FLUID RESISTANCE OF RUBLE FIELD OF ICE

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Abstract

The maximum ice force of a large ice floe acting on structures is generally the ice force produced at the time the floe fractures. When the floe does not reach the point of fracture, or when small ice floes in clusters exert force on structures, the ice force is determined by fluid force(force of wind or flow). Also, whether ice jams are formed is closely related to the intensity of the fluid force. This paper reports on the results we obtained from model experiments on the fluid resistance of water acting on ice floe and a rubble field of ice.

In the experiments, the fluid resistances were measured using model ice of polypropylene, which were grouped into three types;

(1)Level ice floes
(2)Floes with irregular bottom surfaces
(3)Rubble fields of ice.

Experiments on the influence of the irregularities of bottom surfaces on the fluid resistance were also made by changing the configuration, size, intervals, etc. of the floes(2). Furthermore, the changes in the fluid resistance were measured in the process of ice jam formation beneath an ice cover.

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INTRODUCTION

For the design of structures constructed in rivers frozen during winter, one of the most dominant external forces is ice force. It is the force exerted on a structure by the fluid force of a floating ice sheet induced by wind and water flow. The ice force acting on structures does not normally exceed the ice force caused by the failure of the ice sheet at the contact point between the edge of the ice sheet and the structure. The ice force generated by the failure of the ice sheet is therefore usually adopted as the design ice force. However, in a relatively small water area, or when small ice sheets in clusters exert ice forces on the structure, failure of the ice sheet does not occur, and the ice force is thus equivalent to the fluid force. This theory can be applied to reservoirs, lakes, and lagoons, as well as when an ice force is exerted on intake towers, gates, ice booms, etc., by clusters of small ice sheets.

The fluid force is the shearing force and form drag. We have been conducting indoor experiments on the shearing force generated by water flow. In this report we discuss the results of these experiments.

FLUID FORCE ACTING ON ICE SHEETS

The forces acting on ice sheets are buoyancy, lift, gravity, shearing force, and form drag. Among these, the horizontal ice forces exerted on structures are the shearing force and form drag. The shearing force and form drag can be categorized into the following four types: F_{SA}, F_{DA}, F_{SW}, and F_{DW} (Figure 1). F_{SA} is the shearing force generated by the friction between the wind and the surface of the ice sheet exposed above the water. F_{DA} is the form drag caused by wind hitting the exposed part of the ice sheet. F_{SW} is the shearing force created by the friction between the water flow and the submerged ice sheet surface. F_{DW} is the form drag produced by water flow clouting the submerged surface of the ice sheet. F_A is the force of wind exerted on ice sheets equal to the sum of F_{SA} and F_{DA} when the thickness of the ice sheet is constant. F_{SA} and F_{DA} per unit width of the ice sheet can be expressed by equations (1) and (2), respectively:

$$F_{SA} = 1/2\ \rho_A C_{SA} U_{10}^2 L \qquad (1)$$

$$F_{DA} = 1/2\ \rho_A C_{DA} U_{10}^2 (0.1H) \qquad (2)$$

where, ρ_A: air density, C_{SA}: shearing coefficient between the exposed part of the ice sheet and wind, C_{DA}: coefficient of form drag caused by wind, U_{10}: wind velocity at the height of 10 m, L: effective length of the ice sheet, H: thickness of the ice sheet.

In the same manner, the fluid force exerted on the ice sheet is equal to the sum of F_{SW} and F_{DW}. F_{SW} and F_{DW} per unit width of the ice sheet can be expressed by equations (3) and (4), respectively:

$$F_{SW} = 1/2\ \rho_W C_{SW} V^2 L \qquad (3)$$

$$F_{DW} = 1/2\ \rho_W C_{DW} V^2 (0.9H) \qquad (4)$$

where, ρ_W: water density, C_{SW}: shearing coefficient between the submerged surface of the ice sheet and water flow, C_{DW}: coefficient of form drag caused by fluid force, V: water flow velocity.

From the model experiments of Ueda et al., the coefficient of the form drag of the ice sheet effected by wind is approximately 1000 times as large as that of the shearing (frictional) coefficient between the wind and the exposed surface of the ice sheet, and the coefficient of form drag effected by water flow is about 100 times as large as that of the shearing (frictional) coefficient between the water flow and the submerged surface of the ice sheet. Since the surface area of the ice sheet is much greater than the thickness of the ice sheet, the shearing force caused by the friction exerted on the ice sheet is commonly dominant over the form drag exerted on the ice sheet. Let A_S and A_D be the surface area of the ice sheet and the projected area of the ice sheet subject to the force of wind and water flow, which is regarded as resistance, respectively. The A_S divided by the A_D of wind is not much larger than 10^6. The A_S divided by the A_D of the water flow is slightly larger than 10^4. The form drag is therefore less than 1% of the shearing force, which means the form drag can be disregarded in practice.

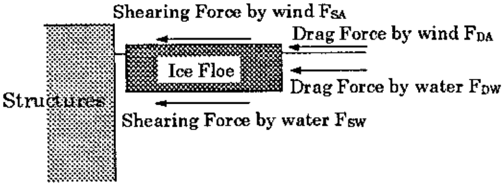


Figure 1 Fluid forces acting on the ice sheet

SHEARING FORCE EXERTED ON A LEVEL ICE SHEET BY WATER FLOW

Experimental method

The model ice sheet on the water surface was pulled at a constant velocity, and the resulting resistance was measured to compute the shearing force produced by the water flow. The experimental device was a 12 meter-long, 80 cm-wide water tank, and a self-propelled push car was installed above a rail laid on the experimental device (Figure 2). The model ice sheet made of paraffin was linked with the push car. During the experiment, the push car was moved at a constant velocity to force the model ice sheet to move. The accompanying water resistance was measured by a load cell.

The thicknesses of the model ice sheets (H) were 2 cm and 4 cm, and their lengths were 30 cm, 60 cm, 90 cm, 120 cm, 150 cm, and 180 cm.

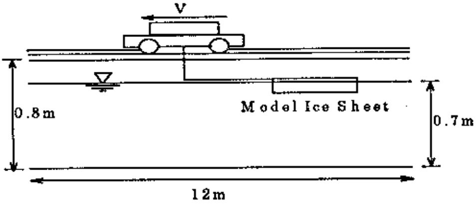


Figure 2 Lateral view of the experimental device

Experimental results

The experimental results show that the force acting on the model ice sheet was nearly proportional to the square of the moving velocity of the model ice sheet. Figure 3 shows the relationship between F_W/V^2 and L, where F_W, V, and L are the force exerted on the model ice sheet per unit width, moving velocity, and length of the floating ice sheet in the direction that the velocity was measured, respectively. The graph in the figure demonstrates that F_W/V^2 increases almost proportionally with L. The coefficient of the shearing force between the ice sheet and water flow, C_{SW}, can be computed from the slope of the regression line determined by applying the method of least square to the data from Figure 3. Regardless of the thickness of the model ice sheet, the computed values of C_{SW} were constant, as follows:

$$C_{SW} = 0.0075\ (H = 2\ \text{cm}),\quad 0.0070\ (H = 4\ \text{cm})$$

Mcphee observed movements of ice in the Arctic Ocean during the summer to measure the relative velocity between ice sheets and water flow and wind velocity at 10 m above the sea surface (U_{10}). The fluid force induced by the water flow was calculated by applying the theory of the equilibrium of force to these measurements. As a result of this calculation, $F_W = 0.0055V^2$ was obtained. Calculating from this equation, we have $C_{SW} = 0.011$, which is slightly greater than our experimental values. However, since the thicknesses and irregularity of the ice sheets were not measured in this experiment, whether the bottom surface of the ice sheets was level or irregular is unknown. The values represented by a dark triangle sign, ▲, in Figure 3 were gained from an experiment using real ice sheets. The average thickness of the ice sheets was approximately 4 cm.

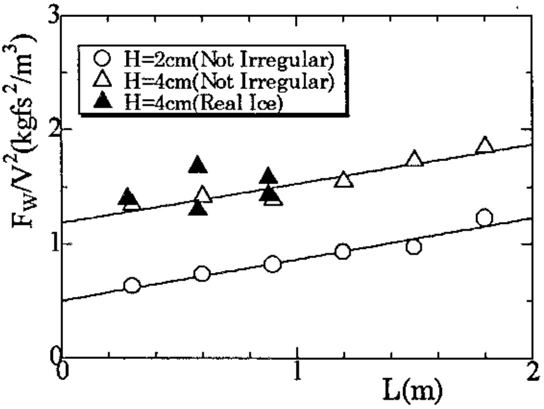


Figure3 shows the relationship between F_W/V^2 and L

SHEARING FORCE EXERTED ON A IRREGULAR ICE SHEET BY WATER FLOW

When dealing with fluid force acting on ice sheets, the surface of the ice sheets is commonly assumed to be level. However, ice sheet surfaces are in practice irregular, which are considered to be exposed to larger fluid force than level surfaces. To research the effects of irregularity on the fluid force acting on the ice sheets, ditches were made on the bottom surface of the model ice sheets (Figure 4). The experimental width of the floating ice sheets was 40 cm, and the experimental length in the direction that the velocity was measured was 60 cm. The width of the ditches (t) was 4 cm, and their depths (k) were 2 cm and 4 cm. Also, four different lengths between the intervals (S) were adopted for this experiment. The experimental results were summarized according to S divided by k: S/k.

The force exerted on the floating ice sheets, F_W, is roughly proportional to the square value of the water flow velocity. Figure 5 shows the relationship between F_W/V^2 and S/k. In the figure, the dashed line and the dotted line show the results of the model ice sheets with a thickness of 2 cm and 4 cm, respectively. Both of these ice sheets were subject to the maximum force around S/k = 7.5. According to the research results of Adachi et al., the resistance due to irregularity reaches its maximum near S/k = 8.0, which almost agrees with our experimental results.

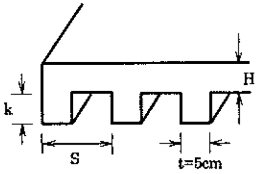


Figure4 Configuration of the bottom surface

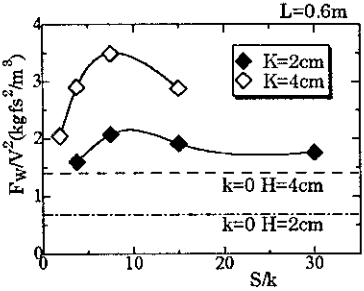


Figure5 Effects of irregularity

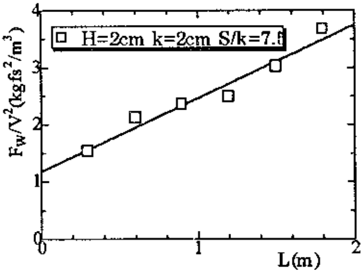


Figure6 Relationship between F_S/V^2 and L

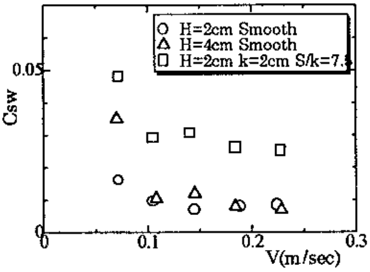


Figure7 Relationship between V and C_{SW}

Figure 6 shows the results of the experiment on the ice sheets with S/k = 7.5 by altering the value of L, the length in the direction that the velocity was measured. The experimental results yielded $C_{SW} = 0.0257$, which is approximately three times as large as C_{SW} of the level model ice sheets.

Figure 7 shows the relation of C_{SW} to the drift velocities of irregular and level ice sheets. Although the figure does not show any obvious correlation between the water flow velocity and C_{SW}, the effects of irregularity can be clearly observed.

SHEARING FORCE EXERTED ON ICE SHEETS BY WATER FLOW

We made a model experiment on the fluid force acting on ice sheets trapped by an ice boom, as well as on their water-covered area, to calculate the shearing force between water flow and the ice sheets (F_W) and the shearing coefficient (C_{SW}).

Experimental method

Polypropylene square model ice sheets with a length of 10 cm were drifted in a 20 m-long, 2 m-wide flat water course where the model ice boom was installed (Figure 8). The ice boom comprised floating bodies fixed by a net underneath them and load cells installed at both ends of the net to measure ice force (Figure 9). The experimental flow velocity was varied between 9.5 and 22.8 cm/sec, and the tension acting on the right and left sides of the wire of the ice boom was measured separately to compute the ice force. Ice sheets with a thickness of 1 cm, 2 cm, and 4 cm were mixed at a proportion of 5:3:1, respectively.

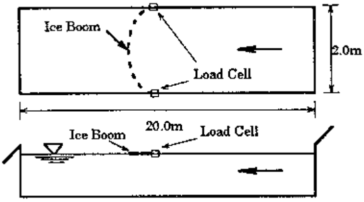


Figure8 Experimental device

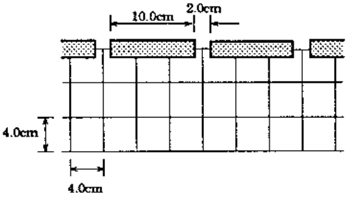


Figure9 Structure of the ice boom

Experimental results

Figure 10 illustrates the relationship between the water-covered surface area of the model ice sheets and the ice force acting on the ice boom at six different water flow velocities. The ice force acting on the ice boom was equivalent to the fluid resistance (equal to shearing force plus form drag) exerted on the ice sheets by water flow. The model ice sheets rarely overlapped each other nor under-turned, and groups of level ice sheets with a uniform thickness were formed at water flow velocities between 9.5 cm/s and 13.6 cm/s (Photo 1). Although the form drag was constant, the shearing force between the ice sheets and the water flow increased owing to the increase in the water flow velocity, and the fluid resistance gradually increased.

Between 14.2 cm/s and 16.2 cm/s, some ice sheets overlapped each other, even when only a small number of ice sheets had drifted, and some under-turned and stuck perpendicular to the net (Photo 2). In this range, the fluid resistance of the ice sheets with a water-covered surface area smaller than 10,000 cm^2 showed a remarkable increase, and the form drag was larger than that when the water flow velocity was between 9.5 cm/s and 13.6 cm/s. Conversely, when the water covered surface area of ice sheets was greater than 10,000 cm^2, the ice sheets rarely overlapped each other, and no additional form drag affected the ice sheets. Only the shearing force was accordingly increased to amplify the fluid resistance.

When the water flow velocity was 18.7 cm/sec, many model ice sheets under-turned, and then they overturned and stuck perpendicular to the net, or overlapped each other to create an ice jam (Photo 3). At this velocity, a slight increase in the surface area covered with water caused a remarkable increase in fluid resistance (ice force). Because overlapped model ice sheets created an ice jam, an actual increase in the thickness of the ice sheets and the irregularity of the bottom surface of the ice sheets brought about an increase in form drag and shearing force.

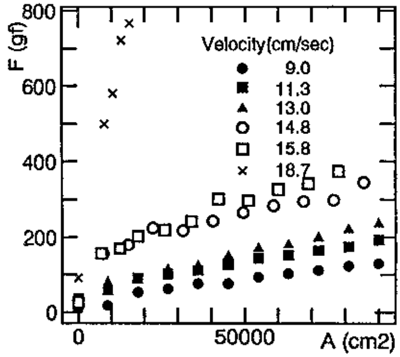


Figure10 Relationship between area covered with water and fluid force

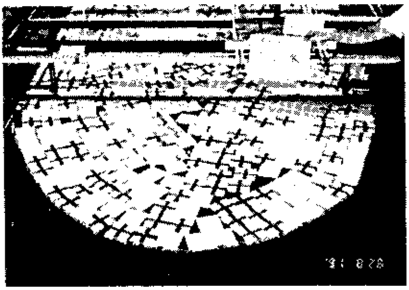


Photo1 Level ice sheets with a uniform thickness

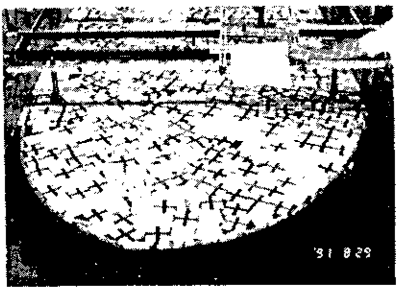


Photo2 Overlapping of some ice sheets

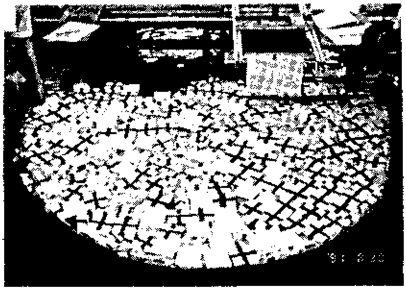


Photo3 Condition of ice jam

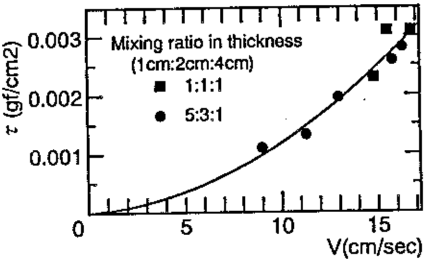


Figure11 Relationship between V and F_{SW}

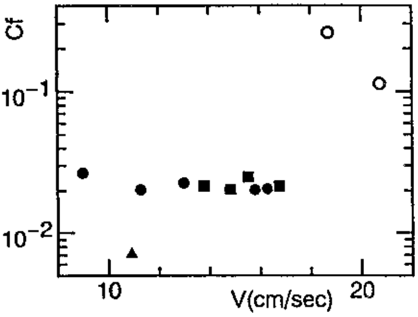


Figure12 Relationship between V and C_{SW}

Figure 11 shows the relationship between water flow velocity and shearing force. The shearing force was calculated at different velocities (from 10 cm/sec to 17 cm/sec) in the range where Figure 10 indicates that the fluid resistance is affected by the shearing force between the water flow and the ice sheets. The shearing force was approximately proportional to the square value of the water flow velocity (Figure 11).

Figure 12 summarizes the relationship between water flow velocity and shear coefficient, C_{SW}, calculated at different water flow velocities. When the flow velocity was smaller than 17 cm/sec, the behavior of C_{SW} was irrelevant to the flow velocity, and its value was approximately $2.1 \times 10\text{-}2$. On the other hand, when the flow velocity was 18.7 cm/sec and the model ice sheets formed an ice jam, the shearing coefficient demonstrated a marked deviation: $C_{SW} = 0.10\text{-}0.25$. The fluid resistance due to ice sheets is therefore affected by shearing force generated by the friction between the water flow and the bottom surface of the ice sheet. The shearing coefficient is profoundly influenced by the irregularity of the bottom surface of ice sheets.

CONCLUSIONS

1) The fluid resistance acting on an ice sheet (F_W) is equal to the sum of the shearing force between the water flow and the bottom surface of the ice sheet (F_{SW}) and the form drag exerted on the submerged part of the ice sheet (F_{DW}). This relationship can be given by equation (5):

$$F_W = F_{SW} + F_{DW} \qquad (5)$$

2) The experimental results can be summarized by the relationship between the length of the ice sheet (L) and the fluid resistance (F_W) divided by the square value of flow velocity (V). Figure 13 shows that L increases almost proportional to an increase in F_W/V^2. By assigning α and β to the intercept and the slope, this relationship can be shown by the following equations:

$$F_W/V^2 = \alpha L + \beta$$
$$F_W = \alpha L V^2 + \beta V^2 \qquad (6)$$

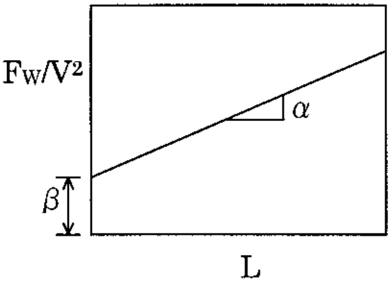


Figure13 Relationship between F_W/V^2 and L

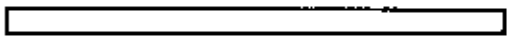
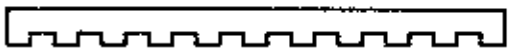
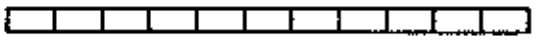
The first term of the right side of the equation (6) is the shearing force (F_{SW}) and the second term is the form drag (F_{DW}). The shear coefficient (C_{SW}) can thus be expressed as:

$$C_{SW} = 2\alpha/\rho_w = 2g\alpha/w \qquad (7)$$

3) The results of the experiment on model ice sheets with different conditions were calculated by equation (7) to find the shearing coefficient (C_{SW}). Table 1 summarizes the conditions of model ice sheets in relation to C_{SW}. The shearing coefficient of level ice sheets was about 0.007. The coefficient of ice sheets with an irregular bottom surface and relatively level ice sheets was 0.020-0.025, and that of the ice jam was 0.10-0.25. Thus, the shearing coefficient of the ice sheets with an irregular bottom surface and the coefficient of ice jam was about three times and over 20 times, respectively, as large as those of level ice sheets. This proves that fluid resistance is influenced by irregularity of the bottom surface of ice sheets and drastically increases due to the formation of an ice jam.

4) Fluid resistance (F_W) has a maximum value of about S/k (the interval between ditches on the bottom surface of ice sheets divided by the depth of the ditches) = 7.5.

Table1 Shearing coefficient of ice sheets (C_{SW}) depending on the condition

Condition of Ice Floes	Shearing Coefficient C_{SW}	General sketch
Level ice sheet	0.0070-0.0075	
Irregular ice sheet	0.0257	
Level ice floes	0.021	
Overlapping of some ice sheets	0.021	
Condition of ice jam	0.10-0.25	

REFERENCES

1) Toshiya Ueda, Hiroshi Saeki, Toshihiko Yamashita, Kunio Enoki(1992); Experimental Research on Fluid Force Acting on Floating Ice Sheets, Proceedings of Civil Engineering in the Ocean(Japan), Vol. 8, pp. 135-140

2) Toshiya Ueda, Toshihiko Yamashita, Kunio Enoki, Fumihiro Hara, Hiroshi Saeki, Oriya Tokuhiro(1992); Moving Velocities of Ice Sheets and Fluid Resistance, Proceedings Cold Region Technology Conference(Japan), pp. 428-431

3) Mcphee M. G.; An Analysis of Pack Ice Drift in Summer, Sea Ice Process and Models, R. S. Pritchard Ed., Washington Univ. Press

4) Shohei Adachi(1964); Experimental Research on Artificial Roughness, Proceedings of Japan Society of Civil Engineers, No.104