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CALCULATIONS OF THE THERMAL REGIME OF EARTHEN DAMS CONSIDERING --ETC(U)
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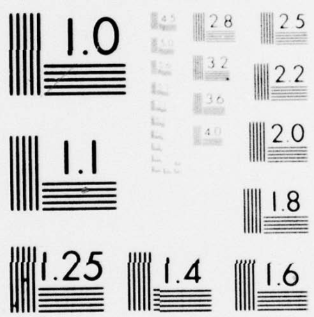

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TL 565

Draft Translation 565
December 1976

CALCULATIONS OF THE THERMAL REGIME OF EARTHEN DAMS CONSIDERING THEIR CONSTRUCTION BY LAYERS

R.T. Shugaeva

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

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Draft Translation 565	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CALCULATIONS OF THE THERMAL REGIME OF EARTHEN DAMS CONSIDERING THEIR CONSTRUCTION BY LAYERS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R.T. Shugaeva		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE December 1976 13. NUMBER OF PAGES 10
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) THERMAL REGIME COMPUTER APPLICATIONS EARTH DAMS MATHEMATICAL MODELS		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The planning and construction of water engineering structures under severe climatic conditions place increased requirements on investigation of the thermal regime of these structures, both during the period of construction and the period of use. A detailed study is presented investigating a number of calculations in the determination of the thermal regime of impervious earthen dams and their bases during the period of construction and the first years of use considering the fact that they are constructed in layers. These		

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DRAFT TRANSLATION 565

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ENGLISH TITLE: CALCULATIONS OF THE THERMAL REGIME OF EARTHEN DAMS CONSIDERING THEIR CONSTRUCTION BY LAYERS

FOREIGN TITLE: (RASCHET TERMICHESKOGO REZHIMA ZEMLIANYKH PLOTIN S UCHETOM POSLOINOGO IKH VOZVEDENIIA)

10 AUTHOR: R.T. Shugaeva

11 Dec 76

12 14p.

21 Trans. of

SOURCE: Izvestiya Vsesoyuznogo nauchno-issledovatel'skogo Instituta Gidrotekhniki, vol. 96, 1976, p.218-224.

v96 p218-224 1976.

CRREL BIBLIOGRAPHY
ASSESSIONING NO.: 27-1967

14 CRREL-TL-565

Translated by Office of the Assistant Chief of Staff for Intelligence for U.S. Army Cold Regions Research and Engineering Laboratory, 1976, 10p.

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CALCULATIONS OF THE THERMAL REGIME OF EARTHEN DAMS
CONSIDERING THEIR CONSTRUCTION BY LAYERS

R. T. Shugaeva

[Translated from IZVESTIYA VSESOYUZNOGO NAUCHNO-ISSLEDOVATEL'SKOGO INSTITUTA GIDROTEKHNIKI, Vol. 96, 1971
pages 218-224]

The planning and construction of water engineering structures under severe climatic conditions place increased requirements on investigation of the thermal mode* of these structures, both during the period of construction, and during the period of use. A detailed study of the thermal mode of the structure and its parts is necessary, considering not only natural conditions, but also the conditions of construction: the time and techniques of construction, etc.

Up to now, calculation of the temperature fields in earthen dams and their bases has been performed for cases when the dam was erected to its entire height. It has been assumed in these calculations that at some moment in time, the dam "instantly" appears, with some predetermined distribution of temperature in the dam and its base. This moment is taken as the beginning of the calculation, and the distribution of temperatures as the initial conditions. In these cases, when the initial conditions are assigned, great assumptions are made. Frequently, the temperature determined by studies made before the beginning of construction is used as the initial temperature in the base; the temperature of the earth as it is dumped is taken as the initial temperature in the body of the dam. Thus, factors which, acting during the period of construction, have a significant influence on the formation of the temperature mode of the structure, are ignored. This may lead to significant variations between calculated data and the actual state of the structure. The need therefore arises to begin calculation at the moment of beginning of construction of the structure and to consider the technology used to construct it.

The author of the present article has performed a number of calculations in the determination of the thermal mode of impervious earthen dams and their bases during the period of construction and first years of use, considering the fact that they are constructed in layers. These calculations can be reduced to solution of the problem of freezing and thawing of soils in areas of complex configuration, the dimensions of which change during the process of calculation.

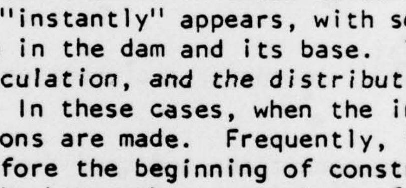

Figure 1

*The term regime should be substituted for "mode" throughout translation.

Let us study two-dimensional area R, limited by line L and broken line ABCD, consisting of dissimilar soils 1, 2 and 3 (Figure 1). Along curve L, the area contacts the air, along broken line ABCD -- the soils. At the initial moment in time, R has some area S and some initial distribution of temperature $t \lesseqgtr 0$. Then, the temperature of the surrounding environment begins changing, leading to a change, as time passes, in R, the area of which also changes, $S = f(\tau)$. Our problem is to trace the dynamics of the temperature field of the area studied throughout the calculation period T considering changes in area from S to S_1 during the course of this time (on Figure 1, area S_1 is limited by curve L_1 and the broken line ABCD).

Let us place the coordinate origin at point B (Figure 1). Then, the mathematical statement of the problem at hand can be represented as follows. Solve the equation

$$\frac{\partial t_1}{\partial \tau} = a_{1,k}\left(\frac{\partial^2 t_1}{\partial x^2} + \frac{\partial^2 t_1}{\partial y^2}\right) \quad \text{in the area of homogeneous frozen soil,} \qquad (1)$$

$$\frac{\partial t_2}{\partial \tau} = a_{2,k}\left(\frac{\partial^2 t_2}{\partial x^2} + \frac{\partial^2 t_2}{\partial y^2}\right) \quad \text{in the area of homogeneous thawed soil,} \qquad (2)$$

with assigned supplementary conditions and conditions at the division boundary of thawed and frozen soils [4]. In equations (1) and (2), $a_{1,k}$ and $a_{2,k}$ are the temperature conductivity coefficients of the frozen and thawed soils, k is the soil number.

Addition conditions include:

a) The initial conditions

$$t(x, y, 0) = \varphi(x, y);$$

b) The conditions at the boundaries of the dissimilar frozen soils

$$\left.\begin{aligned} t_{1,k} &= t_{1,k-1}; \\ \lambda_{1,k}\frac{\partial t_{1,k}}{\partial n} &= \lambda_{1,k+1}\frac{\partial t_{1,k-1}}{\partial n} \end{aligned}\right\} \qquad (3)$$

and dissimilar thawed soils

$$\left.\begin{aligned} t_{2,k} &= t_{2,k+1}; \\ \lambda_{2,k}\frac{\partial t_{2,k}}{\partial n} &= \lambda_{2,k+1}\frac{\partial t_{2,k+1}}{\partial n}, \end{aligned}\right| \quad (4)$$

where $\partial/\partial n$ represents differentiation along a perpendicular to the division boundary between the materials;

c) The boundary conditions at the soil-air interface

$$t_a = \psi(\tau)$$

and

$$\frac{\partial t(x, y, \tau)}{\partial n} = \frac{\alpha}{\lambda}[t(x, y, \tau) - \psi(\tau)], \quad (x, y) \in L,$$

where n is a perpendicular to L; α is the coefficient of convective heat exchange between the soil and the air; λ is the coefficient of heat conductivity of the soil (thawed or frozen) in contact with the air; t is the temperature of the air;

d) The boundary conditions at the interface between area R and the soil and

$$\frac{\partial t(B, y, \tau)}{\partial x} = \frac{\partial t(C, y, \tau)}{\partial x} = 0 \quad \text{where} \quad \begin{aligned} B < y \leqslant A \\ C \leqslant y < D \end{aligned}$$

$$\frac{\partial t(x, B, \tau)}{\partial y} = 0 \quad \text{where} \quad B \leqslant x \leqslant C.$$

At boundary ξ between the thawed and frozen zones of the soil, the following conditions should be fulfilled:

and

$$\left.\begin{aligned} t_1(x, y, \tau) &= t_2(x, y, \tau) = t_0; \\ \lambda_1\frac{\partial t_1(x, y, \tau)}{\partial n} - \lambda_2\frac{\partial t_2(x, y, \tau)}{\partial n} &= \rho\gamma w\frac{d\xi}{d\tau} \end{aligned}\right| (x, y) \in \xi,$$

where t_ϕ is the freezing and thawing point of the water in the soil; n is a perpendicular to boundary ξ; ρ is the latent heat of phase conversion; w is the moisture content of the soil; $d\xi/d\tau$ is the rate of movement of boundary ξ along a perpendicular during the process of freezing ($d\xi/d\tau > 0$) and thawing ($d\xi/d\tau < 0$).

With a change in the area of the calculation space, boundary L moves along the ordinate until it reaches its limiting position L_1. Conditions "b" are fulfilled for all positions of boundary L. The initial conditions in each layer, representing an increment in area S at each moment in time τ_n, are similar to "a," but the beginning of calculation under these conditions is not $\tau = 0$, but rather moment $\tau = \tau_n$, where τ_n is the moment of appearance of the layer numbered n. This is a complex problem in mathematical physics, which cannot be solved by an analytic method.

The author of the present article has solved the problem by a numerical method, based on the use of the explicit method of finite differences and the method of thermal balances [1, 5, 6]. The author has also developed a method of solution of the problem using a digital computer and automatic programming. The basic positions of the method are outlined in [2, 3, 7]. In order to solve the problem as presently formulated, the method has been expanded and supplemented with new statements, allowing the change in area of the space being considered during the process of calculation to be accounted for.

The essence of the additions to the method is as follows. The continual (even or uneven) process of changing the area is replaced by a discrete process. Finite increments of area ΔS_n are divided by a difference grid into elementary blocks, a step in which may differ from a step in the grid for the initial value of S. It is assumed that the area of an increment ΔS_n is a multiple of the area of an elementary block within it and may consist of various soils. The time step $\Delta\tau$ is taken the same for the entire calculation area. Calculation is performed by stages. First, the temperature field is calculated for points in the space with area S (first step). This begins with moment $\tau = 0$ and continues over some time interval $k\Delta\tau$. Then the first increment in area ΔS_1 instantaneously appears with some arbitrary initial distribution of temperature. The second step in calculation is performed for an area $S + \Delta S_1$, beginning at moment $k \cdot \Delta\tau$. The initial conditions for this step are the initial temperature in ΔS_1 and the temperature field in S produced at the end of the first step of calculation. The second step lasts until some moment $(k + \ell)\Delta\tau$, after which a second area increment ΔS_2 with its own initial temperature also instantaneously appears. The dimensions of ΔS_2 and its initial temperature may differ from the dimensions and initial temperature of ΔS_1. By analogy with the second step, the third step is then performed for the area $S + \Delta S_1 + \Delta S_2$. We continue in this manner until the calculation area reaches $S_1 = S + \sum_{1}^{m} \Delta S_n$, where m is the number of increments of area. The calculation may continue for some additional period of time for area S_1. In the computer, all steps in the calculation are performed continually using a single program.

As an example, let us present the calculation of the thermal mode of a dam planned for one of the regions of the far north. The region of construction is characterized by severe climatic conditions. The mean annual air temperature is -7.7 C. The coldest month is January, with an absolute minimum of -47 C. Thaws occur during all the winter months. The temperature rises to +2-5 C. The warmest month is July, with a maximum temperature of +27 C. During the year, there are 128 days with positive mean monthly temperatures. On the average in 1 year there are 312 mm of precipitation, 58% of which occurs during the cold season of the year. During the winter, 120-150 snowy days occur. Therefore, the distribution of snow is quite uneven, and its density is very high.

These severe climatic conditions determine the propagation of permafrost, 170 to 200 m thick with a mean annual temperature of the upper layers of minus 4-6 C. The thickness of the seasonally thawed layer is 0.3-0.4 m in peat beds, 0.5-0.6 m in clay soils and 1.5-2.0 m in wet sand and gravel.

The construction region features marine deposits, characterized by comparatively low ice content of the rock. In the upper 5 to 6 m, the soil is ice saturated and shot through with numberless polygonal and veined ice bodies. The mean moisture content of the upper 5 or 6 m of the deposits is 50%.

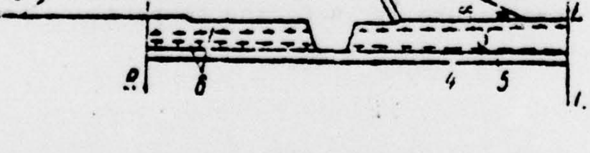

Figure 2. Design Cross Section of Dam.
1, Rock Fill; 2, Soil Deposited in Core of Dam; 3, Pebbles, Gravel; 4, Loam, Clay; 5, Loam, Clay, Highly Moistened; 6, Boundary of Area Which Thaws

The severe climate and complex frozen soil conditions required detailed study of the thermal mode of the planned dam. The planners suggested a frozen type dam for investigation, which was to freeze during the period of construction and the first years of operation. It was necessary to determine conditions required to assure natural freezing of the dam. Otherwise, the dam would have to be frozen by artificial cooling. In order to determine the conditions of natural freezing of the dam, calculation is conducted from the beginning of construction and takes into consideration the technology of construction of the dam. The planners suggested pouring of soil into the body of the dam in layers over its entire length. The calculation was performed for the cross section of the dam and its space considering the layer-by-layer placement of the soil. The design of the dam is shown in Figure 2. In the base of the dam is the thawed area. The downstream prism is built up of unsorted rock fill. The upstream prism, trench backfill and core are made of sand and sandy loam. The boundaries of the full design area are as follows (Figure 2): the contour of the dam, horizontal straight line at a depth of 30 m from the surface, vertical line K-K on the upstream side at 37 m from the axis of the dam and vertical line L-L on the downstream side at a distance of 43 m from the axis of the dam.

It was assumed that the backfill trench would be dug by autumn. During the autumn, soil would be placed in the trench and a two-meter layer of the core of the dam poured over its entire length. This layer would then freeze during the winter. Beginning on 1 June, the construction of the dam would continue. Layers of the following thickness would be poured: in June -- 2 m; in July -- 2 m; in August -- 4 m; in September -- 4 m and in October -- 2 m. The dam would freeze naturally by the end of the second winter, then would be allowed to stand during the summer and freeze once again in the winter. Only after this, would be area be flooded (beginning of operational period).

Initial Conditions

The initial temperature of the soil placed in the summer is 8 C; the temperature of the soil placed in the autumn is 4 C; the temperature at the base of the dam and in the backfill trench is -0.2 C. The initial temperature of the soil in the thawed area and between the thawed area and the base of the dam is 0 C (with the soil thawed); in a layer 2 m thick beneath the thawed area, the temperature is -4 C, the temperature below this layer is -5 C.

Boundary Conditions

The vertical boundaries of the calculated area are taken where transmission of heat is assumed only in the vertical direction. The horizontal boundary is taken at a depth at which the heat of the body of the dam will have practically no influence. The mean monthly temperatures of the water and air are presented in Table 1. The heat-physical characteristics of the soils are presented in Table 2. In the upper 6 m layer of the base, the characteristics of the soils are averaged, in the remaining portions of the design cross section, natural characteristics are assumed.

The step in the difference grid was taken as 2 m, the time step used was variable: $\Delta\tau = 8$ hr during the period of construction of the dam and $\Delta\tau = 144$ hr during the subsequent period. The soil freezing-thawing temperature was taken as - 0.1 C.

TABLE 1

Months	Air Temp, C		Water Temp, C
	Avg. Yr.	Warm Yr.	Avg. Yr.
January	−20.8	−19.7	1
February	−21.9	−20.6	1
March	−20.6	−11.4	1
April	−13.7	−13.3	1
May	−2.9	0.8	0.3
June	5.1	7.8	5
July	10.4	12.3	10
August	9.5	8.3	12
September	4.1	4.0	5
October	−5.2	−5.1	1
November	−13.9	−17.4	0.5
December	−19.5	−13.5	1

TABLE 2

Type of Soil	Moisture Content, w, %	Heat Conductivity		Volumetric Heat Capacity	
		Of Thawed Soil λ_T, kcal/m·hr·C	Of Frozen Soil λ_M, kcal/m·hr·C	Of Thawed Soil C_T, kcal/m^3·C	Of Frozen Soil C_M, kcal/m^3·C
Rock fill	10	1.93	2.90	612	510
Soil placed in body of dam	26	1.35	1.75	705	450
Mixed soil (pebbles, gravel)	50	1.3	2.0	700	500
Loam, clay	11	1.3	1.6	740	460
Moist loam, clay	42	1.5	2.0	770	500

Calculations were performed by computer for 9 years, beginning on 1 January of the first construction winter. It was assumed that the years of construction and beginning of operation would be warm. Therefore, the mean monthly temperatures of the air for the first half of calculation (4.5 years) were taken equal to those of the warmest year, for the second half -- for an average year (Table 1). This assumption provides some reserve in the calculation of time of natural freezing of the dam.

The printout showed the following results of calculation: temperature of points in the central portion of the body of the dam at the end of each calculation half-year and temperature of the entire calculation cross section after 3 months, after 1 year, after 4.5 years and after 9 years from the beginning of calculation. The results are presented in the form of temperature fields at the completion of erection of the dam (1 January of the second construction winter, Figure 3) and at the end of the calculation period

(1 January of the 7th year of operation, Figure 4). The calculation data were also used to construct graphs of the change of temperature with time in the central portion of the body of the dam (Figure 5).

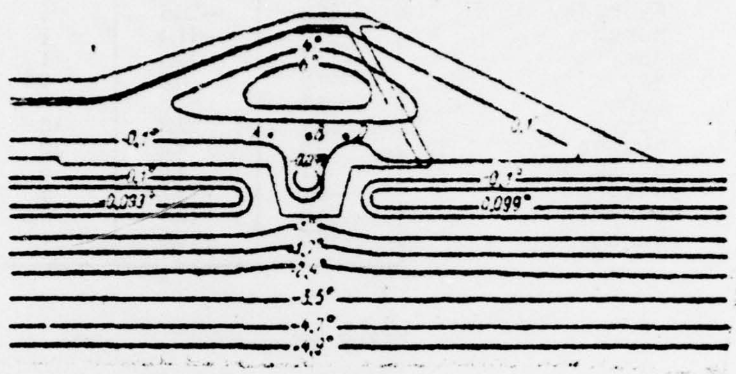

Figure 3. Temperature Field in the Body of the Dam at the End of Construction (1 January of Second Calculation Winter)

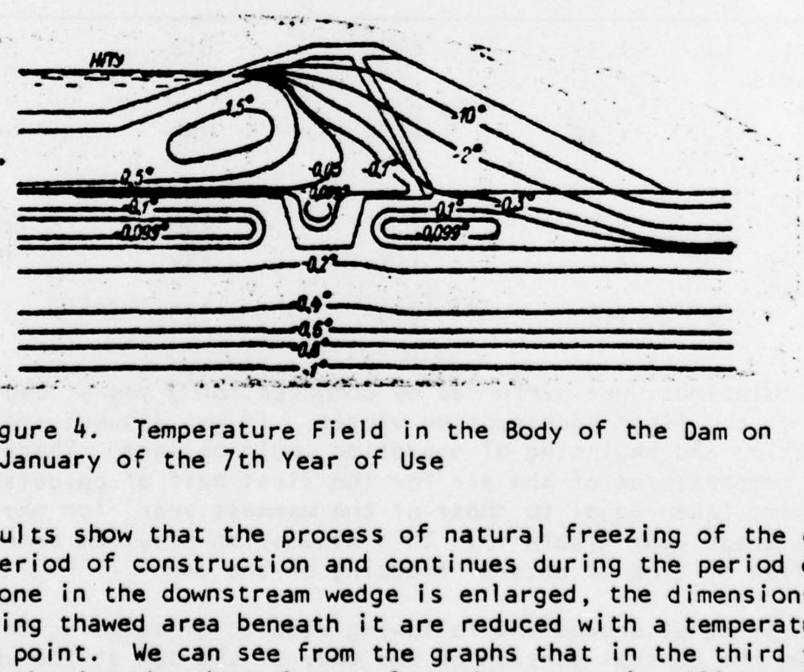

Figure 4. Temperature Field in the Body of the Dam on 1 January of the 7th Year of Use

The results show that the process of natural freezing of the dam begins during the period of construction and continues during the period of use: the frozen zone in the downstream wedge is enlarged, the dimensions of the small remaining thawed area beneath it are reduced with a temperature near the freezing point. We can see from the graphs that in the third year of operation of the dam the thermal wave from the reservoir will reach the central portion of the dam and some increase in temperature in the dam will result. However, after the 5th year of operation the temperature in this area of the dam once more begins to drop (curves B and D in Figure 5), while they stabilize in the upper wedge (curve A in Figure 5). Analysis of the results gives us reason to affirm that an earthen dam constructed under severe climatic conditions can be frozen naturally. To do this, the backfill trench must be prepared by autumn. Placement of soil in the trench beneath the dam and in a 4 to 6 m layer of the body of the dam must be completed by the beginning of winter (the higher the base temperature, the thinner the layer which must be used). This layer without snow will freeze in the winter. The next summer, construction of the dam is continued. For best freezing of the dam, for any given length of construction period, it is desirable that the continuation of construction of the dam be divided into two stages: during the first summer, place 5-6 m of soil and allow it to freeze in the winter, after which the entire dam is placed and allowed to freeze yet another winter, after being constructed to its full height. In the example presented, this multistage construction of the dam is not considered, providing some additional reserve.

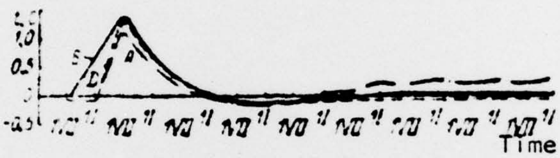

Figure 5. Graphs of Change of Temperature at Points A, B and D in the Central Portion of the Dam with Time

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