STUDY ON FORMATION AND BEHAVIOR OF THE ICE COVER ON COLD REGION RESERVOIR

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GENERAL

In the cold region Hokkaido, ice problems have occurred in the hydropower station. While we have investigated the ice frazil and developed the ice control structure, research on ice formation and behavior on a reservoir where the water level has fluctuated in, have never been performed. In this paper, thickness of the ice cover in a reservoir is discussed from heat balance and ice behavior. From a viewpoint of heat balance, the transition of snow ice thickness on the reservoir during winter period was simulated by a numerical model, considering heat transfer between ice and air, and flow of water, etc. From a view point of ice behavior, by performing a two-dimensional hydraulic model test with simulating reservoir slope, fluctuation of water level, and ice condition, ice behavior around slope of this model was observed, and hydrological behavior to study on ice thickness distribution in a reservoir was confirmed.

KEY WORDS: Ice thickness, Upper reservoir, Pumped storage power station

1. INTRODUCTION

At hydroelectric power stations in Hokkaido, which is a cold region in Japan, frazil ice and sheet ice often cause intake water problems. Mineta et al. (1993) and Yamazaki et al. (1995) conducted observations of ice formation processes and flow velocity distributions under ice covers at Hokkaido Electric Power Company (HEPCO)'s Niupugawa Power Station where such water intake problems occur, and developed and applied a fence-type ice control structure. Pumped-storage power stations owned by HEPCO are mixed pumped-storage power stations that also use the run of the river, so ice problems did not occur because of the heat provided by the influent rivers and the heat energy provided by large reservoirs. In contrast, in the case of an upper reservoir of a pure pumped-storage power station (hereafter referred to simply as "the upper reservoir"), a sufficient amount of heat is not available because there is little inflow from the river. If, therefore, the upper reservoir is constructed at a site where the snow cover thickness is five meters and the lowest air temperature is −25°C, the water intakes may be blocked by ice cover.
Kasai et al. (2003), therefore, conducted field investigations, heat balance analysis and hydraulic model tests to investigate the ice formation process and behavior of the ice cover. In this paper, changes over time in snow ice thickness can be estimated quantitatively from meteorological data obtained from the reservoir site and the reservoir operating. The hydraulic model tests represented increases in snow ice thickness in slope areas caused by changes in water level and yielded new information that can be used to investigate reservoir ice cover thickness.

2. ANALYSIS OF ICE COVER THICKNESS

During pumping operation, the thickness of the upper reservoir ice cover in winter is likely to be smaller than that during non-pumping operation because water flow induced by pumping operation increases the rate of heat exchange between ice cover and reservoir water. Heat balance analysis were conducted, therefore, to estimate time-series changes in reservoir ice cover thickness during non-pumping and during pumping operation, assuming the thermal insulation effect of ice cover and melting of ice cover caused by pumping. For non-pumping operation, Uryu Daiichi Dam, which is under meteorological conditions similar to those at the upper reservoir, was considered. For pumping operation, two cases of flow velocity in the upper reservoir were considered.

(1) Analysis model

1) Enter data such as air temperature, snow cover thickness and the thermal properties of the ice cover into the analysis model.
2) Compare ice cover thickness measurement data obtained from a reservoir where there is little fluctuation in water level or water flow in the reservoir, such as the Uryu Daiichi Dam, and calculated values obtained from the analysis of the cases during non-pumping operation.
3) Perform an analysis by water temperature changes due to heat exchanges, taking into consideration the flow velocity in the reservoir during pumping operation.

Table 1 shows the analysis cases and the input conditions.

<table>
<thead>
<tr>
<th>case</th>
<th>place</th>
<th>calculation time</th>
<th>period</th>
<th>water temperature</th>
<th>place</th>
<th>flow velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-pumping</td>
<td>case 1</td>
<td>upper reservoir</td>
<td>daily</td>
<td>2000FY</td>
<td>1.5°C</td>
<td>0cm/s</td>
</tr>
<tr>
<td></td>
<td>case 2</td>
<td>Uryu Daiichi Dam</td>
<td>1998FY</td>
<td></td>
<td>2.0m below the ice cover</td>
<td></td>
</tr>
<tr>
<td>pumping</td>
<td>case 3</td>
<td>upper reservoir</td>
<td>change</td>
<td>2000FY</td>
<td>reservoir</td>
<td>1cm/s</td>
</tr>
<tr>
<td>operation</td>
<td>case 4</td>
<td>upper reservoir</td>
<td></td>
<td></td>
<td></td>
<td>50cm/s</td>
</tr>
</tbody>
</table>
(2) Analysis method

By reference to the studies of Hirayama et al. (1986), the concept of heat exchange was defined, and the model shown below was constructed. Figure 1 illustrates the concept of heat exchange as a case of single layer. A change in ice cover thickness, $\Delta \eta$, occurs at the underside of the ice cover ($\Delta \eta_1$) and the upper surface of the ice cover ($\Delta \eta_2$) (unit: m).

\[
\Delta \eta = \Delta \eta_1 + \Delta \eta_2 \quad (1)
\]

The amounts of heat exchanged at the ice surface, in the ice cover and in the reservoir water ($\Phi_{ia}$, $\Phi_i$, and $\Phi_{wi}$, respectively; unit: W/m$^2$) can be expressed as follows:

\[
\Phi_{ia} = h_{ia} \cdot (T_{ia} - T_a) \quad (2)
\]

\[
\Phi_i = K_i \cdot \frac{(T_i - T_{ia})}{\Delta \eta} \quad (3)
\]

\[
\Phi_{wi} = h_{wi} \cdot (T_{wi} - T_i) \quad (4)
\]

where

$h_{ia}$, $h_{wi}$: heat transfer coefficients in the ice cover and in the reservoir water (W/m$^2$/°C)

$K_i$: heat conductivity in the ice cover (W/m/°C)

$T_a$, $T_{ia}$, $T_i$, $T_{wi}$: temperature of atmosphere, upper surface of ice cover, underside of ice cover and reservoir water (°C)

If $\Phi_{ia} = \Phi_i$ is assumed,

\[
\Phi_i = \frac{T_i - T_{ia}}{\frac{\Delta \eta}{K_i} + \frac{1}{h_{ia}}} \quad (5)
\]

Since the amount of heat required at the underside of the ice cover, $\Delta \eta_1$, is equal to the difference in the amount of heat transfer at the underside of the ice cover, the following equation is obtained:

\[
\Phi_i - \Phi_{wi} = \rho_i \cdot \lambda \cdot C \cdot \frac{\Delta \eta_1}{\Delta t} \quad (6)
\]

where

$\rho_i$: density of ice (kg/m$^3$), $\lambda$: latent heat of solidification (J/kg), $C$: percentage of water, $\Delta t$: time interval (days)

From Eqs. (4), (5) and (6), the underside of the ice cover, $\Delta \eta_1$, and the upper surface of the ice cover, $\Delta \eta_2$, can be expressed as follows:

\[
\Delta \eta_1 = \frac{1}{\rho_i \cdot \lambda \cdot C} \left( \frac{\Phi_i}{\Delta \eta_1} - \frac{\Phi_{wi}}{\Delta \eta_1} \right) \cdot \Delta t \quad (7)
\]
\[ \Delta \eta_z = \frac{1}{\rho_i \cdot \lambda \cdot C} \left( Q_S + Q_E + Q_N - \frac{T_{j_k} - T_{j_{k-1}}}{\eta_i + \frac{1}{K_i} + h_w} \right) \cdot \Delta t \]  

where \( Q_S, Q_E \) and \( Q_N \) are sensible heat, latent heat and net radiation (unit: W/m\(^2\)), respectively.

The ice cover in nature is not formed as a single layer; instead, it is composed of snow cover, ice cover, snow slush, etc. The analysis is performed, therefore, by constructing a model considering heat balances between these layers. If flow in the reservoir is taken into consideration, the heat transfer coefficient \( h_{wi} \) is used; if it is not, the heat conductivity \( K_{wi} \) is used.

**Table 2** shows the ice cover's physical property values used for the analysis. The physical property values were determined through laboratory tests in which the ice formation phenomenon in the upper reservoir of the pumped-storage power station was reproduced.

**Table 2**  Ice cover's physical property

<table>
<thead>
<tr>
<th>physical property</th>
<th>heat conductivity in ice cover (W/m(^2)/°C)</th>
<th>heat transfer coefficient ice cover and air (W/m(^2)/°C)</th>
<th>heat transfer coefficient ice cover and water (W/m(^2)/°C)</th>
<th>Proportion of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0.561 (^{2)})</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ice</td>
<td>2.24 (^{1)})</td>
<td>estimate for the relation between wind velocity and heat transfer coefficient (^{3)})</td>
<td>( h_w = C_w \cdot V^{0.8} / D ) (^{2)})</td>
<td>1 (^{3)})</td>
</tr>
<tr>
<td>snow cover,</td>
<td>0.3 (^{1)})</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>snow slush,</td>
<td>-</td>
<td></td>
<td></td>
<td>0.53 (^{1)})</td>
</tr>
<tr>
<td>slush ice</td>
<td>2.24 (^{4)})</td>
<td></td>
<td></td>
<td>1 (^{4)})</td>
</tr>
</tbody>
</table>

\(^{1)}\) laboratory tests, \(^{2)}\) chronological table of Science, \(^{3)}\) studies of Takeuchi (1987), \(^{4)}\) same property as ice

(3) Analysis of cases during non-pumping operation

In the analysis of the cases during non-pumping operation, flow velocity in the reservoir is not taken into consideration, and the heat conductivity is used for the calculation of heat balance between the ice cover and the water. According to a water temperature survey conducted at the Uryu Daiichi Dam in 1998, water temperature at a depth of 2.0 m below the ice cover during the freezing season is about 1.5°C. This water temperature, therefore, was used in the heat balance analysis.

**Figures 2 to 5** show the estimated ice cover thicknesses at the upper reservoir of the pumped-storage power station and the Uryu Daiichi Dam in the case1 and case2, and the measured and calculated snow and ice cover thicknesses at a lake near the upper reservoir, the upper reservoir and the Uryu Daiichi Dam.

In the analysis, the physical property values shown in **Table 2** were used. The compressibility of snow slush was assumed to be 0.8; the density of the snow slush layer determined through laboratory testing was 0.94 g/cm\(^3\); and the density of the snow cover layer determined from the field observation results was 0.15 g/cm\(^3\). The measurement data for the lake near the upper reservoir and the Uryu Daiichi Dam were taken from the measured values obtained in 2000 and 1998. The analysis results show good agreement between the measured and calculated values. The total ice cover thickness was smaller (about 80%) than the near-lake land snow cover thickness due to melting as a result of heat balance and the compression of snow slush.
(4) Analysis of cases during pumping operation

Considering of the flow velocity in the reservoir, Takeuchi et al.'s (1987) theoretical formula was used in the analysis as the heat transfer coefficient necessary for calculating the heat balance between the ice cover and the water.

\[
h_w = C_w \cdot V^{0.8} / D^{0.2}
\]

where

- \( C_w \)
- \( V \)
- \( D \)

Figure 2 Calculated and observed value of the upper reservoir (case 1)

Figure 3 Calculated and observed value of the Uryu Daiichi dam (case 2)

Figure 4 Observed of the lake and calculated of the upper reservoir (case 1)

Figure 5 Observed and calculated of the Uryu Daiichi dam (case 2)
heat transfer coefficient (W/m²°C), $V$: flow velocity (m/s), $D$: water depth (m)

$C_w$: coefficient for roughness of underside of ice cover (W·s⁻⁰.⁸/m²⁶°C); 1,622 (laboratory test result)

Two cases of flow velocity in the reservoir were considered; 1 cm/s during power generation and 50 cm/s during pumping. **Figures 6** and **7** show the analysis results considering water temperature changes due to the melting of the ice cover in the case 3 and case 4. Water temperature was calculated assuming an initial temperature of 5°C and a latent heat of melting for ice of 80 cal/g. The quantity of ice melt and the amount of heat used for melting were calculated on a daily basis, and the results were considered at each stage in the quantity and temperature of reservoir water.

The analysis results are as follows;

- In the case 4 where the flow velocity in the reservoir is high, the ice cover melts early. With the progress of heat exchanges in the reservoir, however, water temperature decreases and therefore the ice cover doesn’t melt.
- Regardless of flow velocity, the maximum ice cover thickness ranged from 1.6 to 1.9 m, which are equal to about 50 percent of the maximum ice cover thickness during non-pumping operation (Case 1) and about 40 percent of the snow cover thickness.

### 3. TWO-DIMENSIONAL HYDRAULIC MODEL TEST

Since the available depth of the upper reservoir is large, it is possible that the ice cover slides down the slope so that the thickness of the ice cover near the slope increases. It was therefore decided to observe the behavior of the ice cover and changes in ice cover thickness under the influence of changes in water level by conducting a two-dimensional hydraulic model test using a model of the upper reservoir slope.
(1) Test method

The test apparatus, which was designed on the basis of a scale of the upper reservoir model of 1/70, consisted of a pump, water supply and drainage piping and a water tank. A slope gradient of 1:2.5 was used, and the model was made partially transparent by using transparent acrylic panels. The test apparatus was installed in an outdoor tent and the test was conducted on the proper temperature condition by measuring air temperature and water temperature during winter period so that the ice which was experiment materials did not melt. The available depth of the upper reservoir was assumed to be 45 m. In the test, the process involving lowering the water level from the high water level (H.W.L.) to the low water level (L.W.L.) and then raising it again to the high water level was regarded as a basic cycle, and repeated two or three times. Changes in water level were assumed to be constant. The maximum snow cover thickness at the site under consideration was assumed to be 5 m and the ice cover thickness was assumed to be 2 m. Because snow cover in the upper reservoir tends to be thick, it is likely that the ice cover is composed of soft snow slush instead of hard ice (Kasai et al., 2003). For this reason, about 1.5-m-thick ice was used in the test. To reproduce snow slush conditions, the test was started just after floating ices so that ices did not adhere each other. The slope of the upper reservoir model was made with an acrylic panel with small friction because the real slope is prone to sliding.

(2) Test results

The process of the growth of the ice cover in the model due to changes in water level observed in the two-dimensional hydraulic model test is described below.

1) As the water level fell, the ice cover on the water surface was gradually placed on the slope of the model so that, at first, the forces acting on the entire ice, such as the slip load acting on the ice on the slope and the buoyancy acting on the ice on the water surface, went into equilibrium.

2) As the water level further fell, the slip load acting on the ice on the slope increased until the balance of forces acting on the ice was lost and the ice placed on the slope slid instantly (Photo 1).

3) The ice fragments that began to sink from the water surface dispersed before reaching the intake, and then rose to the water surface again to combine with the floating ice fragments so as to increase the ice cover thickness (Photo 2).
In the single-layer single-cycle test, the maximum ice cover thickness became two or three times as large as the initial thickness, and the maximum thickness occurred at a location on the slope side of the intake. In the three-layer three-cycle (single-layer single-cycle, addition of one layer, one cycle, addition of one layer, one cycle) test, sliding occurred several times because of repeated changes in water level. The maximum ice cover thickness, however, was roughly the same as the result of the single-layer single-cycle test, and the maximum thickness occurred at a location on the slope side of the intake.

From these test results, it can be concluded that although ice cover thickness increases locally near the upper reservoir slope because of changes in water level.

4. CONCLUSION

The results of this study can be summarized as follows;

- The analysis results for ice cover thickness indicate that the ice cover thickness of the upper reservoir is about 80 percent of the snow cover thickness during non-pumping operation and about 40 percent of the snow cover thickness during pumping operation. The ice cover thickness model used for the analysis makes it possible to quantitatively estimate changes over time in ice cover thickness by entering local meteorological data and the operating method of the reservoir.
- In the two-dimensional hydraulic model test conducted to reproduce snow slush conditions, ice cover thickness increased locally near the slope under the influence of changes in water level.
- The maximum ice cover thickness in the case where the upper reservoir is always in operation is considerably smaller than the land snow cover thickness, but ice cover thickness increases locally near the upper reservoir slope under the influence of changes in water level.

REFERENCES