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USING ICE AS WATER-IMPERMEABLE ELEMENT IN ROCKFILL DAMS

(Ispolzovanie lda v Kachestve Vodonepronitsaemogo Elementa v Kamennonabrosnykh Plotinakh)

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This report discusses constructing rock-fill dams with ice cores in the Soviet Union where permafrost soil occurs.

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NOTICE

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Use of Ice as a Water-Impermeable Element in Rock Fill Dams

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At the present time rock fill dams are used extensively in the Soviet Union and abroad. As we know, the anti-filtration elements in them are cores or screens made of water-impermeable materials. After analyzing planning materials and experience in construction of structures under harsh climatic conditions, Gidroenergoproyekt (formerly Gidroproyekt imeni S.Ya. Zhuk) in 1961 suggested constructing rock-fill dams with ice cores in areas where permafrost soil occurs.

The natural conditions in the proposed construction regions are characterized by harsh and prolonged winters, with a considerable thickness of permafrost, which is a positive factor for construction and operation of these dams.

The idea of building frozen dams from local materials is not a new one. As far back as 1792, a frozen earth dam 9.5 meters high was built in Russia at Petrovsk-Zabaykal'sk, and lasted for 137 years.

However, dams made of rock fill with an ice core have not been built since. Therefore, the most important question in solving this problem involves the theoretical possibility of the existence of such a structure.

Studies of the possibilities of building frozen, rock fill dams under harsh climatic conditions occupied the Department of Mechanics of Soils, Foundations, and Bases of MISI imeni V.V. Kuybyshev for a year and a half. During the first stage of the research, the thermal stability of the dam and its statistical calculation were studied. A partially frozen rock fill dam with an ice core was studied; a drawing of it appears in Figure 1.

The principal difficulty in building such a dam under conditions where permafrost soils occur involves the changes in the temperature regime of the body of the dam and its foundation over the course of time. Owing to the warming influence of the water in the reservoir in the body of the dam there is a slow increase in the temperature of the foundation which leads to thawing of the ice. Depending on a number of factors, the initially frozen part of the dam can thaw completely; although it was intended to be a non-filtering one, it could start to allow water to pass through. In the case of a rock fill dam, this leads to catastrophic consequences.

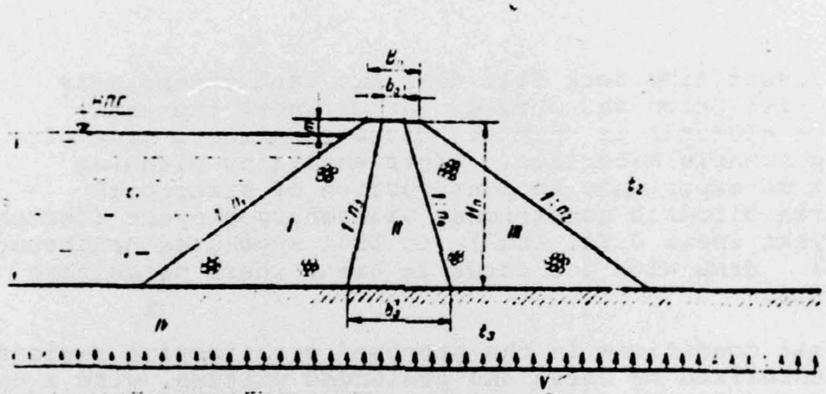

Figure I: Design Diagram of a Dam
I: Rock fill with spaces filled with ice; II: Ice core; III: Rock fill with cavities filled with air; IV: Strong crack-free layer; V: Geometric flow.

Reliable operation of a rock fill dam with an ice core can only be ensured if, as the upper wedge thaws after the reservoir is filled, the ice curtain which prevents water filtration is preserved in the body of the dam, at least during the calculated period of service of the structure. The role of this curtain is played by the ice core. Therefore, the thawing of the dam must not affect it. In addition, it is necessary to see that there is a reliable contact of the frozen zone of the dam with the water-impermeable foundation, or to create in the foundation (if it is of the filtering type) a frozen curtain which is in contact with the ice core of the dam.

It is clear how important it is to determine the change in the temperature field in the body of the dam and foundation as a function of time and to determine whether special measures must be adopted to regulate these changes.

As a result of studies carried out at MISI imeni V.V. Kuybyshev, a method was developed to calculate the nonstationary temperature field of a frozen rock fill dam and a foundation under any given boundary conditions, determined by the natural data of the region. In developing this method, we employed classical equations of thermal conductivity and the familiar solutions of P.A. Bogoslovskiy for frozen earth dams [1, 2].

It was found that in the first approximation the influence of the convective heat transport in frozen rock fill dams may be disregarded. In the following, the basis for adopting this method is presented.

The following boundary conditions were established: an average annual positive water temperature in the reservoir of t_1, an average annual negative air temperature t_2, an initial positive temperature of the surface of the foundation t_3, and geometric degree dt/dn.

At the initial moment (the moment when the reservoir is filled) the entire dam had a temperature of 0°; the spaces in the fill in the upper wedge and core contained ice.

The movement of the zero isotherm in the body of the dam (along the lower slope, in the core on the crest side, and in the foundation at a considerable distance from the lower slope) were determined on the basis of the solution provided by A.V. Lykov for cooling of semi-limited rods with lateral insulation. For these cases, the Lykov formula has the form

$$x = -\frac{t_2}{t_2 - t_e}\sqrt{\pi a \tau}, \qquad (1)$$

where x is the distance from the surface to the zero isotherm; t_e is the average temperature in the freezing zone in time τ; a is the coefficient of thermal conductivity of the material in the frozen zone.[1]

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[1]Here and in the following, when it is necessary to calculate the convective heat transport, the effective values of the thermophysical characteristics will be used.

The increase in the temperature of the foundation at a considerable distance from the upper slope was determined on the basis of a solution provided by A.V. Lykov for the heating of a semi-limited rod with lateral insulation. Since in this case t_e is unknown, an additional system of two equations was assembled: considering t (x, τ) the anticipated temperature at point x and with consideration of the geothermal flow toward the bottom of the reservoir. The system of equations was as follows:

$$\left.\begin{aligned} \frac{t(z,\tau)}{t_e} &= \operatorname{erf}\left(\frac{z}{2\sqrt{a\tau}}\right); \\ t_e &= \frac{t(z,\tau)+1}{2}; \\ \frac{t(z,\tau)}{z} &= \frac{dt}{dn}. \end{aligned}\right| \quad (2)$$

From this we determined the value z, which was the distance from the reservoir to the isotherm t(x, τ) and the value t(z, τ). Thawing of the upper wedge was determined on the basis of the solution provided by L.S. Leybenzon for the thawing of the soil, taking into account the phase conversions by the formula

$$x = \sqrt{\frac{2\lambda t_1}{\rho\gamma w}\tau}, \quad (3)$$

where λ is the coefficient of thermal conductivity of the material in the thawing zone; ρ is the latent heat of melting: γ is the volume weight of material in the thawing zone; ω is the weight moisture content of the material in the thawing zone.

The advance of the zero isotherm from the foundation into the upper wedge and ice core during time Δ τ was determined according to the following formula, compiled on the basis of the thermal balance, taking phase conversion into account:

$$\Delta x = \frac{\lambda \frac{dt}{dn} \Delta\tau}{\rho\gamma w + c_{об}(t_0 - t_{п})}, \quad (4)$$

where c_{vol} is the volume thermal capacity of the material in the thawing zone; t_{dam} is the average temperature of the body of the dam in the thawing region.

For an ice core, γ_w in (4) is expressed by γ_{ice}, the volume weight of ice.

The movement of the zero isotherm from the foundation toward the lower wedge in time $\Delta \tau$ was determined using (4) without taking phase conversions into account.

The temperature field in the foundation was determined by solving the Fourier equation with finite differences, proposed by P.A. Bogoslovskiy [1]. Hence, the total temperature field of the dam and foundation at any moment in time was plotted on the basis of solutions of eight linear problems and one plane problem in the theory of thermal conductivity. Figure 2 shows the temperature fields plotted in this manner for τ_2 = 5 years, τ_4 = 20 years, and τ_7 = 75 years. When τ_7 = 75 years, a stationary regime will have been established for all practical purposes in the body of the dam.

An analysis of the temperature fields shown in Figure 2 will show that during the initial period, the foundation of the ice core will thaw; this is absolutely unacceptable. Having determined the amount of heat expended in thawing the lower part of the core, we can calculate the power of a cooling device that would be required to keep an ice core constantly frozen.

From a statistical calculation of the ice core of the dam, the values of the moments and the shearing forces in a given cross section of the dam were determined as a function of height. The computation was performed assuming elastic functioning of the material by the formulas of P.D. Yevdokimov [3] for the following systems:

1) Core-diaphragm tightly packed at the foundation
2) Core-diaphragm with a sliding seam on the base
3) Core-diaphragm with a hinge in the foundation
4) Core-diaphragm with two hinges along its height.

On the basis of a comparison of the epuras of the moments and shearing forces, it was found that the optimum structural diagram is a stepped core-diaphragm, divided by hinges along its height. The theoretical diagram of such a structure appears in Figure 3.

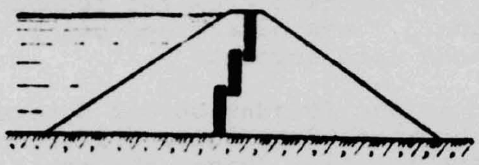

Figure 3 [sic]: Diagram of Stepped Diaphragm Core.

As a result of the studies carried out by MISI imeni V.V. Kuybyshev, it was found that the version of the rock fill dam with an ice core can have sufficient thermal and statistical stability. These studies are continuing, but the results already obtained indicate that such a dam is competitive with other structural varieties.

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