26</td>
<td>38.35</td>
<td>7.91</td>
<td>-5.22</td>
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</tbody>
</table>
Fig. 2-1

Fig. 2-2
Fig. 2-5

Fig. 2-6
Fig. 2-7

Fig. 2-8
Fig. 3-1

Fig. 3-2
Fig. 3-5

Fig. 3-6
Fig. 4-1

Fig. 4-2
Fig. 4-7
**Fig. 5-3**

**Fig. 5-4**
Fig. 5-7
Fig. 5W-1

Fig. 5W-2
Fig. 5W-3

Fig. 5W-4
Fig. 5W-5

Fig. 5W-6
Fig. 5W-7
Fig. 6W-1

Fig. 6W-2
Fig. 6W-5

Fig. 6W-7
Fig. 6W-8

Fig. 6W-10
Fig. 6-4

Fig. 6-5
Fig. 6-6

Fig. 6-7
Fig. 6-8
Fig. 7W-1

Fig. 7W-2
Fig. 7W-5

Fig. 7W-6
Fig. 7W-7
Fig. 7-5

Fig. 7-6
Fig. 7-9