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CONDITIONS FOR ICE JAM FORMATION IN TAILWATERS

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On the basis of studies on the dynamics of the ice cover edge the following peculiarities were found in the formation of jams in tailwaters. Formation of ice jams in tailwaters is a consequence of the dynamic destruction and separation of the edge with increased discharges. The process of dynamic destruction of the edge evolves by the formation of cracks along the shore, debacles, and hummocking on the section within which during discharges the size of fluctuation in the water level is 3-4 times greater than the thickness

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of ice on the edge during its formation. Jams are formed at the jointing of the intact ice cover and the shattered field under the influence of the forces of the flow and pressure of the ice field which exceeds the resistance of the ice. The amount of the greatest jam level is in direct dependence on the amount of maximum water consumption in the period of jam formation. An increase in discharges during the formation of ice jams promotes the increase in capacity of the jam, and as a consequence a reduction in the winter coefficients occurs. Regulation of the GES routine depending on the conditions for ice cover edge formation on the section within the diurnal lag time is a necessary condition for the movement of the edge in the tailwater without jam formation.

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NOTICE

CONDITIONS FOR ICE JAM FORMATION IN TAILWATERS

GOSUDARSTVENNIY GIDROLOGICHESKIY INSTITUT. TRUDY in Russian Vol 227, 1975
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[Article by R. V. Donchenko]

[Text] The section of GES tailwater which is located in the pulsation zone of the edge of the ice cover is characterized by an unstable ice pattern. Under the influence of a diurnal and weekly regulation of the GES during the winter a change in the ice phenomena occurs on this section--alternation of freeze-up with ice drift and moving sludge. Here as a consequence of fluctuation in the water level, and an increase in longitudinal inclinations and current velocities in discharges favorable conditions are created both for the formation of ice jams during the generation of the ice cover, and for the formation of ice jams during its destruction. The conditions for the formation of ice jam phenomena have been previously examined and published in works [4, 5]. This article presents questions of the destruction of the ice cover and the formation of ice jams in the GES tailwaters.

Study of the laws governing the formation of ice jams in tailwaters was based on research of the conditions for stabilization, breaking and shifting of the ice cover edge depending on the GES routine, and the change in thermal and hydraulic characteristics along the length of the tailwater.

For this purpose the following were selected as the subjects of research: tailwaters of the Volga GES imeni 22nd CPSU Congress and the Bratsk GES imeni 50th Anniversary of the Great October. In addition, model studies were made of the mechanism involved in ice jam formation.

Conditions for Stabilization of Ice Cover Edge

The position of the ice cover edge in the tailwater is determined by the heat flows entering the tailwater, the heat emission from the water surface, and the hydraulic pattern on the section of its shift. Stabilization of the edge occurs on the tailwater section where the heat flow is completely expended for heat emission from the water surface, and hydrodynamic stability of the ice cover edge occurs. These conditions can be presented in the following form:

$$Qcpt = SL_0B. \quad (1)$$

$$Fr = \frac{v}{\sqrt{gH}} = \sqrt{\frac{2(\rho - \rho_1)}{\rho}(1 - \varepsilon h)\left(1 - \frac{h}{H}\right)}. \quad (2)$$

According to [9], equation (2) reaches the maximum

$$Fr_{макс} = 0.154\sqrt{1 - \varepsilon}, \quad (3)$$

where Q--consumption of water; t--temperature of water discharged into tailwater; S--heat losses from water surface; Z_0--distance of line of zero isotherm to dam; B--width of river; Fr--Froude number; v and H--velocity of current and depth above edge; ρ_1, ρ --density of water and ice; ε --porosity of ice floe accumulations; h--thickness of ice.

As a consequence of the continuous changes in meteorological conditions, as well as of a diurnal and weekly GES regulation a shift occurs in the edge of the ice cover along the length of the tailwater. Thus, according to the data of studies on the ice pattern of the Volga GES imeni 22nd CPSU Congress, there was an almost diurnal change in its position in the winter of 1963-1964. Here the edge approached close to the dam nine times and the same number of times withdrew from it to a distance of 60-80 km. The main reason for the return movements of the edge was the sharp change in meteorological conditions, and accordingly, a decrease in heat losses from 200 to 100 cal/(cm^2·day). In a number of cases simultaneous reduction in heat losses from 500 to 200 cal/(cm^2·day) and increase in the mean diurnal consumptions of water from 3000 to 7000 m^3/s occurred.

According to the data of many years of observations, the stabilization section is 4 km from the dam in a cold winter, and 64 km in a warm winter.

During one winter the position of the edge changes within 10-30 km; first it approaches the dam by 8-28 km, then it withdraws from it by 16-58 km (1962-63, 1963-64, 1964-65, 1967-68).

In the tailwater of the Bratsk GES for conditions of midwinter (1961-62) and with water consumption of 2000 m^3/ms the least distance of the edge from the dam was 15 km. In warm winters the edge was at a distance of 40-90 km depending on the amount of discharge and the temperature of water entering the tailwater.

The edge of the ice cover completes complex oscillating movements depending on the change in meteorological and hydrological conditions; however, its mean position for a lengthy time interval coincides with the section of stabilization which is located in direct proximity to the line of zero temperatures. Therefore an evaluation of the mean position of stabilization of the ice cover edge for the subject under study can be made by using the calculated dependencies for the position of the line of zero temperatures along the length of the tailwater on the heat losses, temperature and consumption of water entering from the reservoir into the tailwater:

$$L_0 = f(Q, t, S). \qquad (4)$$

Work [4] presents the indicated dependence for the tailwater of the Volga GES imeni 22nd CPSU Congress. The calculation has used the extreme values of Q (2500-8500 m^3/s) and t (0.3-0.1°C) which have been observed during the freezing of the tailwater of the Volga GES, corresponding to 99 and 1% frequency. Calculations for heat losses were made according to the method of heat balance. For the values Q and t accepted above with heat losses above 1000 cal/(cm^2·day) the line of zero temperatures is located at a distance not more than 15 km from the dam. With heat losses 200-300 cal/(cm^2·day) it is separated from the dam at a distance to 100 km.

For the stable position of the ice cover edge it is necessary to also fulfill the second condition, i.e., the resistance of the ice cover edge to the action of external forces.

From an analysis of the data from ice cover formation in tailwaters it follows that the edge is fixed mainly from the layer of sludge, the thickness of which is determined by the conditions of its freezing together and by the hydraulic characteristics of the section of ice formation. In the tailwater of the Volga GES imeni 22nd CPSU Congress the layer of sludge 0.5 m with air temperature -10°C freezes in 5 days. With complete freezing the sludge ice has temporary resistance to shearing equal to 3.7 kg/cm^2.

Having accepted the Froude number as the criterion for the hydrodynamic stability of the ice cover edge one can determine the distance along the length of the water to the edge depending on the thickness of ice. The characteristic values for the initial thickness of ice which forms the ice cover edge in the tailwaters of the Bratsk and Volga GES are given in tables 1 and 2. Depending on the water consumption and heat losses in the period of freezing the initial thickness of the ice fluctuates within 14-33 cm on the Angara and 22-58 cm on the Volga River.

Under the influence of a diurnal and weekly regulation of flow in the tailwater a change occurs in the hydraulic characteristics which results in a disruption in the equilibrium between the forces which act on the ice cover. Sharp oscillations in the water level in the first days of freeze-up lead to its destruction.

The effect of waves of discharges on the stability of the edge position is determined by the amount and duration of the discharge. For each tailwater one can establish the zone of influence of discharges on the stability of the ice cover edge under preset meteorological conditions. As is known, on rivers with relatively small discharges as compared to the river bed capacity

Table 1. Hydrometeorological Conditions for Stabilization of Ice Cover Edge in Tailwater of Bratsk GES

(1) Зимний период, год	(2) Расстояние створа стабилизации кромки от плотины, км	(3) Температура воздуха, °C	(4) Расход воды, м³/с	(5) Скорость течения перед кромкой, м/с	(6) Начальная толщина льда, м
1962-63	25	−10	1000	0,4	0,32
1963-64	83	−23	1500	0,6	0,16
1965-66	65	−8	2000	0,7	0,14
1966-67	80	−28	2200	0,8	0,22
1967-68	100	−26	3200	1,0	0,24
1968-69	68	−21	3200	1,1	0,28
1969-70	75	−14	2800	0,9	0,20

Key:
1. Winter period, year
2. Distance of section of stabilization of edge from dam, km
3. Air temperature, °C
4. Water consumption, m^3/s
5. Velocity of current before edge, m/s
6. Initial thickness of ice, m

Table 2. Hydrometeorological Conditions of Stabilization of Ice Cover Edge in Tailwater of Volga GES imeni 22nd CPSU Congress

(1) Зимний период, год	(2) Расстояние створа стабилизации кромки от плотины, км	(3) Температура воздуха, °C	(4) Расход воды, м³/с	(5) Скорость течения перед кромкой, м/с	(6) Начальная толщина льда, м
1960-61	64	7.5	4700	0.76	0.22-0.30
1961-62	64	−3.2	6750	0.82	0.24-0.57
1962-63	19	−17.2	7580	0.85	0.25
1963-64	12	−20.0	8130	0.88	0.46
1964-65	20	−12.2	4700	0.76	0.33
1965-66	87	−7.0	8160	0.86	0.44
1966-67	15	−13.5	6190	0.79	0.47
1967-68	17	16.3	6950	0.73	0.32
1968-69	4	−20.6	7660	0.85	0.35
1969-70	19	−13.6	7400	0.84	0.58
1970-71	19	−16.1	4860	0.77	0.25

Key:
1. Winter period, year
2. Distance of section of stabilization of edge from dam, km
3. Air temperature, °C
4. Water consumption, m^3/s
5. Velocity of current before edge, m/s
6. Initial thickness of ice, m

the waves of discharge are spread fairly quickly, and conversely, with relatively large discharges the waves are spread over a great distance. In the presence of an ice cover the coefficient of spread for waves of discharge is increased as a consequence of the heightening of total roughness. Especially extensive spreading of discharge waves is observed on the ice jam sections of the tailwater.

A fluctuation in the water level also occurs correspondingly to the change in water consumption in the tailwaters. In winter the size of fluctuations in water level directly at the dam of the tailwater reaches 2-3 m (table 3). As one goes farther downstream there is a reduction in the amount of fluctuation in the level according to the exponential law [2]:

$$A_L = A_0 e^{-\frac{\beta L}{T}}, \qquad (5)$$

where A_0 and A_L--respectively the size of fluctuation in water level directly below the GES and at a distance L km from the GES; T--duration of discharge, h; β--intensity coefficient for spread of waves of discharge depending on the morphological structure of the river bed and on the slope.

Table 3. Greatest Size of Fluctuation in Level in Tailwaters of GES in Winter

GES	Size of fluctuation in level, cm	GES	Size of fluctuation in level, cm
Ivan'kovskaya	130	Volga imeni 22nd CPSU Congress	280
Volga imeni V. I. Lenin	230	Gor'kovskaya	160
Novosibirsk	200	Bratsk	200
Nizhne-Svirskaya	200		

According to the data of research, the limits of daily regulation in winter for the Krasnoyarsk GES reach 160 km, for the Volga imeni V. I. Lenin--150 km, for the Volga imeni 22nd CPSU Congress--100 km, for the Nizhne-Svirskaya--60 km and for the Ivan'kovskaya--40 km. Analysis of the observation materials established that the effect of discharge waves on the stability of the ice cover edge occurs on the section of water near the dam within the diurnal lag time.

Deformations and Destruction of the Ice Cover Edge

The development of the process of dynamic destruction of the ice cover edge occurs in the following sequence:

a) formation of coastal cracks;
b) debacles and hummocking;
c) separation of the edge.

In the passage of discharge waves the fluctations in water level and increased velocity pattern result in the appearance of cracks and a loss in the continuity of the ice cover. With discharge waves the destruction of the edge occurs on the crest of the wave which passes under the ice cover. In buckling the ice cover reaches critical deflections and breaks.

The existing methods of calculation, based on the theory of elasticity and hydromechanics, make it possible to determine the amount of critical rise in water level in which coastal cracks are formed.

By taking into account that at the edge the ice cover is partially connected to the shores, the formula of L. N. Kachanov [6] can be used to compute the critical rise in water level

$$H_n = 34.6\,\frac{\sigma}{\varphi\chi}\sqrt{\frac{h}{E}}. \qquad (6)$$

where H_n--height of rise in level, cm; σ--temporary bending stress, kg/cm^2; h--thickness of ice, cm; E--modulus of elasticity of ice; φ and χ--functions of relaxation determined by calculated graph.

For cases of so-called hinged attachment of the ice cover to the shores the numerical coefficient of calculated formula (6) is taken as equal to 17.3. In calculating the rise in level which elicits the appearance of cracks in the ice cover it is necessary to take into consideration the dependence of $\varphi\chi$ on the intensity of discharge, and of E and σ on the air temperature. Table 4 presents the calculated values for the critical rise in water level for two variants of attachment of the ice cover to the shores under different meteorological conditions.

It follows from table 4 that in the first variant with small thickness of the ice cover (10 cm) formation of coastal cracks should be expected with rises in the level 12-26 cm depending on the air temperature, while with great thicknesses (30-50 cm) 23-51 and 32-64 cm respectively. For the second variant the corresponding calculated values for the rise in level are two times smaller.

Comparison of the calculated and observation data for the tailwaters of the Volga imeni 22nd CPSU Congress, Gor'kovskaya, Rybinsk GES and others reveals the satisfactory agreement of the calculated and measured values.

Thus, according to the data of observation in the tailwater of the Volga GES imeni 22nd CPSU Congress in the winter of 1971-1972 with the ice cover edge located 32 km from the GES the formation of cracks along the shore occurred with a rise in water level 28-32 cm (calculated value for rise in level 24 cm). In the tailwater of the Rybinsk GES with h=16 cm formation of cracks along the shore was observed as a result of a rise in water level by 30-32 cm (calculated--36 cm).

Table 4. Calculated Values for Critical Rise in Water Level (cm)

(1)	(2)		(3)	
	(4)			
	[illegible]	[illegible]	[illegible]	[illegible]
10	12	26	6	13
[illegible]	15	36	8	18
[illegible]	18	43	9	22
[illegible]	20	47	10	24
[illegible]	23	51	11	26
[illegible]	32	64	14	32

Key:

1. Thickness of ice, cm
2. Incomplete attachment of ice to shores
3. Hinged attachment of ice to shores
4. Air temperature, °C

In selecting the variant for attachment of the ice cover to the shores it is necessary to consider the time which the edge was located at the given section and the meteorological conditions of the examined period in order to take into account the effect of the ice freezing together with the shores and at the same time give preference to one of the calculated variants. The time for the freezing together of the sludge cover can be computed by the following formula:

$$\tau = \frac{r_{л}(\gamma_{ш} - \gamma_{л})}{2\lambda t} h^2. \qquad (7)$$

where $\gamma_{ш}$, $\gamma_{л}$--specific weight of sludge and ice; λ--coefficient of heat conductivity of ice; t--temperature of sludge surface; h--thickness of ice; $r_{л}$--latent heat of ice formation.

In order to evaluate the effect of discharge waves on the destruction of the ice cover edge during its passage on various sections of the tailwater a preliminary calculation should be made of the amount of rise in water level depending on the size and duration of discharge waves, and then, by using the calculated values for the maximum rise, the zone of influence of discharge waves on destruction of the ice cover can be determined.

Table 5 gives the values for fluctuation in levels along the length of the GES tailwaters, from which it can be concluded that the effect of discharge on the stability of the edge is within 20-80 km of the GES dam. Thus, for the tailwater of the Volga GES imeni 22nd CPSU Congress with great discharges, and correspondingly with great fluctuations in the level along the length of the tailwater as well, the stability of the edge is disrupted during its movement on the section of tailwater up to 60 km.

As indicated, the formation of cracks along the shore is the first stage in the destruction of the ice cover. After their formation the ice cover will rise together with the water level and operate under load as a semi-infinite slab with floating edge. Under the influence of the dragging force of the flow, as well as the wind load, drop and irregularity in water surface, a loss occurs in the continuity of the ice cover, i.e., breaking up of the ice fields into individual ice floes and their hummocking. If hummocking is not observed in the breakup, but only separation of both parts, then it is evident that this breakup was a result of bending stress which occurred in the ice field from the passage of a wave of brief discharge. Hummocking occurs as a result of a loss in the stability of individual ice floes during compression.

When discharge waves pass on sections of the tailwater where rises in water level exceed the thickness of the ice cover, following the formation of coastal cracks flotation and losses in continuity of the ice cover occur.

Intensive deformations in the ice cover take place mainly with a sharp rise in the level, and often result in the debacle of the river and regression in the edge of the ice cover edge downstream. In this case destruction of the ice cover takes place by breakup of the field with cross cracks which develop when the height of rise in water level is greater than the height of maximum deflection.

The amount of bending moment with the maximum height of deflection can be determined by the formula obtained after integration of the differential equation for the curved axis of ice cover with regard for certain simplifications [11]:

$$m = 200 f_{макс} \sqrt{h^3}. \quad (8)$$

where $f_{макс}$--maximum deflection; h--thickness of ice cover.

The appearance of cracks should be expected if

$$m \geq \frac{\sigma_и h^2}{6}, \quad (9)$$

where $\sigma_и$--resistance of ice to bending.

Having used the data of observations on the intensity of rise in water level during discharges one can determine the thickness of the ice cover at which its destruction occurs depending on the water consumption. Thus, for

Table 5. Spread of Waves of Discharge in Tailwaters [4]

(1) ГЭС	(2) Длительность попуска, ч	(3) Расходы попуска, м³/с		$K = \frac{Q_{макс}}{Q_0}$	(4) Амплитуда колебаний уровня в нижнем бьефе	$\alpha = \frac{Q_{макс} - Q_0}{t}$	(5) Амплитуда колебаний уровня в долях от максимальной по длине бьефа, км												
		Q_0	$Q_{макс}$				2	5	10	15	20	25	30	40	50	60	80	100	120
(6) Иваньковская . .	3,7	7,0	281,5	40,2	1,78	75,0	0,91	0,77	0,51	0,31	0,24	0,19	0,13	0,08					
(7) Красноярская . .	3,0	950	4620	4,9	3,31	1223	0,91	0,87	0,76	0,66	0,59	0,54	0,48	0,40	0,33	0,26	0,16	0,11	0,09
(8) Волжская им. В. И. Ленина	14	1680	7500	4,5	2,01	418	0,96	0,90	0,81	0,71	0,67	0,61	0,54	0,43	0,32	0,21	0,16	0,13	0,11
(9) Камская	13	1000	2500	2,4	1,37	108	0,96	0,93	0,87	0,81	0,75	0,68	0,63	0,51	0,41	0,31	0,29	0,27	
(10) Нижне-Свирская	4	14	1080		1,70	266	0,90	0,80	0,65	0,51	0,45	0,37	0,30	0,20	0,13	0,08			
(11) Волжская им. XXII съезда КПСС	4	3500	8500		1,06	1250		0,95		0,87	0,76		[illegible]	0,41		0,29		0,13	0,08

1. GES
2. Duration of discharge, h
3. Outlays of discharge, m^3/s
4. Size of fluctuations in level in tailwater
5. Size of fluctuations in level in percentages of maximum along length of tailwater, km
6. Ivan'kovskaya
7. Krasnoyarskaya
8. Volga imeni V. I. Lenin
9. Kamskaya
10. Nizhne-Svirskaya
11. Volga imeni 22nd CPSU Congress

example, in the tailwater of the Volga GES imeni 22nd CPSU Congress then the edge is 60 km below the GES dam destruction of the ice cover edge must occur with consumptions of water greater than 6000 m^3/s and thickness of ice at the edge less than 35 cm. The resistance of ice to bending in these calculations is taken, according to [6], as $\sigma_n = 40\ \text{T/m}^2$.

Under the influence of water flow and wind on the section of breakup of the ice fields debacles occur and processes of hummocking and compression of ice develop. Reformation of the ice cover edge essentially takes place due to the dynamic increase in thickness of ice according to the hydraulic characteristics of the section and the meteorological conditions. Debacles dominate which result in the shifting of the ice cover great distances. However with sharp changes in the amount of discharge powerful debacles occur which encompass sections to 20 km. The duration of such debacles reaches 2-3 h.

The sizes of the debacles depend on the correlation of forces which promote and prevent ice movement, i.e., on the amount of active and reactive forces [1, 6]. The active include forces of water and air friction on the lower and upper surfaces of the ice cover and on the weight component of ice in the direction of the flow, while the reactive include forces of resistance by the shores and edge of intact ice cover.

The total amount of hydro- and aerodynamic load on the ice fields as a result of friction of air and water currents on the borders water-ice and air-ice can be presented in the following form:

$$P_n = \alpha_1 v^2 L_1 B \pm \alpha_2 w^2 B L_1, \qquad (10)$$

where BL_1--width and length of the ice field, m; v and w--respectively the velocity of current and wind, m/s; α_1 and α_2--coefficients of hydro- and aerodynamic loads.

It is necessary to note that the action of wind is greatest if its direction coincides with the direction of ice movement. However, this component of the load becomes comparable to the action of the current only with wind velocities over 10 m/s.

A (+) sign is taken for tail wind and a (-) sign for head wind.

Taking into account that the angle between the surface of the flow and the water line is small, the component of ice weight in the direction of the current should be written

$$P_n = \gamma_n h B L_1 I, \qquad (11)$$

where I--slope of water surface.

Having lost continuity, the ice fields border the edge of the ice cover which is attached to the shores. At the edge the ice cover is subjected to compression. When the ice is of relatively small thicknesses the ice field is destroyed under the action of compressive forces for the most part from bending. According to research data debacles develop if the total forces of friction of water and air currents on the borders water-ice-atmosphere and the component of weight in the direction of the current is greater than the maximum possible load σh.

By having data v, w, B, L and h one can evaluate the value of forces which promote debacles, and can find the conditions under which debacles develop. Thus, in the tailwater of the Volga GES imeni 22nd CPSU Congress with a change in water consumption from 4000 to 10,000 m^3/s on sections 1000 m wide the current velocity is increased from 0.7 to 1.2 m/s. Under these conditions debacles of ice cover are possible with thicknesses of ice less than 30 cm.

The calculation accepts the values $\alpha_1 = 20 \cdot 10^{-4} \tau^2/m^4$, $\alpha_2 = 2x10^{-6} \tau^2/m^4$, $\sigma_n = 40\ /m^2$.

Taking into account the graph for the weekly pattern of load at the GES one can hypothesize that the most probable are debacles on sections where the edge moves in the first days of the week due to the sharp increase in discharges and the small initial thickness of the ice cover which had formed in the period of reduced loads (on days off).

The process of hummocking volves during debacles. The formed ice floes under the influence of wind and current are shifted and gradually increase the speed of their movement.

In the process of movement the ice floes which possess a varying supply of kinetic energy hit each other and as a result some of them lose stability, and under pressure from ice with greater kinetic energy they are tipped on their edges and are broken up into parts. In those cases where the kinetic energy of the floating ice floes is not sufficient to destroy, some ice floes creep over others and their hummocking occurs. In hummocking the movement of ice floes in the horizontal plane is disrupted, the rear edge of the ice floe is submerged in the water, while the front edge is raised to a height determined by the mass of ice floe m and the initial velocity of its movement v, i.e.

$$\Delta H = \frac{mv^2}{2P}. \qquad (12)$$

where P--weight of raised section of ice floe.

It is natural that the development of the hummocking process either intensifies or diminishes depending on the velocity and direction of the wind.

In the process of debacles the edge retreats and dynamic thickening of the ice formations occurs, as well as an increase in the irregularity of both the upper and lower surfaces. In those cases where the kinetic energy of of refloating ice masses is not sufficient to destroy or move stopped ice floes a continuous ice field of ice cakes begins to form. As ice accumulates the pressure increases and compression of ice occurs. In addition to forces acting in the direction of the flow, thrust develops, i.e., part of the load begins to be transmitted to the shores. The resistance of the river shores depends on the shape of the shores, the thickness and strength of the ice cover, and the nature of its contact with the shores. Qualitative analysis of the conditions for the dynamic interaction of the ice cover with the shores permits detection only of the general relationships between the forces of resistance of shores and the main determining factors.

It is known that debacles are always accompanied by heaping of ice on the shore. Depending on the shape of the shores, curvature of the slopes, as well as the strength of the ice the nature of deformation of the ice cover is determined. On sections with gently sloping shores the fields are destroyed from bending, or from shearing off under the influence of vertical components of contact forces. On sections with steep shores destruction of the ice field edge is most probable from shearing off. According to research data, the shattered ice field adjacent to the shores has a force effect on the edge less than the monolithic ice field which does not have a strong bond with the shores. Quantitative analysis of the maximum permissible load on the edge by the shattered field is made with regard for the tangential stresses in the friction water-ice, the forces of friction on the shore, and the lateral pressure [1].

Formation of Ice Jams

Under the influence of the current and interaction with shores the ice masses which pile up before the edge begin to thicken. In those cases where the discharges increase, at the edge an ice cover begins to form which is of double or triple thickness depending on the initial thickness of ice and the discharge conditions. This phase of jam formation usually does not result in a significant rise in water level. A further rise in water level and increase in current velocity elicit deformation and compression of the shattered ice field. Essentially a new ice field is formed with thickness and density of the ice floe packing corresponding to the conditions for a new equilibrium between the forces of resistance and deformation.

By using the equation for hydrodynamic stability of the ice cover edge (2) one can compute under what conditions of discharge and values of initial thickness of ice its separation and subsequent formation of a double or triple layer will occur.

For the entire range of change in the water consumption during discharges characteristic for the Volga GES imeni 22nd CPSU Congress separation of the edge on the section near the dam can occur with thicknesses of ice not less than 40 cm (table 6).

With small initial thickness of ice (8-10 cm) formed at low negative temperatures in the period of minimum nightly loads, separation of the edge

Table 6. Characteristic of Hydrodynamic Stability of Ice Cover Edge

Расход, м³/с	Fr	h см			
		ε = 0,1	ε = 0,3	ε = 0,5	ε = 0,7
000	0,05	5	6	8	14
000	0,06	7	9	12	20
000	0,08	12	15	21	36
10 000	0,10	19	24	33	56
12 000	0,11	23	29	41	67
15 000	0,12	26	31	48	80
17 000	0,14	36	47	66	110

Key:
1. Consumption, m^3/s

takes place with any discharge. With an increase in water consumption to 8000 m^3/s the condition of hydrodynamic stability of the edge is fulfilled with thickness of ice 12-36 cm depending on the porosity of the accumulations. Consequently, under these conditions formation of a shattered ice field of double or triple thickness of ice must occur. With a further increase in the consumption of water of discharges a change in the thickness of ice also will occur correspondingly.

Further thickening of the formed continuous ice field at the jointing with the edge of the intact ice cover occurs as a result of collapse under the influence of a hydrodynamic load, which leads to the formation of a jam accumulation. Stability of the jam accumulations is determined by the maximum water expenditures in discharge, the morphometric characteristics of the jam section, and strength and thickness of the ice. The limiting condition for static equilibrium of the jam accumulations is the following expression [8]:

$$\frac{H\sqrt[4]{B}}{\mu\sqrt{Q}}=2.36, \qquad (13)$$

where H--depth, feet; B--width of river, feet; μ=0.26; Q--consumption, ft^3/s.

The stability of jams is maintained until the current pattern changes. If the expression of the left side is less than 2.36 the ice jam cannot counteract pressure and is destroyed. Under tailwater conditions the increase in water consumption during the formation of jams elicits a redistribution of the masses of ice and a retreat of the ice cover edge. Evaluation of the quantity of ice in the jam is made according to the data for changes in the water-permeable capacity on the jam section, by using the method based on the use of reference curves [3].

Table 7. Characteristics of Destruction of Ice Cover Edge in Tailwater of Volga GES imeni 22nd CPSU Congress

(1) Дата	(2) Расход воды, $м^3/с$ (3) максимальный	(2) Расход воды, $м^3/с$ (4) средний суточный	(5) Расстояние кромки от плотины ГЭС, км	(6) Толщина льда кромки, см	(7) Ледовая обстановка
2/II-61	8 500	4780	64	22	Подвижка (8)
9/II-61	10 000	4310	62	24	Подвижка. Отступление кромки (9)
18/II-63	12 600	7580	17	25	Подвижка (9)
24/II-63	12 000	7530	19	30	Подвижка (9)
25/I-64	12 000	7800	64	16	Срыв кромки у Светлого Яра. Затор (10)
18/II-64	7 500	6000	8		Подвижка (9)
24/II-64	13 300	8000	10	32	Подвижка (9)
3/II-65	12 900	7180	45	16	Срыв кромки у Красноармейска (переформирование) (11)
3/III-65	10 000	5960	8	26	Подвижка (9)
2/I-67	13 000	5420	14	8—10	Срыв кромки, затор (12)
25/I-67	15 000	7920	18	47	Подвижка (9)
26/I-68	13 300	6950	45	19	Срыв кромки, затор (12)
19/II-68	13 000	5630	14	40	Подвижка (9)
6/I-69	12 300	4420	64	25	Подвижка (9)
12/I-69	12 300	7140	19	18—20	Подвижка (9)
11/II-70	12 300	7800	19	20	Подвижка, срыв кромки (переформирование) (13)
16/II-71	12 000	7020	64	25	Подвижка (8)
17/II-71	12 300	7180	62	25	Подвижка (переформирование) (14)
19/I-72	15 050	9000	64	10—15	Срыв кромки, затор (12)

Key:

1. Date
2. Consumption of water, m^3/s
3. Maximum
4. Daily average
5. Distance of edge from GES dam, km
6. Thickness of ice edge, cm
7. Ice situation
8. Debacle
9. Debacle. Regression of edge
10. Separation of edge at Svetlyy Yar. Jam
11. Separation of edge at Krasnoarmeysk (reformation)
12. Separation of edge, jam
13. Debacle, separation of edge (reformation)
14. Debacle (reformation)

In laboratory studies of the mechanism for this complicated phenomenon the qualitative characteristics were found for the process of jam accumulation formation and values for the Froude number were obtained for which there is formation of a double and triple layer of ice field, as well as separation of the edge and formation of jam accumulations [10].

One should dwell on the results of full-scale observations made by the Volgograd Hydrometeorological Observatory of the conditions for the formation of jam accumulations during the movement of the ice cover edge in the tailwater of the Volga GES imeni 22nd CPSU Congress. Analysis of the materials for the 11-year period of observations (table 7) revealed that in the tailwater of this GES separation of the edge always occurs if the condition for hydrodynamic stability of the edge (2) is not fulfilled. Depending on the amount and duration of discharge in some cases there are debacles (1960-61, 1962-63, 1968-69, 1970-71), while in others reformation of the ice cover takes place (1964-65, 1969-70) and formation of jam accumulations (1963-64, 1966-67, 1967-68, 1971-72). The edge is stable if it is formed with water consumption and temperature conditions that guarantee the necessary thickness of ice formations. Depending on the climate conditions of the winter period the jams are formed on various sections along the length of the tailwater. In a warm winter the jams form as a result of a shift in the ice cover edge on the section of diurnal lag time from the dam, thus governing the rise in water level which is the maximum for winter. The site of jam formation is for the most part a section 3.5 km below the water station Svetlyy Yar. The greatest jam was observed in the winter of 1971-72 during which the water level at the Svetlyy Yar water station reached 780 cm (only 47 cm below the heighest observed in the spring flood tide). In a cold winter the jam accumulations are formed on the section near the dam during acute discharges and small thickness of the ice cover. Thus, in the winter of 1966-67 a jam of $16.8 \cdot 10^6$ T of ice was formed 15-20 km from the GES dam. An increase in the water consumption during the formation of ice jams produces a redistribtuion of the masses of ice and an increase in the capacity of the jam, which leads to a sharp reduction in winter coefficients. The amount of the greatest jam level is in direct dependence on the amount of maximum consumption of water [5]. By examining the entire set of conditions that determine the dynamics of the ice cover edge in the tailwater one can establish the limits for regulating the GES operating pattern during the ice cover formation in order to prevent the generation of powerful jam accumulations. The solution to this task must be based on the conditions for the stabilization of the ice cover edge depending on the amount of discharges and the weather conditions of the winter period.

Conclusions

On the basis of studies on the dynamics of the ice cover edge the following peculiarities were found in the formation of jams in tailwaters.

1. Formation of ice jams in tailwaters is a consequence of the dynamic destruction and separation of the edge with increased discharges.

2. The process of dynamic destruction of the edge evolves by the formation of cracks along the shore, debacles, and hummocking on the section within which during discharges the size of fluctuation in the water level is 3-4 times greater than the thickness of ice on the edge during its formation.

3. Jams are formed at the jointing of the intact ice cover and the shattered field under the influence of the forces of the flow and pressure of the ice field which exceeds the resistance of the ice.

4. The amount of the greatest jam level is in direct dependence on the amount of maximum water consumption in the period of jam formation.

5. An increase in discharges during the formation of ice jams promotes the increase in capacity of the jam, and as a consequence a reduction in the winter coefficients occurs.

6. Regulation of the GES routine depending on the conditions for ice cover edge formation on the section within the diurnal lag time is a necessary condition for the movement of the edge in the tailwater without jam formation.

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