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STUDIES OF NONSTATIONARY TEMPERATURE REGIME OF FROZEN DAMS MADE OF LOCAL MATERIALS ON PERMAFROST FOUNDATIONS

N.V. Ukhova

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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The specific characteristics of hydraulic engineering construction on permafrost foundations under harsh climatic conditions result in a situation in which the most economic type of dam in the regions is the type made of local materials. A distinction can be made between two methods of constructing dams from local materials on permafrost foundations: the "warm" method, used when construction takes place primarily during the summertime by usual methods, and usually encountered in regions with moderate climates, and "cold," when construction takes place in winter with stratified freezing of the entire dam or →

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STUDIES OF NON-STATIONARY TEMPERATURE REGIME OF FROZEN DAMS MADE OF LOCAL MATERIALS ON PERMAFROST FOUNDATIONS

N. V. Ukhova

Author's Abstract of a Dissertation
in defense of the Degree of Candidate in Technical Sciences

The specific characteristics of hydraulic engineering construction on permafrost foundations under harsh climatic conditions result in a situation in which the most economic type of dam in the regions is the type made of local materials.

A distinction can be made between two methods of constructing dams from local materials on permafrost foundations: the "warm" method, used when construction takes place primarily during the summertime by usual methods, and usually encountered in regions with moderate climates, and "cold," when construction takes place in winter with stratified freezing of the entire dam or its individual elements, or in summer, with subsequent freezing of the structure. The frozen part of the dam is intended to make it impermeable to water.

Reliable operation of partly or completely frozen dams is determined by the temperature regime of the construction and the foundation, which must be such that the frozen "curtain" in the dam does not thaw out during the latter's operation.

The dissertation is devoted to an analytical experimental study of the nonstationary temperature regime of frozen dams made of local materials on permafrost foundations, and constitutes one aspect of the problem of construction of dams on permafrost foundations, analyzed by the group of coworkers of the department under the leadership of Corresponding Member of the Academy of Sciences of the USSR, Doctor of Technical Sciences, Professor N. A. Tsytovich.

The dissertation consists of four chapters.

The first chapter consists of a brief review of the most characteristic examples of frozen dams that have been built from frozen materials (local materials) and the design solution. An analysis of the operating conditions of dams currently in use makes it possible to draw the following conclusions.

1. In cases in which it has been possible to avoid filtration through the body of the dam or the foundation during the operation of the dam, the structure has operated successfully;

2. The overwhelming majority of accidents involving dams made of local materials have occurred in situations when the dam is of the thawed or combination type;

3. Reliable methods of building water-impermeable curtains require maintenance of a stable negative temperature in the body and foundation of the dam.

One might consider that the optimum type of construction to use under permafrost conditions is to build a frozen dam of local materials. In particular the structural solution for such a dam must be based upon heat engineering calculations.

The most complicated feature of the operation of the structure consists in ensuring a stable temperature regime for the dam and its foundation. Due to the thawing influence of the water in the reservoir behind the dam, there is a slow increase in temperature which leads to thawing of the permafrost. Depending on many factors, the initially frozen body of the dam can eventually thaw out completely at the foundation and the dam, designed originally as a non-filtering type, becomes permeable to water. In many instances, this can have catastrophic consequences.

Reliable functioning of frozen dams can be ensured only in situations in which, as a result of the thawing of the upper wedge of the dam after the reservoir has been filled, there remains in its body (at least during the design period of operation of the structure) a frozen zone which prevents filtration of water through the dam. In addition, it is necessary to ensure a reliable degree of preservation of the frozen zone of the dam by using a water-impermeable foundation, or to create in the foundation (if it is of the type which filters water) a frozen curtain, in contact with the frozen part of the dam. Thus, in the general case, the frozen zones of the dam and foundation must be considered jointly.

It is clear from the above how important it is to be able to determine changes in the temperature field of the dam and foundation as a function of time, and to determine whether special measures must be adopted for regulating these changes.

A number of papers by Soviet authors have been devoted to the development of methods of analytical and experimental investigation of temperature regimes for frozen dams and foundations. These dissertations have dealt with had have analyzed the principal views relating to the studies of these authors. It has been demonstrated that the development of solutions relating to the temperature regime of frozen dams and their foundations has followed the following path:

1. Relatively strict analytical solutions for stationary and nonstationary temperature regimes of filtering and non-filtering dams (papers by P. A. Bogoslovskiy, V. N. Grandilevskiy, Yu. N. Stankevich, and in part by I. S. Moiseyev);

2. Engineering (approximate) solutions (papers by A. A Tsvid, in part by I. S. Moiseyev and G. A. Pchelkin);

3. Experimental studies (papers by G. S. Shedrin, V. A. Kudryavtsev, and V. G. Melamed, M. D. Golovko, N. N. Trush, S. V. Tomirdiaro).

The solutions obtained as a result of these studies are characterized by the following:

1. In view of the complexity of the problem of the nonstationary temperature regime of dams made of local materials and their foundations, solutions of the first group cannot be considered general. In the final analysis, these solutions should be viewed as specific problems rather than as a collection of problems relating to this question as a whole.

Engineering calculation methods are very approximate, as the authors themselves point out, and they also relate only to specific problems.

Experimental problems using models are extremely complex; they also solve specific problems only. In other words, the development under laboratory conditions of an operating regime for a structure which corresponds completely to natural conditions will be particularly difficult to create. Computer studies of the temperature regimes of frozen dams are quite promising, but are still in the developmental stage.

2. Existing methods of calculation are applicable only to earth dams; specifically, all except certain solutions by V. N. Grandlevskiy pertain to a situation in which the soil in the dam and foundation has the same thermophysical characteristics. These solutions fail to take into account calculations of the temperature regime of the dam, which comprises several zones with quite different thermophysical characteristics;

3. Known analytical methods and model tests do not provide from the possibility of investigating the temperature regimes of frozen earth-soil and rock-soil dams. The temperature regime of such dams may depend to a large degree upon natural convection which develops in the speces in the rock fill. The problems of natural convection are not reflected in any one of these solutions.

These facts have governed the course of the research described in the dissertation. The goal of these studies was the development of an engineering (but sufficiently precise) method for practical application in calculating the non-stationary temperature regimes of frozen dams made of local materials (sand, argillaceous soil, rock fill, combined types of structures) in regions with harsh climates.

The method to be developed must reflect sufficiently fully the thermal processes taking place in the dam and the foundation, taking various thermophysical characteristics of the zones of the dam and foundation into account. At the same time, however, the calculation must be as simple and convenient as possible, for use by planning organizations.

During the research, the following problems were posed and solved:

I. Basic positions were established for calculating the non-stationary temperature regime of dams made of local materials with and without forced cooling.

II. Practical approaches were developed for calculating non-stationary temperature regimes in frozen dams and their foundations made of local materials.

III. The recommended method of calculating temperature regimes was tested experimentally.

These studies examined only nonfiltering dams, since, as an analysis of the operation of frozen dams made of local materials shows, filtration of water through the body of a dam or its foundation cannot be allowed. When designing structures and their foundations, it is necessary to take measures to guarantee zero filtration. The verification calculations carried out when there is filtration may be performed using a method developed by P. A. Bogoslovskiy.

In the second chapter, analytical studies of the temperature regime are discussed.

In a study of thermal regimes in soil and loose rock, only the equation of thermal conductivity is usually employed; it seems that convection is not of considerable importance in these situations. However, with respect to large-grained, gravel, and especially riprap dams made of [illegible] materials, heat transport does not result in thermal conductivity alone. Under certain conditions, it can be expected that the influence of convection will be considerable. It is particularly important to investigate this question in frozen rock-fill dams, where it is desired to employ lumps of very large size.

[illegible] dissertation studies the influence of natural convection on general heat exchange during the thawing of the dam, in other words, the movement of the liquid as determined by the thermal conditions of the process and by the nature of the liquid, the temperature differential, and the volume of space in which the process occurs.

The mechanism of natural convection in porous bodies has been worked out in papers by Soviet scientists. V. G. Gol'dtman, G. V. Porkhayev, and R. M. Sarkisyan attempted to study convective heat transfer in the general process of heat exchange in thawed soils.

The influence of convection in general heat exchange in granular materials was determined in the dissertation using two methods. The first consists in a joint solution of the equations of thermal conductivity and convective heat transfer as they apply to a specific problem; the second consists in determining the rate of consumption (and therefore the heat flux) with filtration of water through granular material under the influence of a difference in hydrostatic pressure caused by the different density of water at different temperatures.

As a result, identical solutions (at least with an accuracy up to the coefficients) are obtained:

$$\varphi = 1 + 0{,}208 \frac{(\gamma_2 - \gamma_1) K C_B h}{\lambda} \qquad (1)$$

$$\varphi = 1 + 0{,}250 \frac{(\gamma_2 - \gamma_1) K C_B h}{\lambda} \qquad (2)$$

where $\phi = \frac{\lambda_Э}{\lambda}$ is the coefficient of increase in thermal conductivity due to the presence of convective currents;

$\lambda_Э$ is the coefficient of effective thermal conductivity;

λ is the coefficient of thermal conductivity of the material;

C_B is the thermal capacity of water;

γ_1 γ_2 is the specific gravity of water at temperatures t_2 and t_1, with $\gamma_2 > \gamma_1$

K is the filtration coefficient;

h is the depth from the surface of the reservoir to the cross section at which the heat exchange is being studied.

The problem of joint consideration of convection and thermal conductivity amounts to a determination initially of the coefficient ϕ for concrete conditions and then (on the basis of the value of ϕ obtained) $\lambda_э$ is determined by a further computation of heat exchange in granular material, which leads to the laws of the theory of thermal conductivity using in the formulas, instead of the coefficient of thermal conductivity λ, the value of the effective coefficient of thermal conductivity $\lambda_э$.

The nonstationary temperature regime of the frozen dam and its foundation must be viewed in the general case as a spatial problem. At the present time, the problem is one which can hardly be solved in a closed form. If we exclude from consideration the area of contact between the dam and the edges of the canyon, the problem may be viewed as a plane one. It is necessary to deal with the temperature field existing at a given time within the limited finite dimensions of an area with different thermophysical characteristics and different boundary conditions in different parts of the area. The computational scheme for such a problem appears in Figure 1.

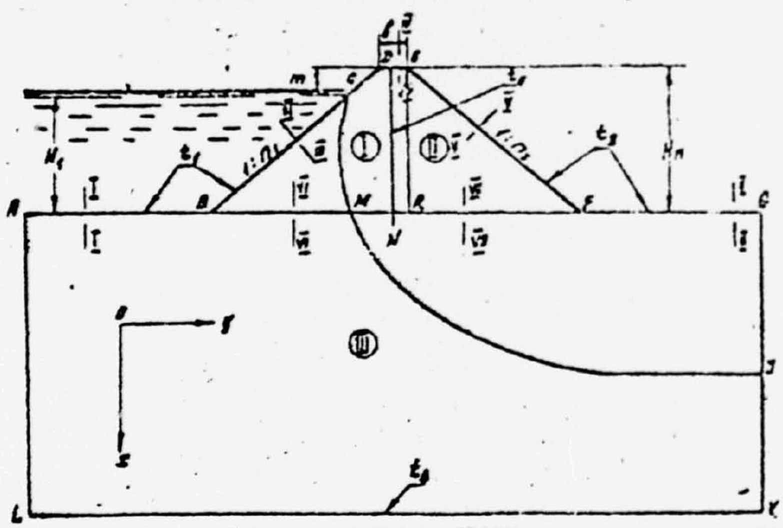

Figure 1. Design Diagram. I - Frozen upper wedge of dam. II - frozen or unfrozen lower wedge of dam. III - foundation with known temperature distribution.

The mathematical problem is formulated as follows:

$$\frac{\partial t}{\partial \tau} = a_т\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) \quad \tau > 0 \quad \text{thawed zone}$$

$$\frac{\partial t}{\partial \tau} = a_м\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) \quad \tau > 0 \quad \text{frozen zone}$$

$$a_т^{I} \neq a_т^{II} \neq a_т^{III}, \quad a_м^{I} \neq a_м^{II} \neq a_м^{III}$$

The initial conditions are:

$$t^{I} = t^{II} = t_o = \text{const},$$
$$t^{III} = f(x)$$

The boundary conditions are:

at the boundary ABC $t_1 = \text{const} > 0°,$

at the boundary CDEFG $t_2 = \text{const} < 0°,$

at the boundary GIK $\frac{\partial t}{\partial y} = 0,$

at the boundary AL $\frac{\partial t}{\partial y} = 0,$

at the boundary KL $t_3 = \text{const},$

at the boundary DN $t_4' = \text{const} < 0°,$

at the boundary CMI $\lambda_м \frac{\partial t_м}{\partial n} - \lambda_т \frac{\partial t_т}{\partial n} = \rho W \gamma_c \frac{d\xi_{(n)}}{d\tau}$

$$t_м(n, \tau) = t_т(n, \tau) = t_0 = \text{const},$$

where n is the normal to the boundary CMI,

at the boundary BR $t^{I}(\tau) = t^{III}(\tau),$

$$\lambda^{I} \frac{\partial t^{I}}{\partial x} = \lambda^{III} \frac{\partial t^{III}}{\partial x},$$

at the boundary RF $t^{II}(\tau) = t^{III}(\tau)$

$$\lambda^{II} \frac{\partial t^{II}}{\partial x} = \lambda^{III} \frac{\partial t^{III}}{\partial x},$$

at the boundary ER $t^{I}(\tau > 0) = t^{II}(\tau > 0),$

$$\lambda^{I} \frac{\partial t^{I}}{\partial y} = \lambda^{II} \frac{\partial t^{II}}{\partial y}.$$

A strict solution to this problem, due to the ambiguity of the initial and boundary conditions and the complexity of the shape of the region in question, is possible but extremely difficult.

The method of calculation proposed in the dissertation is an approximate one and is based upon the following assumptions:

1. The dam and foundation are made up of different types of materials with different thermophysical characteristics, and the dam can consist of various zones; the dam and the foundation do not allow filtration.

2. The temperature distribution at a given moment in time is studied by calculating the nonstationary process on the basis of a number of stationary processes which alternate with one another;

3. The general problem amounts to a series of linear problems and a plane problem, each of which is solved independently;

4. The general temperature field at any moment in time is built up from specific temperature fields which are produced in solving specific problems.

The following initial and boundary conditions are employed:

1. The process of construction is not taken into account and it is assumed that at a given moment in time, which is determined to be the beginning of calculation, there is a dam with a temperature t_0, and the water in the pores or cavities of the material in the frozen zones is in the form of ice, t_0 being the freezing point of the material in the various zones of the dam;

2. The temperature at the boundary on the reservoir side is constantly positive; the temperature at the boundary with the air side is constantly negative;

3. The distribution of the temperature in the foundation at the initial moment in time is described analytically.

The method of computation shown in Figure 1 is considered to be general for all types of frozen dams and their foundations made of local materials. Under field conditions, the structural arrangement can always be reduced to this computational scheme, with various changes which have no influence upon the nature of the calculations.

The change in the temperature field is a function of the composition of the materials in the zones of the dam and foundation, and the initial temperature distribution can be accomplished without or with aggregate conversions of the water in the pores or cavities of these materials. In the first case, for the calculations of the temperature field, the general solutions of A. V. Lykov are used as they pertain to the changes in temperature in semi-organic bodies without lateral heat losses. In the second case, the calculations are performed using the Stefan formula or on the basis of an expansion of equations representing thermal balance.

In the general form, the temperature regime of a frozen dam and its foundation is solved on the basis of special problems which apply to the cross sections shown in Figure 1.

Problem I. Change in temperature in a semi-finite body without lateral temperature losses and with a constant surface temperature:

a) Heating or thawing of the foundation at a sufficient distance from the upper slope, due to the heat from the reservoir (cross section I-I). The general solution for heating has the form

$$t(x,\tau)=t_1\operatorname{erfc}\frac{x}{2\sqrt{a_0\tau}}=-\frac{1}{2\sqrt{\pi a_0\tau}}\int_0^{\infty}f(\xi)\left[\exp\left(-\frac{(\xi-x)^2}{4a_0\tau}\right)-\right.$$
$$\left.-\exp\left(-\frac{(\xi+x)^2}{4a_0\tau}\right)\right]d\xi \qquad (3)$$

where $T(x, \tau)$ is the temperature at a point with a coordinate x at a moment in time τ;

a_0 is the coefficient of thermal conductivity of the material in the foundation;

if a variable x is substituted for ξ in the function $f(x)$, determining the initial temperature distribution in the foundation, it becomes $f(\xi)$.

With a negative temperature in the foundation at the initial moment in time, approximated by a straight line, the solution will have the following form:

$$\Delta\xi_1\approx\sqrt{\frac{\Delta\tau_1}{B}}. \qquad (4)$$

where: $$B=\frac{\rho W_{0}\gamma_{co}-3bC_{o6\text{м}o}+0.5t_{1}C_{o6\text{т}o}}{2\lambda_{\text{т}o}t_{1}}\ *$$

b is the initial value of the negative temperature at the surface.

b) Cooled or frozen foundations at a sufficient distance from the lower slope, owing to the negative temperature of the air (cross section II-II). The total solution for cooling will have the form of (3) with substitution of the variable.

With a positive temperature in the foundation, at the initial moment in time approximated by the straight line, the solution for freezing will amount to (4), where

$$B=-\frac{\rho W_{0}\gamma_{co}+3mC_{o6\text{т}o}-0.5C_{o6\text{м}o}t_{2}}{2\lambda_{\text{м}o}t_{2}}$$

m is the initial value of the positive temperature at the surface.

c) Thawing of the upper slope due to the heat from the reservoir (cross section III-III). The solution amounts to the Stefan equation.

d) Cooling of the crest and cooling or freezing of the lower slope due to the negative air temperature (cross sections IV-IV and V-V). The general solution amounts to the following equation:

$$t(x,\tau)=t_{2}\left(1-\operatorname{erf}\frac{x}{2\sqrt{a_{\text{пм}}\tau}}\right) \qquad (5)$$

If the lower wedge is made of nonfrozen soil, the problem of cooling is the same as the problem of freezing and is solved by the Stefan formula.

Problem II. Change in temperature in adjacent semi-finite bodies without lateral temperature losses.

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* Here and below, the subscript "o" will refer to the characteristics of the material of the foundation, while "p" will refer to the characteristics of the material of the dam; "t" represents the thawed state, and "m" the frozen state.

The solutions to this problem amount to a change in temperature in the dam on the base side under the influence of the temperature field of the foundation (cross sections VI-VI, VII-VII).

a) Contact of the unfrozen zone of the dam with the frozen foundation. The change in temperature in the foundation is described by the equation:

$$t(x,\tau) = -\frac{1}{2\sqrt{\pi a_{ом}\tau}}\int_0^\infty f(\xi)\left[\exp\left(-\frac{(\xi-x)^2}{4a_{ом}\tau}\right)\right.$$
$$\left.-\exp\left(-\frac{(\xi+x)^2}{4a_{ом}\tau}\right)\right]d\xi. \qquad (6)$$

The depth of freezing of the dam is determined by the expression

$$\xi_n = \frac{b\left(1-\frac{\xi'}{2H_м}\right)}{\rho w_н \gamma_{ск}}\tau, \quad \frac{\dots}{2\lambda_{ом}C_{ом}\tau}, \qquad (7)$$

where ξ' is the depth to which the temperature changes in the foundation during time τ;

H_M is the thickness of the permafrost in the foundation.

b) Contact of the frozen zone of the dam with the frozen foundation. The general solution has the following form:

$$\frac{t(x,\tau)}{t_c} = \frac{K_\varepsilon}{1+K_\varepsilon}\left(1+\frac{1}{K_\varepsilon}\operatorname{erf}\frac{x}{2\sqrt{a_{ом}\tau}}\right) \quad x>0, \text{ (foundation)} \qquad (8)$$

$$\frac{t(x,\tau)}{t_c} = \frac{K_\varepsilon}{1+K_\varepsilon}\operatorname{erfc}\frac{x'}{2\sqrt{a_{м}\tau}} \quad 0<x. \quad \text{(dam)} \qquad (9)$$

where $K_\varepsilon = \frac{K_\lambda}{\sqrt{K_a}}, \; K_a = \frac{a_{ом}}{a_{м}}, \; K_\lambda = \frac{\lambda_{ом}}{\lambda_{м}}, \; t_c = t_к\frac{1+K_\varepsilon}{K_\varepsilon},$

t_K is the temperature at the contact.

c) Contact of the frozen zone of the dam with the thawed foundation. The change in temperature in the foundation is described by (6), with substitution of the variable. The depth of thawing of the dam is determined by the expression:

$$\xi_1 = \frac{m + \frac{t_-}{A} m_2 t}{2 W_{H} \gamma_{CK} + \ldots} \ldots \overline{\ldots_{0T} C_{0T} \tau}, \qquad (10)$$

where A is the distance from the contact to the point in the foundation with temperature [?] which the heat exchange between the dam and the foundation does not influence.

d) Contact of the nonfrozen zone of the dam with the thawed foundation. The general solution has the form of equations (8) and (9), with substitution of the thermophysical characteristics of the frozen material for the thermophysical characteristics of the thawed part.

Problem III. Calculation of the temperature field of the foundation. A plane problem is considered. In order to plot the nonstationary temperature field in the foundation at any moment in time, the method recommended by P. A. Bogoslovskiy is employed, involving a graphic analytical solution of the equation of nonstationary thermal conductivity, expressed in finite differences.

The construction of a general temperature field for the dam and foundation for a given moment in time, with a temperature distribution which is known at a given moment in time on the basis of the calculated cross sections, amounts to the solution of the Dirichlet problem. To solve this problem, the dissertation employs the method of iteration. With some experience in plotting the general temperature field of the dam and foundation, there are only two or three approximations in the iteration process. In other words, it is possible with a degree of accuracy adequate for practical purposes, to construct a temperature field using only curvilinear interpolation.

In addition to the basic problems discussed above, the dissertation presents solutions to other problems which may be encountered in the course of calculation:

1. Zero isotherms from an area with certain thermophysical characteristics to an area with different ones (change in temperature in the laminated thickness);

2. Temperature fields calculated on the basis of certain cross sections superimposed on one another.

3. Calculation of forced cooling.

The third chapter is devoted to practical applications of the calculation of nonstationary temperature regimes of frozen dams made of local materials and foundations.

For convenience in using the analytical relationships set forth in Chapter II, this chapter deals with the following questions:

a) rules for labeling the design diagrams;
b) the sequence of the calculations;
c) examples of calculation.

The design diagram for a frozen dam and its foundation is prepared in the following sequence:

1. In accordance with the structural diagram, the physical and thermophysical characteristics of various structural zones of the dam and foundation are determined;

2. The influence of convection on the thawing of the upper wedge is estimated;

3. The geometric parameters of the design diagram are determined, corresponding to the dimensions of the structure;

4. Boundary conditions are established for the computation.

The temperature field of the dam and foundation is composed at a given moment in time after the conditional beginning of the calculation. The calculated moments in time are selected in accordance with the problems posed prior to the calculation.

In the design diagram, at each moment in time, cross sections are selected along which temperature calculations are performed. The cross sections must reflect as fully as possible temperature changes in the areas of the dam and foundation in question.

The chapter presents a detailed set of instructions on the order of the calculations using the formulas obtained. The applicability of certain formulas to the characteristics of certain practical cases is estimated.

The method developed in the dissertation in accordance with the instructions of the Gidroproyekt Institute imeni S. Ya. Zhuk calculated the temperature regimes of three types of frozen dams on the Vitim and Tsipa Rivers. For the conditions on the Vitim River, a frozen rock-fill dam 50 meters high was examined completely; for the conditions on the Tsipa River, there are two versions of a partially frozen rock-fill dam 35 meters high with an ice core, one with forced cooling and one without forced cooling.

To illustrate the practical applications of calculating the nonstationary temperature regime of frozen dams with permafrost foundations, the dissertation provides the example of calculations of a version of a dam on the Tsipa River without forced cooling and the final result of the calculation of the temperature regime of a frozen dam on the Vitim River.

The calculations were performed with the following boundary conditions:

a) average annual temperature values at the surface of the dam and foundation on the reservoir side were -6° for both sides;

b) average annual temperature values at the surface of the dam and the foundation at the lower slope were as follows: for a dam on the Vitim River, -6.5°; for the dam on the Tsipa River, -8.0°;

c) in the foundation of both dams, taliks extended through the entire thickness of the permafrost.

The results of the calculations demonstrated that normal conditions existed for operation of the dam on the Vitim River. In the case of the dam on the Tsipa River, during the initial years, operation was possible for a thawed foundation made of an ice core; this was not allowed. If we assume preconstruction freezing of the foundation of this dam for six winter months, subsequent normal operation of the structure will be ensured. This was possible, but only by replacing preconstruction freezing of the structure by forced cooling.

The fourth chapter presents experimental studies of the temperature regimes of models of frozen dams. The principal problems in the experimental studies consisted in the following:

1. A study of the possibility of modeling nonstationary temperature regimes of dams and foundations;

2. Checking the developed method for calculating nonstationary temperature regimes.

The laws for modelling thermal processes in a homogeneous medium with boundary conditions of the first order for a one-dimensional problem were formulated by G. S. Shadrin in the form of certain conditions of scale relationships. In the simplest case, these conditions result in a situation in which, by preparing a model from the same materials as in nature and ensuring equality of the time scales of the model and the actual structure, the tests must be carried out under the temperature conditions existing in the field. This makes it possible to model the temperature regimes of homogeneous dams and foundations. For inhomogeneous dams, the modeling conditions are considerably complicated. It turns out in practice that it is impossible to model strictly multilayered media with substitution of the materials in the layers, which is necessary for example in modeling frozen rock-fill dams. For such structures, the following example is used in the dissertation.

1. The materials of the model were selected so that their physical and thermophysical characteristics were as close as possible to the characteristics of the materials at the site;

2. On the basis of the materials adopted for the model and for the real dam, the scales for modeling these characteristics were established;

3. The temperature scales were established for the frozen and thawed zones and were equal to unity. From the conditions of the scale relationships, the possible limits for the changes in the time scales were calculated. It was assumed that the time scales were the same in the frozen and thawed zones. As a result, it turned out that the time scales in the different zones of the dam and foundation fell within certain limits, which became more similar as the physical and thermophysical characteristics of the materials of the model became more and more similar to the material at the site;

4. As the scale for modeling the entire system as a function of time, the average value was taken from time scales calculated for separate zones.

Experiments on models were conducted in an NKR-1 refrigerated chamber under approximately the conditions existing in frozen dams on the Vitim and Tsipa Rivers. The following models were studied.

1. Completely frozen homogeneous dam without forced cooling (Experiment 1);

2. Partially frozen inhomogeneous dam with forced cooling (Experiment 2);

3. Partially frozen inhomogeneous dam without forced cooling (Experiment 3).

The models of the dams were constructed in a collecting-distributing framework flume. The linear modeling scales were assumed to be 1:100.

The experiments consisted in the following. Using fine-grained homogeneous sand in the flume, a partially or completely frozen dam was built. The stratified foundation at the site was modeled by a layer of cement solution which was 0.5 H_n in the first experiment and 1.3 H_n in subsequent experiments.

To measure the temperature in the body and foundation of the dam in the first experiment, copper-constantan thermocouples were used in the first experiment, while in the second and third experiments chromel-capel thermocouples were used. There were 35 to 42 such units. The e.m.f. was measured using an M-198.3 millivolt-microammeter. The unit recorded temperatures with an accuracy of 0.2°.

The constant boundary conditions in the experiments were as follows:

a) in the upper pool -- as a result of the presence of the water, whose temperature was kept constant by means of a system of instruments (a heater, a double impeller, a contact thermometer).

b) in the lower pool -- by negative air temperature in the chamber;

c) in the foundation -- by a device in the bottom of the flume, below the lower limit of the foundation, a system of instruments (a hot-air fan or the exhaust from a vacuum cleaner, a contact thermocouple), simulating the heat flux from the core of the dam;

d) in the cooling system of the dam (shaft and the gallery), by connecting the intake from a vacuum cleaner. As a result, a vacuum developed in the gallery. The cold air from the chamber, drawn through the shaft, passed through the gallery and cooled the core.

The model of the dam and foundation, following preparation and assembly of all of the instruments, was left for five days to reach a constant temperature. The boundary conditions were created at a moment assumed to be the beginning of calculation: water was poured into the upper pool, all of the devices in the upper and lower pools as well as the forced cooling were switched on, and the final temperature of the body of the dam and foundation were measured.

The first experiment lasted 125 hours. A stationary temperature regime was established in the model of the dam 75-100 hours after the start of the experiment. Subsequent thermocouple readings differed only slightly from the values at 75-100 hours. During the period of establishment of a stationary temperature field in the model of the dam and foundation, the average air and water temperatures were equal to +6.3° and -2° respectively. Regardless of such unfavorable boundary conditions, a frozen zone was preserved in the body of the dam, ensuring that it had antifiltration stability.

The second experiment lasted 60 hours. The stationary temperature field was established 38 hours after the start of the experiment. The boundary conditions of this experiment were quite stable. The average temperatures were as follows: water, +5.6°; air, -2.9°; cooling gallery, -1.2°; lower limit of foundation, -1.5°. The model of the dam operated normally.

The third experiment lasted 40 hours. The boundary conditions in this experiment were also stable. With average temperature values of +1.9° for the water, -2.4° for the air, and -1.0° at the lower limit of the foundation, the model of the dam operated normally.

Experiments with models showed that even under rigorous temperature conditions for operation of the equipment, reliable operation is ensured. A comparison of the time required to produce a steady state in the dam, obtained from studies of models, taking into account the average time scale of the entire system, showed satisfactory agreement with the time of development of the steady state in the calculations.

In addition to the model investigations, the dissertation also presented some stationary temperature fields constructed on the EGDA-9/60. The same equipment arrangements were studied as in the calculations and experiments on models. A comparison of the temperature fields obtained on the EGDA-9/60 with the stationary temperature fields of the models of the dams showed good agreement. The stationary temperature fields, calculated by the method developed in the dissertation, based upon the solution of problems involving nonstationary thermal conductivity, showed good agreement with the results of models using the EGDA-9/60.

An analysis of the results of the experiments and their comparison with the results of the calculations indicates that the method developed in the dissertation for calculating the nonstationary temperature regime of frozen dams built from local materials and of their foundations is sufficiently accurate.

GENERAL RESULTS

1. The principal factor determining the reliable operation of a frozen dam is the temperature regime of the structure and the foundation. When investigating the temperature regime of a frozen dam, it is of practical interest to represent the temperature field of the dam and foundation at a given moment during the operation of the dam, so that its stability will be assured at all times.

2. Contemporary studies of the temperature regimes of frozen dams are developing along two main paths. The principal trend involves analytical investigations, which include strict and approximate methods of calculation. The second consists of experimental studies.

Due to the complexity of the problem, strict solutions are considered only in partial cases. Known engineering solutions are very approximate and also apply only to specific problems.

None of the solutions discussed in the dissertation, with general heat exchange, consider the influence of natural convection. This can occur in the pores or cavities of the material in the thawing zone of the dam.

Model studies are extremely complex and tedious. The rules for modeling complex frozen dams have not yet been fully worked out.

3. The purpose of the studies described in the dissertation was to produce a sufficiently accurate engineering method for calculating nonstationary temperature regimes in frozen dams made of local materials, and an experimental check for this method.

4. The proposed method of calculating the nonstationary temperature regime and foundation is approximate. It was devised for a type of dam which consists in the general case of several zones with different thermophysical characteristics. The thermophysical characteristics of the foundation may differ from the characteristics of the zones of the dam.

5. The problem of heat exchange is viewed as it applies to the most dangerous cross section, perpendicular to the shaft of the dam. The essence of the method consists in this problem being expanded into a series of one-dimensional problems and one plane problem, each of which is solved independently. The general temperature field of the dam and foundation at a given moment in time is determined on the basis of temperature fields calculated by means of these problems.

6. Natural convection within the general thermal exchange occurring during the thawing of a dam and foundation must be accounted for by the method proposed in the dissertation. This method can be used not only in calculations for the thawing of frozen dams, but also to describe other cases of freezing and thawing of soils.

7. Experiments on models and constructions on an electro-hydraulic integrator established that even under severe temperature conditions in the dam, a considerable part of the lower wedge does not thaw, ensuring normal operation of the structure. The use of systems for artificial cooling (galleries) improves the temperature regime of the structure.

8. An analysis of the results of the experiments on models indicated that the temperature regimes of frozen inhomogeneous dams and foundations can be modeled. For this purpose, known modeling conditions are employed, and are also used to determine the time scale of the entire system, developed in the dissertation. In modeling it is necessary to try to make different zones of the model of the dam and foundation from materials with physical and thermophysical characteristics similar to those encountered at the site.

9. Comparison of the results of the calculations with the results of experiments on models and constructions on an electro-hydraulic integrator confirm the reliability of the proposed method of calculation.

10. Practical examples of calculation of temperature regimes of dams and their foundations, developed in the dissertation, may be recommended for practical planning. Examples are given for calculations of temperature fields of versions of frozen rock-fill dams planned by Gidroproyekt on the Vitim and Tsipa Rivers.

The main body of the dissertation has been published in the following articles:

1. N. V. Styrova (Ukhova): "Construction of Frozen Rock-Fill Dams on Permafrost Soils." Trudy Soveshchaniya Seminara na Obmenu Opitom Stroytel'stva, na Vechnomerzlykh Gruntakh (Noril'sk, November 1962), Vol. II, Krasnoyarsk, 1964.

2. N. A. Tsytovich, V. A. Vesolok, N. B. Styrova (Ukhova). "Use of Ice as a Water-Impermeable Element in Rock-Fill Dams." Trudy Koordinatsionnykh Soveshchaniya na Gidrotekhnike VNIIG. Vol. 10, 1964.

3. N. V. Ukhova: "Approximate Calculation of Nonstationary Temperature Regime of Rock-Ice Dams." Trudy Koordinatsionnykh Soveshchaniy na Gidrotekhnike VNIIG. Vol. 23, 1965.

4. N. V. Ukhova: "Consideration of Convective Heat Exchange During the Thawing of Water-Saturated Soil." Materials of the 8th All-Union Interdisciplinary Meeting on Geocryology (Behavior of Permafrost Soil). No. 1, Yakutsk, 1966.