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SIMULATION OF FLOW AND THERMAL CONDITIONS DOWNSTREAM OF LIMESTONE GENERATING STATION

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ABSTRACT

The Limestone Generating Station has a 1330 MW installed capacity. It is the largest hydroelectric station in Manitoba Hydro's system. The station supplies a significant percentage of peak load. It is operated in a daily and/or weekly cycling mode. An anchor ice dam forms every winter in the Sundance Rapids area downstream of the station. The anchor ice forms in mid-November, thickens to 2-3 m by late January then decays as the weather warms. The anchor ice dam often stages the water level by more than 1m at the tailrace causing annual winter generation losses of $1 to 2 million. A coupled flow-temperature model is used to study the flow and ice formation characteristics in the Sundance Rapids area of relatively high velocity flow under the influence of cycling hydropower station outflows. The flow model is an explicit characteristic upwind finite element model for two-dimensional transitional flows. The dry-and-wet bed problem is treated by a simple robust approach.

INTRODUCTION

The Limestone Generating Station (Station) is located on the Nelson River in Northern Manitoba. The Sundance Rapids is located approximately 3 kilometers downstream of the Station. The flow from the Station passes through relatively shallow areas before reaching the Sundance Rapids section. Downstream of the rapids, the river is relatively deep. Frazil ice forms within a short distance downstream of the dam with frazil clusters float on the surface. An anchor ice dam forms every winter at Sundance Rapids, which results in up to a 1.5 meters staging at the Limestone tailrace (Figure 1). Winter observations have been made from 1997 to gather flow and ice condition data. In this paper, results of flow and thermal condition simulations are presented, which were undertaken to provide a better understanding of the flow and associated thermal-ice conditions in the tailrace of the Station.

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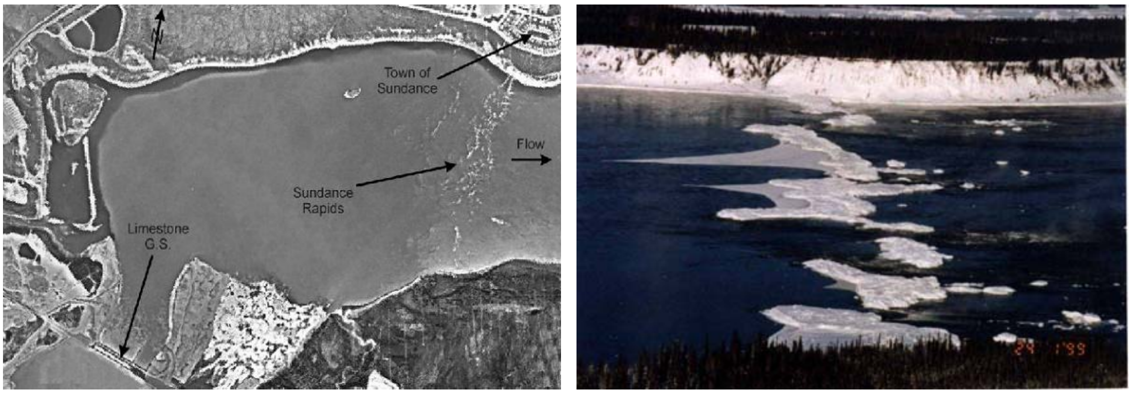

Fig. 1. Aerial view of the area from Limestone Generating Station
to Sundance Rapids and the anchor ice dam

WINTER OBSERVATIONS OF ANCHOR ICE FORMATION

Field observations have been made by Manitoba Hydro since 1997. It has been observed that the anchor ice dam staging effect generally starts in mid-November due to the sudden air temperature drop. The water discharge typically varies in daily cycles ranging from about 1,500 to 4,500 m^3/s. Frazil ice attachment to the bed is usually the main mechanism for anchor ice growth. Due to the daily cycling of the station outflow, the ice dam is formed by a combination of anchor ice and aufeis growth. Anchor ice and border ice upstream of the Rapids can release and contribute to the development of the ice dam. The mechanisms that contributed to the ice dam formation in the Sundance Rapids are considered to include: 1) anchor ice growth by frazil attachment and supercooling effect; 2) aufeis growth; and 3) anchor ice and border ice released from upstream. The resulting ice dam effectively closes off 80 to 90% of the channel width, restricting flow except a few small opening slots and resulting in up to a 1.5 m increase in tail water level at the station by the end of winter (Manitoba Hydro 2000).

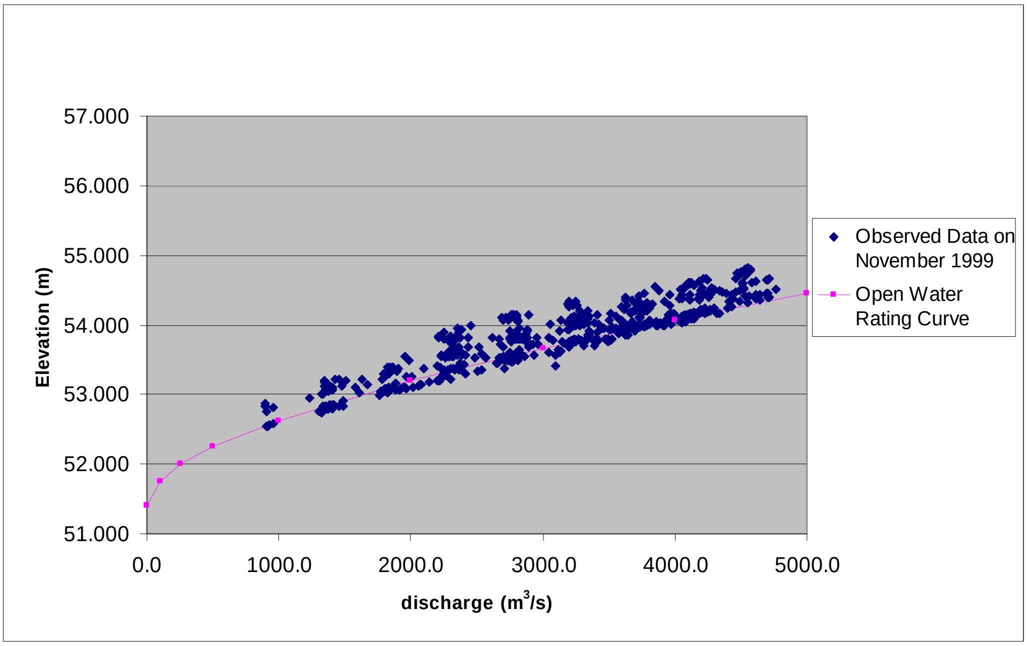

Fig. 2. Limestone tailrace staging during November 1999

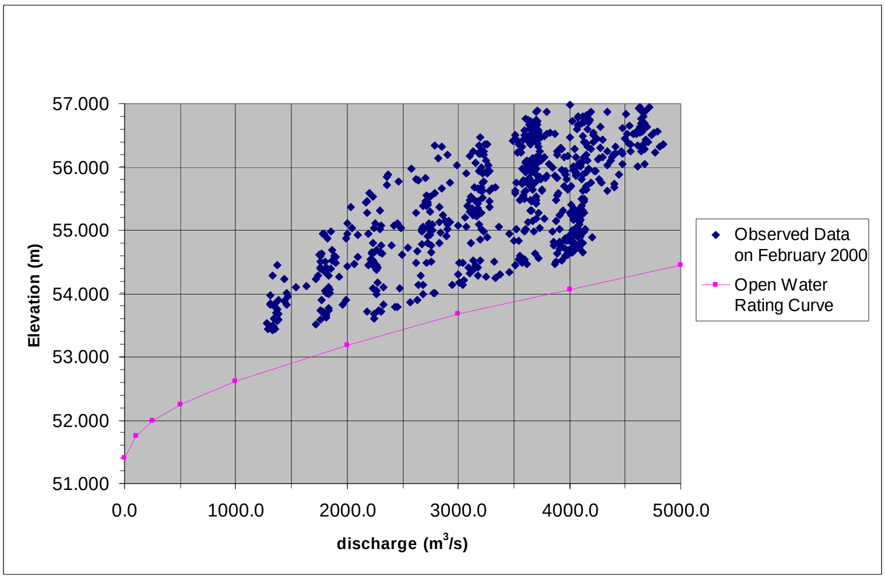

Fig. 3. Limestone tailrace staging during February 2000

Plots of tailrace elevation vs. water discharge, as show in Figures 2 and 3, are generated from the recorded data for the months of 1999-2000 winter to show the anchor ice dam staging effect. It can be seen that the staging effect was less than 1 meter in November. It went up to more than 2 meters in February.

THE NUMERICAL MODEL

A two-dimensional finite element numerical model with coupled hydrodynamic and thermal-ice components has been developed to simulate the flow as well as the water temperature and frazil ice concentration of the river. The hydrodynamic sub-model solves the two-dimensional, depth-averaged, unsteady flow equations. The streamline upwind Petrov Glerkin concept (Brooks and Hughes 1982, Hicks and Steffler 1992, and Berger and Stockstill 1995) is used in the finite element model with an explicit implementation. The model is capable of simulating transitional flows (Liu and Shen 2003). A simple technique is used to treat dry-and-wet bed conditions. A small flow depth and large bed resistance is automatically assigned to the dry area, so that the flow velocities at the 'dry' areas become negligibly small to approximate the dry bed condition. The main component of the thermodynamic sub-model is to simulate the water temperature. A finite element model with optimum added viscosity is used for both water temperature and frazil concentration.

The model domain extends from the tailrace of the Limestone Generating Station to downstream of the Sundance Rapids. At the upstream boundary, i.e. the generating station tailrace, the time-dependent water discharges are specified. At the downstream boundary, water surface elevations are specified according to the rating curve developed in a previous study (Manitoba Hydro 2000). Several soundings were made in different years to provide data for channel bathymetry. Some discrepancies were found between different data sets (Manitoba Hydro 2000). Additional survey is being planned to resolve these discrepancies before a detailed calibration can be made. The bathymetry and the model domain used in the present simulation are presented in Figure 4. The black lines indicate the sounding lines from field surveys.

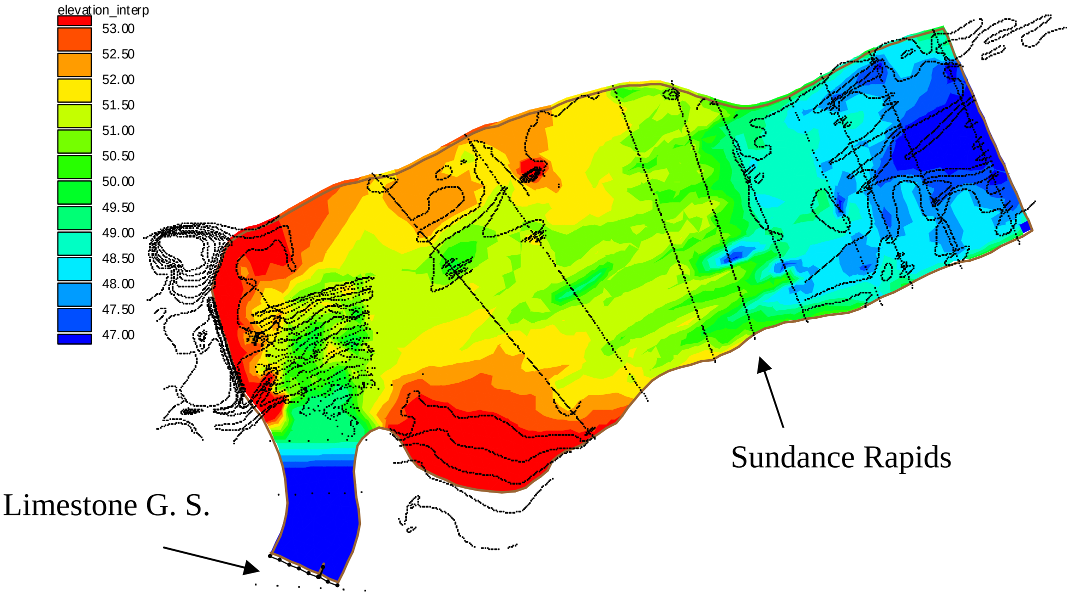

Fig. 4. Bathymetry used in the simulation

The first two days of November 1999 are simulated to demonstrate the capability of the model in simulating cycling discharge with dry- and-wet bed conditions. Figure 5 shows the comparison of simulated and observed water surface elevation at the tailrace along with the rating curve. Figure 6 shows the simulated water depth at a low flow (1000 m^3/s) condition. Figure 7 shows the simulated water depth at high flow (3500 m^3/s). It can be seen that during low flow, many parts of the river bed, especially at the Rapids, are exposed. The water discharge pattern at the tailrace, i.e. the upstream boundary condition is also shown in Figures 6 and 7.

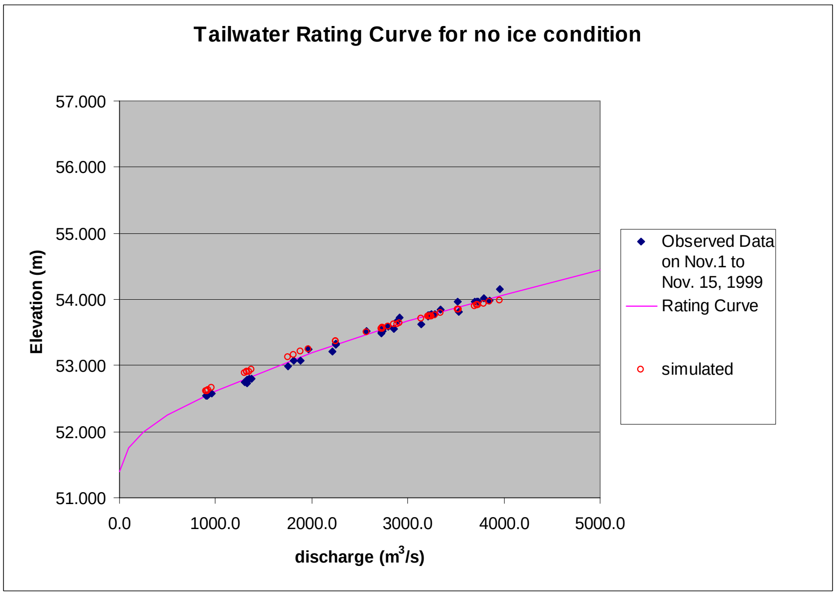

Fig. 5. Simulated water surface elevation at Tailrace

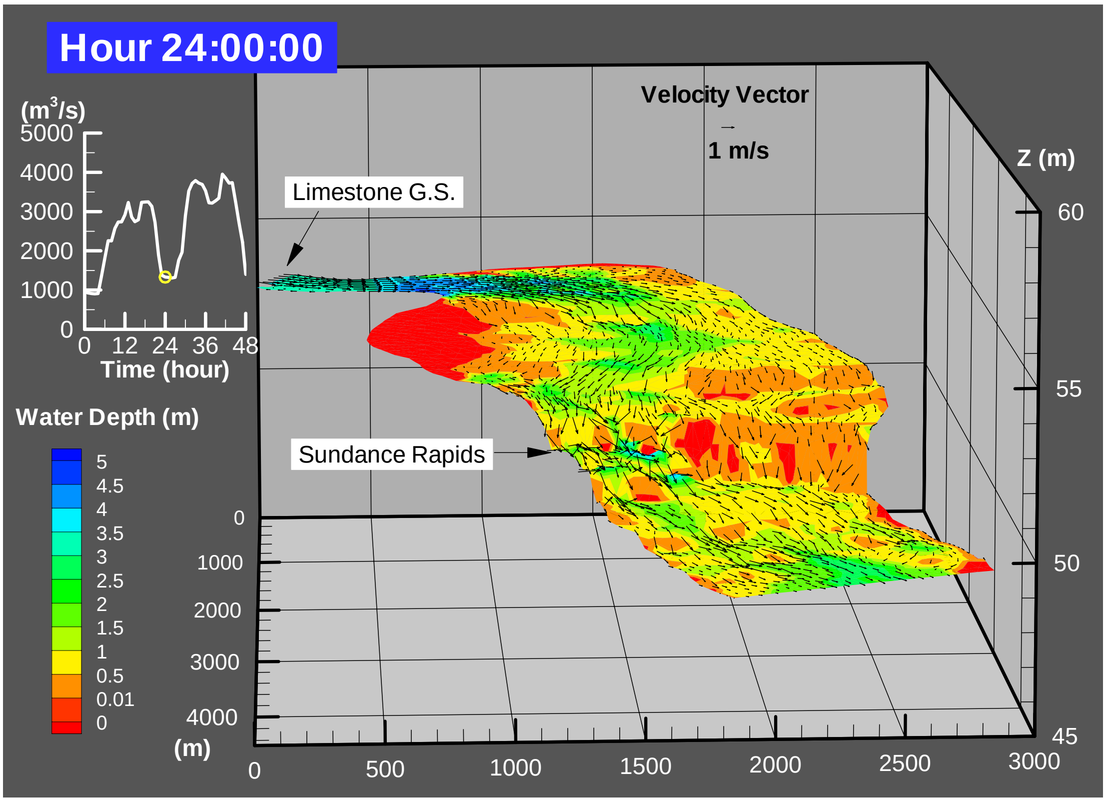

Fig. 6. Simulated water depth and velocity at low flow (Q=1000 m^3/s)

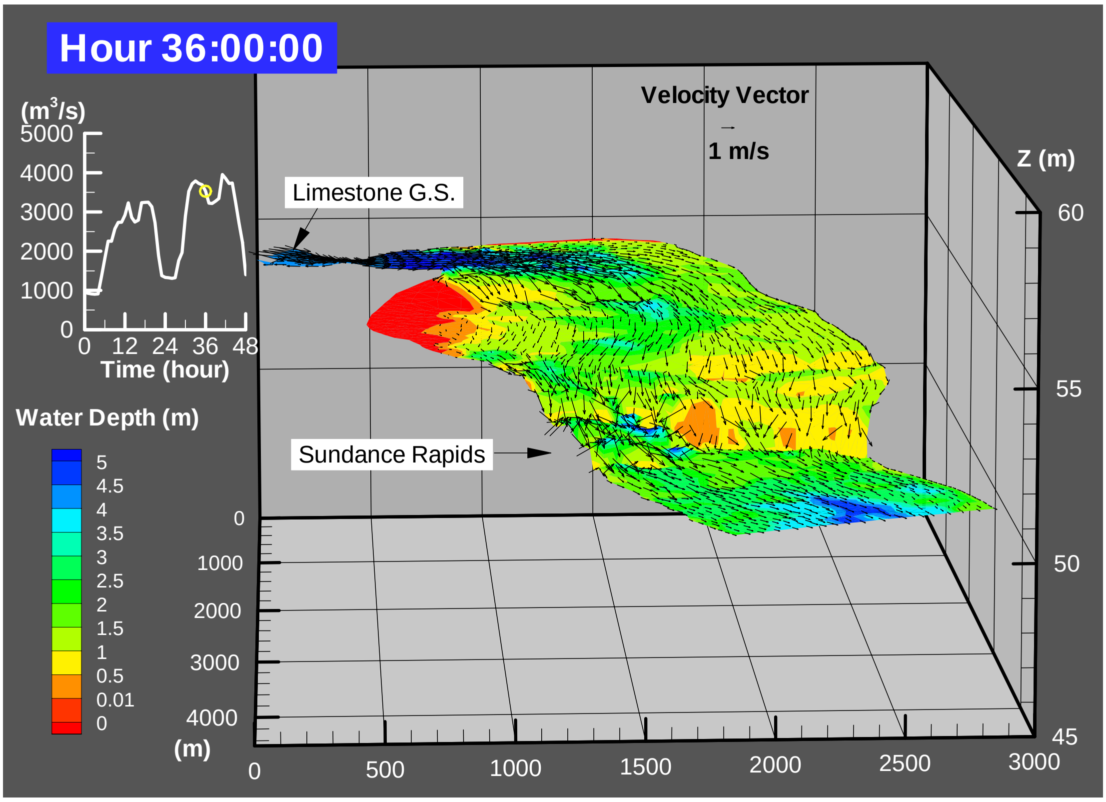

Fig. 7. Simulated water depth and flow velocity at high flow (Q=3500 m^3/s)

It was observed that, from Nov. 16, 1999, the air temperature dropped suddenly (figure 8) and the staging effect developed. A 96-hour simulation was conducted, for the period of Nov. 16 to Nov. 19. A composite sine function is used to interpolate the daily maximum and minimum air temperature, as shown in Figure 8, to better reflect the diurnal air temperature variation. The staging and water discharge during this time period are shown in Figures 9 and 10. The water temperature and frazil concentration distributions are affected by the air temperature variation and also by the water discharge cycling. The simulated water temperature and frazil concentration distributions, assuming that the water temperature of the discharge from the station is 0.05°C, are shown on Figures 11 and 12 at the end of the simulation (hour 96).

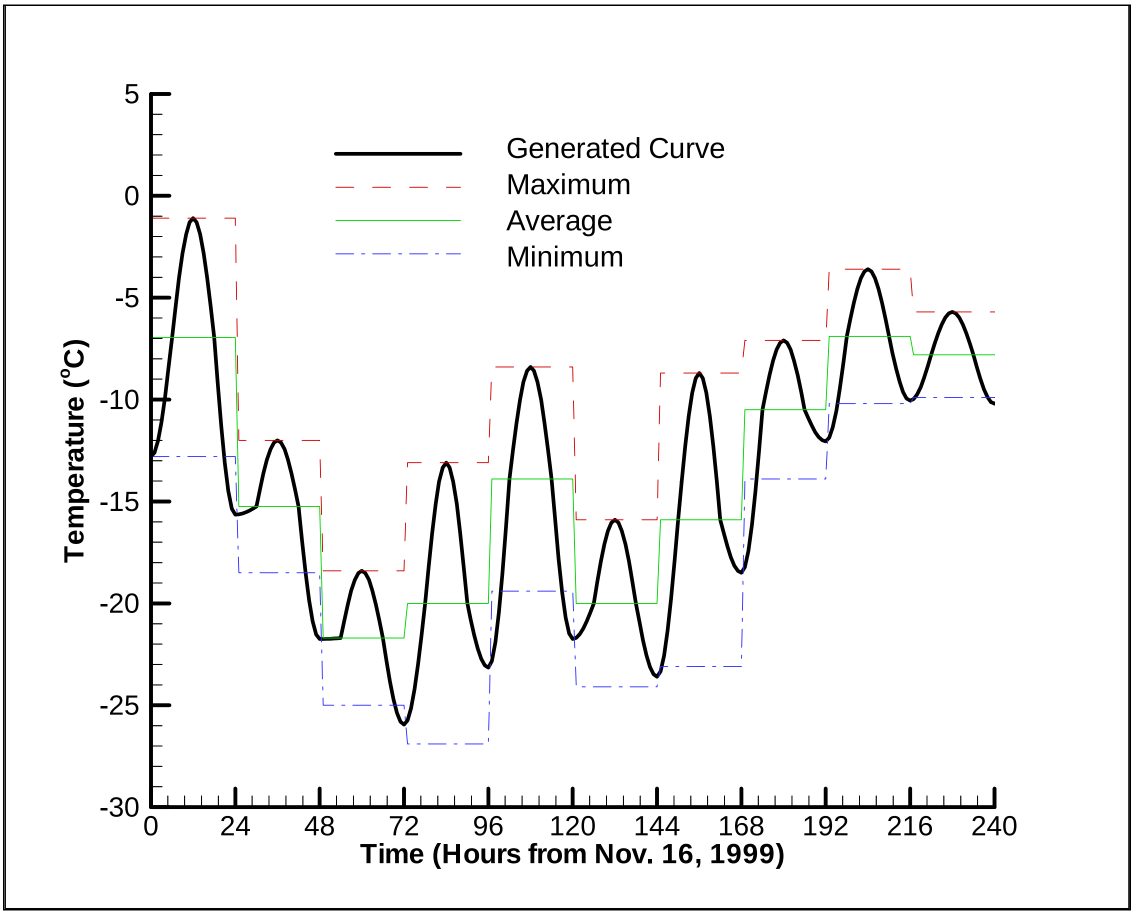

Fig. 8. Air temperature from Nov. 16, 1999

CONCLUSIONS

A coupled two-dimensional depth-averaged flow and thermal-ice model is developed. The flow model is capable of simulating mixed flow conditions with the capability of treating dry-and-wet bed conditions with fluctuating discharges. The thermal-ice model is capable of simulating water temperature and frazil concentration distributions. The model is applied to the tailwater of the Limestone Generating Station to simulate the flow and water temperature/frazil ice conditions. The model is to be extended to study the formation of anchor ice dams in the Sundance Rapids area of the river reach.

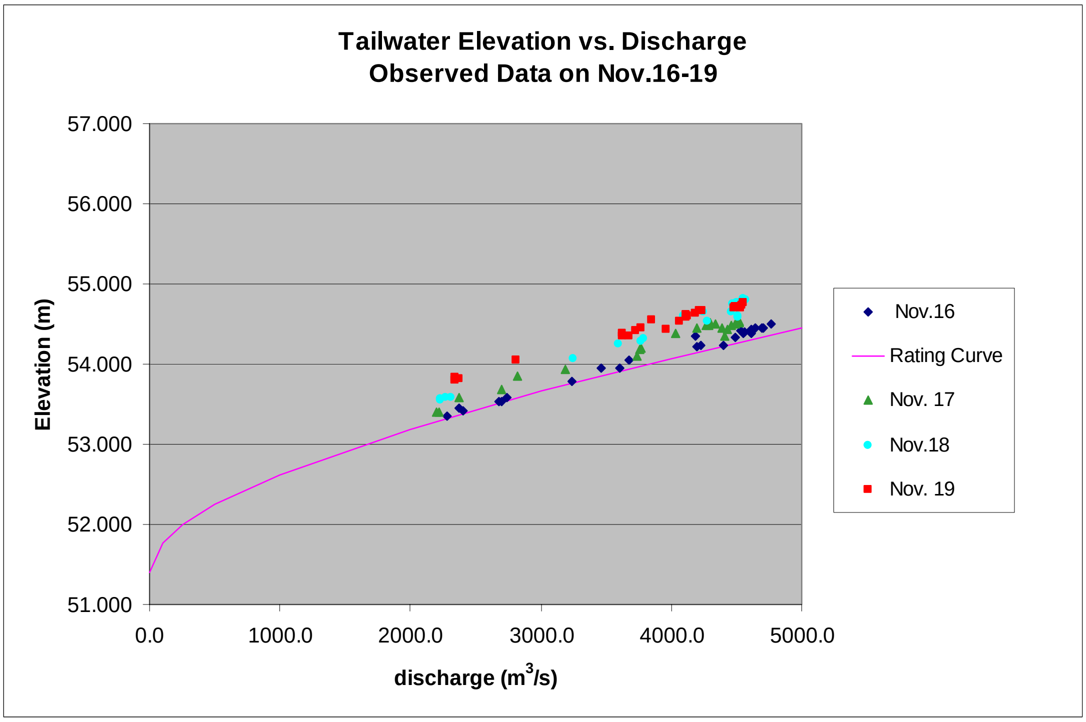

Fig. 9. Staging effect of anchor ice development in Nov.16 to 19, 1999

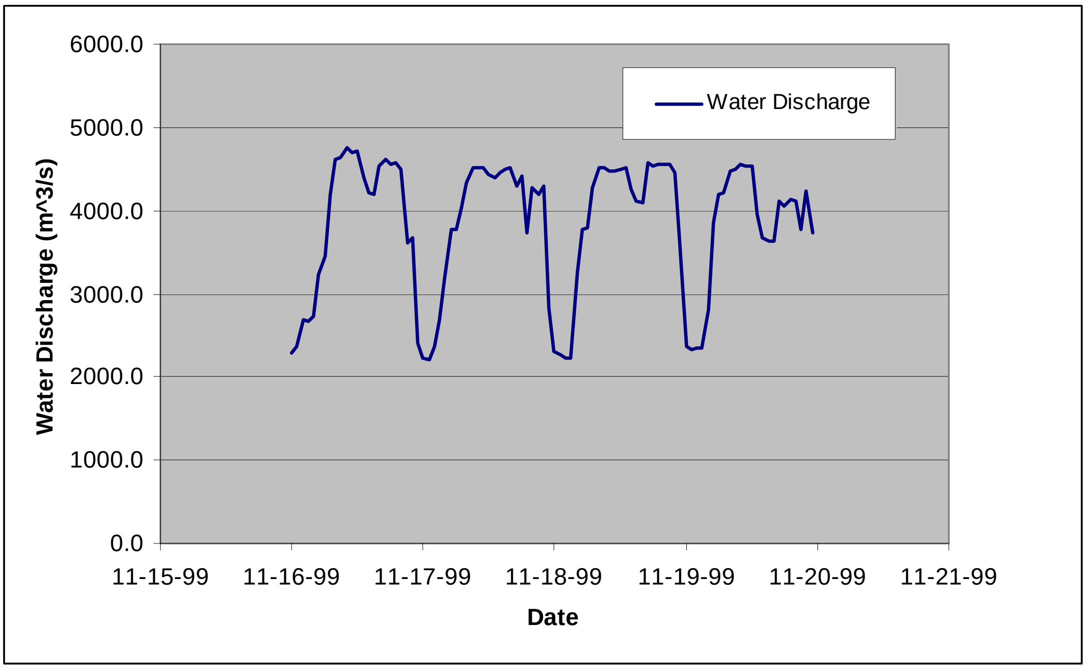

Fig. 10. Water discharge variation from Nov. 16 to 19

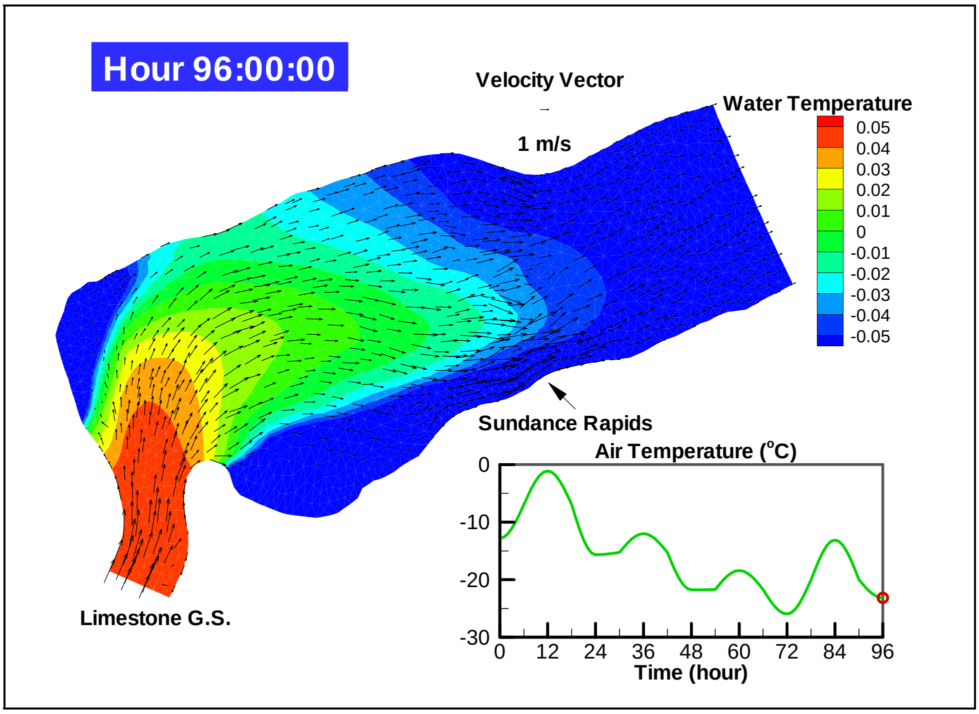

Fig. 11. Simulated water temperature distribution

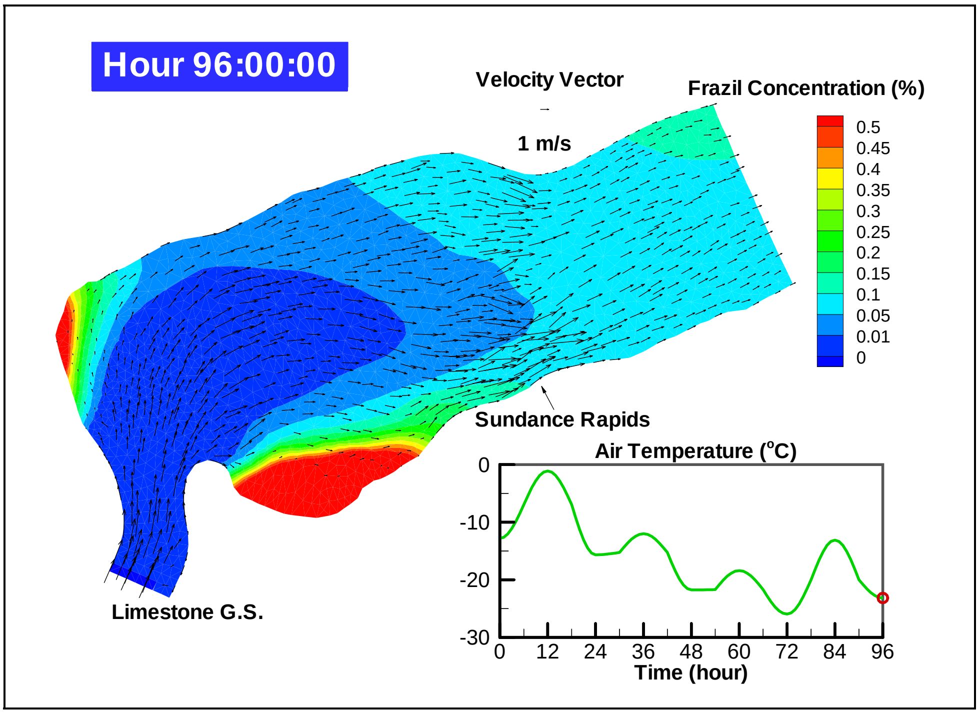

Fig. 12. Simulated frazil ice concentration

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EXPLOITING SPECIFICS OF THE HYDRAULIC ENGINEERING STRUCTURES OF THE WATER POWER PLANTS IN WINTER PERIOD

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The experience which was received for many years of the hydraulic engineering structures exploiting let to provide of their safety exploitation and to create the safety complete sets and constructions as the system of the normative base standards.

80-years period of the mass building of the water power plants which is beginning from the GOELRO-plan we can divide in two steps.

On the first step usually were constructed a not high power water power plants with derivative tape of construction which let to use the low height dams for this purpose. Some of them like Kondopojskaya water power plant in Karelia, Niva-2 water power plant on the Kola peninsula and the most water power plants which are located in Caucasus region and in Central Asia. The exploitation specifics of the derivative water power plants in winter period connected with problems of the struggle with an ice forming inside of water and ice and shuga influence on waterways of the water power plants like: channels, water intake structures of the water power plants, ice outlets and shuga outlets. In this time worked up the ways of the struggle with ice and shuga for providing of capacity for work of equipment of the water power plants which are usually were not unified into power engineering systems. This water power plants were enough autonomous units of the electric power supply for their regions which made them too responsible for this purpose.

The struggle with ice and shuga we can divide on active and passive ways. The active way of the struggle was directed on preventing of the negative influence of ice and shuga on the water power plants like creation of the special complete sets of constructions, the heating systems and the passing regimes.

The passive way including the struggle with consequences of the anchor ice dam forming, the blocking up of the water conduits and the ice covering of the mechanical equipment.

On the first step (from 1920-s to 1940-s) usually was used the passive way like modernization of the mechanical equipment which was used for liquidation of

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consequences of the blocked up turbine gratings, organization of the heating supply (hot water, steam and others).

Organization of ice-protected walls (like on the Volkhov and Nizhne-Svirskaya water power plants) played their own role in protection from the ice but did not give the real results in the struggle with the ice inside of water and with shuga. The pump settling basins which were widely used on mountain rivers (The Chiriksky cascade of the water power plants in Central Asia) also did not give the real results in settling and passing of shuga.

Worked up the system for the heating of turbine gratings (direct electric power through the pivots, inductive method for the heating of pivots and others). Was shown the limited possibility of this systems but anyway they were projecting and installing even during the second constructing period of water power plants. So, for example, on the Kuibyshevskaya water power plant (as on the V.I.Lenin Volzskaya water power plant) which was opened for exploitation in 1960-s the originally designed system for the heating of gratings later was removed out of the structure.

The rich experience was received on power engineering systems located in the North-West part of Russia during all this time (on the Leningrad, Karelia and the Cola peninsula power engineering systems). The Volkhov water power plant several times was stopped from the blocking up of turbine gratings with the shuga .After that the upper sections of construction were removed out of the structure for the heating process. Today this problem completely solved by using of the intensive complete freezing which was realized by removal of water power plant out of the daily head regulation with deducing of discharges (speeds of the stream).After that the ice inside of water can come to the surface and organize the complete freezing forming process. All this information was shown in instructions for exploitation of the hydraulic engineering structures. Establishment of the ice cover in reservoirs and waterways as one of the most effective (active) action was used in the first winter period of the water power plant exploitation. Later this method was widely used in all exploiting system of the water power plants. But some mistakes of the operating personnel in using of this action reduced to the hard accidents. As a good example of that was a situation on the Niva-2 water power plant which belongs to the Kolenergo power engineering system. For installation of the complete freezing was used the wooden pivots in the waterway. Later the wooden pivots under loading oscillations was moved with an ice to the water intake structure and completely blocked up the waterway. The solving of this problem on the Niva-2 water power plant was founded in 1960-s when the large enough Kolenergo power engineering system was formed.

Was determinated that absolutely possible to avoid of the ice forming inside of water in waterway by the growing of speed of the stream and by cutting off the time of cooling process of enough “hot” water which was taken by the Niva-1 water power plant from reservoir of the lake of Imandra. This method also was used on the Sevano-Rozdansky cascade of water power plants in Armenia.

On the second step of construction of water power plants in the Soviet Union (post World War II period in 1960-s and 1970-s) usually were constructed the middle size and the large size water power plants on the Volga and Dniper rivers as in Kazhakhstan and in Siberia with large reservoirs and high enough dams (more than 20 meters high). The problems which was connected with the ice forming inside of water and with influence of the shuga on waterways is almost gone now (become with a not high of probability).But the problems which is connected with the ice influence on the dam gates were retained. If construction of water power plants is calculated with an ice loadings, so in this case the gates must be protected from the ice pressure. During this time were elaborated and installed the methods for the holding of polynya infront of the gates. The basic methods now which are using for the holding of polynya by the barbotage structures infront of the gates with using of air which is going from the sill of the gate along the pressure face, or holding of polynya by the stream-forming structures which give the jet of water along the pressure frontage. Determined all conditions for using of this methods. Also was determined that this methods are effective with the presence of the temperature stratification infront of the gates.

Another very seriously problem of exploitation of the hydraulic engineering structures and their equipment during winter period was the serving of possibility of the water dropping in winter period. Usually it connected with regulation possibilities of reservoirs with providing of work of the water power plant cascade in case if on one of the water power plants the working equipment was out of work , as in case of repair work of the broken equipment or if equipment was stopped with necessity for the passing of water according to sanitary or other reasons. In the most cases the passing of the flood realize with the high enough temperature of air outside of winter period.

For providing of winter exploitation of water power plants we need the heating of the slot constructions and protection of pressure face of the gates from underwater ice covering. For the solving of this problems we have enough of home and foreign experience in this field. Methodic for the heating of the slot constructions just the same like for the gratings: direct electric power, inductive electric heating, oil heating or other. Now we have the problem with reconstruction of the heating systems which were out of work. In this field we have brand new elaborates which were created in the B.E.Vedeneev All-Russia Research Institute of Hydraulic Engineering. This new elaborates were created on the base of using the silicon organic elements. Their using for reconstruction of the heating systems which was out of work made this problem much easy because now we do not need the expensive repair works which in the most cases connected with replacement of the different parts of construction. This new elaborates made the completely new situation for using of the modern methods in optimization of electricity discharges for the heating process by installation automatic control systems with a program supply which is operate depends from our decision.

Today we can say that exploitation of the hydraulic engineering structures in winter period connected with technical solutions which we can choice depends from conditions and different tasks of exploitation. Very important to develop methods for prognosis of exploitation conditions: hydrometeorological and technological.

Prognosis of hydrometeorological factors is a very difficult problem. For the solving if this problem not enough to have a list of the statistic observations. Manifestation of the hydrometeorological factors depends not just from the complete set of construction and technical solutions but from the exploitation regimes in the most cases.

During winter exploitation of the hydraulic engineering structures we must to use the active ways in struggle with different negative influences. Very important to use different ways in control of the negative influences on the first step of projecting of the hydraulic engineering structures with using of all exploitation experience in this field and most which was used in winter period.

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ENSURING OF OPERATION OF WITHDRAWALS IN FRAZIL-ICE CONDITIONS

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ABSTRACT

On the rivers with a long period of ice flow, difficulties in water collecting can occur. The purpose of this paper is working out hydraulic ways of withdrawal strainer protection against frazil and avoiding supercooling effect inside the system. This paper concerns difficulties arising in the operation of river withdrawals situated in the frazil producing river stretches. Methods of calculations of frazil flow parameters are given. The construction of water strainers of umbrella-like type and system of collector well heating on the basis of compositional resistive materials (CRM) ensuring safe operation of withdrawals in frazil-ice conditions are proposed. The results of experimental analysis of the new strainer construction and the parameters of the new heating system of the water collector well are represented.

METHOD OF ESTIMATION OF WATER SUPERCOOLING AND FRAZIL DISCHARGE COMING INTO WITHDRAWALS

On the large rivers like the Neva and the Amur the period of autumn frazil flow can continue rather long, sometimes up to more than a month. In the period of frazil flow and the beginning of freezing-up there are plenty of polynyas – 'factories of frazil'. At this time withdrawals can have ice difficulties connected with blocking of the strainer windows with passing frazil and their freezing in supercooled water. The method of estimation of water supercooling and frazil discharge coming into water collectors is based on the Pekhovich model (Pekhovich, 1983). According to this model a few stretches along the river can be described, every of which has a definite number of ice thermal parameters: 1) the stretch of water supercooling to the section of inside water ice formation; 2) the stretch going from this section to the section of frazil flowing up; 3) the stretch of growing supercooling to the section of maximum supercooling ; 4) the stretch of supercooling decrease to the section of maximum intensification of inside water ice formation; 5) the stretch to the ice edge. The mentioned stretches are separated from each other with distinct sections and have the definite water temperature t , its gra-

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dient along the flow $\frac{dt}{dx}$, the concentration of surface frazil β_f, intensity of frazil formation S_f, frazil discharge Q_f and its gradient along the flow $\frac{dQ_f}{dx}$ (table 1) (Pekhovich, Tregub, 1980; Tregub, 1997). The detailed method of estimation of the mentioned section positions was given in (Tregub, 1977).

Table 1. Ice Thermal Conditions for Typical Sections along River Flow

№	Section	Parameters of ice thermal state					
		$t, {}^oC$	$\frac{dt}{dx}, \frac{{}^oC}{m}$	β_f	$S_f, \frac{Wt}{s}$	$Q_f, \frac{m^3}{s}$	$\frac{dQ_f}{dx}, \frac{m^2}{s}$
1	Zero isotherm	0	<0	0	0	0	0
2	Beginning of inside water ice formation	<0	<0	~0	>0	>0	>0
3	Beginning of frazil flowing up	<0	<0	$0<\beta_f<1$	>0	>0	>0
4	Maximum of water supercooling	<0	0	$0<\beta_f<1$	>0	>0	>0
5	Maximum intensity of frazil formation	<0	>0	$0<\beta_f<1$	>0	>0	>0
6	Ice edge	~ 0	≥0	~ 1	≥0	≥0	~ 0

The position of the maximum supercooling section is calculated with the formula

$$x_{\max} = \frac{2\, h_b\, L_{v.f} \cdot V \cdot P_{x.\max}}{\alpha_1 (-\vartheta_e)}, \tag{1}$$

where $P_{x.max}$ dimensionless parameter taken from the following relations:

$$P_{x.max} = -\beta_{f.max} - ln\left(1 - \beta_{f_{max}}\right), \tag{2}$$

$$\beta_{f.max} = -P_{max} + \sqrt{(P_{max}+1)^2 - 1}, \tag{3}$$

$$P_{\max} = \frac{\alpha_1\, b\, (-\vartheta_e)}{2\, L_{v.f} \cdot V\, h_b}, \tag{4}$$

α_1, ϑ_e – heat transfer coefficient and equivalent air temperature (Recommendations, 1986); b – width of the flow: V – flow speed; h_b – initial ice thickness (Recommendations, 1986); $L_{v.f}$ – volumetric latent frazil formation heat.

The position of the section of maximum intensity of frazil formation $x_{m.f}$ is calculated analogously with x_{max}, but using $\beta_{m.f}$ instead of $\beta_{f.max}$ in formula (2)

$$\beta_{m.f} = Y - \frac{2}{3} P_{x.max}, \tag{5}$$

$$Y = U_1 + U_2, \tag{6}$$

$$U_{1,2} = \sqrt[3]{w_1 \pm \sqrt{w_1^2 + w_2^2}}, \tag{7}$$

$$w_1 = P_{x.\max}^2 \left(0{,}296\, P_{x.\max} - 0{,}67 - \frac{c_v Q}{\alpha_1 b^2} \right), \tag{8}$$

$$w_2 = -0{,}22\, P_{x.max} \left(3 + 2\, P_{x.max}^2 \right), \tag{9}$$

c_v – volumetric thermal capacity; Q – river water discharge.

The water temperature in the stretch between the section of maximum supercooling and maximum frazil formation intensity can be found with help of the relation (Tregub, 1997):

$$t = \exp\left(-\int_0^x \frac{\alpha_1\, b \left(1 - \beta_f\right)}{c_v \cdot Q} dx \right) \left\{ \frac{1}{c_v\, Q} \int_0^{x_{\max}} \left[\alpha_1\, b \left(1 - \beta_f\right) \vartheta_e + \right. \right.$$

$$\left. \left. + L_{v.f}\; v \cdot h_b\, \beta_f^2 \right] \exp\left(\int_0^{x_{\max}} \frac{\alpha_1\, b \left(1 - \beta_f\right)}{c_v\, Q} dx \right) dx \right\}. \tag{10}$$

The frazil discharge which can get into the withdrawal $Q_{f.w}$ is calculated on the basis of the assumption that after getting into the strainer the water supercooling disappears completely:

$$Q_{f.w} = -\frac{c_v\, Q_w \cdot \Delta t}{L_{v.f}}. \tag{11}$$

Where Q_w – water discharge coming into the strainer; Δt – water supercooling compared with 0° C. The given formulas were used for calculation of water supercooling and frazil discharge on the section of the strainers.

There have been tried a lot of ways to prevent frazil getting into withdrawals (e.g. with using compressed air, electrical heating of the strainer windows). But as a rule those ways are too expensive and consume great quantity of energy for heating. Even in case of avoiding ice formation on the strainer windows, supercooled water gets inside and after crystallizing into frazil it blocks the water-supply system. As a result of a scientific analysis of different protections a hydraulic way of preventing frazil and other impurities getting into withdrawals was chosen, which allowed creating an umbrella-like type of strainers with a hydraulic vortex motion under the withdrawal cap.

Using hydraulic vortex motion for controlling oil impuraties and frazil. Using hydraulic way of controlling impurities and frazil at the strainers is based on the creation a vortex motion at the withdrawal entry. This motion keeps different type of floating impurities from getting into the withdrawal with help of umbrella-like strainers and a 'hydraulic round-about', which spins water by pumping it through tangential-oriented pipes (Shatalina, etc., 1994). The impurities getting into the flow are carried out from under the withdrawal cap. The proposed version of a 'hydraulic round-about' can protect oil impurities, frazil, whitebaits, water plants, etc from getting into withdrawals. The construction of the 'hydraulic round-about' under the cap of the umbrella-like strainer is shown in fig.1.

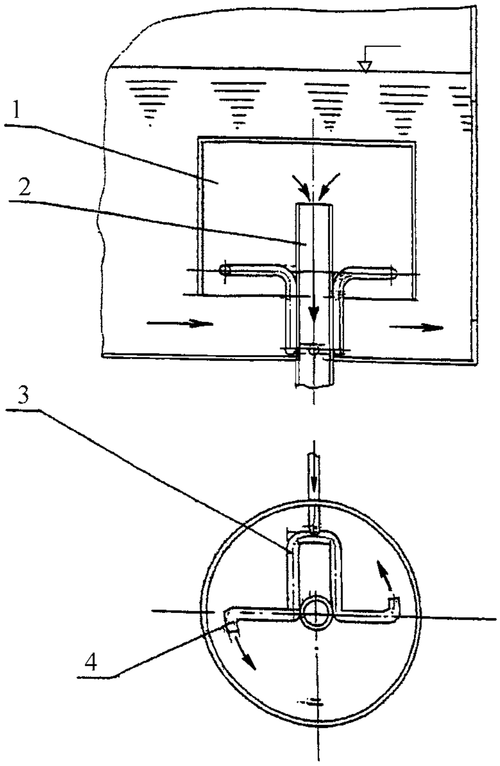

Fig.1 The construction of the 'hydraulic round-about' under the cap of the umbrella-like:
1 – the cylindrical part of the withdrawal cap; *2* – the strainer;
3 – the pipe, delivering water to the 'hydraulic round-about'; *4* – L-shaped nozzles

Experimental investigations of the 'hydraulic round-about'. Investigations of the 'hydraulic round-about' was performed on the withdrawal model scaled down as 1 to 23. With the diameter of the 'umbrella' 0,280 m and its height 0,191 m.Under the 'umbrella' there were two tangential-oriented nozzles with diameters 0,012 m. The water discharge of the withdrawal was 0,2 – 0,5 l/sec, the discharge of the 'hydraulic round-about' changed from 0,1 to 0,5 l/sec. The equipment was built in the available hydraulic test bench, which had a delivery tank (with the fall of 2 m), a supply and a working part of 2,0 x 0,58 1,26 m in size, two centrifugal pumps with discharges 10 l/sec and 3 l/sec. Water delivered both to the working part of the bench imitating a river flow and to the 'hydraulic round-about'. The pump with the larger discharge kept the tank water level constant and the second pump imitated the pump collecting water from the river. The water discharges were adjusted with help of measure diaphragms according to the difference of the piezometer levels. The accuracy of the discharge measurement was 0,5 – 1,5 %.

The purpose of the tests was to define the range of the operation parameters of the ‘round-about’ with different concentration of impurities coming under the withdrawal cap. These are the parameters which were varied during the tests: the discharge of the ‘hydraulic round-about’; the initial concentration of the impurities withdrawal discharge ; the vertical position of the tangential nozzles. In the result of the tests the quantity of the impurities both driven away from under the cap and accumulated under the withdrawal cap were found. For three different positions of the nozzles 3 series of tests were performed. Except this the tests were carried out for both the active and inactive withdrawal. Polyethylene of low pressure with density 970 kg/m^3 and particle diameters 3–5 mm was used to model impurities and frazil. The masses of the particles both driven away from the withdrawal and accumulated under the cap were weighed on a scale with 0.01 g accuracy. The effect of the operation of the ‘hydraulic round-about’ was estimated according to the mass of the impurities driven away from under the withdrawal cap. The impurities amounted 2–10% of the water mass coming into the withdrawal. The greater amount of impurities came under the withdrawal cap the greater percent of the initial mass was driven away from under the cap as a result of operating the ‘hydraulic round-about’. The direction of the ‘hydraulic round-about’ jets (clockwise or anticlockwise) and its position comparatively with the ceiling of the ‘umbrella’ as well as with the end of the collector pipe under the ‘umbrella’ and the lower edge of the ‘umbrella’ proved to be very important parameters. Using the data in fig.2, the influence of the parameters can be estimated.

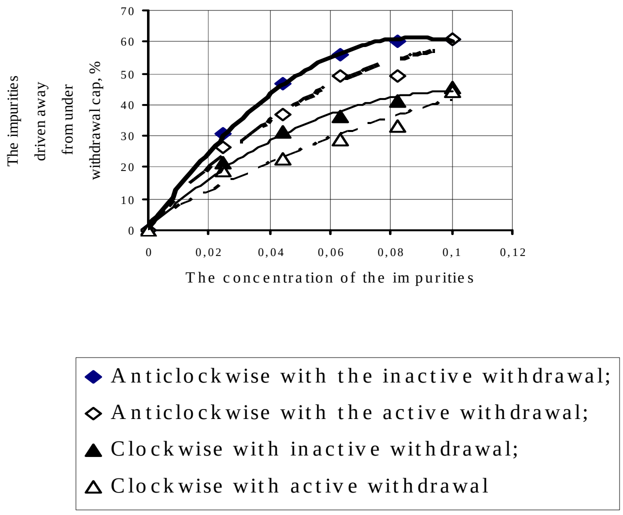

Fig.2. The dependence of the emission of impurities from under the withdrawal cap in percent from the concentration of impurities in the flow and direction of the ‘hydraulic round-about’ jets (the cap is located 0,0515 m above the withdrawal; water discharge of the ‘hydraulic round-about’ is 0,24 l/sec)

Among other factors, the greater quantity of impurities come with water the greater percent of them is driven away from under the withdrawal cap and the water coming into the system is freed of them better. With any quantity of impurities coming under the withdrawal cap, the effect of ‘round-about’ operation is 12 - 20 % higher if the tangential-oriented nozzles are directed anticlockwise. The further tests were performed with the anticlockwise nozzles and the fact will not be mentioned any more. With the inactive withdrawal the efficiency of the impurities removal is about 10 % higher than with the active one. If there are a few withdrawals, this fact allows cleaning the area under the withdrawal cap when one of the withdrawals is inactive. Using this model and the given size of the strainer more than 60 % of the impurities can be removed from under the withdrawal cap in this way.

The influence of the umbrella ceiling position in reference to the collector position is seen well in fig.3. The analysis of the given curves shows that the removal of the 'umbrella' ceiling 0,08 m from the strainer level leads to the extremely low efficiency of the 'round-about' (the emission of the particles is about 30 %). The reduction of the distance to 0,05 m increases the efficiency almost twice. The further reduction of this distance to 0,03 m does not practically influence the efficiency. Three different vertical positions of the tangential-oriented nozzles of the 'hydraulic round-about' were tested, which showed the lower position was impractical, since the jets went from under the 'umbrella' without creating the effect of water acceleration under the withdrawal cap. As to the upper position, in this case the nozzles were situated too close to the strainers windows that made extra impurities get inside the system. After that all the further tests were performed with the middle position of the nozzles. In addition two positions of the nozzles along the 'umbrella' diameter were tested: in 5cm from the 'umbrella' edge and close to the collector pipe. The latter position proved to be ineffective. In the test the particles moved actively vertically, but the absence of the horizontal movement did not drive the particles from the strainer. That is why the main and recommended position of the nozzles close to the 'umbrella' edge was chosen.

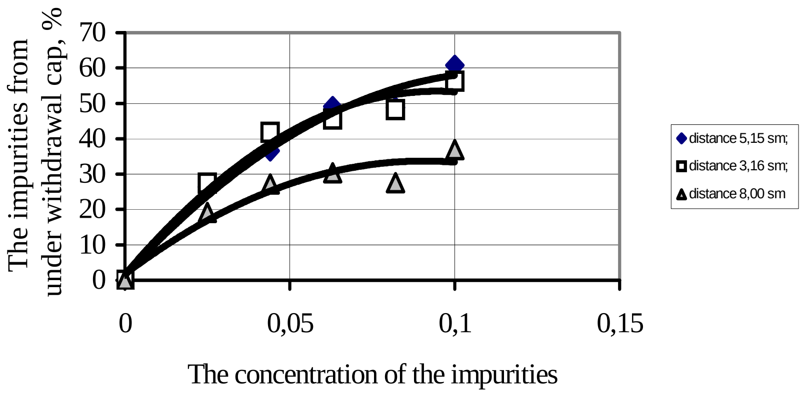

Fig.3. The dependence of emission of impurities from under the withdrawal cap in percent from their concentration in the flow with different positions of the cap over the active withdrawal and the water discharge of the 'hydraulic round-about' 0,24 l/sec

The developed type of the strainer does not allow suspended impurities and frazil to get inside the system. Supercooled water, however, can get there freely. For controlling the frazil formation inside the water supply system, collector well heating is proposed to use to avoid supercooling. Different kind of wells can be used for this purpose, where a block of heaters can be installed. Crystallization starts when supercooled water gets into the pipe leading from the strainer to the collector well. As frazil particles grow they begin to flow up. The size of ice particles, when the process of their flowing up starts is defined by the expressions given in (Zakharov, Beilison, Shatalina, 1972) at the flow speed 1,23 m/sec and Shezy coefficients 40,9 $m^{0,5}$/sec. According to those relations the size of the flowing up particle is d_f =7,5 mm. The time needed for the particle to reach the size d_f =7,5 mm can be found by the empiric formula of D.N.Bibikov (Tregub, 1997)

$$\tau_f = \frac{(0{,}5\, d_f)^{1{,}5}}{0{,}345\,(0{,}96 \cdot V^{0{,}47} + 0{,}32)(-t_w)} \quad . \tag{12}$$

At the maximum possible supercooling t_w = –0.04 °C, τ_f = 381 sec. For example, if the length of the pipe is 120 m water passes it in τ_t = 100 sec. In this time the particles of frazil formed in the supercooled water according to formula (12) grow to diameter d_t = 3 mm. In the delivering pipe as frazil forms supercooling reduces. As a result the water temperature coming into the collector well can be estimated by the following formula:

$$t = t_в \cdot \left(1 - \frac{d_t}{d_f}\right) = (-0{,}04) \cdot \left(1 - \frac{3}{7{,}5}\right) = -0{,}024\ °\text{C}.$$

When water gets into the collector well the flow widens, supercooling disappears and intensive inside water ice formation starts. To prevent blocking of the collector wells MO-2 with frazil it is necessary to give the water as much heat as needed to get rid of the supercooling. For carrying out of the listed tasks both the power and the type of the heater for operation of the collector well is necessary to determine. The necessary power of the heater is found on the basis of the thermal balance equation, according to which the heating power is used for both increasing the water temperature up to t_0 = 0 °C and the thermal output into the air:

$$\frac{c_v\, W}{\tau_0}(t_0 - t_w) + \alpha_1\, F\,(t_0 - \vartheta) + \lambda_e \frac{(t_0 - t_s)}{\delta_e} \cdot F = N \ , \tag{13}$$

where W – the water collector well volume; $\tau_0 = \frac{W}{Q}$ – the time of water exchange in the well; t_w – water temperature at the well exit (t_w~0,5° C); $F = \frac{\pi d_w^2}{4}$ – the area of the well water-air contact; ϑ – air temperature; concrete thermal conductivity; λ_e – heat concluctivity of concrete; t_s – average long term soil temperature of the river floor; δ_e – concrete well wall thickness. For the collector well with the diameter 4 m , the height 9 m, the wall thickness 0,5 m and the temperatures t_s = 4^o C, ϑ = –26^o C the necessary power of the well heating is N = 127 kWt. The heating zone is to be located on the well floor close to both water delivering and withdrawing holes. Free convection developed in the water because of the heat coming up from the heater situated in the lower part of the well is favourable to the water temperature increase and the frazil melting. For steady-state heating of the collector wells the system consisted of flat heaters with active elements made of compositional resistive materials (CRM) is worthwhile using. With the power of the well heating equal 127 kWt, 64 kWt are necessary for the heating of the side well walls in the zone of water delivering and withdrawing and 63 kWt are needed for the floor heating. Active heating elements developed by the authors and made up of different CRM are proposed to be used. As one of the possible solution a special material with positive coefficient of resistance-temperature dependence is suggested. The material is composed on the basis of astringent bitumen with electrical conductive and inert additions (electrical conductive bitumen – ECB) (license application № 2002118348, priority of 08.07.2002, the positive resolution for license presentation of 08.01.2004). The principle of the material action is as follows: the resistance is retained quite small till the temperature reaches the value, above which the resistance grows quickly with the temperature growth. As this takes place, the resistance growth is much quicker than the growth of the temperature and the reduction of the current intensity assists it. It leads to the reduction of the heater consumed power. By contrast in case of the system cooling the resistance lowers and the heating grows.

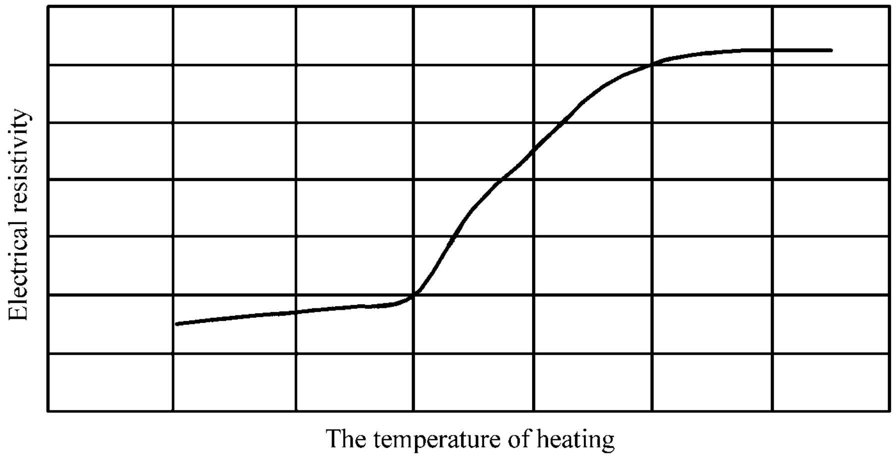

Fig. 4. The dependence of ECB resistivity from the heating temperature

So more intensive heating takes place in the more cooled areas, which leads to the constant temperature of the whole system. Owing to such a self-regulation of the electrical characteristics of the material no special electrical systems of regulation are needed to heat the well. Furthermore in this case the overheating of neither the most active element in the heater or the well itself is impossible. The recommended maximum temperature of the active heating ECB element is +90 °C. One more advantage of the proposed material is the fact that the latter can be used in the wide range of moisture content up to the using it in water without changing its electrical parameters. One of the possible heaters with ECB consists of six active heating elements of 100x200x40 mm in size and with nominal power 0,25 kWt, connected in series and placed in the metal box. Such a heater is of 650x270x50 mm in size and has a power 1,5 kWt and operates at the voltage 220 V. Except ECB active heating CRM elements made of astringent phosphate can be used in the heaters. Such a heater consists of 10 active elements connected in series of 650x270x50 mm in size, has the power 1,0 kWt and the operating voltage 220 V. The recommended maximum temperature of the active heating element of this type is 100 °C. The It is worth noting that using CRM allows creating the heaters operating in the wide voltage range. The arrangement of the heating elements in the heater can be different. For ensuring both electrical and hydro isolation special mastic is poured into the heater box. The exterior heater surface is covered with anticorrosive coating. It is recommended to connect the heaters across since in this case even if one or more heaters fail the whole system continues operating. The warming up system of the collector well is to be automatically switched on as the water temperature at the end of the delivering pipe is –0,01 °C and switched off as it is +5 °C.

The combined usage of the umbrella-like strainers with the 'hydraulic round-about' and the heating system of the collector wells will allow avoiding frazil-ice difficulties at the withdrawals.

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THE NUMERICAL MODELING OF HYDRO-ICE-THERMAL PROCESSES IN RESERVOIRS

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ABSTRACT

Mathematical modeling of hydro-ice-thermal processes has been considered in a number of papers (e.g. Wake and Rumer, 1979; Alexandrov et al, 1992). In this paper a time-dependent 2D (plan) model of ice-thermal processes is viewed, in which for the process of ice cover formation the first approximation of uneven temperature profile (in depth) is taken into account. The algorithm of numerical solution of hydro-ice-thermal problem was worked out and its verification was carried out. The numerical results of the hydro-ice-thermal regime and their comparison with the in-situ data of the Volga-Don NPP reservoir-cooler are given.

MATHEMATICAL MODEL

The conservative form of the shallow water equations with due regard for the friction on the bottom, the wind influence and Coriolis' forces looks like

$$\frac{\partial h}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = q \; ; \tag{1}$$

$$\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{Q_x Q_y}{h}\right) = -gh\frac{\partial H}{\partial x} + \Omega_c Q_y - \frac{\tau_{bx}}{\rho_w} + \frac{\tau_{wx}}{\rho_w} + \frac{1}{\rho_w}\frac{\partial h\tau_{xx}}{\partial x} + \frac{1}{\rho_w}\frac{\partial h\tau_{xy}}{\partial y} \tag{2}$$

$$\frac{\partial Q_y}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x Q_y}{h}\right) + \frac{\partial}{\partial y}\left(\frac{Q_y^2}{h}\right) = -gh\frac{\partial H}{\partial y} - \Omega_c Q_x - \frac{\tau_{by}}{\rho_w} + \frac{\tau_{wy}}{\rho_w} + \frac{1}{\rho_w}\frac{\partial h\tau_{yx}}{\partial x} + \frac{1}{\rho_w}\frac{\partial h\tau_{yy}}{\partial y} \tag{3}$$

$$Q_x = hu_x,\ Q_y = hu_y,\ \tau_{bx} = \rho_w C\, Q_x\ ,\ \tau_{by} = \rho_w C\, Q_y\ ,\ C_{cur} = g\frac{\sqrt{Q_x^2 + Q_y^2}}{C^2\, h^2}\ ,\ C = \frac{1}{n}h^{1/6},$$

$$\tau_{wx} = \tau_w \cos\theta_w,\ \ \tau_{wy} = \tau_w \sin\theta_w,\ \ \tau_w = \rho_a\, \kappa^2 \ln^{-2}\left(\frac{z}{z_0}\right)W^2,\ \ z_0 = 0{,}0144\frac{\tau_w}{\rho_a g}$$

The averaged in depth shear stresses τ_{xx}, τ_{xy}, τ_{yx}, τ_{yy} can be represented in the form (the indexes i, j correspond here to x, y)

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$$\frac{h\tau_{ij}}{\rho_w} = \nu_t \left[\frac{\partial (hu_i)}{\partial x_j} + \frac{\partial (hu_j)}{\partial x_i} \right] .$$

Here h – water depth; $H=h+z_B$ – the level of the free water surface; z_B – the bottom level; u_x, u_y – the projections of the averaged (in depth) velocities on the axes x, y; $\Omega_c = 2\omega \sin\varphi$ – Coriolis' parameter; ω – angular velocity of the Earth rotation; φ – the area latitude; g = 9.81 m/s^2 – the acceleration of gravity; ρ_w – the water density; ρ_a – the air density; τ_{bx}, τ_{by} – the projections of the friction forces on the axes x, y; ν_t – turbulent viscosity coefficient; C – Chezy coefficient; n – roughness coefficient; C_{cur} – the coefficient of the bottom friction owing to the flow; τ_{wx}, τ_{wy} – the projections of the wind shear stress on the axes x, y; θ_w – the angle between the wind direction and the axis x; κ = 0,4 – Karman's constant; W – the wind speed on the height z (compared with the surface level); z_0 – the roughness coefficient of water surface; $q(x, y)$ – the intensity of the mass source in the point with the coordinates (x, y). The viscosity coefficient ν_t can be determined on the basis of the Prandtle's model

$$\nu_t = \kappa u_* h\,,\;\; u_* = \rho_w^{-1} \sqrt{(\tau_{bx}^2 + \tau_{by}^2)}\,.$$

The heat transfer equation in the context of the 2D (plan) model is derived on the basis of the averaging in depth 3D equation of transferring and has a form

$$\frac{\partial \overline{T} h}{\partial t} + \frac{\partial \overline{T} h u_x}{\partial x} + \frac{\partial \overline{T} h u_y}{\partial y} = \frac{\partial}{\partial x}\left(\mu_T h \frac{\partial \overline{T}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\mu_T h \frac{\partial \overline{T}}{\partial y} \right) + \frac{1}{\rho_w c_w} (\Phi_S + \Phi_B + q_T)\,. \quad (4)$$

Here $\overline{T}$ – averaged (in depth) water temperature; μ_T, μ_T – the total thermal diffusivity coefficient with regard to dispersion; c_w – specific heat of water; Φ_S – the heat-flux density on the water surface; Φ_B – the heat-flux density on the bottom; q_T – the intensity of the internal heat sources. The calculation of the heat-flux density Φ_S is performed on the basis of (Methodic Recommendation, 1976; Recommendation, 1979; Recommendation, 1986).

The changing of the ice thickness on the water surface is determined according to the relation

$$\rho_I L \frac{d\, h_I}{d\, t} = \Phi_{SI} - \Phi_{IW} \quad . \quad (5)$$

Here ρ_I – the ice density; L – the latent melting heat; h_I – the ice thickness; Φ_{SI} – the heat-flux density on the boundary of ice-air (from ice to air); Φ_{IW} – the heat-flux density on the boundary of ice-water. The relation (5) is used in two cases – when there is already ice cover ($h_I > 0$) or when the calculated surface water temperature T_{SW} gets lower than the temperature of water freezing ($T_{SW}<0$). If there is snow on the ice surface the surface temperature T_{SS} on the contact with air can be found (in the assumption of the linear distribution of the temperature along the thickness of the ice and snow) from the relation (where Φ_{SS} – the heat-flux density on the boundary with air when there is snow on the ice surface, h_S – the thickness of the snow cover)

$$\frac{1}{\dfrac{h_S}{\lambda_S} + \dfrac{h_I}{\lambda_I}} T_{SS} = \Phi_{SS} \quad .$$

It is significant that the radiation thermal transferring, the evaporation transferring and conventional transferring are all taken into account when Φ_{SS} (Φ_{SI}) is calculated according to (Recommendation, 1986).

The surface water temperature T_{SW} (without ice cover) as a first approximation is determined in the assumption of the linear character of the heat flux changing along the depth

$$T_{SW} = \overline{T} + \Phi_{SW} \frac{h}{3\lambda_{WZ}} - \Phi_{BW} \frac{h}{6\lambda_{WZ}} \quad . \tag{6}$$

Here λ_{WZ} – the thermal diffusivity coefficient in the vertical direction; Φ_{SW} – the heat-flux density on the boundary of air-water; Φ_{BW} – the heat-flux density on the bottom of the reservoir. Since the relation (6) is only used with the proviso that ice formation starts on the water surface ($T_{SW}<0$) the thermal diffusivity coefficient λ_{WZ} is calculated for the case corresponding to the existing ice cover according to (Recommendation, 1979). If the ice cover exists the roughness coefficient n in (2), (3) is determined from (Belokon', 1950)

$$n = \left(n_W^{3/2} + n_I^{3/2}\right)^{2/3} \quad .$$

Here n_W – the roughness coefficient of the reservoir bottom; n_I – the roughness coefficient of the lower ice surface. If the ice cover exists it is also assumed that the wind shear stress is equal to zero.

NUMERICAL ALGORITHMS

The solution to the equations (1) – (4) was realized by means of the numerical schemes of the second order accuracy in space and time (explicit and implicit schemes Roe, Lax-Freiederics, Curant-Isaakson-Rees, Harten-Lax-Van Leer) (Prokofiev, 2002: Klimovich, 2003). All the considered schemes showed satisfactory reliability for the solution of the hydro-thermal problem. The verification of the numerical algorithms of the hydro dynamics (1) – (3) was performed on the basis of comparison the calculation results with the experimental and in-situ data for subcritical, critical and supercritical flows. The verification of the solution of the heat transfer equation (4) was made with help of comparison the numerical results with the available analytical solutions.

NUMERICAL RESULTS

The numerical modeling of the development of the hydro-ice-thermal situation in the water reservoir-cooler of Volga-Don Nuclear Power Plant (NPP) was carried out for the autumn-winter period (from October, 2002 to January, 2003). For the mentioned period there was all the necessary in-situ information concerning average day hydro meteorological conditions in the region of the Volga-Don NPP. The calculations were performed on the 84×32 grid with the difference step on the dimensional coordinates equal 100 m. Since there was no data on the snow cover it was assumed that there was not any snow on the ice. The average water level in the reservoir was taken equal to 35.8 m. The water discharge of the plant was defined equal to 36.8 m^3/sec.

For the calculations of the temperature distribution in the intake channel and the tail-race one dimensional non-stationary model was used. The length of the tail-race was ≈4.8 km, the average width – ≈100 m, the average section area – ≈300 m^2. The intake channel length was ≈800 m, its average width – ≈80 m, its average section area – ≈300 m^2. The total thermal diffusivity coefficient with regard to dispersion was supposed to be proportional to the unit discharge $\mu_T = \alpha(Q_x^2 + Q_y^2)^{1/2} + 0.14 \cdot 10^{-6} \mathrm{m}^2/\mathrm{s}$ and was determined on the basis of the in-situ data for the period from October 16, 2002 to December 8, 2002 (when there was no ice cover on the reservoir). In Fig.1 the comparison of the calculated and the in-situ data of the water temperature on the entrance of the NPP is shown.

The presented data on modeling of the hydro-ice-thermal situation in the Volga-Don NPP cooler reservoir for the period from October 16, 2002 to January 12, 2003 (when there was full average day meteorology data) showed that the beginning of ice formation in the reservoir was on December 1. According to the in-situ data the first shore ice in the area of the additional water pump station (AWPS) was observed on December 1 and the ice cover formation in the area of AWPS started on December 5. According to the calculations an ice formation in the intake channel began on December 10. As for the in-situ data the first shore ice formation in the intake channel took place on December 9. The maximum ice thickness in the period was observed in the eastern part of the reservoir-cooler and was ≈0,45 m. The maximum ice thickness in the intake channel was 0.25 m and was observed near the NPP pump station entrance. As for the tail-race there was not ice cover formation there. Some results on the calculations of the hydro-ice-thermal situation in the reservoir-cooler are shown in Figs 2-7. There was a qualitative agreement between the numerical results (the ice thickness and the place of the ice-hole at the exit of the tail-race) and both the visual in-situ observation data and the photographs obtained from the Volga-Don NPP.

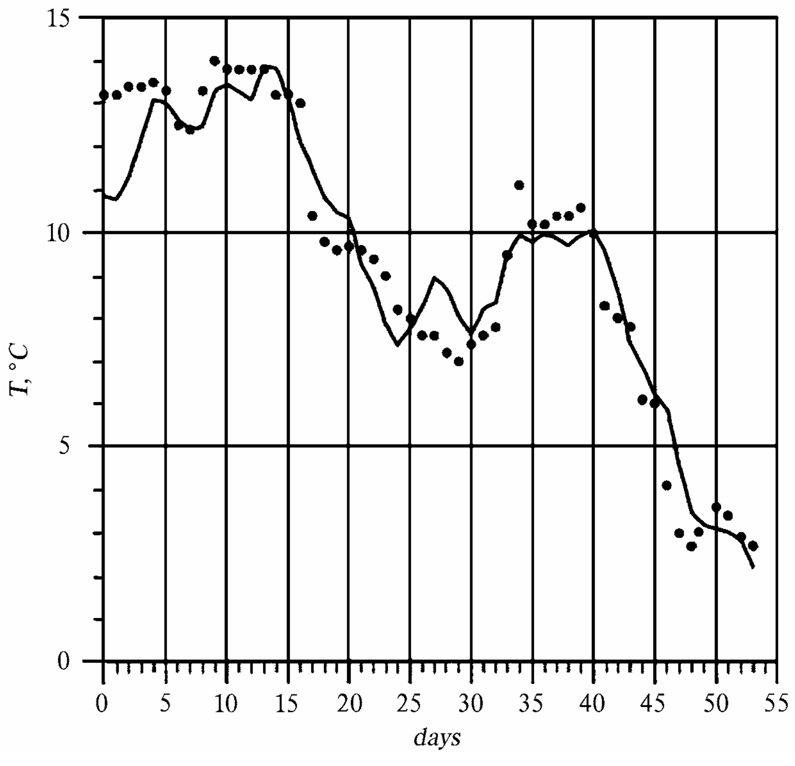

Fig. 1. The variation of the temperature at the Volga-Don NPP entrance for the period from October16, 2002 (0 day) to December 8, 2002(53rd day) (—— – calculations; • – in-situ data)

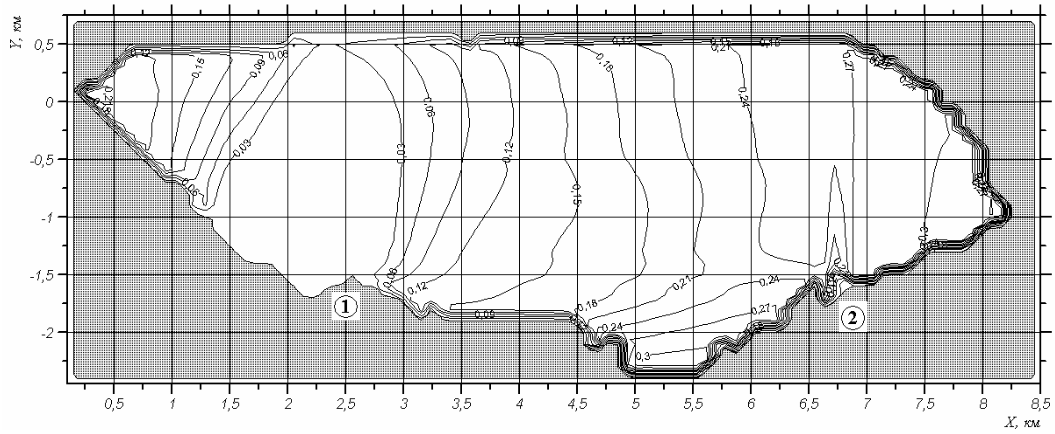

Fig. 2. The ice thickness distribution in the Volga-Don NPP reservoir-cooler
on December 18, 2002 (1 – the exit of the tail-race; 2 – the entrance of the intake channel)

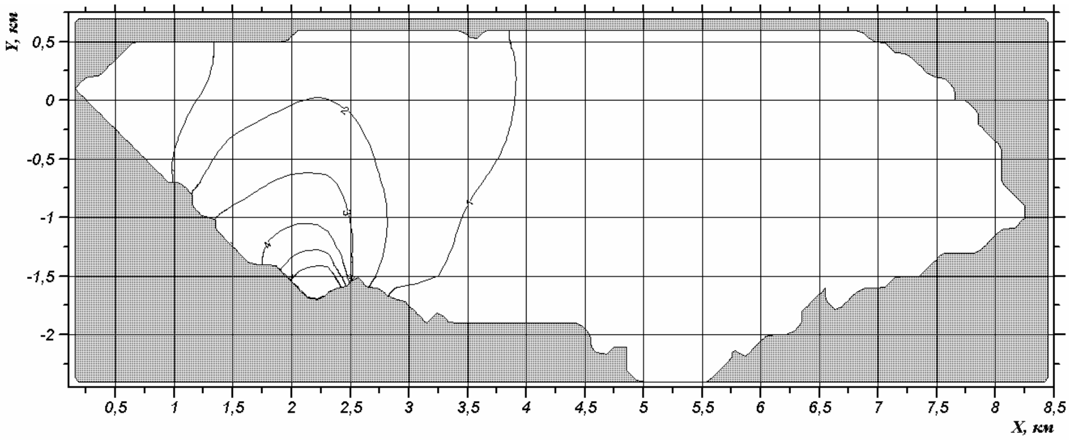

Fig. 3. Temperature distribution in the Volga-Don NPP reservoir-cooler on December 18, 2002

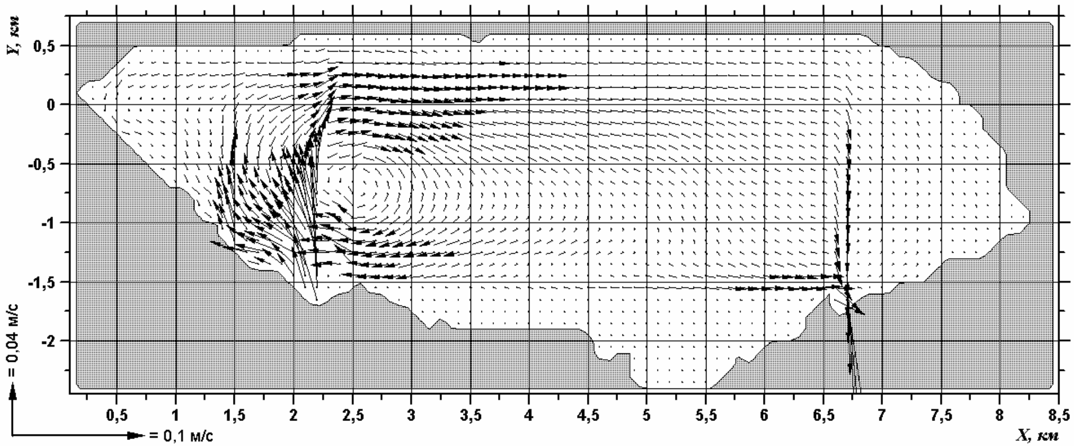

Fig. 4. Vectors of the flow velocities averaged in depth in the Volga-Don NPP reservoir-cooler
on December 18, 2002

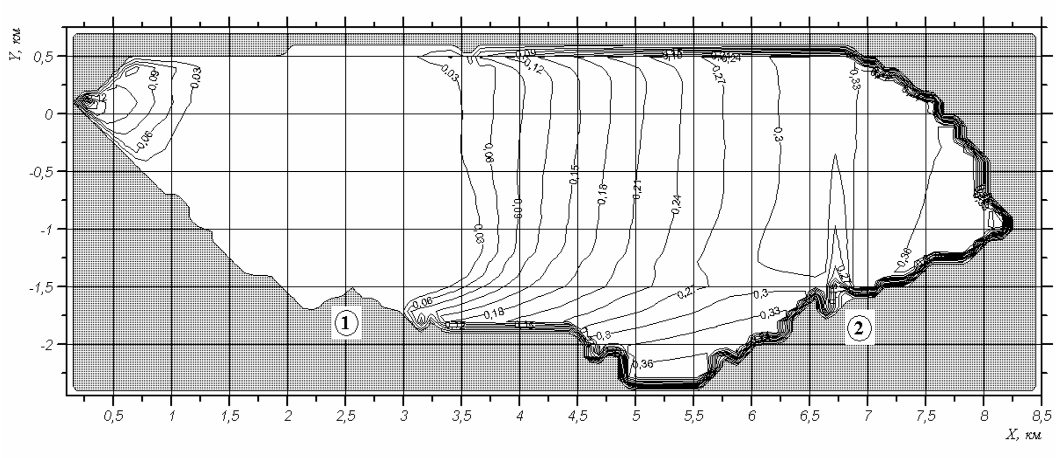

Fig. 5. The ice thickness distribution in the Volga-Don NPP reservoir-cooler
on December 23, 2002 (1 – the exit of the tail-race; 2 – the entrance of the intake channel)

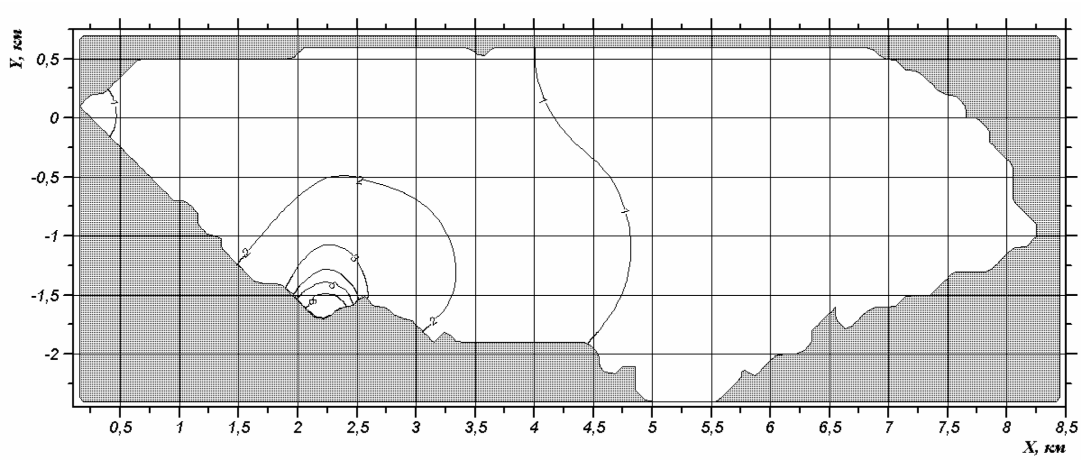

Fig. 6. Temperature distribution in the Volga-Don NPP reservoir-cooler on December 23, 2002

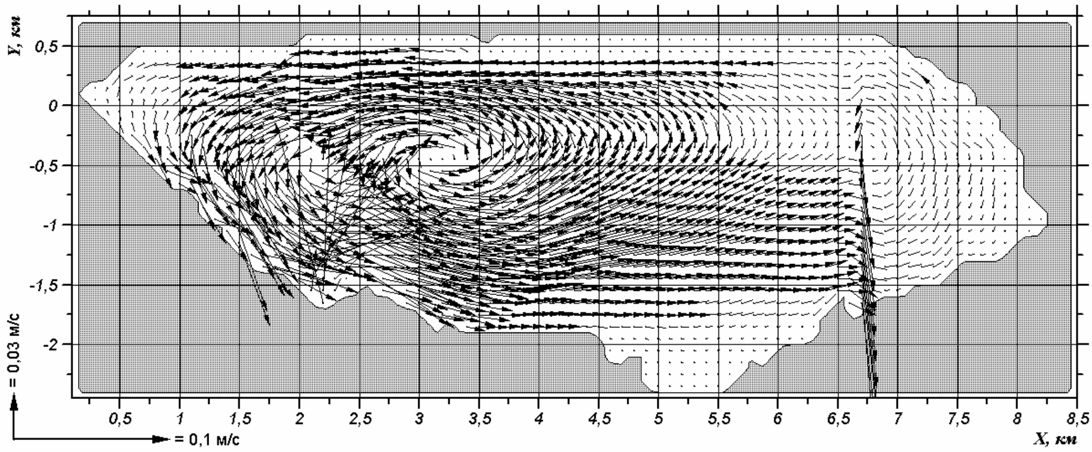

Fig. 7. Vectors of the flow velocities averaged in depth in the Volga-Don NPP reservoir-cooler
on December 23, 2002

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HYDROPLUS FUSEGATE SYSTEM: ANALYSIS OF WINTER MONITORING DATA AT THE KHOROBROVSKAYA HPP

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ABSTRACT

"Hydroplus" fusegates (fuse link) is innovative effective technology to reduce water level fluctuations at upstream during crest discharge pass and to increase operate reliability, because neither hoisting equipment, no power supply are needed for their service. Also fusegate technology basing on "fuse link" principle, ensures a pass of rare floods.

Throughout the world fusegate technology becomes more popular being adopted both in hydrounits under construction and under renewal. However, up to now fusegates have been adopted mostly in the countries with warm or tropical climate.

First in Russia these fusegates have been installed on the Dam of Khorobrovskaya midget power plant for testing service. Hydraulic Research Centre (HRC) of JSC NIIES performed spillway monitoring during two winters 2001-2002 and 2002-2003. Resulting material describe fusegate service properties in winter conditions.

Analysis of obtained material and recommendations to expand fusegates application zone for the climatic conditions of Russia are given in the Paper.

The conditions of ice pass during floods and winter discharge through the crest of fusegates are also under consideration. Some other constructions of fusegates type ensuring ice pass during overflow of flood discharge through the crest of fusegates, worked out in HRC of JSC NIIES, are proposed.

Russian Utility RAO has built a 160-kW experimental hydropower plant on the Nerl-Volzhskaya River for field testing of new technologies. One such technology recently tested is the Hydroplus Fusegate System. Testing results show that the Fusegates can be a viable alternative to conventional gates, which have presented numerous problems in the past, for use on small HPP spillways, even in the harsh Russian winters.

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Russian HPPs' Operating Conditions

The majority of small HPPs in central Russia have spillway structures located in the riverbed. As a rule, the spillways are equipped with mechanical gates. When the gates are closed, they form the main part of the water-retaining structure.

In many cases, HPPs are abandoned due to mechanical gate malfunctions causing partial or complete failure of the spillway structure during large spring floods. Such failures are generally the result of mechanical breakdowns caused by insufficient maintenance, shutdown of the electric energy required for operation or human deficiency. As these problems reoccur in remote areas, the use of conventional gates for HPP construction or refurbishment cannot be considered. On the other hand, the use of a free spillway would jeopardize the economics of the project, the height of the chute being then insufficient. Thus, the feasibility of small HPP in central Russia strictly depends on the possibility to implement new technologies which would not suffer the same weaknesses and would be adaptable to typical conditions on Russian rivers.

In this framework, RAO has been looking for innovative solutions to upgrade old HPPs. For this purpose, they recently built a 160-kW experimental hydropower plant on the Nerl-Volzhskaya River (a tributary to the Volga River) for field testing of new technologies.

Spillway

The spillway design takes into consideration dam operation in typical Russian winter and spring ice-affected conditions. It consists of a combination of fixed concrete labyrinth sections with two smaller sections for gate accommodation.

The concrete labyrinth sill has a similar design to the Snare Cascade Hydro Project (Northern Territories, Canada), a concept never used before in Russia (*Slopek R., Leseberg G., Al Nashir J., 1996*). It comprises eight cycles of trapezoidal layout with a 6.3 meter step (Figure 1).

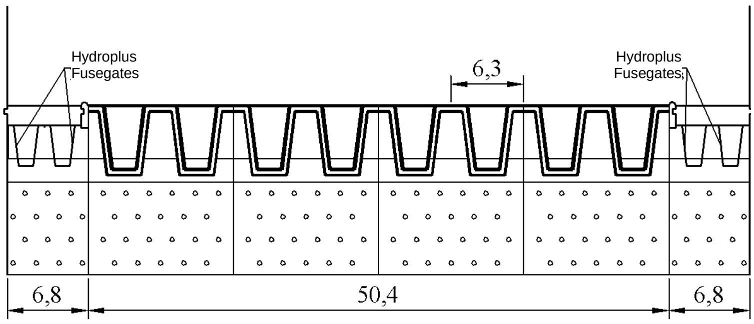

Fig. 1. Labyrinth Spillway (measurement unit : m)

The height of the labyrinth walls, which have a downstream slope, is 5.5 m with an average thickness of 0.5 m. The fixed concrete labyrinth spillway upper edges are steel-lined to reduce damages to the concrete due to ice friction during spring spilling period.

This fixed labyrinth spillway portion is combined with two 6.34 m wide spans, one on either side, which are designed to accommodate various new types of spillway gates.

Within the frame of the TACIS Project ERUS-9802 financed by European Community, funds were allocated to RAO to conduct research works for selection and field testing of the most appropriate automatic spillway gates applied to small Russian HPPs. After studying different systems at the design stage, such as rubber dams, self-operating gates and Fusegates, JSC NIIES of RAO chose to go forward with the Fusegate technology, for this system does not rely on supply of energy during operation and does not contain any mechanical part. Therefore, the lateral spans are presently equipped with two sets of steel labyrinth Fusegates which are 1.75 m high and 3.15 m wide (Figure 2).

Top view Section A – A

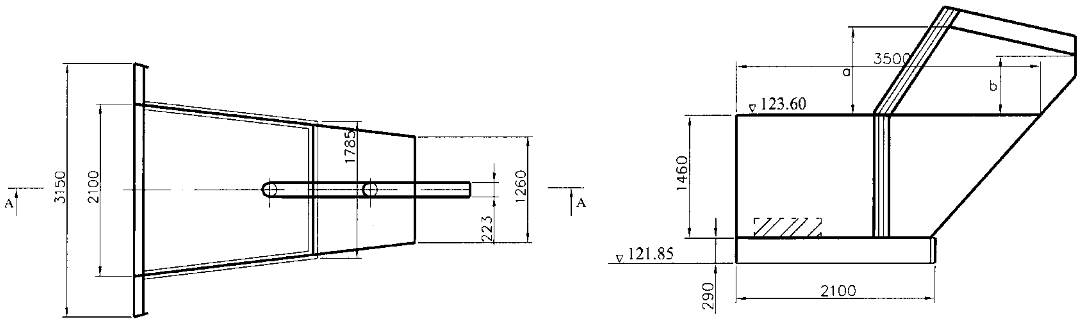

Fig. 2. Classic Type of Hydroplus Fusegate

Russian standards for hydraulic steel structures were used for structural calculations of the Fusegates. An extra load of 0.087 Mpa is applied to the structural design calculations for ice expansion effects inside the Fusegates bucket. It should be noted that Fusegates can withstand plastic deflection of several millimetres, without jeopardizing their operation. Fusegates stability is adjusted by using steel ballast located in the upstream part of the bucket for a total weight of 5.9 tons (Fusegate No. 1). A feature worth mentioning is that the Fusegates' crest is set 10 cm higher than the fixed concrete labyrinth crest. Hence, moderate flows, which are frequent during winter period, spill over the concrete labyrinth only, delaying ice-jam risks on the Fusegates structures. Moreover the Fusegates are positioned 1.8 m downstream from upstream concrete face of the spillway, inside the experimental spans, whose width is chosen to transfer ice pressure expansion effects to the concrete structure (the arching effect).

Hydraulic Model Tests

Prior to finalizing the detail design of the spillway, the fixed labyrinth spillway performances as well as Fusegates behaviour were validated in the NIIES hydraulic laboratory in Moscow.

The effects of thermal expansion of ice, ice floes and reservoir level fluctuation on Fusegates stability were also analyzed on the basis of results of previous laboratory model tests implemented at the National Research Centre (NRC) in St. John's, Newfoundland (Canada) and in NIIES in Moscow (Russia).

Winter Monitoring

Further to the conclusive results of the hydraulic model tests, the Fusegates were installed on site on the experimental spillway spans during the summer of 2001. Monitoring was performed on a weekly basis at the dam during winters 2001/2002, 2002/2003 and 2003/2004. Various parameters were recorded such as air temperature; ice and snow cover thickness, potential movements and deformation of the Fusegates. During the ice melting period, the overspilling head over the fixed labyrinth and over the Fusegates was also reported.

In the winter of 2001/2002, the period of negative temperatures began in mid-November. In the second week of December, the temperature fell down to -20^{o}C. Then between mid-December and the beginning of January, it fluctuated between -10^{o}C to -12^{o}C (Figure 3). During this period, ice thickness reached 50 cm at the surface of the reservoir and 60 cm upstream of the Fusegates (Figures 4 and 5). The Fusegate buckets, wells and drainage holes were frozen through. The downstream side of the spillway was covered with solid ice up to 10 cm thick. Ice was formed on the vertical faces of the Fusegates on the downstream side and on the walls of the concrete labyrinth. At the end of the first week and throughout the second week of January, there were temperature swings from -21^{o}C to -2^{o}C during three days, followed by a sharp drop of temperature to -23^{o}C and a rise to +2^{o}C. Up to mid-February, the temperature fluctuated around 0^{o}C with an amplitude of -4^{o}C to +4^{o}C (Figure 3, curve 1).

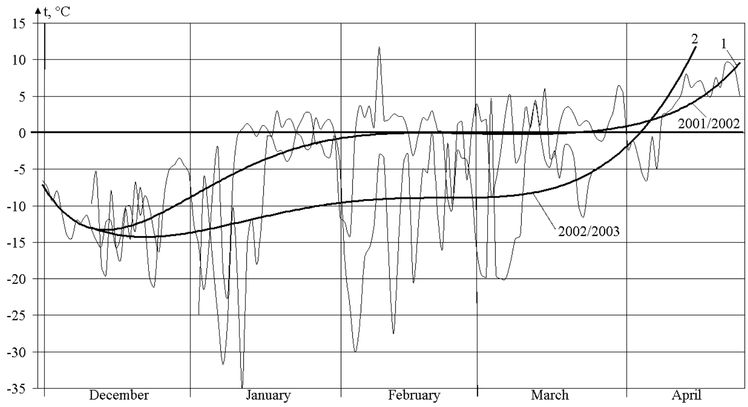

Fig. 3. Plot of daily average temperature at Khorobrovskaya hydrounit for winter period of 2001/2002 and 2002/2003

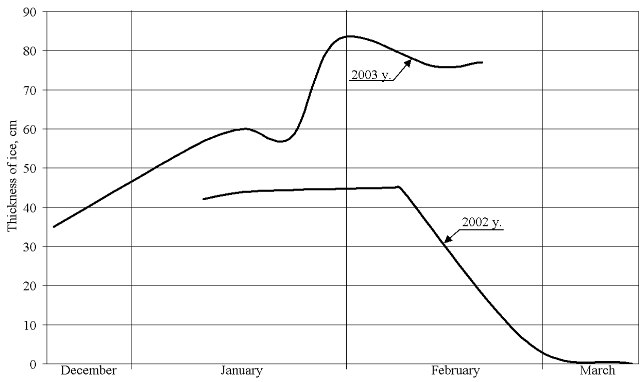

Fig. 4. Ice Thickness Variation beside Fusegate No. 3

Despite these severe conditions, no displacements or noticeable deformations of the Fusegate elements were observed, nor disturbances in the operation of the concrete labyrinth.

It should be noted that there was no Hydroplus Fusegate crest overflow during the winter months, as its edge level is 10 cm higher than the labyrinth spillway crest level. The

HPP turbines were not operating during that winter, so full discharge passed through the labyrinth and headwater level variations were equal to few centimetres.

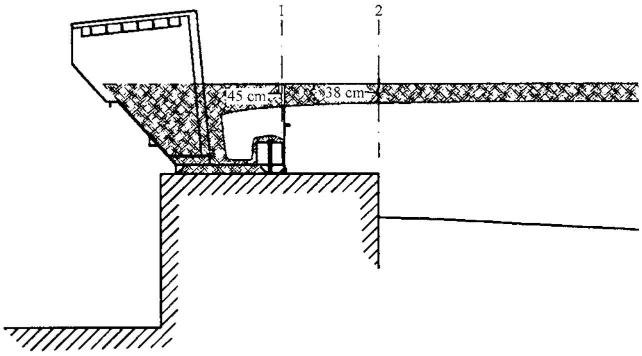

Fig. 5. Ice Thickness beside Fusegate No. 3 in January and February 2002

When the duration of the thaws (periods of positive temperature) exceeded one week, all the ice from the tail water side melted (Photo A) and the Fusegate drainage system began to operate again. A gap filled with free water was formed on the inner side along the perimeter of the bucket, due to high heat conductivity of the metal faces. Free sheets of ice along the upstream side of the Fusegates started moving.

Photo A. Hydroplus Fusegates during Thaw of February 2002

Throughout the whole monitoring period, no leakage was noticed through the visible sections of the Fusegate seals. The winter of 2002/2003 happened to be especially cold. During almost the entire period, the temperature fluctuated with substantial variation. Until mid-January, freezing weather became more severe, reaching record temperatures for this region, with the lowest being -35^{o}C (Figure 3, curve 2). The temperature then rose to ±4^{o}C but in early February it dropped again to -30^{o}C. Looking at the plot of average temperatures, it is obvious that the first months in 2003 were more severe than the ones in 2002 by approximately 8°C. However, the rise in temperature which typically happens before the spring floods occurred earlier in 2003 than in 2002.

Maximum flood discharge in spring 2002 did not exceed a 55 m^3/sec. and in spring 2003 it reached a 104 m^3/sec.

From January to April 2003, no overflow through Hydroplus Fusegates was observed. Water inside the Fusegates was frozen up from crest to bottom (Photo B, figure 6), while at the same time in 2002 a space with unfrozen water remained inside of the Fusegates. Ice within the lower part of the well and at the bottom of the Fusegates melted after the floods started, overflowing Fusegate edge.

Photo B. Hydroplus Fusegates during Frost of March 2003. (t = -20°C)

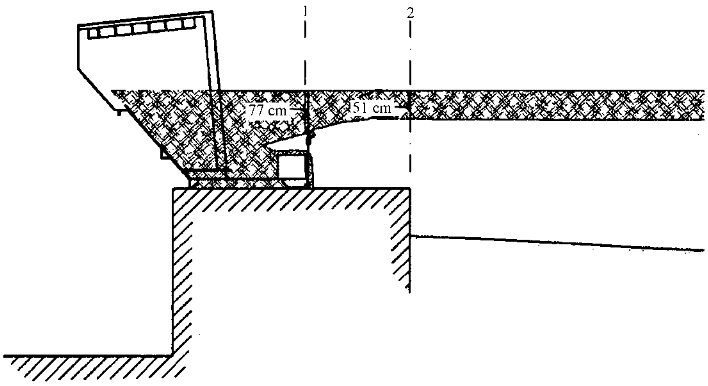

Fig. 6. Ice Thickness beside Fusegate No. 3 in January and February 2003

Ice level in all Fusegate wells differed little from the headwater level. This is due to the freezing of the Fusegate bucket and drainage holes. However, during the winter of 2003/2004, water and ice were not to be seen in any Fusegate buckets.

According to the monitoring winter 2002/2003 discharge did not exceed 10 to 15 m^3/sec. Ice thickness variation immediately in front of the installed Fusegates during winter is

shown (Figure 4). Along the front crest face (site 2) in the winter of 2002/2003, there were cracks in the ice due to the headwater level variation not exceeding 10 cm, while the ice and frozen Fusegates on the crest remained fixed.
HPP has started operating in winter 2003/2004. By the end of January, inflow discharge became less than the discharge of two turbines and the headwater level decreased by 15 cm below labyrinth crest level. Two cracks formed in front of the Fusegates and the ice broke off the frozen Fusegates (Photo C and figure 7). Then one of the turbines stopped and headwater level started rising. No new cracks were formed and ice displacement occurred along the existing cracks as the ice was less solid and had less strength compared to solid ice. During all this period, no fusegate displacement was observed. Ice thickness in this period was more than 30 cm.

Photo C. Ice cracks in front of Hydroplus Fusegates
Ice thickness is more than 30 cm and level fluctuation about 15 cm
(February 2004)

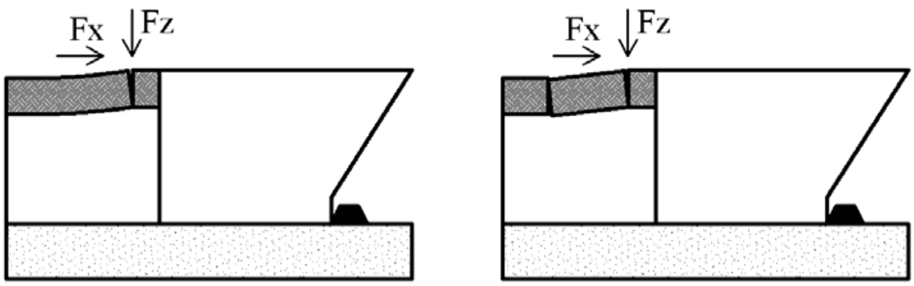

Fig. 7. Cracks Development Scheme

During the water level raising, flowing over the labyrinth crest started again. With hard frost and small discharges, both the vertical and the sloped labyrinth sides became encrusted with ice under the overflowing nappe. In case of Hydroplus Fusegate crest overflowing, such ice can considerably increase the tilting moment and reduce Fusegates stability. Therefore winter monitoring is on going regarding this matter.

According to monitoring in spring 2002 and 2003, floods on the Nerl River started at positive average daily temperatures. Then an interlayer of water appeared between the Fusegate walls and the ice. But inside the Fusegates, ice did not float up and it melts few days after crest overflowing has started.

Small ice drifting could be observed a few days before the maximum flood. Ice blocks measuring up to 1 m^2 broke off the floe and fell over the labyrinth. The main ice mass did not pass over spillways and it melted in the headwater.

CONCLUSION

With its innovative design, Khorobrovskaya spillway combines the advantages of ungated spillways to the performance of gated spillways. It is particularly suitable for ice-affected projects located in remote areas. After three years of records, the Fusegates have shown their capacity to operate under harsh winter conditions. They *enhance dam safety* during flood periods, *increase HPPs reservoir storage capacity* and *improve the discharge capacity* when required.

Monitoring has shown that Hydroplus Fusegates are stable in various temperatures, including ice conditions, when Fusegates' crest constant overflow can be prevented. Roof-like ice builds forms over the Fusegate labyrinth during hard frost. They are held by surface ice along the sill edge and in the centre. If there are wells, this "roof" will be frozen on the well and will create the Fusegate overturning moment. In such conditions, it is therefore recommended to use another type of Hydroplus Fusegates.

Concrete labyrinth spillway can be used in severe climate regions. It does not cause any complications both with and without crest overflow when temperatures are not below – 30^oC.

Ice loads do not affect Hydroplus Fusegates as long as these loads are shifted to the downstream direction in relation to the pier heads, since the ice breaks off along the line of the pier heads during water level fluctuation. The relationship between the span width and the portion of the pier length projected towards headwater will be the subject of further studies.

Testing of the Fusegates will continue at Khorobrovskaya HPP and specifically the testing of recoverable Hydroplus Fusegates.

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WATER TEMPERATURES AT DIFFERENT REGULATION REGIMES IN SULDALSLAGEN, A NORWEGIAN SALMON RIVER

Aanund Sigurd Kvambekk[1]

ABSTRACT

Suldalslagen is one of Norway's best salmon rivers, famous for the large salmons. Since 1986 the river has been extensively regulated. Today most of the water is directed through a power station and the discharge in the river reduced. A lot of effort has been made to find the amount of water needed to sustain the salmon tribe. The water temperature depend on the discharge and is an important factor for the growth rate of the fish and also the time they leave the river. We have therefore simulated the water temperatures under three possible regulation regimes and even how it would have been without the regulations. A low discharge in winter and spring, reduced from 12 to 6 m^3/s, may five-double the number of days with ice production and raise the spring temperatures with 3-4 ^oC.

INTRODUCTION

Suldalslagen is one of Norway's best salmon rivers, famous for the large salmons. Since 1986 the river has been extensively regulated. Today most of the water is taken away from the river and directed through the Hylen power station (fig. 1). A lot of effort has been made to find the amount of water needed to sustain the salmon tribe. Since the water temperature depend on the discharge and is an important factor for the growth rate of the fish and the time they leave the river, we have simulated the water temperatures under several regulation regimes and even how it would have been without the regulations.

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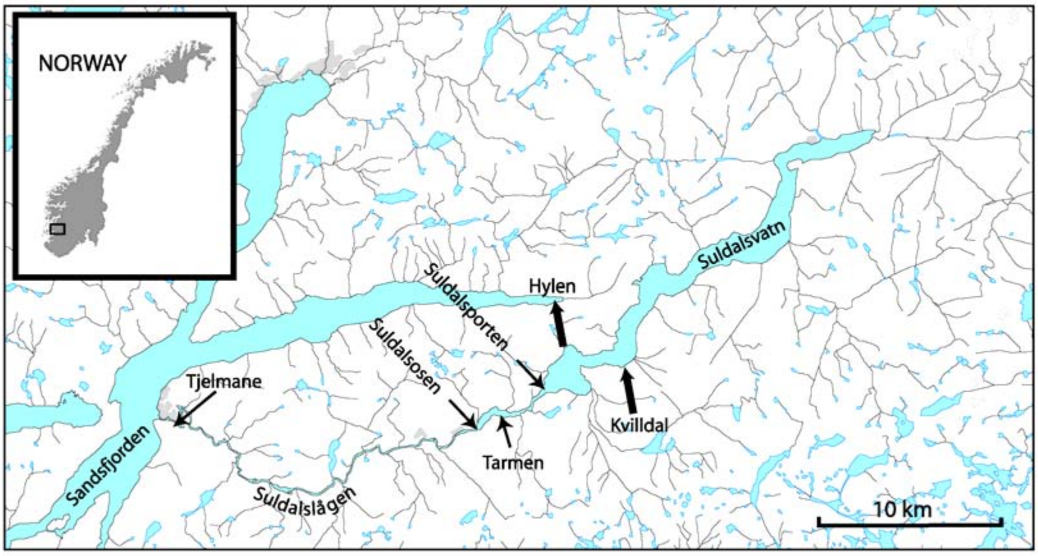

Fig. 1. Suldalslagen from Lake Suldalsvatn to the sea (Sandsfjorden). Kvilldal and Hylen are hydro power plants and the heavy arrows indicate the flow direction

MODELS

We used the two-dimensional lake model QUAL2E (www.epa.gov/docs/QUAL2E_WINDOWS/index.html) to model the water temperatures in Lake Suldalsvatn.

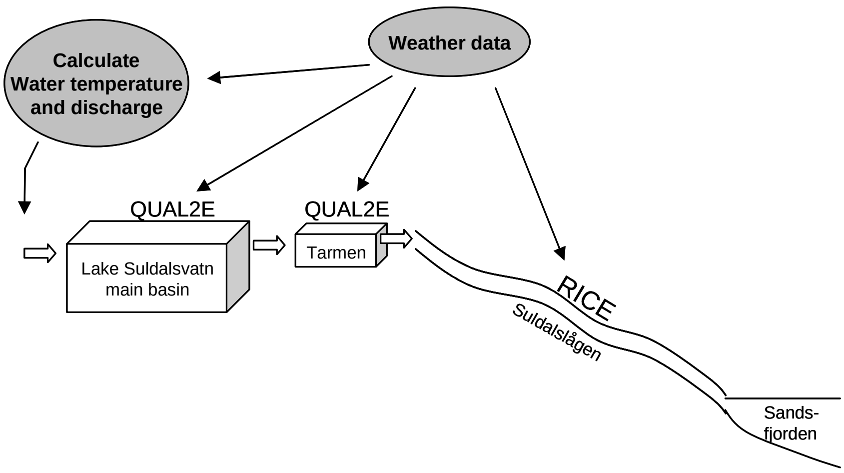

Fig. 2. A sketch of the simulations from Lake Suldalsvatn to the sea

The lake is naturally divided at a shallow and narrow threshold called Suldalsporten. The upper basin is more than 300 m deep while the lower part is less than 40 m deep. To be able to use a rough grid net we divided the simulation into two simulations where the Suldalsporten was regarded as a river between two lakes. The river from Suldalsosen to the sea (Tjelmane) was analysed by the one-dimensional model RICE (Lal & Shen, 1989). Fig. 2 gives an overview of the simulations.

Each of the lake models used two elements in the length direction and had a vertical resolution close to 3 m. The river was modelled as a channel with constant shape and constant inclination. The channel shape and the bottom roughness was optimized to fit the measurements.

UNREGULATED FLOW

The water temperatures with an unregulated flow were calculated for the period 1931-2002. The first regulation upstream lake Suldalsvatn started in 1966, but the major change in Suldalslagen came after the start-up of Kvilldal and Hylen power stations in 1980. Today most of the water from Lake Suldalsvatn leaves through Hylen directly to the sea.

The most complete weather data available were from Bergen 100 km to the northwest. The air temperature were adjusted to fit the Suldal area, and the wind strength were indirectly tuned in the model by the setting of a wind coefficient (=0.85). We had sufficient of discharge measurements to construct an unregulated discharge series with a correlation coefficient above 0.9. The really weak point in the input data was the complete lack of water temperature measurements in the major rivers. Upstream lake Suldalsvatn there are some lakes that affects the water temperature. After some test runs we concluded that the temperature into the lake was similar to the temperature at Tjelmane where Suldalslågen enters the sea, both temperatures affected by lakes. We reconstructed a water temperature series based on this knowledge and correlation between measured air temperatures (Bergen) and water temperatures.

We ran the QUAL2E model from 1931 to 2002 and obtained a water temperature series for unregulated condition at the outlet of lake Suldalsvatn (Suldalsosen). From measurements (see Fig. 3) we calculated the standard deviation in the error to be 0.7 ^{o}C on a monthly basis and 0.8 ^{o}C on a daily basis. Compared with the natural variations this is quite satisfactory considering the relative poor input data. The largest errors occur in January-February when the model often got a lower water temperature than what was observed. This was probably caused by an ice cover on the lake which forms in some cold and calm periods. The model did not manage to build an ice cover, probably due to daily averaged wind data that seldom gave zero wind.

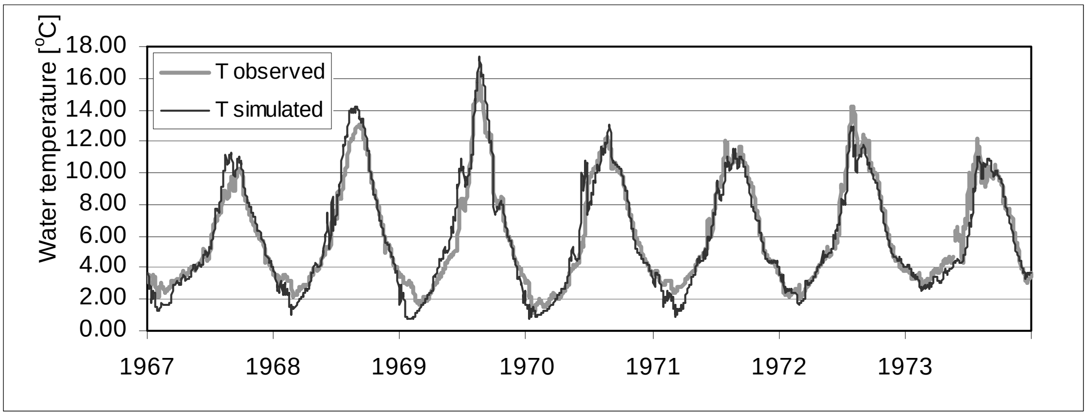

Fig. 3. Observed and simulated water temperatures at Suldalsosen from 1967-73

We also modelled the unregulated water temperature at the lower end of Suldalslågen using RICE. We used the output from the QUAL2E model as upstream input in the RICE model. Fig. 4 shows an example of the simulated and observed values.

Fig. 4. Simulated and measured water temperature at Tjelmane, and measured water temperature at Suldalsosen

The water temperatures from the tributaries have been measured, but the contribution is generally of no importance, except in flood episodes and at discharges below 10 m^3/s from Suldalsosen. To simplify the model, we entered all the tributaries at the upper end. That introduces an error since the actual inflow points are at several points down along the river. We partly corrected that error from measurements of the actual temperature increase/decrease. The standard deviation in the error became just slightly higher than at Suldalsosen (≈1 ^oC) since the major error came from the input temperature.

REGULATED FLOW

Suggested regulation regimes

The water in Suldalslagen could have been led through Hylen hydro power station in stead. In a way, the water in Suldalslagen is a loss for the power company. The problem is to find the optimal amount of water, giving sufficient provision for life in the river and sufficient money to the power company. One exciting combination is to lower the discharge in the spring and early summer to raise the water temperature. On the other hand, this increases the power production. We have simulated the water temperatures with three different strategies of water release through the dam at Suldalsosen;

FR1: 12 m^3/s in the winter time, but 7 m^3/s i shorter periods. Three short floods in May/June up to 130 m^3/s. Weekly pulsing in the summer between 42 and 55 m^3/s. Two short autumn floods up to 220 m^3/s. Same release every year, but the periods with 7 m^3/s may come in a cold period.

FR2: Low discharge, 6 m^3/s, from October to mid June. Three small and short floods in the spring up to 30 m^3/s. Weekly pulsing in July-September between 40 and 70 m^3/s. One autumn flood in the end of October up to 180 m^3/s

DR: 23 % of calculated unregulated flow. Limited to never above 250 m^3/s and never below 6 m^3/s.

All temperatures are compared with unregulated conditions. The regimes FR1 and FR2 has fixed values from year to year, regardless of the climate. DR is a dynamic regime that changes from year to year and is given as a percentage of the natural flow, here 23 %. Fig. 5 shows an example from 1999.

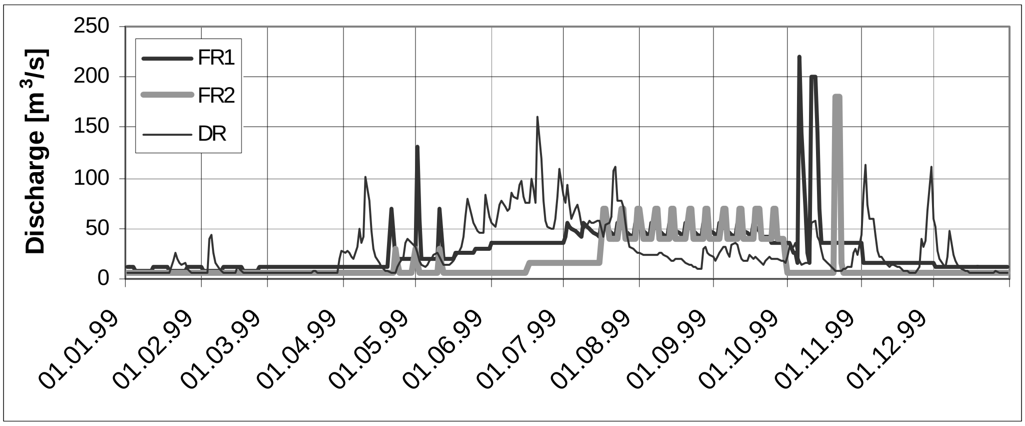

Fig. 5. The discharge at Suldalsosen in 1999 with the three regulation regimes

Outflow At Suldalsporten and Suldalsosen

The introduction of Kvilldal hydro power station 5 km upstream Suldalsporten changed the hydraulic situation in the lower part of Lake Suldalsvatn. In the unregulated situation the normal situation was transport of “surface” water out through the shallow Suldalsporten. Today frequent changes in the water temperature indicate that the water that passes Suldalsporten periodically comes from deeper layer in lake Suldalsvatn. This is confirmed with hourly measurements from the upper 50 m. The water from Kvilldal may come from deep layers in reservoirs (cold in summer) and may come from surface creek intakes (warm in summer). The water temperature, and hence the density, governs the depth that the discharge water is buffered in Lake Suldalsvatn. The excess of water in this layer sets up a pressure that pushes water from this depth across the threshold at Suldalsporten. From Suldalsporten the water temperature may change to Suldalsosen where we have our measurements.

Since we have measurements from the lake upstream Suldalsporten, and from Kvilldal, we may calculate the water temperature at Suldalsosen:

- Calculate the storage depth by comparing the Kvilldal temperature with the measurements from the lake.
- Assume that the transport is at the maximum at this depth and decreases to zero at a distance above and below this depth. The transport height depends on the discharge and is assumed to equal the square root of the discharge. Calculate the mean temperature of these water masses passing Suldalsporten.
- Use QUAL2E to calculate the changes down to Suldalsporten.

Fig. 6 compares the calculated values and the observed values at Suldalsosen in 1999. We had sufficient data in the five years 1996, 1998-99 and 2001-02. The standard deviation of the error was on a daily basis between 0.4 and 0.6 ^oC for the five years, indicating that the physical process is understood.

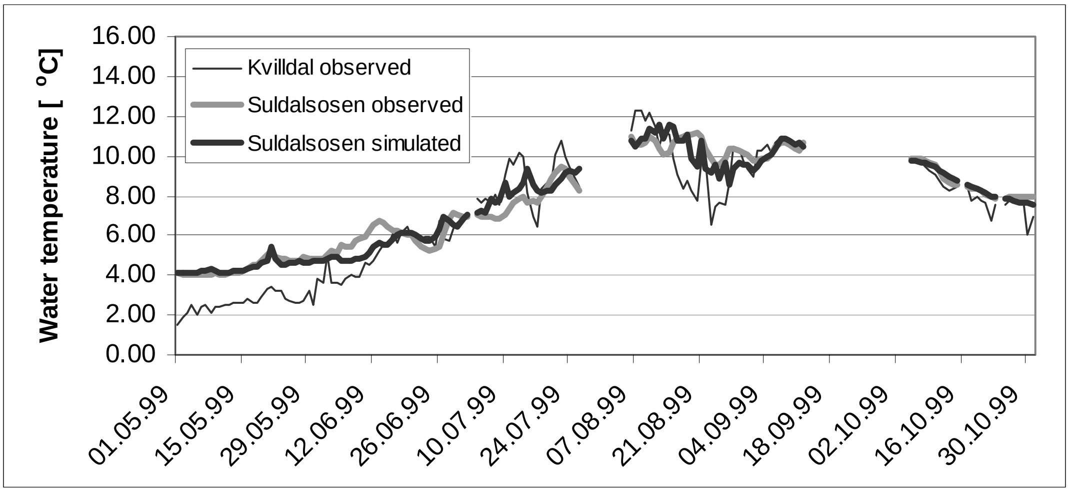

Fig. 6. Simulated and observed temperatures at Suldalsosen in May-Oct 1999. Also the water temperatures in the discharge water from Kvilldal hydro power station is shown

Water temperature at the suggested regulation regimes

We manipulate between the different regimes by changing the discharge in Hylen. If we want higher outflow to the river, we lower the discharge in Hylen, and visa versa. To calculate the water temperatures at different regulation regimes we have to assume that the conditions upstream Suldalsporten is unchanged. This is fulfilled for short term changes, but may not be true with considerable changes over a long period. We calculated water temperatures in the same way as explained in the previous chapter. An increasing discharge therefore releases water from a thicker layer since the thickness is equal to the square of the discharge.

Again we used RICE to model the water temperature changes down Suldalslagen, Fig. 7 shows the average water temperature differences from the unregulated case, at the upper end (Suldalsosen) and at the lower end (Tjelmane). The differences have been smoothed with a sliding 30 day average. The simulation shows that the water temperature can be substantially manipulated by regulating the release of water from Lake Suldalsvatn. A temperature of several degrees will have large impacts on life in the river.

We have used the water temperature simulations as an indicator for ice production in the river. The water temperature was never below zero at the upper end, but in cold periods it reached the freezing point on its way down to Tjelmane.

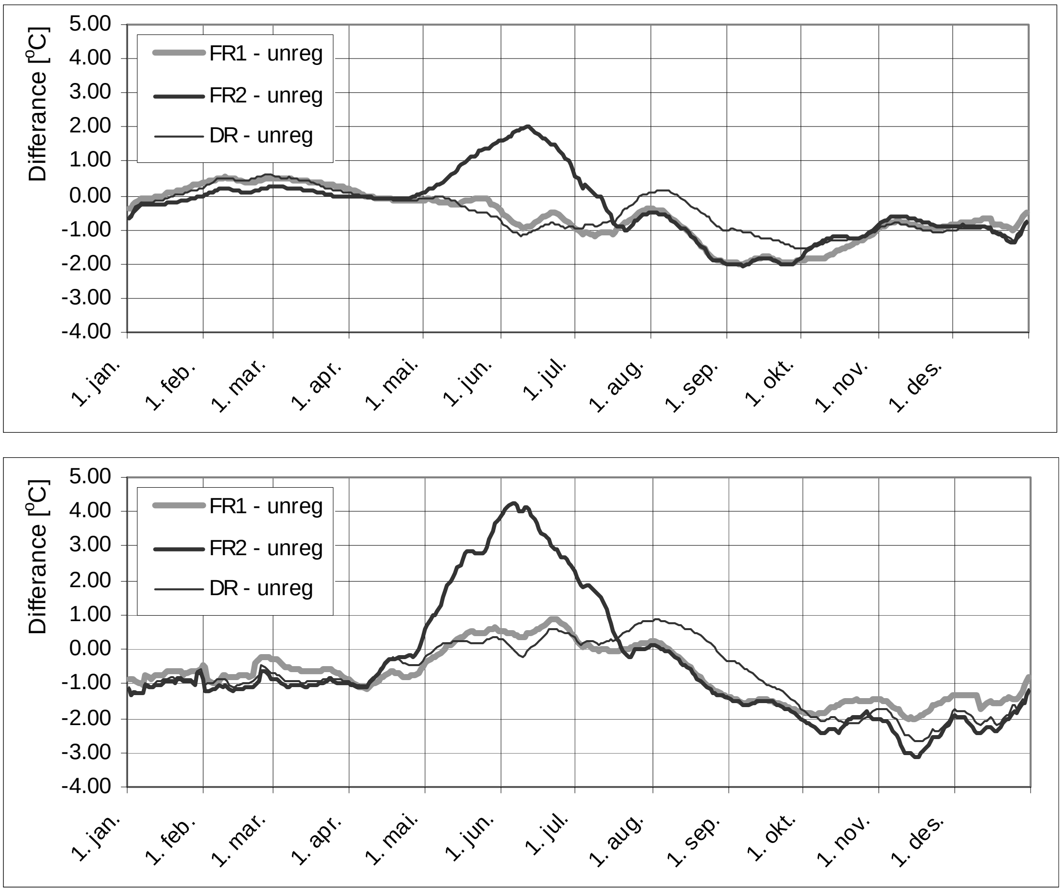

Fig. 7. Water temperatur differences between simulated values at a regulation regime and at an unregulated river. The differences have been smoothed with a sliding 30 day average. The upper figure shows the differences just downstream lake Suldalsvatn (Suldalsosen) and the lower figure shows the differences at the outlet to the sea (Tjelmane)

CONCLUSION

- Low discharge in the river increases the energy exchange with the atmosphere.

- Ice production will be more frequent with low winter discharge (FR2 and DR) in the lower part of the river. In our five year test period the number of days with ice production were five-doubled from the observed 9 to 41 when we lowered the discharge from 12 m^3/s to 6 m^3/s, but even then the ice periods seldom lasted more than 20 days.

- Low discharge in spring and early summer (FR2) yields higher water temperature in the river. The temperature in the lower part of the river will be 3-4 ^oC higher than both the unregulated river and a river with the other suggested regulation regimes. In the upper part the river will be 1-2 ^oC warmer than in the unregulated case, and 2-3 ^oC warmer than in the other regimes. Day to day and year to year variations increases with low discharge.

- In dry summers in August-September a downscaled natural discharge (DR) will give 1-2 ^oC warmer water than the in other regimes, and almost as warm as in the unregulated river.

- We find the smallest difference between the suggested regulation regimes in winter/spring in years with a high discharge from Kvilldal hydro power station. That induces less vertical temperature difference upstream Suldalsporten, and hence not so dependent of the thickness of the withdrawal layer.

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RESEARCH OF ICE CONDITIONS FOR THE STRUCTURES OF TUGUR TIDE POWER STATION

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ABSTRACT

For work of hydrotechnical structures in difficulties ice condition is required the development of actions for maintenance of its careful exploitation. The results of nature research had permitted to begin the development of actions for protection from ice influence in bases structures of Tugur tide power station.

The energy of tide power stations is essential alternative for thermal and atom power stations. There are on in Russia many regions with high value of tide. Particularly, Kola peninsula – the value of tide is about 4 m, Lumbov Gulf - about 7 m, Mezen Gulf - about 9 m. The essentials values of tide are observed in Okhotsk sea, for example, in Penzhin Bay - about 13 m, in Tugur Gulf - about 9 m. In the regions of these water areas are difficulties ice and climatic conditions that are considered by designation, construction and exploitation of tide power stations.

The above mentioned Tugur Gulf lies in west part of Okhotsk sea.

The length of lied from north to south Tugur Gulf is 74 km and the width is about 37 km. The Shantar islands from north side are natural protections by influence of ices (The tides power stations, 1994).

The length of dam of tide power station with the building of station lied inside of it will be 18 km. The water will be passed as well across water aggregates as across culvert holes.

For careful exploitation of aggregates including in period of Freeze-up must be developed respective actions.

For reception of dates about ice conditions in Tugur Gulf by small level of scrutiny for this question (Monosov and other, 1991) was necessary the carrying out of ice-research works in Tugur Gulf. Particularly, the air and ice investigations bas carried out, including ice-mesure survey and determination of ice and water salinity.

Resulting of investigations are received the dates, permitting to determine the bases characteristics of ice regime of Tugur Gulf in natural conditions.

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It was established, that first ice formations appear autumn and winter on shallow-water lots in form of border and of primary ice in November, the thickness of fast ice achieves 30 cm. In middle December the floating ices thickness about 40-45 cm cover practically all area of Gulf (7-8 balls), and end December increase these values respectively above 70 cm and 9-10 balls. In period from January to April is covered the Gulf completely with hummock ice (Karnovich and other, 1994) preferentially in form of big floe and fine- and large brash ice (Fig. 1) thickness about 1,4-1,5 m. The height of hummock achieves 4,0 m.

Fig 1. The variety of ice formations in Tugur Gulf

The development of ice masses to end of winter in conditions of constant moving by velocity about 1 m/s provided tide about half of day durability (The tide power stations, 1994) bring to occurrence of grounded hummocks (Fig. 2) and of floebergs height about 3-4 m, there are also ice bulks. In mouth of r.Tugur near the Gulf (south part of the Gulf) achieved width of fast ice is 2,5-3,0 km and the thickness is 1,5-1,7 m.

The period of icebreaking continues in Tugur Gulf from May to August.

The water salinity in Tugur Gulf is about 34‰, and the ice salinity is 6‰. In part of Okhotsk sea lied near Tugur Gulf (West part of Tugur peninsula – to East of Tugur Gulf) in summer period was these values respectively 7,5‰ and 1,5‰.

The received dates had permitted the further development of actions for prevent of un-favorable ice influence on the Tugur tide power station.

Fig. 2. Grounded hummock by drying in Tugur Gulf

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MODELING OF ICE COVER IN EXPERIMENTAL BASINS

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ABSTRACT

Physical modeling of ships and hydraulic structures interaction with ice is impeded, mainly, by the difficulties of creation of adequate ice cover model. Practical and theoretical aspects of modeling are reviewed. It is shown that under impossibility of the full satisfaction of the similarity theory requirements, partial modelling can bring useful results if similarity criteria set, ice cover model and methods of data expantion were chosen rationally. Similarity criteria, allowing widening of model ice cover search area, are formulated. Effective ice cover models, allowing modeling of resistance to ice destruction and methods of data expantion are suggested. Research results are verified by numerous experiments in ice experimental basin.

Complexity of processes of interaction of ships and constructions with ice not always allows to make authentic mathematical model of such interaction. At the same time necessity of reception of the information about ships ice qualities during their designing makes address to modeling experiment.

At known criteria of modeling [6] the most natural way is selection of the material simulating an ice cover and satisfying these criteria. However, until now the model of an ice cover completely satisfying much figurative conditions of modeling is not created yet. Therefore, search of new materials satisfying conditions of similarity and development of techniques of recalculation of tests results at partial similarity are of great interest.

At the decision of task on modeling, interaction of the vessel and hydraulic engineering constructions with ice in ice pool, the big degree of detailed elaboration of this component is necessary since this component has the greatest densities in balance of full ice resistance and in the most sensitive way depends on "quality" of lab ice.

On the basis of extensive experience of natural supervision, we shall present process of destruction of ice as follows. Stem of the ice breaker, contacting the ice rumples an edge of an ice cover and bends it. In process of vessel stem movement , normal pressure of stem on ice grows. It occurs until bending pressure in ice cover do not achieve breaking point and there will be first radial crack before stem. At its occurrence there is a redistribution of pressure in an ice plate then one more or several radial cracks are formed

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from each board, going from stem to periphery. The further bend of an ice field results in occurrence of a concentric crack with the center on stem and radius

$$r = 1/\alpha;\ \alpha = \sqrt[4]{\frac{\rho g}{D}},$$

where α – parameter of a bend of an ice plate on the elastic basis, $D = \frac{Eh^3}{12(1-\nu^2)}$ – cylindrical rigidity of an ice plate, ρ – density of water, g – gravitational acceleration, α – the module of normal ice elasticity, h – thickness of an ice plate, ν – Poisson factor of ice.

Formation of a concentric crack does not result in loss of carrying ability of an ice cover. First, it is because at big radial sizes ice plates (at the further load) continue bending, and second, with occurrence on coast of a crack of the significant contact pressure interfering ice breach. Therefore character of connection between loading and a deflection at kinematic load has a step kind. To each step of the curve loading-deflection corresponds occurrence of the next concentric crack, and new cracks are formed from periphery to the center (stem). The bend occurs until there will come a breach of ice on the nearest to stem concentric crack.

Because of nonlinearity of the ice cover destruction diagram it is necessary to know breaking force value, but it is insufficient information for the description of interaction of the vessel with ice, and it is also necessary to have information on the work necessary for ice cover destruction.

At modeling of a vessel movement in a continuous ice field, using division of full resistance into components we shall consider resistance of destruction of ice R_p. Necessary condition of ice destruction modeling is geometrical similarity of destruction picture in the plan at which performance the number and an arrangement of ice contact points with the case at model movement will be identical with natural. Similarity of destruction pictures is determined by similarity of tensely deformed conditions (TDC) of ice plates for which definition we shall use differential equation of plates bend, on the elastic basis resulted in a dimensionless form.

$$\frac{D}{\rho g L^4}\nabla^4 \overline{w} + \overline{w} = 0, \tag{1}$$

where $\overline{w} = w/L$ – a dimensionless deflection; L – characteristic linear size in the plan.

From the equation (1) follows, that the TDC of an ice cover for a nature and models will be similar if

$$\frac{D}{\rho g L^4} = idem \tag{2}$$

As $\rho_n = \rho_m$ and $g = const$ expression it is possible to transform to

$$\frac{D_n}{D_m} = \frac{L_n{}^4}{L_m{}^4} = \lambda^4, \tag{3}$$

where λ – the module of geometrical similarity.

Indexes "n" and "m" are nature and model accordingly.

Thus, at observance of a condition (3) similarity of pictures of ice destruction in the plan will be provided.

It is shown, that at geometrically similar picture of ice destruction in the plan, the module of ice destruction resistance recalculation

$$\lambda_{R_p} = \frac{R_d^{\text{n}}}{R_d^{\text{m}}} = \left(A_z^{\text{n}} / L_{\text{m}}\right) / \left(A_z^{\text{m}} / L_{\text{m}}\right) = \lambda_{A_z} / \lambda ,$$

where λ_{A_z} – scale of an ice cover destruction energy.

The analysis of natural researches of physicomechanical characteristics of an ice cover [2 … 6, etc.], and also experience of modeling of ice in ice pool has shown, that the central question of modelling is the choice of the base characteristic of ice which should answer a number of requirements, and results of natural and modeling researches of ice have allowed to formulate these requirements:

- to describe behaviour of ice under loading as full as possible;

- to suppose direct measurement in natural and modeling experiments;

- to be not subject to scale effect.

As a result of the analysis it has been established, that energy of destruction meets the requirements to the base characteristic of ice at modeling and consequently can be accepted as this base characteristic at development of criterial ratio and modeling experiment technique in ice pool.

Energy of destruction A_{z_i} depends on mechanical properties of ice and geometry of an ice plate in a zone of contact to the case. And A_{z_i} is the most full characteristic of mechanical properties of an ice cover from the point of view of destruction by ships, covering in an integrated kind all stages of destruction from formation of cracks up to a full breach. Application of this criterion "smooths" some discrepancies in modeling separate stages of destruction. For definition λ_{R_d} there is no necessity to know value A_{z_i} for each kind of a configuration of ice plates in a point of contact. It is required to know only the relation (scale) destruction energies of an ice cover of a nature and model λ_{A_z} which at similar geometry depends only on properties of ice. Therefore at experimental definition of λ_{A_z} it is possible to use results of tests of ice plates of a various configuration, for example, infinite or a semiinfinite in the plan. The resulted dependences do not contradict the classical theory of modeling [6], since at performance of its requirements λ_{R_d} =λ3 however they allow to expand search of ice model. So, for example, to receive ways of tests results recalculation for nature for the set model of an ice cover.

One of them is the model of fresh-water ice received in development pool. Natural ice possesses increased bend durability, what the classical theory of modeling demands. Therefore the opinion on impossibility of its application is widely distributed as model of an ice cover. The idea of use of natural ice at modeling resistance of destruction will consist in indemnification of the increased durability by smaller thickness of an ice cover. It is possible to allocate the part of ice resistance connected to destruction of ice experimentally. For a nature, resistance of destruction is recalculated on the dependences received with use of the theory of similarity and dimensions [2, 5]:

$$R_d^{\mathrm{n}} = \lambda^3 R_d^{\mathrm{m}}; \quad \upsilon_{\mathrm{n}} = \lambda\sqrt{\upsilon_{\mathrm{m}}}; \; h_{\mathrm{n}} = \lambda^{4/3}\lambda_E^{-1/3} = \lambda^{3/2} h_{\mathrm{m}},$$

where λ_E – the relation of modules of elasticity of natural and thin fresh-water ice.

For check of an opportunity of such modeling in ice pool tests of a scale series of the ice breaker of project É-47, the ice breaker of the project 1105, the international model of R-class and others have been carried out. Scales of models varied from 1:13,5 till 1:50. Results of tests have shown satisfactory convergence with the natural data. Recalculation of resistance for a scale series of ice breaker R-47 has not revealed significant scale effect. Besides satisfactory results turned out at essential reduction in labour input and cost of tests. Visual supervision, the analysis of a photo and filmings have shown, that the geometrical sizes of fragments of ice and their form, and also process of interaction for courts with traditional forms is close to observable in natural conditions. This way of modeling is not opposed more strict, based on selection of model of an ice cover adequate material. However it allows to expand volume of researches with use of the inexpensive equipment, has simple technology, and is, in essence, unique at test seminatural models in open reservoirs. The resulted dependences can be used for recalculation of ice resistance from the prototype. But this way is not ideal. In particular, the parity between gravities and elasticity of an ice plate is not kept, energy of local destruction of an edge of ice is unsatisfactorily modeled at contortion.

Searches of models of an ice cover more full satisfying conditions of similarity and possessing high adaptability to manufacture have led to creation of composite construction of ice model (1071515 and 1559593).

Modeling ice represents multi-row layer of polythene granules of high pressure (granular polyethelene ice – *GP-ice*), in regular intervals distributed on water surface and exposed to frost on a part of the thickness (fig. 1).

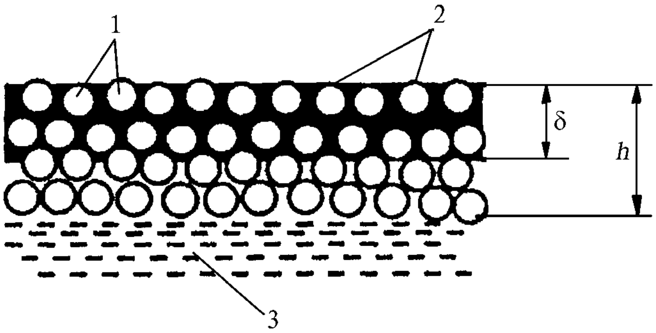

Fig. 1. Composite model of an ice cover:
1 – particles of polythene; 2 – natural fresh-water ice; 3 – water

The surface of water in the pool with the help of the mechanized dosing out device becomes covered by a layer of the granulated polythene of a high pressure, and then is exposed to frost on the certain thickness. Thus resulted bend durability of modeled ice is reduced due to reduction of effective cross-section of the natural ice which is taking place as layers of a "cellular" design and weak adhesion of polythene with ice.

At frosting through all layer thickness of modeling ice h_m thickness is determined by thickness of a layer of particles. Change of parameters of destruction can be made changing the size of granules. At negative temperatures adhesion of polythene with ice makes 70 … 190 kPa, that is quite comprehensible to large-scale models (λ=7 … 10). The variant when layers of granules are exposed to frost not on all thickness is applied to small models, and on size δ. Using model of an ice cover of the described design it is possible to satisfy simultaneously the basic conditions of similarity, including

$$f=idem;\ \rho_i/\rho\ =idem;\ Fr\ =idem;\ E/\sigma\ =idem;\ D/\left(\rho g L^4\right)\ =idem,$$

where f – factor of a covering-ice friction, ρ_i – density of ice, Fr – Froude number, σ – strength of ice on a bend.

Durability and elasticity of an ice cover thus is modeled by a thin layer of natural ice with the connections weakened by polythene, and resistance of fragments ice floes with polyethylene granules. Experimental researches have shown, that diagrams of destruction of such ice $z=f\ (w)$ up to critical values breach loadings $_{zm}$ and a deflection $_{wp}$ are practically similar to diagrams of destruction of a natural ice cover.

At recalculation of results of tests it is necessary to have in view, that mechanical properties of ice are modeled by thickness of the exposed to frost layer δ, and gravitational and inertial properties the general resulted thickness of ice layer $h_{\mathrm{m}} = h_{\mathrm{n}} / \lambda$ and the condition $f=idem$ satisfies. Thickness of composite construction ice is determined by weight of polythene particles $_{mn}$ and natural ice $_{mi}$, accounting for unit of a surface of ice cover S and their density. Thickness of the exposed to frost layer calculated on dependence $\delta = (m_n + m_n)(\rho_n S)$, where $_{mn}$ – weight of particles of the polythene connected to ice. The density of the exposed to frost layer ρ_n is determined by method of hydrostatic weighing pieces of ice in kerosene, and their area S by planimetry.

Composite construction modeling ice with stable characteristics is easy to prepare in open pools during winter time, and fluctuations of temperature influence, basically, only the period of ice preparation. Thus productivity of work is few times higher in comparison with other known ways, for example, at air temperature -10 C the cycle of carrying out of experience makes 1 … 1,5 hours. Significant amount of models tests of different ships, including ice breakers, ice-breaker and ice-cleaner attachments, ships and platforms on an air cushion which have shown good correlation with the natural data in qualitative and quantitative relations.

CONCLUSION

In the conclusion it is necessary to note, that use of the described methods of modeling of ships ice resistance assumes carrying out of regular experimental researches of destruction of a natural and modeling ice cover and accumulation of the data on destruction energy.

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