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V.A. Medvedev

April 1978

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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This report discusses the construction of the Vilyuy hydroelectric power plant which was built in the Soviet Union in an area of continuous permafrost.

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NOTICE

FIELD OBSERVATION OF THE STRUCTURAL CONDITION OF THE VILYUY HYDROELECTRIC POWER PLANT

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The Soviet-American Working Seminar, "Engineering Inspection and Monitoring Hydrotechnical Structures and Measuring Apparatus for These Purposes", 14 - 18 December, 1977, USA, Moscow, 1977

The Vilyuy hydroelectric power plant is the hydroelectric pioneer under the severe conditions of the Far North. The hydrotechnical structure was built in an area of continuous permafrost, a significant distance away from main transportation lines. The region is characterized by a very cold Winter with little snow and a short Summer. Winter lasts longer than 7 months. The mean annual atmospheric temperature is -8.2°C.

The hydrological regime of the Vilyuy River is characterized by an extremely uneven intra-annual flow distribution: the maximum flow rate of the Spring high water period during construction reached about 13,000 m^3/sec, while the minimum Winter flow rate was 3.5 m^3/sec. In some years the river almost totally freezes. The lack of necessary experience in the design and construction of large dams under such conditions posed an extremely complicated problem both for designers and construction workers.

The developed blueprints, the instructions compiled for carrying out construction work and the use of equipment were constantly refined and altered in the course of building the hydrotechnical facilities.

The construction of one hydroelectric power plant with the hydroelectric power plant building located on the right bank of the river was initially planned. Subsequently, the project underwent a major revision. Research, design and scientific research work continued during construction, methods of carrying out work and the schedules of passing the construction-term flows varied, while the projects of expanding auxiliary enterprises and residential settlements were compiled. In the final execution, the hydroelectric power plant was built in the form of two hydroelectric power plant subcenters sited mirror-wise on both banks of the river. The capacity of the hydroelectric power plant more than doubled in comparison with the original project.

1. The Layout of the Hydroelectric Power Plant.

The hydroelectric power plant forms a reservoir over 420 km long and having a volume of 36 - 42 km^3.

The dam is the stone-faced type with a screen consisting of gravel-rocky clay. The dam has a maximum base width of about 310 m. In plan, the dam has been made slightly curvilinear in order to prevent formation of cracks in the screen during settlement of the stone facing. The transition zone between the screen and the stone facing has been made in the form of a two-layer filter. Crushed stone with an individual stone size of 0 - 40 mm was used for the first layer and crushed stone with an individual stone size of 0 - 150 mm was used for the second. Each layer is 3 m thick.

The screen was made of argillaceous-rocky earth found several kilometers from the dam. A feature of this earth is its very high heterogeneity factor ($F = d_{60}:d_{10}$ = 800 - 1000). Experience in using such earth in dam building was nill. Extensive laboratory and field investigations were carried out for the purpose of establishing the suitability of such earth for screen building. An experimental dam about 10 m high was built from earth in the construction area. The dam was used to test the feasibility of piling-up the earth in the water, the permissibility of using frozen earth, its compressibility, etc. A technology of laying the argillaceous soil was developed as a result of the above and the technical specifications for screen building were compiled.

The intake channel to hydroelectric power plant-1 was dug in a rocky massif on the right bank of the river. The maximum excavation depth is about 70 m, and the bottom width is 40 m. A water intake point with four intake openings 9 X 18 m in size is located on the left-hand side. The length of the channel to the water discharge point is 515 m. The bottom and slopes of the channel are unfaced, with the exception of the water intake area.

The water discharge point is a continuation of the intake channel and consists of one opening 40 m wide covered by a lock segment 14 m high. The lock is remotely operated with the aid of two winches located in towers on the right and left banks. The water discharge channel is a continuation of the water discharge facility and is made in the form of a rapid flow channel with a ramp on the final stretch. The bottom and sides of the channel are concrete-faced. In plan, the channel has a curvilinear aspect. The initial stretch beyond the water discharge point is made in the form of a banked turn. The specific flow rates are 150 m^3/sec. The slopes of the rapid flow stretch, the shape of the bank turn and the parameters of the ramp were selected on the model in the River Hydraulic Laboratory of the Vedeneyev All-Union Scientific Institute of Hydrotechnology.

The hydroelectric power plant-1 water receiving point was cut into the left side of the water discharge channel above the water discharge point. The intake openings give over to pressurized aqueducts 6 m in diameter. An open type (without connecting link) water intake was employed due to the necessity of building up the pressure front in the operating process to the elevation marker of the second level. Therefore, the emergency-maintenance locks were installed in the machine room and the water intake was only equipped with grates and maintenance locks.

The pressurized aqueducts of the hydroelectric power plant-1 are about 100 m long each. The upper part is faced with concrete and the lower part is faced with metal.

The building of HEPP-1 is located in the rocky, right bank trench. It is a semisubterranean type building. It contains four rotating vane turbines with disc-shaped working locks.

The hydraulic components are designed for operation of the hydroelectric power plant at a maximum pressure head of 68 m. These are the most high pressure rotatable vane turbines in the USSR. The right bank unit facility of the HEPP-1 has a control room, an auxiliary room with loading dock, an enclosed distributor, administrative and housekeeping rooms.

The hydroelectric power plant located on the left bank includes the following: a short intake channel faced with concrete, a closed-type water intake in which the maintenance and emergency locks are installed, surface pressure aqueducts and a ground level hydroelectric power plant building. The machine room contains four radial-axial turbines. An auxiliary room has been built on the top side of the hydroelectric power plant building. Somewhat below the water intake, on the rock floor, a closed distributor device building has been constructed. All buildings have metal skeletons and are faced with prefabricated reinforced concrete slabs.

2. Cement Operations and Monitoring the Operation of the Cement Screen.

One of the problems which required immediate solution during compilation of the project and beginning construction of the pressurized facilities was reinforcing the rocky shore abutments and foundations, i.e., building a cement screen under permafrost conditions. The selection of compositions of injected solutions capable of normal hydration and hardening at below zero temperatures, as well as the selection of compositions for the thaw zones were important.

The necessary compositions were selected at the Vedeneyev VNIIG. Cement underlayers were constructed in the foundation below all pressurized hydraulic structures of the HEPP-1 water intake, the dam, the water intake channel of HEPP-2, the water intake of HEPP-2 and the adjacent sides. These were used to carry out work to seal the thaw cracks with cement solution. The concrete pouring was carried out in two stages. Initially, the coupling zone with an increased level of crack formation was cemented, then, proportional to base thawing, deep cementing was carried out. Concrete pouring operations along the channel melt were carried out first.

Coupling cementing and deep screening in the foundation of the Vilyuy hydroelectric power plant dam in the area of the channel melt were carried out in the following sequence:

a) the lower row of coupling cementing;

b) the upper row of coupling cementing;

c) the lower row of the deep screening;

d) the upper row of the deep screening.

Coupling concrete pouring was planned for the entire length of the channel melt and was carried out along the entire front. The depth of boreholes for the coupling cementing was assumed to be 4 m, measuring from the foot of the concrete. The distance between boreholes was 2 m.

Because coupling cementing was carried out in the presence of increasing levels of the upper stretch of water, pressure during concrete pouring was assumed to range from 5 to 8 kgf/cm^2 depending on the water level in the reservoir.

Work on the deep screen was carried out after the completion of both rows of the coupling concrete works. Both rows' boreholes were poured full of concrete in two lines with a 4 m space between holes. Cementing pressure for each area was designated following a hydraulic testing of the survey boreholes and ranged from 8 to 20 kgf/cm^2.

Quality control of deep cement screen work was carried out with the aid of hydraulic testing of monitoring boreholes.

Piezometers were installed in the foundation to monitor the operation of the cement screen.

3. Field Observations of the Condition of Structures and Foundations.

The largest volume of field observation work both in the construction and operating periods was carried out on the stone-fill dam. During construction, the basic observations were carried out over the temperature conditions of the foundation and settlement of the stone facing. An elevated deformation capability of the stone facing was noted according to measurement results. This is chiefly due to the lack of any special measures to pack the unsorted rock when building the dam and to the great height of the filled rock layers (14 - 15 m). The purpose of the observations was to determine temperature changes in the screen, the dam foundation and the stone facing, to study cryogenic deformations of the screen, and to investigate ice formation in the body of the dam.

Observations of the installed KIA are made by personnel of the hydraulics section of the hydroelectric power plant, the Vilyuy permafrost station, the Kuybyshev MISI and VNIIG. The indicated scientific research institutes have the improvement of principal design solutions, checking individual structural components, as well as the development of new methods and techniques of organizing and carrying out work to build large hydrotechnical structures in regions with permafrost and under the conditions of a severe climate, besides making a general evaluation of the condition of the structure.

Based on observations, the generalization and analysis of data on the dam's temperature conditions, etc., it was established that the distribution of temperature in the dam is characterized by a complex volumetric unsteady regime with three characteristic zones' being present:

a) a zone of positive temperatures - the upper prism below the NSL, the main part of the screen, as well as part of the subscreen area of the lower prism, which gradually increases due to screen and filter thawing;

b) a zone of permanent negative temperatures - the lower part of the 30 - 40 m high support prism and its base, the left bank abutment of the dam;

c) a zone of sign-variable (plus and minus) (according to seasons of the year) temperatures - the upper part of the dam and a narrow region in the body of the support prism near the mean annual zero isotherm (5 - 10 m thick). The boundaries of the zones change but their rate of migration is low.

It was established that the decisive factor in the formation of the temperature condition of the lower prism is convective air heat exchange. Two opposing processes occur in the lower prism: the formation of ice and its sublimation with transport into the atmosphere by the ascending air flow. The process of ice formation prevails over its sublimation. This leads to the gradual accumulation of ice and hoarfrost in pores of the stone facing and partial or complete blockage of such pores.

The cooling effect of the lower prism led to refreezing of the subchannel melt in the foundation of its lower wedge to a depth of up to 58 m, which made it possible to refrain from carrying out the second stage of concrete pouring operations (deep cementing).

The cooling effect of the lower prism on the screen in the operating period is significantly less than the warming effect of the reservoir and does not permit one to maintain the lower edge of the screen in the frozen state due to the natural convection of air in the lower prism.

Deep cooling of the lower prism was facilitated by the fact that in 1969 the mean annual air temperature was one of the very lowest (-9.4^{o}), while in the Summer of 1970 deep cementing of the subchannel melt was carried out. Subsequently, a process of temperature rise in the lower prism began. The formation of the thermal regime of the lower prism in the years of operation is characterized by the following phenomena:

a decrease in the rate of air movement;

a decrease in the amplitude of seasonal temperature fluctuations in the greater part of the prism;

an increase in the zone of positive temperatures;

a general rise in prism temperature.

The scope of seasonal temperature fluctuations of the stone facing of the lower prism decreased 1.5 times on the whole from 1969 through 1976. The decrease in permeability of the facing due to settlement and ice formation made the temperature field of the lower prism more homogeneous.

Direct control over the flow rate of the filtration flow via the screen was not provided. At present, an unsteady character of filtration exists in the screen.

On the whole, analysis of the results of observations on KIA beyond the stone-faced dam enables one to conclude that the condition of the dam corresponds to the design solutions and the dam is in good operating condition.

The organization of concrete pouring work, the use of local materials, and the selection of the required types of concrete taking the climatic conditions into account are a quite complicated task. A veritable series of field and laboratory investigations was carried out. The result of these was the compilation of technical conditions and making the fundamental design decisions.

The pressurized concrete structures - the water intake, the intake channels, the water discharge and the water discharge channel - were poured in small units. The maximum grade of concrete is M-400, Mrz-400, V-12.

Over 10 years of operation, visual observations have not detected any faults and changes in the surfaces of the concrete pressurized structures, with the exception of the water discharge channel.

The water discharge channel, which initially handled a specific flow on the order of 150 m^2/sec, received significant cavitation damage to the concrete facing of the bottom. Reinforcing the bottom slabs with concrete of increased strength proved to be poorly effective since the bottom was uncovered for 10 months out of the year. The surface of the concrete becomes rough and is again subject to cavitation breakdown. For the purpose of protecting the bottom concrete against damage, field investigations were carried out on the construction of aerator platforms which ensure a supply of air to the near-bottom flow layer. The implementation of this measure made it possible sharply to reduce cavitation intensity. The basic types of observations carried out at the Vilyuy hydroelectric power plant are given below.

Type of Observations	Methods
1. Settling of the hydrotechnical structures	Control surface and depth marks are installed. These are leveled over assigned intervals of time.
2. Horizontal displacements of the dam	Determined by the transit method with the aid of movable markers and the theodolite.
3. Thermal regime of the stone facing, foundation of the dam and screen	Controlled with the aid of thermoresistor transducers laid in the body of the dam.
4. Filtration through the stone foundation and contact filtration	Controlled with the aid of pressure piezometers installed in the cement gallery.
5. Filtration in structures	Filtration pressure is determined with the aid of piezometers; flow rates are determined with the aid of measuring aqueducts and measuring volumes.

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6. Crack formation	Determined visually, as well as with the aid of triaxial crack meters and crack meters with arrow-type indicators.
7. Settlement of the service buildings	By means of levelling the control markers.
8. Vibration of buildings and structural components	Measured with the aid of measurement vibrotransducers.
9. Swelling and crack formation in the upper part of the screen	With the aid of laid measurement transducers.
10. Ice formation	Visually estimated.
11. Chemical analysis of filtering water	By means of sampling with subsequent laboratory analysis.
12. Hydrological observations:	
a) HD and NB levels	Monitored with the aid of selsyn transmitters
b) Water and air temperature	Determined with the aid of thermometers with a division scale of 0.2°
c) Flow rate in the lower stretch	Calculated according to tables plotted on the basis of data obtained experimentally.