Forecast of temperature and filtration regime of melt dams with liquid coolers

Nikolai Aniskin and A Antonov
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia
E-mail: nikolai_aniskin@mail.ru; Antonov.An.S@yandex.ru

Abstract. The article discusses a joint temperature and filtration problem in relation to soil dams with seasonal liquid coolers operating in permafrost conditions. The problem is solved using the finite element method in a locally-variation formulation. A numerical model of the temperature and filtration regime of the “dam-base” system has been developed. Studies have been carried out with consistent consideration of the main operating factors. The results of the study of the temperature and filtration state of the structure, taking into account the factors of heat and mass transfer and phase transitions, showed that the use of liquid coolers is well suited for creating a monolithic frozen curtain at the stage of the start of the structure operation. The obtained regression equations can be used at the initial design stage (feasibility study) or for the analysis of the temperature regime of existing ones.

1. Introduction
Regions with severe climatic conditions occupy more than 70% of the territory of the Russian Federation. To solve various problems of the national economy (energy and hydropower, water supply, mining, etc.), the creation of reservoirs is necessary. At the same time, soil dams are most often used as water-supporting structures. The construction and operation of these structures takes place at significant negative temperatures, which in some cases can lead to various kinds of complications up to emergencies. An example of such situations is the soil dam of the Kureyskaya and Kolyma hydroelectric stations [1, 2].

For soil dams constructed in the permafrost zone, it is extremely important to ensure the appropriate temperature and filtration regime of the “construction-base” system. A bed of frozen and thawed soils is the base of the considered in the permafrost zone structures. Deviation from the desired mode of construction and base can lead to thawing of frozen soils and, as a result, to an increase in their permeability and deformability. As is known, in permafrost zone, two types of soil dams are used - thawed and frozen. To ensure the impermeability of thawed dams and basis, frozen curtains, created with seasonal coolers are often used. Depending on the refrigerant used, they can be divided into air and liquid ones [3, 4].

Statistics of emergencies of soil dams in permafrost are known. Due to violations of the temperature and filtration regime in the first three years of operation, approximately 70% of low-pressure soil dams are damaged [5, 6]. The causes of the emergency were [7, 8]: 1) the rapid degradation of permafrost at the base, and, consequently, a change in the physical and mechanical
properties of soils; 2) insufficient depth of the freezing columns when the frozen curtain does not overlap the under-bed talik; 3) the wrong choice of the type of freezing system and / or refrigerant (in this case, a continuous frozen curtain, which is operational for a year does not form).

In [9], the results of studies of the influence of the main acting factors on the formation of the temperature and filtration regime of the “soil dam-base” system for the design of a soil dam with air seasonal coolers with natural circulation were presented [3, 4]. The purpose of the research, the results of which are presented in this paper, is to assess the possibility of using liquid coolers with forced circulation to freeze the soil of the dam body and create a continuous frozen curtain with insufficient deepening of liquid coolers. This paper presents a methodology for solving the joint temperature and filtration problem for the “dam-base” system and some results of the analysis of the influence of acting external factors.

2. Methods
Numerous scientific studies have been devoted to questions of calculating the filtration, temperature, and joint temperature and filtration regimes of soil dams and their basis, both in the Russian Federation and abroad, including using numerical methods widely used in recent years [10–15].

The solution of the temperature and filtration problem for the soil medium at the minimum porosity is reduced to the solution of the following differential equation [1]:

\[
\frac{\partial t}{\partial t} = a_x \frac{\partial^2 t}{\partial x^2} + a_y \frac{\partial^2 t}{\partial y^2} + a_z \frac{\partial^2 t}{\partial z^2} - \frac{C_x \gamma_r}{C_m \gamma_h} \left( \nu_x \frac{\partial t}{\partial x} + \nu_y \frac{\partial t}{\partial y} + \nu_z \frac{\partial t}{\partial z} \right)
\]

(1)

The solution of differential equation (1) taking into accounts the boundary conditions and phase transformations is reduced to functional minimization [1].

The numerical solution of the temperature and filtration problem was implemented by the authors in the FILTR_FAZ software package [15]. It was used to solve temperature and filtration problems in the framework of this study.

To determine the optimal method for creating a waterproof frozen curtain in a solid dam under permafrost conditions, the author used a factor analysis technique [16, 17, 18], which allows achieving the desired result with the least number of solutions. The response function obtained based on factor analysis will allow one to analyze the degree of influence of each of the selected factors and to predict the magnitude of the response at any of their values in the selected change intervals.

The object of the study was a thawed earth dam, in which a frozen curtain created using seasonal liquid coolers with forced circulation is used as an anti-filtering element [3]. Freon with a constant operating temperature of -20 °C was chosen as a coolant. The height of the structure was 20 m (most of the erected dams built in harsh conditions are low or medium pressure structures).

The calculated thermophysical and filtration properties of the soils of the dam and the base, the values of air and water temperatures, adopted for a full factor study, are similar to those adopted in [9]. Special attention was paid to comparing the temperature distribution fields obtained in solving problems taking into account phase transitions in soils and without them.

The following factors affecting the temperature-filtration regime were considered:

- \( X_1 \) - upstream level. Low- and medium-pressure facilities are most often built for drinking and household needs, so a significant change in the upstream level is possible during the year. Variation of the upstream level mark was carried out in the range of values from 12 to 18 m, a central point was at the mark of 15 m (the mark of the dam base was taken as the zero mark);
- \( X_2 \) - upstream slope (\( m_1 \)). Substantial changes are possible depending on the construction technology and characteristics of the dam soil. The magnitude of the slope was from 1.5 to 3.5, a central point \( m_1 = 2.5 \);
- \( X_3 \) - filtration coefficient (\( K_f \)) of thawed soil at the base of the structure. As a result of the facility operation, thawing of ice inclusions that do not have continuous distribution is possible. In this regard, \( K_f \) can vary significantly. \( K_f \) in the performed studies varied within the acceptable values for fine-grained sand (from 2 to 10 m/day with a central point of 6 m/day);
Climatic parameters of the construction area. The climatic conditions in the area of Mirny (Russian Federation) were chosen as the initial data for creating a simulation mathematical model. The climate in this region is sharply continental, cold winters alternate with short-term, but warm summers. The absolute minimum temperature is \(-44{\degree}C\), the absolute anomalous maximum is \(33{\degree}C\). The thickness of the snow cover is more than 1 m. The city is assigned to the regions of the Far North. The warmest year recorded in the region was taken as the upper boundary of the variation parameter; the coldest year was taken as the lowest one. The average value of the factor is the average monthly temperature of the months for the entire observation period. The water temperature is taken according to the average values for the area.

The design scheme of the considered “dam-base” system with average values of selected factors is presented in Figure 1.

![Cross section of soil dam with average values of factors](image)

Figure 1. Cross section of soil dam with average values of factors

To select the optimal design parameters under various operating conditions, response functions were selected and regression equations were compiled. The following parameters were taken as a response function: soil temperature at a distance of 3 m from the axis of the liquid cooler towards the upstream at 10 m (\(T_1\)), soil temperature at a distance of 3 m from the axis of the liquid cooler towards the upstream at \(-10\) m (\(T_2\)), the depth of talik freezing at the base of the frozen curtain (\(L\)).

3. Results and discussions

The results of solving the temperature and filtration problem in the form of isochromatic temperature in the calculation domain for the variant with average factors are presented in Figure 2. The calculation results showed that the use of liquid coolers will quickly create a frozen curtain of sufficient power (the curtain creation time is 150-180 days). The frozen curtain has different capacities in the dam body and in the under-bed talik. This is explained by a powerful filtration flow under the structure, which carries additional heat. The average temperature of the soil at 2 m from the axis of the liquid cooler is from \(-5.5\) to \(-6.3\) °C.

The talik at the base of the frozen curtain gradually decreases in the initial period, but its full freezing at given refrigerant temperatures is impossible, due to an increase in filtration rates at the base and at a greater heat influx. The thickness of the talik is from 1.9 to 2.8 m.

From the downstream side, during the 3 years of operation, the thawed core is converted. It is formed due to the initial conditions, and the annual thawing of soils. Varying the ambient temperature leads to a change in the position of the “zero” isotherm from the upstream side.

Thawing of perennial frozen rocks at the base mainly occurs in the first 3 years, then the rate of degradation slows down. For a more accurate prediction of the process of perennial frozen rocks thawing, an estimated period of 10-12 years is required.
Figure 2. Temperature isochrums of the control variant when using liquid coolers in the third year of operation: a) January b) April c) July d) October
The resulting regression equations after eliminating unimportant factors have the following form:

- soil temperature at a distance of 3 m from the axis of the liquid cooler in the direction towards the upstream at 10 m ($T_1$):
  \[ T_1 = -10.778 - 1.236X_1 - 1.273X_2 + 1.262X_3 - 1.233X_4 - 1.236X_1X_3 + 1.251X_1X_3 - 1.254X_1X_3 + 1.262X_2X_3 - 1.233X_2X_4 + 1.249X_3X_4 + 1.238X_1X_4 + 1.238X_1X_3X_4 \]

- soil temperature at a distance of 3 m from the axis of the liquid cooler towards the upstream at -10 m ($T_2$):
  \[ T_2 = -8.206 - 1.242X_1 - 1.246X_2 + 1.262X_3 - 1.242X_4 + 1.245X_1X_3 - 1.242X_2X_3 + 1.250X_1X_4 + 1.250X_1X_3X_4 + 1.250X_2X_3X_4 + 1.238X_1X_4 + 1.238X_1X_3X_4 + 1.238X_1X_3X_4 \]

- the depth of talik freezing at the base of the frozen curtain ($L$).
  \[ L = 1.29 - 0.24X_2 + 0.74X_3 - 0.54X_4 + 0.16X_1X_3 + 0.16X_1X_4 + 0.23X_2X_3 - 0.16X_2X_4 + 0.09X_1X_3X_4 - 0.18X_1X_3X_4 - 0.07X_1X_3X_4 \]

Analyzing obtained results, it can be noted that the selected variation factors indirectly affect freezing of talik ($L$). Factor ($X_4$), which is responsible for the climatic parameters of the region, affects only the temperature of the dam body, and makes a minimal contribution to the creation of a frozen curtain when using liquid coolers. They allow creating a stable temperature field from the zone of seasonal freezing of thawing to thawed soil at the base of the frozen curtain (Figure 2).

At the next stage of the research, it was decided to replace the factor ($X_6$); instead of the climatic factor, the value of the temperature of the refrigerant was considered. This allowed us to study the possibility of freezing the talik at the base of the curtain and determine the maximum permissible depth. The temperature of the coolant simulated the type of refrigerant used at soil freezing. Variation of factor ($X_6$) was carried out in the temperature range from -10 to -50 °C. As in previous studies, the upstream slope ($X_2$), the upstream level ($X_1$), and the $K_i$ of the base ($X_3$) were taken into account.

The response factors were the depth of freezing of the under-bed talik at the base of the frozen curtain ($L$), the thickness of the frozen curtain at -10 m ($H$), and the soil temperature at 4 m from the axis of the liquid cooler towards the upstream at -10 m ($T_7$).

The results of solving the temperature and filtration problem in the form of isotherm temperature in the computational region for two calculation options are presented in Figure 3. For option No. 1, the following values of factors were specified in the planning matrix: upstream wall mark - 12.0 m; the upstream slope - 1: 1.5; base soil filtration coefficient: 10 m/day; refrigerant temperature -10 °C. For option No. 10, compared with option No. 1, only the value of the upstream slope was changed, which was taken 1: 3.5.

The obtained regression equations for this stage of research after the exclusion of unimportant terms are as follows:

- frozen curtain power at -10 m:
  \[ L = 9.405 + 0.789X_1 - 0.642X_2 + 0.670X_3 - 4.822X_4 - 2.207X_1X_2 - 1.069X_1X_3 - 1.794X_1X_4 + 0.694X_2X_3 + 0.549X_2X_4 + 3.413X_3X_4 - 0.085X_1X_2X_3 - 0.578X_1X_2X_4 - 0.786X_2X_3X_4 + 0.114X_1X_2X_3X_4 - 2.650X_1X_2X_3X_4 \]

- depth of talik freezing:
Analyzing the results, we can clearly trace the dependence of the freezing intensity of the frozen curtain on the size of the talik at its base. When the talik closes, the body of the curtain quickly freezes to 10-15 m; and the thawing of the base stops (Figure 3, a). In the presence of talik, the intensity of the curtain freezing decreases and is 4-6 m depending on the temperature of the refrigerant (Figure 3, b).

The depth of talik freezing is most influenced by factor \( X_3 \) \( K_f \) of the base. The higher the filtration rate, the more intense the degradation of perennial frozen rocks and the lower talik thickness can be frozen. When calculating for a period of 3-5 years, off-line filtration through thawed rocks is possible; and in some cases this leads to emergency situations at structures.

The factor \( X_2 \) of the upstream slope has the greatest effect on the temperature of the soil at 4 m from the axis of the liquid cooler. The slighter the slope, the greater the distance of the filtration flow and the less its warming effect, and therefore the soil temperature is lower. If the factors \( X_1; X_2 \) and \( X_3 \) are correctly varied, it is possible to choose the optimal construction design when deepening the liquid cooler into perennial frozen rocks.

\[
H = 3.115 + 0.4X_1 + 0.2X_2 + 0.772X_3 + 0.459X_4 - 0.155X_1X_2 + 0.361X_1X_3 -
0.32X_1X_4 + 0.127X_2X_3 + 0.987X_2X_4 - 0.752X_3X_4 - 0.196X_1X_2X_3 + 0.115X_1X_2X_4 -
0.222X_2X_3X_4 + 0.769X_2X_3X_4 - 1.057X_1X_2X_3X_4
\]

• the soil temperature at 4 m from the axis of the liquid cooler towards the upstream at −10 m:

\[
T = -9.773 - 0.674X_1 + 0.76X_2 + 0.0198X_3 + 8.828X_4 + 1.125X_1X_2 + 0.642X_1X_3 -
0.852X_1X_4 - 0.632X_2X_3 - 0.873X_2X_4 - 1.328X_3X_4 - 0.219X_1X_2X_3 + 0.498X_2X_3X_4 -
0.477X_1X_2X_3 + 1.318X_1X_2X_3X_4
\]

Analyzing the results, we can clearly trace the dependence of the freezing intensity of the frozen curtain on the size of the talik at its base. When the talik closes, the body of the curtain quickly freezes to 10-15 m; and the thawing of the base stops (Figure 3, a). In the presence of talik, the intensity of the curtain freezing decreases and is 4-6 m depending on the temperature of the refrigerant (Figure 3, b).

The depth of talik freezing is most influenced by factor \( X_3 \) \( K_f \) of the base. The higher the filtration rate, the more intense the degradation of perennial frozen rocks and the lower talik thickness can be frozen. When calculating for a period of 3-5 years, off-line filtration through thawed rocks is possible; and in some cases this leads to emergency situations at structures.

The factor \( X_2 \) of the upstream slope has the greatest effect on the temperature of the soil at 4 m from the axis of the liquid cooler. The slighter the slope, the greater the distance of the filtration flow and the less its warming effect, and therefore the soil temperature is lower. If the factors \( X_1; X_2 \) and \( X_3 \) are correctly varied, it is possible to choose the optimal construction design when deepening the liquid cooler into perennial frozen rocks.

![Figure 3. Temperature isochroms when varying the temperature of the refrigerant of liquid coolers: a) option No. 10 (with talik freezing); b) option No. 1 (talik size is 2.2 m)](image-url)
The upstream level ($X_1$) has an average effect on all indicators of the structure; the variation in the draft and filling of the reservoir allows one to take into account the real mode of operation of the facility, as well as the additional heat influx.

Variation in the refrigerant temperature ($X_4$) has the greatest effect on the capacity of the frozen curtain and soil temperature. The study found out that the selection of the optimum temperature of the liquid refrigerant allows one to guarantee the freezing of taliks at the base with a capacity of up to 1 m.

4. Conclusions
   1. The use of liquid coolers is well suited for creating a monolithic frozen curtain at the stage of the start of a building usage.
   2. Variation in the dam design and selection of the cooler’s refrigerant can guarantee talik freezing at the base of the structure with a capacity of up to 1 m.
   3. Based on the results of the work, regression equations are obtained that can be used at the initial design stage (feasibility study) or for the analysis of the temperature regime of existing ones.

References

[1] Aniskin N.A. 2006 Temperaturno-filtratsionnyy rezhim osnovaniya i plotiny Kureyskoy GES vo vtorom pravoberezhnom ponizhenii [Temperature-filtration mode of foundation and dam Kureiskaya HPP the second right bank lowering] Vestnik MGSU [Proceedings of Moscow State University of Civil Engineering] no. 2 pp. 43–52 (In Russian)

[2] Aniskin N.A. 2006 Temperaturno-filtratsionnyy rezhim osnovaniya i plotiny Kureyskoy GES vo vtorom pravoberezhnom ponizhenii [Temperature-filtration mode and the base of the dam hydroelectric Kureiskaya second right bank lowered] Vestnik MGSU [Proceedings of Moscow State University of Civil Engineering] № 2 pp. 43—52

[3] Makarov V.I. 1979 Protivofil'tratsionnye merzlotnye zavesy v gruntovykh plotinakh merzlogo tipa. Stroitel'stvo i ekspluatatsiya gidrotekhnicheskikh sooruzheniy v Zapadnoy Yakutii [Antifiltration cryogenic veils in ground dams of frozen type Construction and operation of hydraulic structures in Western Yakutia] Novosibirsk Nauka pp. 26-51 (In Russian)

[4] Gidrotekhnicheskie sooruzheniya (rechnye). [Hydraulic structures (river)] 2011 Moscow ASV 581 p. (In Russian)

[5] Guzenkov S.N., Stefanishin D.V., Finogenov O.M., Shul’man S.G. 2007 Nadezhnost’ khvostovykh khozyaystv obogatitel’nykh fabric [Reliability tail farms processing plants] Belgorod «Vezelitsa» 674 p. (In Russian)

[6] Chzhan R.V. 2015 Geokriologicheskie printsipy raboty gruntyovkh plotin v kriolitozone v usloviyakh menyayushchegosya climata [Geocryological principles of operation of embankment dams on permafrost in a changing climate]. Fundamental’nye issledovaniya [Fundamental Research] no. 9-2 pp. 288–296 (In Russian)

[7] Foster M., R.Fell..Spannagle 2000 The statistics of embankment dam failures and Accidents Canadian Geotechnical Journal 37(5) pp. 1000–1024

[8] Zhang R.V. 2014 Monitoring of small and medium embankment dams on permafrost in changing climate Sciences in Cold and Arid Regions 6(4) pp. 348–355

[9] Bereslavskiy E.N. 2009 Matematiceskoe modelirovanie filtratsionnykh techeniy pod gidrotekhnicheskimi sooruzheniyami [Mathematical modeling of filtration currents under hydraulic engineering structures] Nauchnye vedomosti BelGU [Bulletin of BSTU.] no.5 pp. 32—46. (In Russian)

[10] Gorokhov E.N. 2012 Virtual’nye 3D-modeli temperaturno-kriogannogo rezhima gruntyovkh plotin v kriolitozone [A virtual 3D model of temperature-cryogenic regime of embankment
dams on permafrost] Privolzhskiy nauchnyy zhurnal [Privolzhsky Scientific Journal] no. 3 pp. 188–193. (In Russian)

[11] Guzenkov S.N., Stefanishin D.V., Finogenov O.M., Shul’man S.G. 2007 Nadezhnost’ khvostovykh khozyaystv obogatitel’nykh fabric [Reliability tail farms processing plants] Belgorod «Vezelitsa» 674 p. (In Russian)

[12] Krylov D.A. 2012 Matematicheskoe modelirovanie temperaturnykh poley s uchetom fazovykh perekhodov v kriolitozone [Mathematical simulation of temperature fields with phase transitions in the permafrost zone] Nauka i Obrazovanie [Science and Education] no.4 pp. 1–26 (In Russian)

[13] Markhilevich O.K. 2009 Primenenie metodov modelirovaniya geofil’tratsii pri proektirovanii gidrotekhnicheskikh sooruzheniy [Application of methods of simulation of geofiltration in the design of hydraulic structures] Gidrotekhnicheskoe stroitel’stvo [Hydrotechnical Construction] no. 4 pp. 61–72. (In Russian)

[14] Korshunov A.A. 2016 The Impact of Freezing-thawing Process on Slope Stability of Earth Structure in Cold Climate / A.A.Korshunov, S.P.Doroshenko, A.I. Nevzorov Advances in Transportation Geotechnics 3 The 3rd International Geotechnics (ICTG 2016) Procedia Engineering Vol. 143 p. 682–688

[15] N.A.Aniskin, A.S. Antonov. 2017 Numerical Modelling of Tailings Dam Thermal-Seepage Regime Considering Phase Transitions Modelling and Simulation in Engineering Volume 2017 Article ID 7245413 10 pages https://doi.org/10.1155/2017/7245413

[16] Gorsuch, R. L. 1983 Factor Analysis Hillsdale, NJ: Lawrence Erlbaum Associates

[17] Adler Yu. P., Markova E.V., Granovsky Yu.V. 1976 Experiment planning in search of optimum conditions M.: Nauka pp 70-92.

[18] Kim, J. -O., Mueller, C. W. 1978 Factor Analysis: Statistical methods and practical issues.