Simulation model of thermal-seepage regime of thawing dams with permafrost curtain

N A Aniskin¹ and A S Antonov¹,²

¹Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia
²Branch of JSC «Design, survey and research institute «Hydroproject» named after. S.Y. Zhuka»—«Research institute of energy structures» (Branch of JSC “Institute Hydroproject”—“NIIES”), Volokolamskoye Highway 2, Moscow, 125080, Russian Federation;

Antonov.An.S@yandex.ru

Abstract. The paper considers the joint thermal-seepage problem applicable to earth dams and dykes operating in conditions of permafrost. The problem is being solved using the finite elements method in the local-variation setting. There was worked out the model of thermal-seepage regime of the system «dam-foundation base» applicable to the tailings dike. Estimation is given to the impact of heat-mass transitions and phase changes of the liquid in earth pores on the dike state. Investigations have been done with further consideration of these factors. The results of investigation of the thermal-seepage state of the structure with consideration of factors of heat-mass transition and phase changes show that the results of calculations correspond to field data. Ignoring these factors or one of them distorts the real picture of the dike thermal-seepage state.

1. Introduction

Development of northern regions of the Earth is closely connected with development of power engineering and hydraulic construction needed for the supplying of the population with cheap electric power and water for water supply needs.

However severe climatic conditions of the regions complicate the putting into operation of hydraulic projects. Low absolute temperatures and permafrost at foundation base complicate the work progress, and in some cases result in disruption of normal operation of structures. As example, one may mention emergency situations at Kureika and Kolyma HPPs [1].

A wide use was made in conditions of severe climate of earth in hydraulic structures. In their designing, an extremely important problem in conditions of spreading the permafrost materials is reliable forecast of the thermal-seepage regime of the system «dam-foundation base». In most cases the engineering-geological structure in the area of construction is inhomogeneous and consists of stratifications of permafrost and thawing layers. In some cases the heating effect towards the movement of seepage flow results in thawing permafrost materials at foundation bases of projects thus leading to the increase of seepage permeability, the increase of loss from the water reservoir, loss of bearing capacity. Besides, there may arise local areas of soils removal. As it is known, in such
climatic conditions it is possible to use earth dams and dikes of two types – thawing and permafrost. To ensure permeability of dams of thawing type and foundation base, use is often made of permafrost curtains made with the aid of seasonal operating cooling devices (SOCD). Depending on the used refrigerant they may be divided into the air and liquid ones [2]. Solution of joint thermal problems for such designs is most complicated, because it is necessary to take into account a big number of the varied with time factors: climatic, engineering-geological, technological (parameters of permafrost curtain, type and temperature of the refrigerant therein), etc.

By specialists’ evaluation about 70% of completed earth low-head dams, constructed in severe climatic conditions, receive damages in the first three years of operation due to disruption of thermal-seepage regime [3,4]. Most often the causes of emergency situations at such projects are as follows [5,6]:

- insufficient depth of freezer columns when the permafrost curtain does not cover the underbed talik;
- the wrong choice of the type of the freezing system and/or the refrigerant (in this case the solid permafrost curtain is not formed for working during one year);
- quick degradation of permafrost at foundation base and consequently change of physical and mechanical properties of materials (in this case the seepage flow passes over the permafrost curtain in thawing materials with big values of seepage coefficient $K_t$).

The purpose of the completed investigation is the evaluation of the possible use of the air SOCD with natural circulation for materials freezing of the dam body and creation of the solid permafrost curtain with insufficient depth of SOCD. This paper describes the solution methods of joint seepage-thermal problem for the system «dam-foundation base» and some analysis results of the impact of external factors.

2. Problem statement

Problems of calculation of seepage, thermal and joint thermal-seepage regimes of earth dams and their foundation bases are covered by a great number of investigations both in Russian Federation and in Europe and in Asia including using numerical methods widely for the last years [7,8,9,10,11,12].

As it is known, for materials with minimum porosity the solution of thermal-seepage problem is reduced to solving the differential equation [1]:

$$\frac{\partial t}{\partial \tau} = \alpha_x \frac{\partial^2 t}{\partial x^2} + \alpha_y \frac{\partial^2 t}{\partial y^2} + \alpha_z \frac{\partial^2 t}{\partial z^2} - \frac{C_T}{\gamma_B} \left( v_x \frac{\partial t}{\partial x} + v_y \frac{\partial t}{\partial y} + v_z \frac{\partial t}{\partial z} \right)$$

(1)

Solution of differential equation (1) with due account of boundary conditions and phase changes is reduced to minimization of the functional $F$ [1]:

$$\Phi = \iiint_{\Omega} \left[ \frac{1}{2} \left( a_x \frac{\partial t}{\partial x} \right)^2 + a_y \left( \frac{\partial t}{\partial y} \right)^2 + a_z \left( \frac{\partial t}{\partial z} \right)^2 \right] + \frac{1}{2} \left[ \gamma_B \frac{\partial W}{\gamma_c} \frac{\partial t}{\partial \theta} \right] dxdydz$$

$$+ \iint_{\Omega_1} \int_{\Omega_2} \beta(t - t_{\text{avoid}}) \gamma d\Omega$$

(2)

where: $(v, gradt) = v_x \frac{\partial t}{\partial x} + v_y \frac{\partial t}{\partial y} + v_z \frac{\partial t}{\partial z}$ - scalar product of vectors of seepage velocities in axes $x,y,z$ and temperature gradient;

$\Omega_1, \Omega_2$ – surfaces to which the boundary conditions were assigned of the 2$^{nd}$ and 3$^{rd}$ types.

Numerical minimization of functional (2) was made by authors in software system «FILTR_FAZ» [13]. It was used for solution of thermal-seepage problems in the framework of this paper.

In the completed investigations for determining the optimum method of creation of impermeable permafrost curtain in the thawing dam body in conditions of permafrost, use was made of the methods of experiment planning [14, 15, 16], permitting to obtain the desired result with few solutions. This
procedure is also called the factor analysis, because with a small number of varied factors influencing on the structure regime, it is possible to determine the contribution of each of them.

The main problem of the design study of simulation models is the search of the response function having the form [17]:

\[ Y_i = b_0 + b_1X_1 + \ldots + b_nX_n + b_{12}X_1X_2 + \ldots + b_{1n}X_1X_n + b_{23}X_1X_2X_3 + \ldots + b_{1234}X_1X_2X_3X_4 \]

(3)

where: \( Y_i \) – the desired response function; \( X_1, \ldots, X_n \) – study factors; \( b_0, b_1; \ldots; b_n \) – coefficients.

The obtained on the basis of factor analysis the response function will permit to analyze the extent of impact of each of the chosen factors and forecast the response values at any their magnitudes in the chosen change intervals.

3. Numerical experiment

As the investigation object, preference was given to the thawing earth dam wherein as a seepage control feature, use is made of the permafrost curtain created using air SOCD with natural air circulation. The structure height was taken equal to 20 m (most of the completed in severe conditions earth dikes and dams are low and average head structures).

Consideration was given to the following factors affecting the thermal-seepage regime:

- \( X_1 \) - upstream level (UL). Low and average head structures most often are constructed for domestic and potable water needs enabling drastic change of UL during the year. Variation of UL elevation was made in the range of values from 12 m to 18 m with the central point at elevation 15 m (the dam base elevation is taken equal to zero elevation);

- \( X_2 \) - ratio of upstream slope (m). Depending on the procedure of erection and characteristics of the dam materials there may be some essential alterations. The value of ratio of slope was taken from 1,5 to 3,5 with central point with \( m = 2,5 \);

- \( X_3 \) - seepage coefficient (K) of the thawing material in the structure foundation base. Project operation can result in thawing-out of ice inclusions without solid spreading. In this connection \( K_f \) can change within essential limits. \( K_f \) in the completed investigations varied within limits of acceptable values for fine sand (from 2 m/day to 10 m/day with central point 6 m/day);

- Climatic parameters of the project area. As initial data for creation of the simulation mathematical model, preference was given to the climatic conditions in the area of the town of Mirny (Russian Federation) with drastically continental climate and cold winters intermittently with a short but warm summer. Absolute minimums of temperature: \(-44^\circ C\), absolute anomalous maximum +33 \(^\circ C\). The snow cover thickness is over 1 m, the town belongs to regions of Extreme North. The temperature values accepted for full factor investigations are given in Table 2. As the upper limit of the varying parameter there is accepted the warmest year of the fixed in the region, as the lower one – the coldest one. The factor mean value is mean monthly temperatures of months for the whole observation period. Water temperature is accepted according to mean values for the region, the temperature in the air SOCD with natural circulation is accepted in winter months (November-March) 10\(^\circ C\) higher than the ambient air temperature (which corresponds to test data), in the summer months the SOCD is not used.

The design scheme of the considered system «dam-foundation base» with average values of chosen factors is given in fig.1. Design heat-physical and seepage properties of the dam and foundation base materials in the prepared model are given in Table 1.

For consideration of the depth and design of freezer columns, the following calculation variants were made:

- the air SOCD with natural air circulation, the depth of permafrost curtain does not reach permafrost rocks, the solution is obtained with due account of phase changes;

- the air SOCD with natural air circulation, the depth of permafrost curtain does not reach permafrost rocks, the solution is obtained without phase changes;
additional investigations of temperature impact of the circulating air in SOCD in this variant 
(t, °C), replaced the climatic parameters of construction, annual temperatures were taken by average 
values.

![Figure 1. Cross section of earth dam at average values of factors](image)

**Table 1. Design heat-physical and seepage properties of materials**

| № | Description               | Coef. of heat conductivity C, W/m°C | Volumetric heat capacity C, kJ/(m³°C) | Thermal diffusivity a 10⁻³, m²/hr | Seepage coef. Kf, m/day |
|---|---------------------------|-------------------------------------|--------------------------------------|-----------------------------------|------------------------|
| 1 | Loamy (dam body)          | 1,548                               | 1,935                                | 3100                              | 2100                   | 1,791                  | 3,317                | 0.3 |
| 2*| Tali sands medium (-1)     | 1,548                               | 1,935                                | 3100                              | 2100                   | 1,791                  | 3,317                | 2.00 |
|   | Tali sands medium (+1)     | 1,548                               | 1,935                                | 3100                              | 2100                   | 1,791                  | 3,317                | 10.00 |
|   | Tali sands medium (0)      | 1,548                               | 1,935                                | 3100                              | 2100                   | 1,791                  | 3,317                | 6.00 |
| 3 | Permafrost material        | 1,45                                | 1.55                                 | 2933                              | 2227                   | 1,879                  | 2,506                | 1*10⁻⁸ |
| 4 | Permafrost curtain         | 1,548                               | 1,935                                | 3100                              | 2100                   | 1,791                  | 3,317                | 1*10⁻⁸ |

* – designation of properties of materials at varying $K_f$.

Special attention was paid to comparison of temperatures spreading fields obtained at solution of 
problems with due account of phase changes in materials and without them.

As response functions for the variant of calculation using the air SOCD with natural air circulation, 
there were accepted:

- material temperature in axis SOCD at elevation -11 m (on the boundary of permafrost curtain 
and talik) in April ($T_1$);
- material temperature in axis SOCD at elevation -11 m (on the boundary of permafrost curtain 
and talik) in October ($T_2$);

Total there were conducted 2 full-factor experiments whose plan consists of 17 members at 4 
varying factors. These problems were solved in quasi-volumetric setting. For all calculation cases the 
finite elements grid was bridged in the area of permafrost curtain, coefficient sizes are 1 m in this area. 
Total used in description of the calculation area were 10 125 elements and 12 696 nodes. All problems 
were solved in joint thermal-seepage setting. At every step in the step-by-step manner and thermal
problems were solved. The seepage problem solution resulted in determining the values of seepage velocities in the design area which were used in solving the thermal problem (differential equation 1 and functional 2).

Table 2. Temperature values accepted for full-factor investigation

| Characteristics                        | Months | Months |
|----------------------------------------|--------|--------|
|                                        | I      | II     | III    | IV     | V      | VI     | VII    | VII    | I      | IX     | X      | XI     | XII    |
| Outdoor air temperature, °C varying parameter «-1» | -43    | -34    | -27    | -14    | 0      | 10     | 13     | 8      | 1      | -17    | -31    | -35    |
| Water temperature, °C                  | 4      | 4      | 4      | 4      | 6      | 9      | 4      | 4      | 4      | 4      | 4      | 4      |
| Temperature in the air SOCD            | -33    | -24    | -17    | -4     | -      | -      | -      | -      | -7     | -21    | -25    |
| Outdoor air temperature, °C varying parameter «+1» | -20    | -29    | -11    | 4      | 9      | 21     | 20     | 20     | 10     | -3     | -6     | -28    |
| Water temperature, °C                  | 4      | 4      | 4      | 4      | 5      | 17     | 16     | 16     | 6      | 4      | 4      | 4      |
| Temperature in the air SOCD, °C        | -10    | -19    | -1     | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| Possible minimums of temperatures, °C  | -42    | -37    | -22    | -12    | 1      | 12     | 15     | 11     | 1      | -16    | -31    | -39    |
| Possible maximums of temperatures, °C  | -23    | -22    | -8     | 3      | 10     | 19     | 20     | 18     | 13     | -3     | -9     | -22    |

From results of solution of the thermal problem, correction was given to the seepage coefficients of the dam and foundation base materials: in case of material change over to permafrost state, the seepage coefficient value was taken equal to $1 \times 10^{-8}$ m/day, with its thawing, the value was taken according to Table 1. This iterative process at every step with time was conducted till complete convergence of the problem. Fig.2 shows the final solution of seepage problem for the dam at average values of varied factors: ratio of upstream slope $m = 1:2.5$, upstream level 15.0 m and the seepage coefficient value of the dam body materials $K_f= 2$ m/day.
Figure 2. Seepage heads distribution, ratio of upstream slope 1:2.5; upstream level 15.0 m; seepage coefficient of dam body material $K_f = 2$ m/day

4. Results of full-factor experiment

The solution of seepage-thermal problem for each variant of plans of two full-factor experiments resulted in obtaining the temperature field for the design time moments. Pictures of temperature distribution for the 3rd design year for the variant with average values of the considered factors are given in fig. 3

One may note the following features of the temperature regime of the design and foundation base. In January (fig. 3,a) under impact of the air negative temperatures in SOCD in the dam body and upper layers of the foundation base, under formation is the permafrost curtain which does not cover the seepage layer. The curtain bottom reaches elevation – 12.0 m.

In April of the mean year with temperature (fig. 3,b) the SOCD does not work. The process of degradation of the permafrost impervious core begins. On the surface of the crest and downstream slope the permafrost zone still remains.

In the summer time (fig. 3,c) using the air SOCD the materials are not being cooled. The lower part of permafrost curtain is fully thawed resulting in more intensive materials thawing of the dam body and the permafrost curtain. There appears the hydraulic communication between ponds.

As of October (fig. 3,d) (during which the mean monthly temperature passes through 0°C), in the thawing material of the foundation base and the dam body a zone remains with lower temperatures from 0°C to 0.3°C. Conservation of the zone of lower temperatures shows the possibility of use of the air SOCD with natural air circulation to keep the permafrost curtain in the working condition after its build-up.
Figure 3. Isochromes of the check variant temperatures at using the air SCOD for the 3rd year of operation: a) January b) April c) July d) October

Regression equations for the chosen responses after exclusion of non important members have the form (the variant with due account of the water phase changes):
- for the material temperature in SOCD axis at elevation -11 m (on the boundary permafrost curtain – talik) in April of the 3rd year of operation:
\[ T_i = -5.11 + 1.59X_1 + 0.44X_2 + 3.64X_4 + 1.01X_1X_2 - 1.5X_1X_3 + 0.47X_2X_3 - 2.03X_2X_4 + 1.52X_3X_4 - 1.08X_1X_2X_4 + 0.54X_1X_2X_4 + 1.09X_2X_3X_4 - 0.46X_1X_2X_3X_4 \]

- for the material temperature in SOCD axis at elevation -11 m (on the boundary permafrost curtain – talik) in October of the 3rd year of operation:

\[ T_i = -3.42 + 0.86X_1 + 2.59X_2 + 0.87X_1X_2 - 0.86X_1X_3 - 0.85X_2X_4 + 0.86X_3X_4 - 0.87X_1X_2X_4 + 0.87X_1X_3X_4 + 0.87X_2X_3X_4 \]

As follows from the obtained equations, the formation of permafrost, curtain practically is not affected by factor \( X_1 \) (seepage coefficient \( K_f \) of thawing material at the structure foundation base) with the accepted boundaries of change (from 2 m/day to 10 m/day). Nor it affects the response function \( T_2 \) and hardly affects the response function \( T_1 \) factor \( X_2 \) (ratio of upstream slope \( m_i \)). The remaining considered factors are sufficiently important for the response functions. One may note the most important impact of the climatic factor \( X_1 \), which is quite explainable since the air temperature in SCOD directly depends on the outdoor air temperature. Considerable enough is the contribution of factor \( X_1 \) (UL), since during the water reservoir draw-down in the cold period of the year the low and average head projects there appears an additional cold flow on the side of the dam upstream slope. And on the contrary, at the impounded water reservoir, it serves as heat protection of the upstream slope and the adjacent foundation base.

Similarly the analysis included the results obtained from the problem solution without consideration of occurrences of heat-mass transition and phase changes (classic temperature problem). This resulted in obtaining the temperatures field given in fig. 4.

**Figure 4.** Isochromes of temperatures of the check variant at solution without consideration of occurrences of phase changes and heat-mass transition a) April of the 3rd year; b) October of the 3rd year.

In the first several months of operation there occurs the complete freezing-through the underbed talik at negative temperatures below -10°C and the build-up of solid permafrost curtain. The developed permafrost core maintains the structure impermeability during all over the operation period. These
results are not confirmed by field observations at real projects, by operation experience and the analysis of occurrences at thawing dams in severe climatic conditions. Pure temperature solutions, evidently cannot describe the processes developing in the dam body in the first several years after construction. Also complicated is the regime of the thawing dam with a permafrost curtain wherein the bypass seepage begins to develop over the thawing materials.

5. Conclusions
1. For the temperature regime forecast of the earth dam with permafrost curtain a solution is necessary of the joint thermal-seepage problem with due account of phase changes.
2. On the basis of the completed investigations one can state that with the aid of the air SCOD with natural air circulation it is not possible to create a sufficiently deep solid permafrost curtain in the dam body at insufficient biting deeper of SCOD. In doing so the talik at the foundation base is conserved. In the summer time a considerable degradation of permafrost curtain takes place.
3. Use of the air SCOD with natural circulation for creation of solid permafrost curtains is low-effective, however there is a possibility of their combined use jointly with liquid SCOD to keep the developed regime of structure operation.
4. The work resulted in obtaining regression equations which can be used at the start of designing the similar projects (feasibility study) or the analysis of the temperature regime of the existing ones.

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