Calculation of the fracture of ice fields at a concentrated drop

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Abstract. Ensuring the passage of ice through the spillway structures in the spring remains relevant today. The problem is posed to let ice pass during the operational period with small sizes of transitory openings. Of the many activities aimed at solving this problem, it is worthwhile to focus on the creation of a concentrated drop in the water surface, on which the ice floe breaks. This allows ice to pass through the spillways without hindrance. The goal is to improve the structural elements of the hydroelectric complex, including an additional threshold, on which a concentrated drop is formed, which contributes to the fracture of ice fields. A method for calculating the size of ice floes entering the overhangs is considered, taking into account the dynamics of the flow, the slope and speed of the ice floes. The article also provides an analytical method for calculating bending moments and distance to the section, where the magnitude of the moment reaches an extreme value. Some results of laboratory studies of a free surface are given, which allow obtaining a number of coefficients that can be used in the obtained analytical dependences for determining bending moments.

1. Introduction

Catastrophic floods and extreme hydrological events can cause tremendous damage to the water sector. These problems are being discussed more and more actively in the world and in Russia [1-4]. Also, the sad consequences and flooding of lands cause difficult conditions for the passage of ice on some rivers. Hence it follows that it is necessary to carry out measures to prevent and eliminate floods, inundations and other harmful effects of water [5-8]. These issues can be solved both by regulating the river flow and by creating elements of hydraulic engineering facilities that allow for the successful passage of ice. The experience in the construction and operation of large hydroelectric complexes has shown that ice fields, moving through a concentrated drop, formed under the influence of an insufficiently disassembled upper bulkhead of the pit of the first stage, break into separate ice floes. Their passage through the comb does not present any particular difficulties [9].

The objectives of this work are:

- Consideration of the possibility of using the above idea (creation of a concentrated drop) to ensure the passage of ice through low-pressure waterworks with a limited width of the spillways;
- obtaining analytical dependencies to determine the bending moments and distances where the magnitude of the moment reaches an extreme value, which will justify the dimensions of the designed structures.
2. Materials and methods

It seems expedient to install an additional sill or some kind of structure in front of the main structure, providing the creation of a free surface drop [10].

The solution to the problem of ice destruction at the drop is reduced not only to determining the length of the strip breaking off from the ice field, but also to determining the size of ice floes that do not break at the drop (Fig. 1). It should be noted that the fracture of ice floes is influenced by their inclination when moving through the drop, the shape of the free surface of the flow and, to a lesser extent, by the deflections of the ice floes. Therefore, it is necessary to consider the destruction of ice at a concentrated drop without taking into account elastic deformation, but taking into account the position of the ice floe in the vertical plane.

![Figure 1. Ice break at a concentrated drop and schemes of loads acting on the ice floe](image)

1 – main spillway; 2 – auxiliary sill; 3 – broken off part of the ice floe; 4 – ice field

3. Results

The solution to the problem includes two stages. In the first one, the position of the ice floe at the drop is considered (angle of inclination, amount of immersion, etc.); on the second, bending moments and stresses arising in the ice field during its movement through the drop are determined.

In case of uneven movement, the position of the ice floe in the water flow is determined using the following systems of equations [11].

\[
\begin{align*}
F_{\tau} &= -F_a \sin \alpha + F_g \sin \alpha + R_\tau \cos(\alpha - \varphi) + R_n \sin(\alpha - \varphi) \\
F_{i}^{(in)} &= F_a \cos \alpha - F_g \cos \alpha + R_\tau \sin(\alpha - \varphi) + R_n \sin(\alpha - \varphi)
\end{align*}
\]

(1)

Here \(F_{\tau}^{(in)}\) and \(F_{i}^{(in)}\) are the components of the inertial force in the direction of the axes \(M\) and \(N\); \(F_a\) is the Archimedean force; \(F_g\) is the force of gravity; \(R_n\) is the projection onto the normal to the surface of the ice floe of the resultant of the hydrodynamic forces acting on the ice floe from the liquid side; \(R_\tau\) is the component of the resultant tangent to the surface of the ice floe; \(\varphi\) is the angle of inclination of the ice floe; \(\alpha\) is the angle between the horizontal line and the tangent to the trajectory of motion of the center of gravity of the ice floe.

The forces included in system (1) are described by the following dependencies:

\[
F_{\tau}^{(in)} = m_f \frac{dv}{dt}; F_{i}^{(in)} = m_f v^2\tau
\]
where $m_f$ is the mass of the ice; $r$ is the radius of curvature of the trajectory of the ice floe; $t$ is time; $V$ is the absolute speed of ice movement.

$$F_g = \rho_f g B h l,$$

Here $B$ is the width of the ice floe; $\rho_f$ is ice density.

$$R_t = f B l \frac{V^2}{2},$$

where $f$ is the coefficient of friction; $V_r$ is the relative speed of movement of water and ice; $\rho$ is the density of water.

$$R_n = k_n B l \rho V^2; \quad F_d = \rho g B \sum_{i=1}^{n} \Delta S_i,$$

$\sum_{i=1}^{n} \Delta S_i$ is the area of a part of the section of an ice floe immersed in water; $k_n$ is the coefficient of the ice floe shape.

To determine the magnitude of the bending moments, we choose an arbitrary section $x-x$ (Fig. 1), relative to which the moment of all forces applied to the left is equal to

$$M_x = \rho g B \cos \varphi \sum_{i=1}^{n} \Delta S_i x_i + \frac{1}{2} F_r^{(in)} x \sin \alpha - \frac{1}{2} F_g x \cos \varphi - \frac{1}{2} R_n x \cos(\alpha - \varphi) - \frac{1}{2} F_n^{(in)} x \cos \alpha,$$

(2)

From which it is possible to determine the distance $x_0$ to the section with the maximum value of the moment.

To solve equations (1), (2), (3), additional dependencies are required that describe the free surface of the flow, the trajectories of the center of gravity of the ice floe and its speed of movement.

The type of equation that best describes this or that phenomenon was selected, and then its coefficients were found from laboratory data.

Therefore, to describe the free surface of the flow in the coordinate system $\xi$ and $\chi$ (Fig. 2), we use the following dependence:

$$\xi = a \frac{\chi^2}{z_0} + b \chi,$$

where $a$ and $b$ are experimental coefficients, which can be determined from the following empirical dependencies: $a = -0.32 z_0^2 + 0.3 z_0 - 0.1; \quad b = 0.75 z_0^2 - 1.6 z_0 + 0.8$.

(Figure 2. Scheme of the position of the coordinate axes and the relationship between them

1 – position of the ice floe at time $t = 0$;

2 – movement trajectory of the center of gravity of the ice floe)
The trajectory of motion of the center of gravity of an ice floe in the X and Y coordinate system can be described by the following equation:

$$ Y = z_0 \left( 1 - e^{-\frac{k}{z_0}} \right), $$

where $z_0$ is the value of the concentrated drop; $k$ is an empirical coefficient. At $z_0 < 0.92h$ for $k$, the following dependence was obtained $k = 0.001l^2 - 0.01l + 0.35$.

The origin of coordinates X and Y, as can be seen from Fig. 2, is located at a distance $l/2$ from the end of the decay curve downstream and at a distance of $0.42h$ from the free surface of the tailwater.

Let us use the following equation to describe the speed of the ice floe through the drop:

$$ V = V_0 + A(1 - \cos \omega t), $$

where $V_0$ is the initial velocity of the ice floe at the time $t = 0$, at which the center of gravity of the ice floe is located at a distance $(l + \chi_0)$ in the Y, X coordinate system; $A = (V_{\text{max}} - V_0)$; $V_{\text{max}}$ is the maximum speed that an ice floe of length $l$ can develop when moving over the drop $z_0$; $\omega = \pi/T$, where $T$ is the time during which the ice floe acquires a speed from $V_0$ to $V_{\text{max}}$. Laboratory studies of the speed of ice movement at a concentrated drop made it possible to obtain dependences for $A$ and $T$ in the following form:

$$ A = m_1z_0^2 + m_2z_0 + c; \quad T = m_3z_0 + c_1. $$

Here, $m_1, m_2, m_3, c$ and $c_1$ are coefficients depending on the size of the ice floe along the flow, $m_1 = 0.014l - 2.8; m_2 = -0.016l + 4.3; m_3 = -0.0032l^2 + 0.245l; c = -0.003l + 0.6; c_1 = 0.5l + 0.5$. [12]

The path $S$ traversed by the ice floe in the period from 0 to $t$ can be found as the following integral:

$$ S = \int_0^t V \, dt = V_0t + A \left( t - \frac{1}{\omega} \sin \omega t \right). $$

Thus, at time $t$, the center of gravity of the ice floe is at a distance of

$$ x = l + \chi_0 - S $$

from the origin of the X, Y system.

The cross-sectional areas of the part of the ice floe immersed in water were found by dividing it into elementary areas $\Delta S$.

Having received expressions for calculating the moments and for other design schemes, it is possible to determine the stresses in dangerous sections of the ice floe:

$$ R = \frac{M}{W} $$

The ice floe collapses if condition $R > R_i$ is met, where $R_i$ is the ultimate bending strength.

4. Discussion

The presented results make it possible to carry out calculations of the broken parts of the ice floe, which, in turn, affect the choice of the size of spillway spans. The device of an auxiliary threshold in front of the main spillway (or other structural elements) facilitates the breaking of ice floes, which ensures unhindered passage of ice and reduces the risk of catastrophic situations.

In the theoretical solutions obtained when fulfilling the set goal, additional factors of the passage of ice floes through a concentrated drop are taken into account, namely, the angle of their inclination.

Calculations based on the obtained dependencies present certain difficulties; therefore, it is planned to use them in the future as a basis for creating mathematical models that allow taking into account many factors that describe the entire process of the passage of the spring ice drift.

5. Conclusion

Based on the differential equations of motion of a rigid body in a liquid with a sufficiently complete consideration of the forces acting on the ice floe from the flow side, dependences were obtained that allow determining the bending moments arising when the ice floe moves through the drop and the length of the breaking off part of the ice floe, which affects the width of the transverse holes.

The performed laboratory studies of the free flow surface between the auxiliary sill and the spill made it possible to use the developed theoretical solutions for practical calculations.
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