EFFECT OF ICE ON WATER FLOW AT SALOMA LAGOON

Shunsuke Makita¹, Hiroshi Saeki¹ and Atsumi Furuya²

ABSTRACT
Saloma Lagoon, on the Okhotsk coast, has two inlets to the open sea: a natural inlet (the first inlet) and an inlet constructed in 1978 (the second inlet). This lagoon is used intensively for aquaculture of shellfish, such as scallop and oyster, because it is relatively deep and has the same salinity as the open sea. Semi-closed water areas like Saloma Lagoon are very calm, making them ideal for aquaculture. However, there is also the risk that the water quality may suddenly decrease. In order to use the lagoon for sustainable aquaculture, it will be necessary to consider water exchange toward maintaining the water quality. In Saloma Lagoon, hanging aquaculture facilities are used for scallop culture. These are installed underwater to avoid influences of freezing and ice floe during winter. To maintain the water quality of Saloma Lagoon, it will be necessary to have a clear understanding of the flow conditions during the freezing period. In this study, the flow conditions of the lagoon are simulated to clarify influences of freezing and drift ice in winter.

INFLUENCES OF ICE COVER AND ICE FLOES ON FLOW CONDITIONS
Water circulation in the lagoon decreases in winter, because ice cover results in increased friction between water and the underside of the ice. There are concerns regarding the reduction of water exchange, because ice floes that reach the shore accumulate near the lagoon inlets and restrict the seawater flow into the lagoon. Ice floe normally reaches Saloma Lagoon during the period from January to February. Tides cause ice floes to pass through the two inlets into the lagoon. These ice floes collide with aquaculture facilities, severely damaging them. To prevent such damage, a 13-span ice boom was installed at the first inlet.

Accumulation of ice floes
When ice floe reaches to ice cover or ice booms, moment occurs in the ice floes due to fluid force and flow separation. This causes the ice floe to under-turn and become trapped under the ice surface. These ice floes remain

Figure 1: Ice floes under the ice cover

¹ Kita-13, Nishi-8, Sapporo, 060-8628, Japan
² 3-15-6-21, Tsukisamu-higashi, Toyohira-ku, Sapporo, 062-0053, Japan
under the existing ones because of frictional resistance; continually accumulating to form ice jams. The underside of an ice jam is geometrically complex; thus, the shearing force of an ice jam is great. This greatly reduces the flow of water from the open sea into the lagoon, which is one cause of water quality deterioration.

**Advantage of ice booms**
At the inlet without an ice boom, ice floes form an ice jam under the ice cover. The floes in such a jam are not discharged because of frictional resistance with the ice cover, and the ice jam does not break apart even when lagoon water flow out the sea. However, with ice booms, the ice jams form on the seaward side and is not subjected to frictional resistance. When water flows out, these jams break up and are discharged into the open sea, which improves water exchange. Trapping ice floes with ice booms is also effective for improving water exchange, because it promotes break up of ice jam.

**SIMULATION OF FLOW CONDITIONS IN THE LAGOON**

**Calculation method**
For flow calculation, we used a multi-level model. The spatial scale and motion scale of water subject to analysis differed for horizontal and vertical direction. Therefore, in this model the horizontal direction is analyzed using a mesh. For the vertical direction, the water is divided by layer, with the thickness of layer considered only for the surface layer and with only the vertical flow component considered for underlying layers. Therefore, this model is suitable for analyzing flow conditions in a semi-closed water area where vertical flow such as the lifting of nutrients by upwelling is important. Figure 2 shows the calculation area. Calculation was made by dividing Saloma Lagoon and the area 500 m offshore from the first inlet into a 100-m mesh. The first inlet is 300 m wide and 10 m deep on average. Its water surface area is 90,000 m$^2$. The second inlet is 50 m wide and 5 m deep on average. The water surface area is 15,000 m$^2$. As the boundary condition, Sommerfeld’s open conditions were set for AB, BC and DA, as access leading to the open sea. Variations in external tide for a 24-hour period and a semi-tidal range of 0.5 m were given only to the boundary AB.

**Coefficients**

**Friction coefficient of water surface** Although the friction coefficient of water surface varies complexly according to wind, flow, etc., the constant $\gamma_a^2 = 1.3 \times 10^{-3}$ is often used. This constant was not used for calculation, because the lagoon froze over and the influence of wind is negligible on ice-covered water.

**Coefficient of friction at bottom** In the multilevel model, the constant $\gamma_b^2 = 2.6 \times 10^{-3}$ obtained by Hasen through tidal current observation is often used. This value was used in this study.
Coefficient of friction of water Although there are no proper evaluation methods, the value that is $1/10 \sim 3/4$ of the coefficient of friction at bottom is commonly used. In this calculation, the constant $\gamma = 5 \times 10^{-4}$ was used.

Coefficient of horizontal vortex viscosity Although this coefficient varies according to the state and scale of motion, a value nearly equal to the coefficient of horizontal diffusion is commonly used. The value equal to the coefficient of horizontal diffusion was used for this calculation.

Coefficient of horizontal diffusion It is known that this coefficient is proportional the scale of motion raised to the $4/3$ power. It is calculated using the following equation:

$$K_h = cL^{4/3}$$  \hspace{1cm} (1)

where $c$ is a constant (about 0.01) and $L$ is the grid size.

Calculation conditions

The ice floes trapped by the ice boom are exposed to the high-velocity flow passing through the lagoon inlet, which helps to form the ice jam. Because the ice jam has large shearing friction and affects the surrounding flow, it should be considered in flow calculations for seawaters where ice floes enter. Thus, the following three conditions were used in our calculation:

Condition 1.1: No freezing on lagoon
Condition 1.2: Lagoon frozen over
Condition 1.3: Lagoon frozen over and ice jam at ice boom

The friction coefficient at water surface used in the calculation is substituted for by the coefficient of shearing force, $C_{sw} = 7.7 \times 10^{-3}$, for the flat ice floes, and by the coefficient of shearing force, $C_{sw} = 1.3 \times 10^{-1}$, for the ice jam at the ice boom. Coefficients have been assumed by the authors through experiments. The location of the ice boom is as shown in the calculation mesh of Figure 3.

Calculation results, and discussion

Calculated flow velocity vectors of maximum inflow are shown in Figure 4. Under condition 1.1 (no freezing on lagoon), inflow from the first inlet passes far into the lagoon, diffuses widely, and nearly reaches the center of the lagoon. Under condition 1.2 (lagoon frozen over), the velocity of inflow at the inlet is smaller than for condition 1.1, due to resistance of ice cover, and the diffusing flow does not reach the center. In condition 1.3 (lagoon frozen over and ice jam at ice boom), the inflow at the inlet is affected by the great resistance of the ice jam and diffuses at the ice boom. Although the flow diffuses slightly, it never reaches the center of the lagoon; thus, the water quality
there may deteriorate. Comparison of the maximum flow velocities under conditions 1.1, 1.2 and 1.3 is shown in Figure 5. The quantities and the ratios of the quantities at the second inlet to those at the first inlet under the same conditions are shown in Figure 6.

Figure 4: Results of flow condition simulations
Very little difference is observed between conditions 1.1 and 1.2 in terms of the flow velocity and the quantity. However, under condition 1.2 there is slightly less inflow at the first inlet and slightly more at the second inlet. The ratio of the inflow rate at the second inlet to that at the first inlet is about 8% under condition 1.1 and 9% under condition 1.2. It is possible that the inflow at the first inlet decreases because it is wider than the second inlet and thus has large open surface that is easily affected by the resistance of ice cover. This would lead to an increased difference between the water level of sea and lagoon. However, the second inlet has smaller open surface subject to ice; thus, this might be why the inflow increases. Under condition 1.3, the inflow velocity at the first inlet decreases remarkably and the inflow at the second inlet increases. The ratio of the inflow rate at the second inlet to that of the first inlet is as large as 16%. As in condition 1.2, the inflow from the first inlet decreases due to the great resistance of the ice jam and the difference in the water level between sea and lagoon increases, which must contribute to the increased inflow from the second, ice-jam-free inlet.

Figure 7 compares the total inflow rate at the two inlets under the three conditions. The total inflow rate under conditions 1.1 and 1.2 is almost the same, because under the latter condition the decreased inflow at the first inlet is compensated for by the increased inflow at the second inlet, but the total inflow at is reduced to about 70% under condition 1.3. The total inflow rate is affected more by the ice jam at the ice boom than by the ice cover. Additionally, because the decreased inflow at the first inlet is offset by the increased inflow at the second inlet, the inflow rate at the second inlet, though small, is important in mitigating the decrease in total inflow rate resulting from the ice jam. Improvement of the second inlet could prove effective in increasing the exchange of water between sea and lagoon.
EFFECTS OF THE SECOND INLET ON WATER EXCHANGE

Evaluation of water exchange capacity

Repairs are planned for the second inlet, an artificial inlet that has become decrepit. As described above, when the inflow rate at the first inlet decreases due to ice jam at the ice boom, the total inflow rate at the two inlets does not change greatly because of the increased inflow at the second inlet. In the following discussion, we compare the condition of the present second inlet with that of a repaired inlet twice the width of the present one, to examine the possibility of the repairs increasing the water exchange. The calculation is done for two conditions:

Condition 2.1: Lagoon frozen over and ice jam at ice boom
Condition 2.2: Lagoon frozen over, ice jam at ice boom, and doubled width of second inlet

Calculation method

Mass transfer simulation was done for a mass initially diffused at a uniform density in the lagoon, and the water exchange capacity and the mass transfer capacity were evaluated on the basis of residual rates of the diffused mass; suspended solids, after one cycle of tide. Diffused mass transfer is calculated by the advective diffusion equation. The initial density of the diffused mass is as follows: $SS = 1.0$ in the lagoon and $SS = 0.0$ in the sea.

Calculation results, and discussion

Figure 8 shows the residual rates of the diffused mass after one cycle, and Figure 9 shows the density distribution of the diffused mass. The residual rate of diffused mass decreases more under condition 2.2 than under condition 2.1. Thus it is clear that water exchange between Saloma Lagoon and the sea will increase after repair of the second inlet. At and around the first inlet, the inflow from the sea stays near the inlet, thereby decreasing the mass density. At the second inlet, under condition 2.2, the area with low mass density extends to the left and to the center. Thus it is expected that widening of the second inlet will increase water exchange throughout the lagoon.

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Figure 8: Residual content

Figure 9: Density distribution of diffused mass
CONCLUSIONS

1) Flow conditions were simulated for three different conditions: “no freezing on lagoon,” “lagoon frozen over,” and “lagoon frozen over and ice jam at ice boom.” Because of their great resistance, ice jams affect the flow conditions more than does ice cover.

2) When an ice jam forms, the flow rate after one cycle decreases to 70% of that under the condition of ice-free surface. The ice jam seems to hinder water exchange.

3) When the inflow at the first inlet decreases due to ice jam, the difference between the water level of sea and lagoon increases, and inflow at the second inlet increases. Thus, the second (ice-boom-free) inlet is significant regarding water exchange between sea and lagoon.

4) Assuming the width of the second inlet were doubled, the residual rate of diffused mass in the lagoon would decrease and the area with decreasing density of diffused mass would reach the center of the lagoon. Thus, it is expected that widening of the second inlet will increase water exchange throughout the lagoon.

REFERENCES
