EXPERIMENTAL STUDY ON THE PROCESS OF ICE JAM DEVELOPMENT

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Abstract

Most rivers flowing in cold regions freeze over in winter. In rivers in Canada, the northern part of U.S., Northern Europe, Russia, etc., floods and local scouring at the base of bridge piers are caused by ice jams developed in the melt period. Ice jams also act on bridge piers as a horizontal ice force, or as a force pushing up superstructures. Understanding the process of ice jam development and its shape is indispensable to find especially the mechanism of local scouring near bridge piers when ice jams are generated. However, this process has not been clarified.

In this report, we give the results of three experiments to understand the process of ice jam development and its shape. First, we experimented on the movement of ice floes at the edge of an ice cover, and found the characteristics of their movement and the critical Froude number when they go beneath the ice cover. Second, we experimented on the stopping of ice floes under an ice cover and obtained the critical Froude number when an ice floe stops. From the results of these two experiments, we give the conditions under which ice jams are generated, using the Froude numbers.

In addition, we made a model experiment on the occurrence of ice jams at an ice cover by making a group of ice floes, and we observed the process of ice jam development and its shape.

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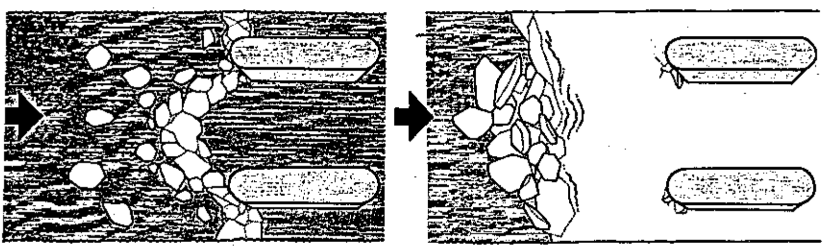
INTRODUCTION

Ice jams in frozen rivers occur at meanders, narrow sections, junctions, forks, places where cross-sections of river channel suddenly change, and places where bridge piers are constructed. Ice jams occurring at bridge piers not only act on piers and superstructures as ice forces, but also hastens marked localized scouring around the bridge piers. Two patterns of ice jam development at bridge piers exist (Fig. 1). First, ice floes form arches at piers when an ice cover is not around the piers, which trap the following ice floes causing ice jams. Hara et al. (1992,1993) examined experimentally the conditions of arch formation due to ice floes when several piers are in a watercourse. Second, when an ice cover is around the piers, ice floes go underneath the ice cover at the edge of an ice cover by under-turning in succession forming ice jams. Here, bridge piers prevent the ice cover, which floats because of a rising water level, from flowing downstream, so all the fluid resistance that ice jams and an ice cover receive is supported by piers. Ice jams gradually develop until the contact pressure between the piers and the ice cover exceeds the strength of ice, so causing break-up of the ice jam. Ice jams that flow downstream rapidly not only act on piers as an ice force, but hastens abrasion by high contact pressure between piers and ice jams. But the conditions of the occurrence and the process of development of the latter type of ice jam have not been clarified.

In this study, we clarified experimentally the formation of ice jams when an ice cover is around a bridge pier, and we observed experimentally the process of ice jam development and its shape from ice floes floating in groups.



(a)Ice Floes form arches (b)Ice floes go underneath the ice cover by under-turning

Fig.1 The pattern of ice jam development at bridge piers

THE PROCESS OF ICE JAM DEVELOPMENT

Fig. 2 shows schematically the process of ice jam development. First, ice floes go underneath at the edge of an ice cover by under-turning, half-turning, and sliding. Then they stop under the ice cover, and overlap one another to gradually form ice jams. Therefore, when ice jams occur with an ice cover around the piers, the main factor is that the ice floes go underneath the edge of the ice cover, and stop under the ice cover. So we made model experiments on the movement of ice floes at the edge of an ice cover and under an ice cover, and we examined the conditions of ice jam formation around the edge of an ice cover.

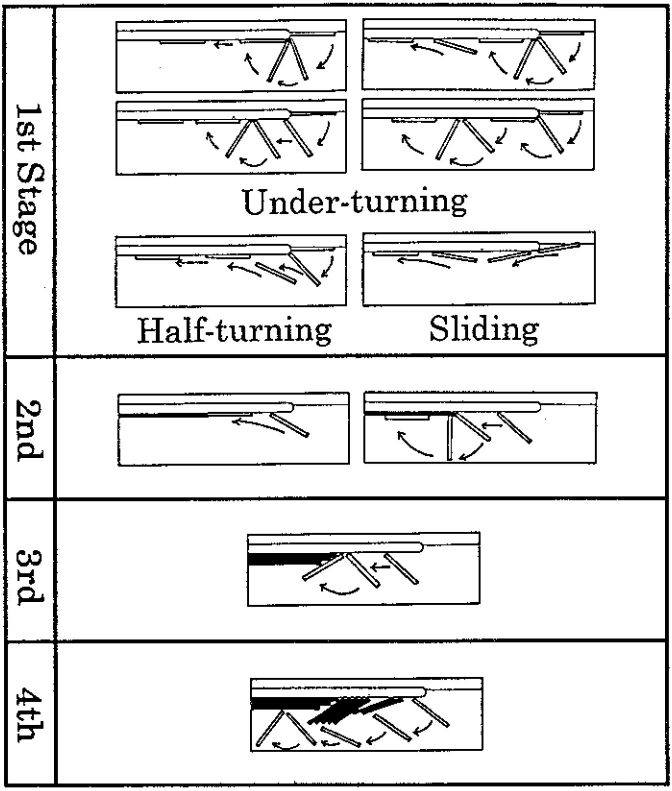


Fig.2 The process of ice jam development

EXPERIMENTAL METHOD

Experimental scale was 1/20. Hara et al. (1992) showed that Froude's law of similarity of the movement of ice floes is satisfied to the extent of 1/150.

Fig. 3 shows the experimental watercourse, which was 12m long, 0.6m deep, and 1.0m wide. A plate glass that enabled us to observe the movement of ice floes at the edge of and under the ice cover was set in one side of the watercourse. A model ice cover of 1.0m wide, 1.0m long and 2cm thick placed on the water. We floated the model ice floes from upstream of the ice cover, and observed the movement of ice floes at the edge of the ice cover and the conditions of stopping. We used a polypropylene plate of approximately the same specific gravity as real ice for the model ice cover and the model ice floes, and we found that the kinetic friction coefficients of polypropylene(dry condition 0.188; wet condition 0.146) were also approximately the same as those for real ice. We made four kinds of edge shape of the ice cover; rectangular, semi-circular, an edge with an upward cut of 45° , and an edge with an downward cut of 45° (Fig. 4). The model ice floes were square, simulating real ice floes surveyed in field studies, many of them either a square or a pentagon. The lengths of the ice floe sides, L, were 5cm, 7cm, 10cm, and 13cm, and the thickness of ice, h, varied at 1cm, 2cm, 3cm, and 4cm. These measurements of L and h were equivalent the actual river measurements of 1m, 1.4m, 2m, and 2.6m for length, and to 20cm, 40cm, 60cm, and 80cm for thickness. We varied the flow

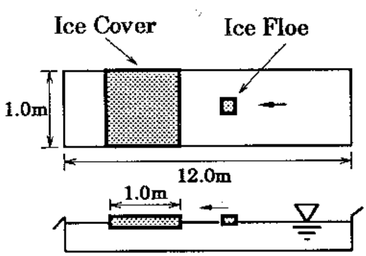


Fig.3 The experimental watercourse

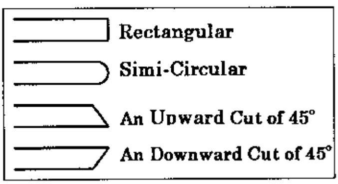


Fig. 4 Edge shape of an ice cover

velocity from 5 to 30cm/sec by changing the discharge rate of the pump; this experimental flow velocity was equivalent to 22~134cm/sec in the actual river. The experimental flow velocity was measured by a flow velocity meter installed upstream of the ice cover every time an ice floe arrived at the edge of the ice cover.

RESULTS AND DISCUSSIONS

Experiment on the Movement of Ice Floes at the Edge of an Ice Cover

We classified the movement of ice floes at the edge of an ice cover into five categories (Fig. 5): A is no movement of ice floe at the edge; B is the movement of an ice floe under the ice cover while it turns itself down pivoting on one of the edges of the ice cover which acts as the fulcrum and result in the original top surface being at the bottom (called under-turning); C is the movement of an ice floe under the ice cover by sliding (called sliding); D is the movement of an ice floe, which turns itself in the same way as B but a quarterway and goes under the ice cover by sliding (called half-turning); and E is the movement of an ice floe resulting in the floe resting against the edge of the ice cover half in and half out of the water (called pile up), which was scarcely observed in this experiment.

Fig. 6 shows the force acting on the ice floes at the edge of an ice cover, the drag force, the shearing force, and the net buoyancy. The equation for

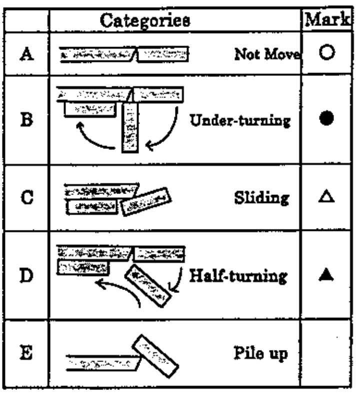


Fig.5 Categories of movement of ice floes

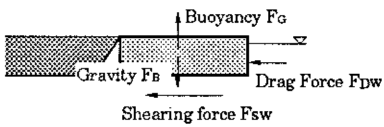


Fig.6 The force acting on the ice floe at the edge of an ice cover

the balance of moments acting on these ice floes is:

$$\frac{1}{2}C_D\rho_W V^2 hL\cdot\frac{h}{2}+\frac{1}{2}Cs\rho_W V^2L^2\cdot h-\frac{1}{2}C_L\rho_W V^2L^2\cdot L-(\rho_W-\rho_i)gL^2h\cdot\frac{L}{2}=0 \qquad (1)$$

where: C_D: drag coefficient of water; Cs: shearing force coefficient of water; C_L: lift coefficient; ρ_W: density of water; ρ_i: density of ice; $\Delta\rho=\rho_w-\rho_i$; L: length of a side of an ice floe; h: thickness of ice; V: flow velocity: g: acceleration of gravity.

Equation (1) can be rewritten as:

$$F_e=\frac{V}{\sqrt{\frac{\Delta\rho}{\rho_W}gh}}=\frac{1}{\sqrt{\frac{1}{2}C_D\left(\frac{h}{L}\right)^2+Cs\left(\frac{h}{L}\right)-C_L}}=f\left(\frac{h}{L}\right) \qquad (2)$$

Here, we can express densimetric Froude number, Fe, in which the specific gravity of ice is a function of the ratio, h/L, of ice thickness and length of ice floe. Therefore, the experimental results were expressed as a relationship between Fe and h/L.

Fig. 7 shows the relationship between Fe and h/L for each edge shape of

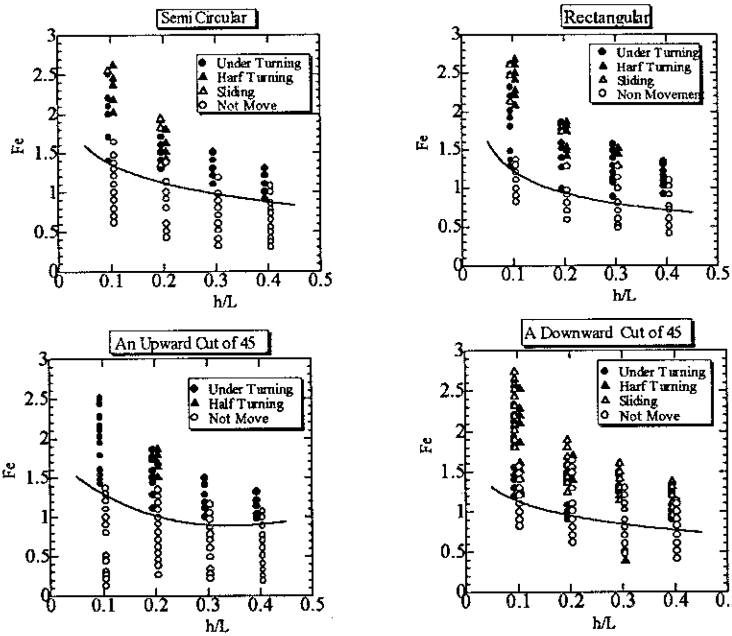


Fig.7 Relationship between Fe and h/L for each form of the edge of ice cover

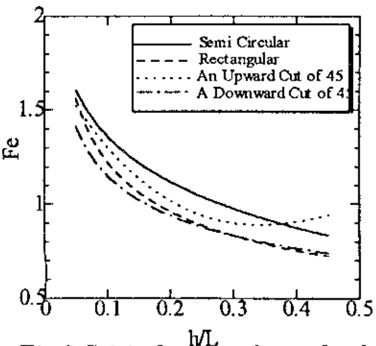


Fig.8 Critical curves for each edge shape of ice cover

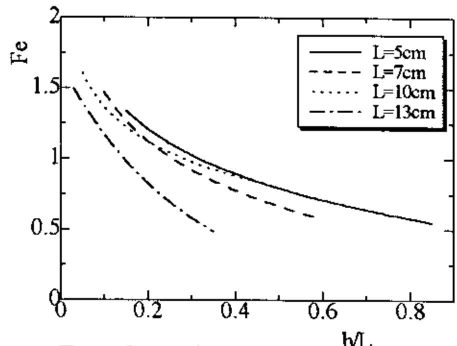


Fig.9 Critical curves for the effect of side length of ice sheet

ice cover, varying the thickness of ice floe at 1cm, 2cm, 3cm, and 4cm. We plotted the graph using symbols ○,●,△,and▲ for forms A, B, C, and D, respectively. The curves of the graphs indicate the critical conditions an ice floe goes under the ice cover. Most of ice floes went under the ice cover by under-turning at the upward cut edge, by under-turning or half-turning at the semi-circular or rectangular edges, and by most of the ice floes sliding at the downward cut edge. Fig. 8 compares the critical curves for each ice cover edge shape. The critical conditions of ice floes going under the ice cover, show that the greatest difference occurring between ice floes going under semi-circular ice cover edge with some difficulty and ice floes going under an upward cut ice cover edge the easiest. Fig. 9 compares the critical curves for the effect of ice floe sides of lengths 5cm, 7cm, 10cm, and 13cm with a semi-circular ice cover edge. This figure shows that the longer the side length of ice floe, the easier the ice floes go underneath the ice cover.

Experiment on the Stopping of Ice Floes under the Ice Cover

The forces acting on the ice floe under the ice cover are the drag force, the shearing force, and the friction between ice sheets (Fig. 10). The equation for the balance of these forces is:

$$\frac{1}{2}C_D\rho_w V^2 Lh + \frac{1}{2}Cs\rho_w V^2 L^2 + Cs\rho_w V^2 Lh - (\rho_w - \rho_i)g\mu_k L^2 h = 0 \qquad (3)$$

where, C_D: drag coefficient of water; Cs: shearing force coefficient of water;

ρ_w: density of water; ρ_i: density of ice; $\Delta\rho = \rho_w - \rho_i$; L: length of a side of an ice floe; h: thickness of ice; V: flow velocity; g: acceleration of gravity; μ_s: kinetic friction coefficient between ice.

Equation (3) can be rewritten as;

$$F_e = \frac{V}{\sqrt{\frac{\Delta\rho}{\rho_w} gh}} = \sqrt{\frac{2\mu_k}{C_D\left(\frac{h}{L}\right) + Cs\left(1 + 2\frac{h}{L}\right)}} = f\left(\frac{h}{L}\right) \qquad (4)$$

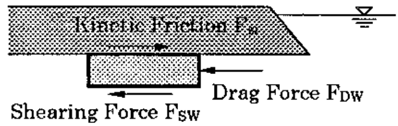


Fig.10 The force acting on the ice floe Under the ice cover

For the movement of an ice floe under the ice cover, we can express the densimetric Froude number Fe as a function of the ratio, h/L again. Therefore, the experimental results were also expressed as a relationship between Fe and h/L.

Fig. 11 shows the conditions of ice floes with side length 10cm and varying ice thickness of 1cm, 2cm, 3cm, and 4cm stopping under the ice cover. We plotted the graph using symbols ● for ice floes which stop under the ice cover, ○ for ice sheet which pass through downstream under the ice cover, and ▲ for conditions intermediate between ● and ○. The curves on the graph show the critical conditions of an ice floes that stops. The area under the curves indicate ice floes that stopped under the ice cover near the edge. Fig. 12 shows the critical curves for ice floes with side lengths 5cm,7cm,10cm

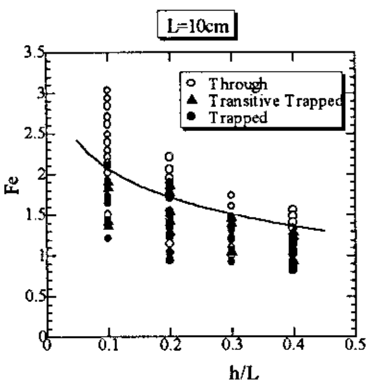


Fig.11 The conditions of ice floes stopping under the ice cover

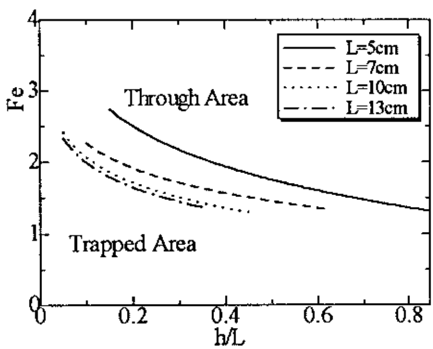


Fig.12 Critical curves for each sides length of ice floes

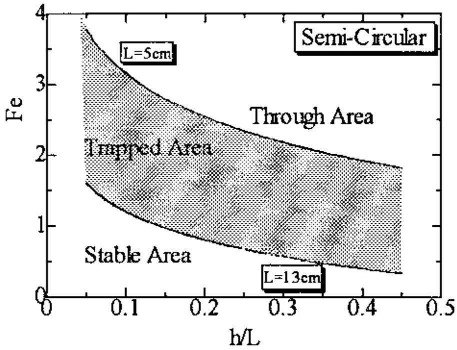


Fig.13 The conditions of ice jam formation

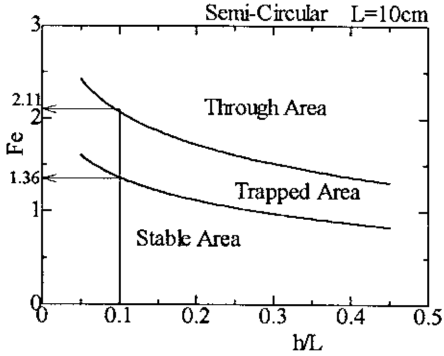


Fig.14 The condition of ice jam formation for L=10cm

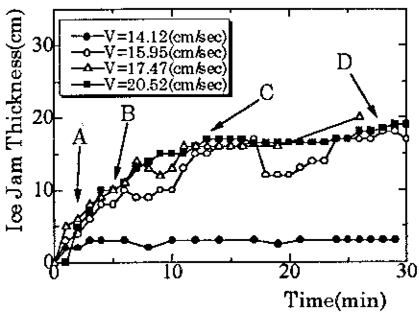
and 13cm. The fact that the shorter is the length of ice sheet, the easier an ice floe stops under the ice cover is clear, and the shorter is the length of ice floe, the greater is the contact pressure between ice per unit area.

Condition of Ice Jam Formation

The results of the two experiments show the conditions of ice jam formation (Fig. 13). In the stippled area on the graph shows the ice floes that went underneath the edge of the ice cover, and stopped under the ice cover near the edge. The lower limit of the stippled area shows the results where ice floes with side length 13cm go underneath an ice cover with a semi-circular edge most easily, and the upper limit of the stippled area shows the results where ice floes of side length of 5cm stop most easily under the ice cover.

EXPERIMENT ON THE ICE JAM DEVELOPMENT

Using the same watercourse for the two experiments, we made a model experiment on the process of ice jam development, and we observed the shape of the ice jam. In this experiment, we used polypropylene plate for the model ice floes with a side length of 10cm, and an ice thickness of 1cm. The edge of the ice cover was semi-circular. Fig. 14 shows the ice jam with



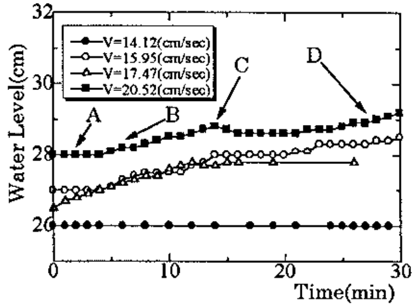


Fig.15 Changes on ice jam thickness   Fig.16 Changes of water level

these conditions. From this graph, the range of Froude numbers where ice jams formed was 1.36～2.11. The flow velocities calculated from these Froude numbers were 13.5～20.9cm/sec. In the experiment, the ice jam thickness and the water level upstream from an ice cover were measured.

Figs.15 and 16 show the changes on ice jam thickness and water level in the process of the ice jam development. At the flow velocities of 15.95, 17.47 and 20.52cm/sec, ice jams formed. The water level upstream from the ice cover rose 1～2cm as the ice jam thickness increased. But about 10 minutes after the experiment started, ice jam thickness and water level were constant. At the velocity of 14.12cm/sec, ice jams did not form, and a uniform group of ice floes formed upstream of the ice cover. At this velocity, water level was constant. Fig. 17 shows schematically the conditions of the ice jams

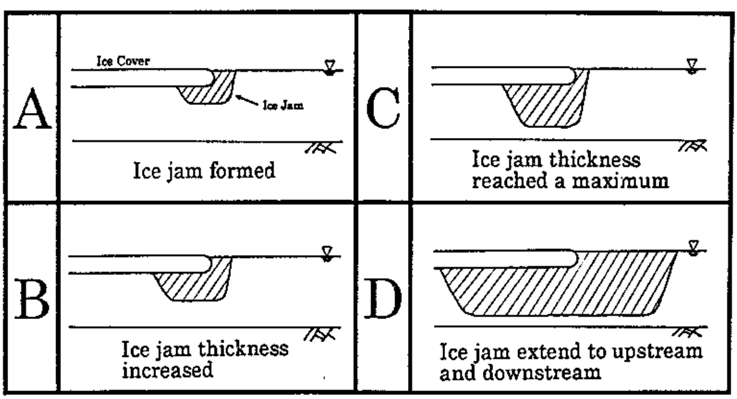


Fig.17 The conditions of the ice jams

at the stages of A, B, C, D in Figs.15 and 16. The ice jams gradually formed near the edge of the ice cover (A), the ice jam thickness increased with time (B), and for each velocity the thickness reached a maximum about 10 minutes after the experiment started (C). This is because the increased velocity caused by the formation of the ice jam stopped the development of the ice jam. And after that ice jams started to extend upstream and downstream of the location where the first ice jams formed (D).

CONCLUSIONS

(1) There are two patterns in ice jam development around the bridge piers. First, ice floes form arches at piers and trap the following ice floes. Second, ice floes go underneath the ice cover in succession, and stop under an ice cover to form ice jams.

(2) The movement of ice floes at the edge of an ice cover is classified into three forms, under-turning, half-turning, and sliding.

(3) For the movement of ice floes at the edge of an ice cover, we can express the densimetric Froude number Fe as a function of the ratio h/L, of ice thickness and length of ice sheet.

(4) Ice floes go underneath the ice cover the easiest when edge form is downward cut, and the most difficult when edge form is semi-circular. And the longer the side length of ice sheet, the easier the ice floes go underneath the ice cover.

(5) For the movement of ice floes under the ice cover, we can express the densimetric Froude number Fe as a function of the ratio h/L again.

(6) The shorter the side length of ice sheet, the easier the ice floes stop under the ice cover.

(7) From the results of two experiments, we obtained the conditions under which ice jams are generated, using the densimetric Froude number.

(8) In a model experiment on ice jam development at an ice cover by making a group of ice floes, ice jams were formed at the velocity of more than 15(cm/sec). At the velocity of less than 14(cm/sec), ice jams weren't formed, and a uniform group of ice floes were formed upstream of the ice cover.

(9) In this experiment, the water level upstream from the ice cover rose as the ice jam thickness increased. But about 10 minutes after the experiment started, ice jam thickness and water level were constant.

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