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Determination of technological parameters of rock freezing systems based on the condition of maintaining design thickness of ice wall

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Abstract
Artificial freezing ensures the formation of a temporary ice wall around the shaft under construction, which prevents groundwater penetration into the shaft and increases the strength of rocks around the unsupported walls of the shaft until the permanent support is erected. The purpose of the study is to carry out thermotechnical calculation of ice wall with subsequent theoretical analysis of changing ice wall thickness with shifting to the passive freezing stage. The idea of the study is to determine these technological parameters based on the condition of maintaining the design ice wall thickness at the stage of passive freezing. The methodology and results of thermotechnical calculation of ice wall for the clay layer as applied to the case of the shafts under construction of a potash mine in the Republic of Belarus are presented. The thermal calculation of the ice wall was carried out numerically in the ANSYS software package using the finite element method. The findings of the numerical multiparameter modeling allowed theoretical analysis of ice wall thickness decrease with shifting to the passive freezing stage with higher brine temperature. The decrease in ice wall thickness was studied both during normal operation of the freezing station and at emergency operation mode caused by the failure of one of the freezing columns. Special attention in the analysis was paid to studying the influence of the duration of the active freezing stage and the distance between the columns on the decrease in the ice wall thickness. When analyzing changes in ice wall thickness at different distances between the freezing columns, it was found that the most common column spacing in the range from 1.1 to 1.3 m requires observing restrictions on the duration of active freezing to prevent a critical decrease in ice wall thickness during the passive freezing stage or decreasing the distance between the freezing columns. In this case, preservation of positive dynamics of ice wall thickness growth is ensured. For the clay layer considered in the study and the distance between the columns from 1.1 to 1.3 m, the minimum time of active freezing is also about 4.3 months. As a result of the analysis, the technological parameters of the freezing system (duration of the active freezing stage and the distance between the freezing columns) were determined, at which the ice wall thickness at the passive freezing stage did not become lower than the minimum permissible values calculated based on the strength and creep conditions.

Keywords
construction, mine shaft, rocks, groundwater, freezing, ice wall, thermotechnical calculation, modeling, process parameters, freezing column, emergency mode

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СТРОИТЕЛЬСТВО ГОРНЫХ ПРЕДПРИЯТИЙ И ОСВОЕНИЕ ПОДЗЕМНОГО ПРОСТРАНСТВА

Научная статья

Определение технологических параметров систем замораживания пород из условия поддержания проектной толщины ледопородного ограждения

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Аннотация
Искусственное замораживание обеспечивает формирование вокруг строящегося ствола временного ледопородного ограждения (ЛПО), препятствующего проникновению подземных вод в ствол и повышающего прочность горных пород в окрестности незакреплённых стенок ствола до возведения постоянной крепи. Целью исследования является проведение теплотехнического расчета ЛПО с последующим теоретическим анализом изменения толщины ЛПО при переходе на стадию пассивного замораживания. Идея исследования заключается в определении этих технологических параметров исходя из условия поддержания проектной толщины ЛПО на стадии пассивного замораживания. Представлена методика и результаты теплотехнического расчета ЛПО для слоя глины применительно к случаю строившихся стволов одного калийного рудника в республике Беларусь. Теплотехнический расчет ЛПО проводился численно в программном комплексе ANSYS с использованием метода конечных элементов. Результаты численного многопараметрического моделирования позволили провести теоретический анализ уменьшения толщины ЛПО при переходе на стадию пассивного замораживания с более высокой температурой рассола. Исследовалось уменьшение толщины ЛПО как при нормальном режиме работы замораживающей станции, так и в аварийном режиме работы, связанном с выходом из строя одной из замораживающих колонок. Особое внимание при анализе уделялось исследованию влияния длительности стадии активного замораживания и расстояния между колонками на уменьшение толщины ЛПО. При анализе изменения толщины ЛПО при различных расстояниях между замораживающими колонками получено, что для наиболее распространенных расстояний между колонками в интервале от 1,1 до 1,3 м требуется соблюдать ограничения по длительности активного замораживания для предотвращения критического уменьшения толщины ЛПО на стадии пассивного замораживания либо уменьшать расстояние между замораживающими колонками. В этом случае будет обеспечено сохранение положительной динамики роста толщины ЛПО. Для рассмотренного в работе слоя глины и расстояний между колонками от 1,1 до 1,3 м минимальное время активного замораживания также составляет около 4,3 мес. В результате проведенного анализа определены такие технологические параметры системы замораживания (длительность стадии активного замораживания и расстояния между замораживающими колонками), при которых толщина ЛПО на стадии пассивного замораживания не становится ниже минимально-допустимых значений, рассчитанных из условий прочности и ползучести.

Ключевые слова
строительство, шахтный ствол, горные породы, подземные воды, замораживание, ледопородное ограждение, теплотехнический расчет, моделирование, технологические параметры, замораживающая колонка, аварийный режим

Финансирование
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Introduction

The construction of mine shafts in watered soils and rocks is carried out with the use of special methods. One of the most widespread special methods of shaft construction at potassium mines is artificial freezing of rocks [1, 2]. The purpose of artificial freezing is to form a temporary ice wall around the shaft under construction, which prevents groundwater penetration into the shaft and increases the strength of rocks around the unsupported walls of the shaft until the permanent support is erected [3–5].

The sinking of a mine shaft starts only after the formation of a closed contour of ice wall with a design thickness which is determined on the basis of strength and creep conditions [6, 7]. Calculation of ice wall for strength and creep is usually carried out for a certain uniform negative temperature of the rocks composing it [8]. Since in practice the temperature distribution in an ice wall volume is heterogeneous, an important issue in determining the ice wall thickness based on the calculated temperature field is the selection of isotherms, which correspond to the ice wall boundaries. In practice, as a rule, two types of isotherms are used [5]:

1) temperature of actual freezing of water in the pores (about 0 °C);

2) temperature at which strength and rheological properties of frozen rocks were measured (−4 … −12 °C).

Based on the published information on artificial freezing of rocks [3, 5, 9], it can be assumed that both methods of selecting ice wall boundary isotherms are applicable at the stage of active freezing of the rock mass, when the freezing brine temperature takes minimum values, and the brine flow rate takes maximum values. However, it was shown in [5] that during the passive freezing stage with higher temperatures and lower brine flow rates, there may be a temporary decrease in ice wall thicknesses to values below the minimum allowable ones, determined based on the strength and creep conditions. To a greater extent, such a decrease in ice wall thickness is characteristic of the second method of selecting ice wall boundary isotherms. A decrease in the ice wall thickness is observed during passive freezing both in the normal operation mode of the freezing station, and in the emergency mode, which may consist in the failure of one or more freezing columns [10].

Another important issue is the selection of the distance between neighboring freezing columns and, as a consequence, the total number of freezing columns [11–14]. The issue of changes in ice wall thickness at the passive freezing stage calculated at different distances between freezing columns was not sufficiently investigated in the existing Russian and foreign literature. This issue is relevant in terms of ensuring the reliability of ice wall and the safety of mining operations in shafts under construction with the use of artificial freezing method.

The present study continues the research presented in the paper [5]. The purpose of both the previous and the present paper was to carry out thermotechnical calculation of ice wall with subsequent theoretical analysis of changing ice wall thickness with shifting to the passive freezing stage. In the previous paper [5], the emphasis was placed on carrying out a comparative analysis of calculated ice wall thicknesses using different isotherms and the dependence of ice wall thickness decrease at the passive freezing stage. The present paper attempted to deepen and continue the earlier analysis of the dynamics of ice wall thickness at the passive freezing stage. Particular attention was paid to the influence of the duration of the active freezing stage and the distance between the columns on the ice wall condition. The idea of the study is to determine these technological parameters based on the condition of maintaining the design ice wall thickness at the stage of passive freezing.

Mathematical model

We considered the problem of freezing a rock mass by a circular circuit of freezing crowns under the brine scheme. It was assumed that the following physical processes play an essential role in the formation of ice wall in a rock mass [15]:

1) conductive heat transfer (thermal conductivity);

2) phase transition of water in the pores of the rock mass;

3) heat transfer between the rock mass and the brine circulating in the columns.

As a result of movement of brine with negative temperature in the freezing columns, the surrounding rock mass is gradually cooled and frozen. An ice zone is formed in it, where the pore water is considered completely frozen, and a cooling zone, in which the rock mass is not frozen, but has a lower temperature than in natural conditions at a depth in question. The so-called transition zone (mushy zone), where ice and water are present simultaneously, is also sometimes distinguished between the ice zone and the cooling zone [16, 17].

When modeling heat transfer in a frozen rock mass, the following list of simplifications is accepted:

1) the rock mass has isotropic and homogeneous thermophysical properties in the ice and cooling zones;

2) the phase transition of pore water occurs completely in some small given temperature interval;

3) the vertical component of heat fluxes is negligibly small compared to the horizontal one;

4) at the initial moment of time, the rock mass is completely water-saturated;

5) water in the pore space of the rock mass is considered stationary;

6) local thermal equilibrium between solid rock particles, water, and ice in each elementary volume of the watered rock mass;

7) the centers of the mouths of the freezing columns are located on a circle, and the columns themselves are oriented strictly vertically and separated from each other by the same distance.

The third assumption makes it possible to switch from a three-dimensional problem to a two-dimensional one. However, this assumption requires additional comments. It is applicable only if we consider a mid-section of a horizontal layer of rocks of sufficiently large thickness (more than 10 m), and the time interval of modeling in this case is also limited (less than 200 days). In this case, the influence of vertical heat fluxes will initially take place only at the boundaries of the considered layer of rocks with the adjacent upper and lower layers. As time passes, this effect will spread deep into the rock layer and, at a certain point, when it reaches its midline horizontal section, will lead to a significant distortion of the temperature field as compared to the purely two-dimensional case; from that timepoint, the third assumption cannot be applied.

The introduced assumptions 1, 3, 5, and 7 allow concluding that there is rotational symmetry in the problem. This significantly simplifies the geometric model and allows not to consider the horizontal section of the rock mass as a whole, but to consider its separate sector bounded by the two main planes of the ice wall [5]. The geometric model of the sector of a frozen rock mass is shown in Fig. 1. This model was further used for numerical calculations.

In the geometric model of the rock mass layer, there are several boundaries, *S*, *V*, *B* and *I*. The boundary *I* represents the inner boundary of the computational domain. It "cuts off" and removes from the consideration a small volume of the rock mass near the origin of coordinates (the center of the freezing contour). It was introduced to avoid constructing a finite-element mesh around an acute angle touching the rotational symmetry axis of the computational domain. This makes it possible to improve the quality of mesh elements and increase the stability of the numerical solution. The boundary I should be shifted as much as possible to the rotational symmetry axis of the domain so that the "cut off" volume of the rock mass is negligibly small compared to the total volume of the rock mass subjected to thermal influence.

The mathematical model of the rock mass subject to the thermal influence of the freezing columns is based on the energy balance equation in enthalpic form [18, 19]:

$$\frac{\partial H(T)}{\partial t} = \left[\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) \right], \qquad (1)$$

$$\lambda = \lambda_{lq}(1-\varphi_{ice}) + \lambda_{sd}\varphi_{ice}, \qquad (2)$$

where H – specific enthalpy of rocks, J/m^3; x, y – orthogonal coordinates, m; t – time, s; λ_{lq}, λ_{sd} – thermal conductivities of the rock mass in the cooling and ice zones, respectively, W/(m·°C); λ_{ice} – rock iceness, m^3/m^3.

The energy balance equation is supplemented by the equations of state:

$$H(T) = H_0 + \begin{cases} \rho_{lq}c_{lq}(T-T_{lq}) + \rho_w nL, & T_{lq} \le T \\ \rho_w nL\cdot(1-\varphi_{ice}), & T_{sd} \le T < T_{lq}, \\ \rho_{sd}c_{sd}(T-T_{sd}), & T < T_{sd} \end{cases} \qquad (3)$$

$$\varphi_{ice}(T) = \begin{cases} 1, & T < T_{sd} \\ (T_{lq}-T)/(T_{lq}-T_{sd}), & T_{sd} \le T < T_{lq}, \\ 0, & T_{lq} \le T \end{cases} \qquad (4)$$

where H_0 – reference specific enthalpy of rocks at temperature I_{sd}, J/m^3; c_{lq}, c_{sd} – specific heat capacities of the rock mass in the cooling and ice zones, respectively, J/(kg·°C); ρ_{lq}, ρ_{sd} – densities of the rock mass in the cooling and ice zones, respectively,

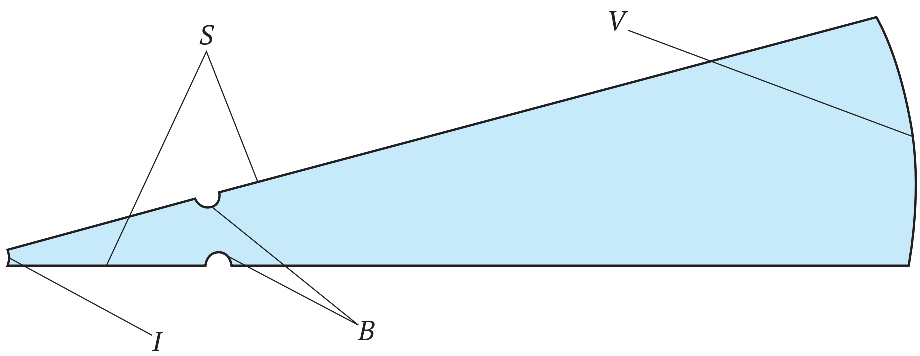

Fig. 1. Computational domain and its boundaries:
S – symmetry; *B* – walls of freezing columns; *V* – outer boundary corresponding to intact rock mass; *I* – inner boundary

kg/m³; T_{lq} – temperature of the beginning of pore water crystallization (or liquidus temperature), °C; T_{sd} – temperature of the beginning of pore ice melting (or solidus temperature), °C; L – specific heat of pore water crystallization, J/kg; n – porosity of the rock mass; ρ_w – density of water, kg/m³.

In addition, model (1)–(4) is supplemented by boundary and initial conditions:

$$\left[\lambda\frac{\partial T}{\partial N}-\alpha(T_{fb}(t)-T)\right]\bigg|_B=0, \quad (5)$$

$$T\big|_V=T_0, \quad (6)$$

$$\frac{\partial T}{\partial N}\bigg|_S=0, \quad (7)$$

$$\frac{\partial T}{\partial N}\bigg|_I=0, \quad (8)$$

$$T\big|_{t=0}=T_0, \quad (9)$$

where $T_{fb}(t)$ – brine temperature in the freezing columns, °C; T_0 – temperature of intact rock mass at a distance from the freezing circuit, °C; α – coefficient of heat transfer from the rock mass to the brine through the wall of the freezing column, W/(m²·°C); N – coordinate along the normal to the considered boundary of the computational domain, m.

The water phase transition from liquid to solid state and vice versa is accounted for in the model by setting the nonlinear function (3) of specific enthalpy H dependence on temperature T. In a short temperature interval [T_{sd}, T_{lq}] this function increases sharply by a value equal to the latent heat of the phase transition $\rho_w nL$ in the unit volume of the watered rock mass. This approach to accounting for the phase transition is called enthalpic and is widely used in problems with phase transformations in solids [16, 18].

Same to studies [5, 10], the emergency operation mode of the freezing system is connected with shutdown (failure) of one of the freezing columns at the moment of transition to the passive freezing mode. The freezing column shutdown is modeled by setting a zero heat transfer coefficient in the time interval starting from the moment of transition to the passive freezing mode.

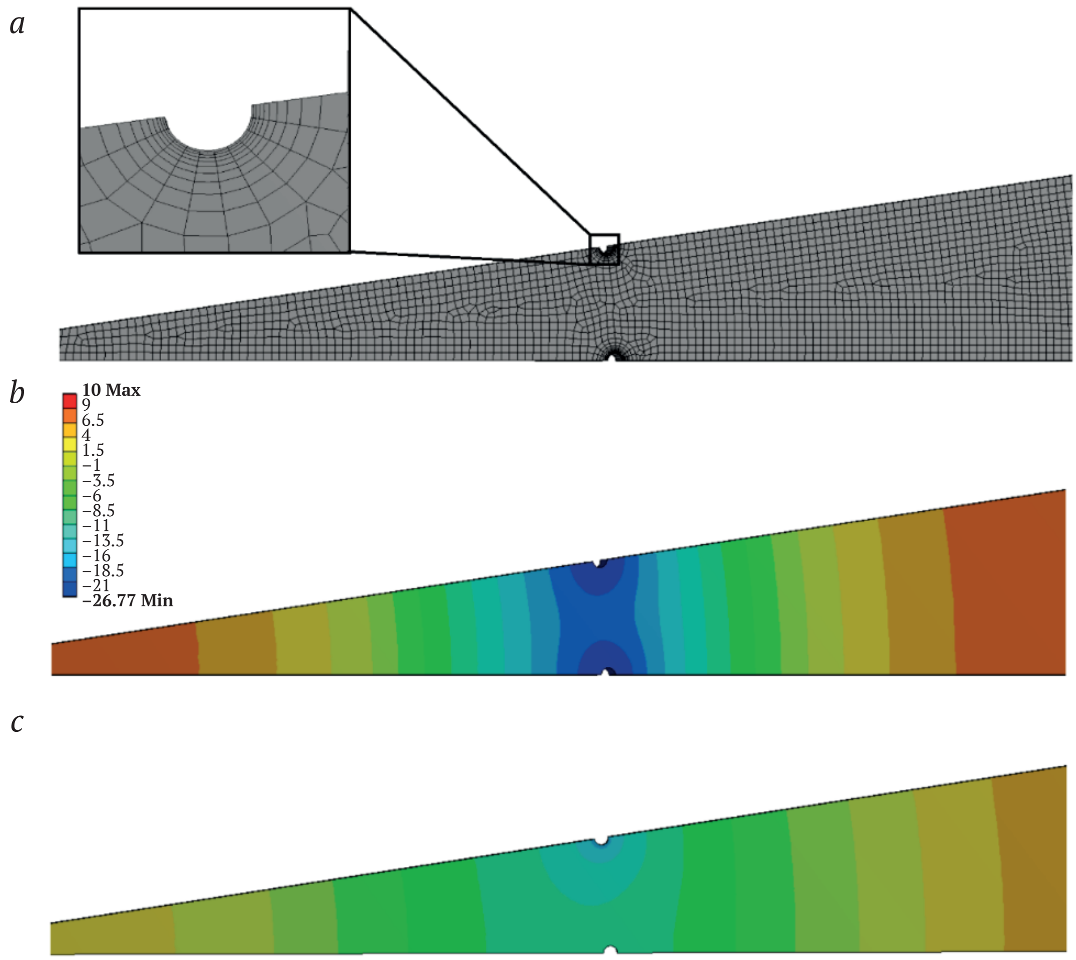

Fig. 2. Finite-element model of the rock mass layer (*a*), calculated temperature distribution in it at the stage of active freezing (*b*) and at the stage of passive freezing during emergency shutdown of one of the columns (*c*)

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The authors believe that the passive freezing mode is the most dangerous in terms of faults and accidents. This is due to the fact that, firstly, at the beginning of the passive freezing mode (stage), a change in the operating mode of the freezing station occurs, which itself increases the risk of failure of individual elements of the freezing system. Secondly, shaft sinking and supporting are carried out exactly at the stage of passive freezing. In the practice of shaft construction, there were many cases when freezing columns failed due to severe deformation of rocks before the erection of the advancing concrete support [2, 20, 21]. In addition, shutdown of part of the freezing columns is one of the possible measures to reduce the amount of heat withdrawn from the rock mass during the passive freezing stage [14, 22].

In addition, at the end of the active freezing stage, additional measuring procedures are often carried out in shafts under construction, aimed at verifying that the continuous ice wall reaches the specified thickness [23, 24]. These measurements can be carried out both in control and in freezing wells (e.g., ultrasonic control or thermometric measurements). This also increases the risk of damage to the freezing columns.

Numerical modeling technique

A numerical solution for the problem (1)–(9) was found using the finite element method in the ANSYS software package (Thermal Transient module). The solution was constructed on a grid consisting of rectangular elements (see Fig. 2, *a*). The size of the grid elements in the computational domain and the grid thickening parameters near the freezing columns were selected on the basis of preliminary modeling so as to ensure that the solution was independent of the discretization method.

As parameters for the numerical calculations, the initial data for the rock freezing project for the conditions of the potash mine shafts under construction in the Republic of Belarus were taken. The clay layer was investigated as one of the most thermally conductive layers in the interval of the being frozen rocks. The main thermophysical properties of the rock layer under consideration are presented in Table 1. The density of rocks in the ice zone was assumed to be equal to the density of rocks in the cooling zone. The thermal conductivities in the ice and cooling zones presented in the Table are atypical for the clay layer in question. This is due to several factors: the presence of sand interlayers in the clay, high in-situ pressure (about 1 MPa), and low porosity. In addition, it should be noted that the rock thermal conductivity and humidity values indicated in Table 1 were slightly (within 15 %) corrected in comparison with their initial values in the process of thermophysical model adjustment based on temperature measurements in control thermal wells at the construction site.

Table 1

Thermophysical properties of clay layer

Property	Value
Thermal conductivity (ice zone), W/(m·°C)	4.30
Thermal conductivity (cooling zone), W/(m·°C)	2.64
Heat capacity (ice zone), J/(kg·°C)	900
Heat capacity (cooling zone), J/(kg·°C)	1712
Initial temperature of rocks, °C	10
Liquidus temperature, °C	–0.4
Solidus temperature, °C	–0.9
Density (kg/m^3)	1840
Porosity, decimal quantities	0.158

At the active freezing stage, freezing brine moves in the columns at constant temperature of –30.4 °C. When passing to the passive freezing stage, the brine temperature uniformly rises to –20 °C during 5 days. The flow rate of the freezing brine during the active and passive freezing stages is constant and amounts to 240 m^3/h. The heat transfer coefficient calculated according to the method given in [5] is 62.5 W/(m^2·°C). The outer boundaries of the ice wall were determined by the isotherm T_d = –8 °C, at which the design thickness of the ice wall was calculated based on the strength and creep conditions.

The radius of the outer boundary of the computational domain is 40 m, and the radius of the inner boundary (cut off zone) is 0.25 m. The contour of the freezing columns has a radius of 8 m. The freezing columns have an outer diameter of 0.146 m and an inner diameter of 0.136 m. The distance between the centers of neighboring freezing columns was assumed to be about 1.2 m (the case of 42 freezing columns, distant from each other at the same distance).

Fig. 2, *b* shows the calculated temperature distribution in the sector under consideration for the moment of time of 50 days (the active freezing stage). The smallest value of the ice wall thickness at the stage of active freezing was observed along the lock plane of the ice wall, while at the passive stage, at emergency shutdown of one of the freezing columns (see Fig. 2, *c*, time moment of 100 days), it was observed along the main ice wall plane. For this reason, the minimum of the two thickness values calculated along the main plane and the lock planes of the ice wall was taken as the ice wall thickness.

Influence of the active freezing time on the ice wall condition

Time dependences of ice wall thickness were calculated for several different variants of transition to passive freezing: after 50, 100 and 150 days (Fig. 3). The dashed line represents the curves corresponding to the emergency shutdown of one of the freezing columns, and the solid line represents the accident-free transition to the passive freezing stage.

Analyzing Fig. 3 allowed concluding that during the transition to passive freezing in both emergency and normal modes, a short-term decrease in the ice wall thickness took place. This was evidenced by the characteristic "depressions" on the curves of ice wall thickness dynamics. They were especially characteristic for the case when the duration of the active freezing stage was minimal and amounted to 50 days. As the duration of active freezing increased, the depth of these "depressions" decreased, and eventually, starting from a certain point in time, the decrease in the ice wall thickness at the passive freezing stage stopped. In the case under consideration, this point in time was between 100 and 150 days.

The depth of the "depressions" in the ice wall thickness – time curves in Fig. 3 can be estimated by introducing the following quantitative criterion: the maximum ice wall thickness decrease ΔE [5]:

$$\Delta E = \max(0;\ E_a - E_d), \tag{10}$$

where E_d is the design (minimum permissible) thickness of ice wall, which was achieved at the end of the active freezing stage, m; E_a is the minimum thickness at the passive freezing stage, m.

In [5], a detailed quantitative analysis of this criterion for two rock layers, clay and chalk, was produced. As a result, it was found that at small durations of active freezing of a rock mass (less than 100 days), the decrease in ice wall ΔE thickness essentially nonlinearly depends on the duration of active freezing that was connected with the features of heat transfer near the internal and external ice wall fronts.

In the present paper, we focused on another interesting fact about criterion (10). For longer periods of active freezing of a rock mass (more than 100 days), the value ΔE decreases with increasing duration of the stage of active freezing of rocks and eventually turns to zero, both in the case of trouble-free operation of the freezing system and in the emergency case of shutdown of one of the freezing columns. Physically this conclusion is logical in view of the fact that the longer the stage of active freezing lasts, the deeper the rock

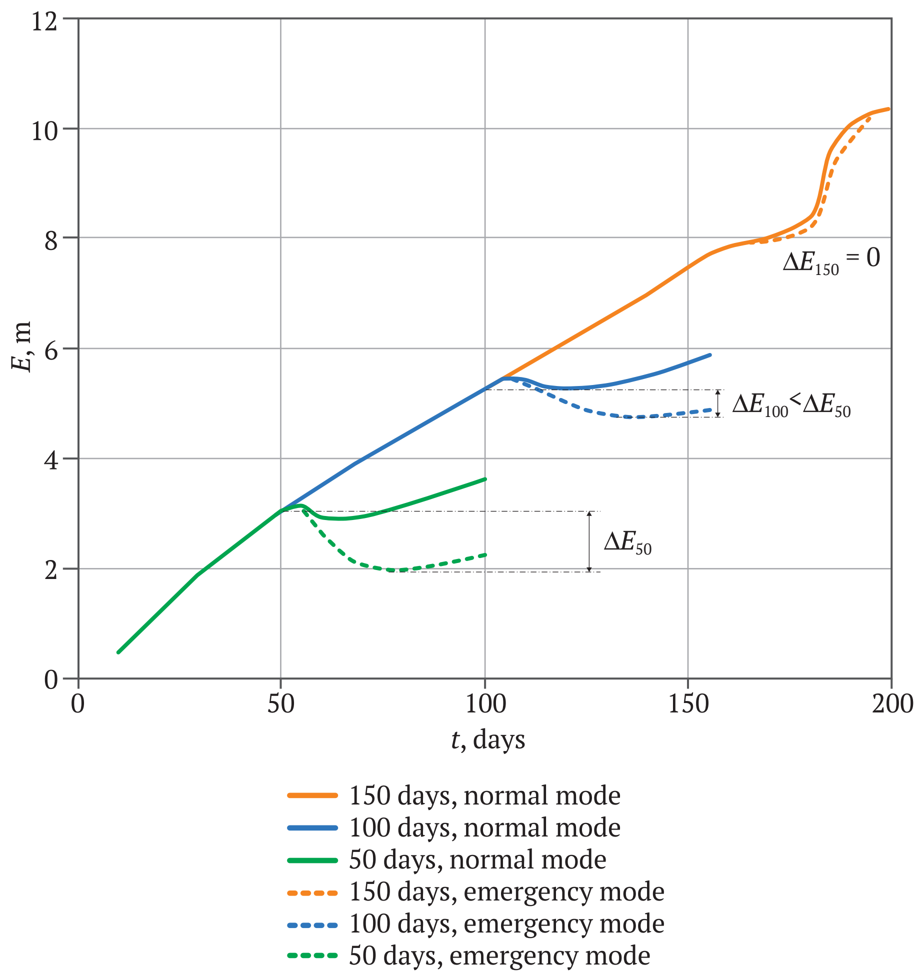

Fig. 3. Dynamics of ice wall thickness E (m) during the transition to passive freezing

mass can be cooled and frozen and, consequently, the higher the persistence ("inertia") of heat flows in it. Persistence in this case means the ability of the frozen rock mass to maintain negative temperatures for a long time after the cooling productivity of the freezing station was reduced.

In view of this conclusion, it is reasonable to select the duration of active freezing of rocks based on condition $\Delta E = 0$. This condition, in fact, means that at the stage of passive freezing, the ice wall thickness should not decrease to the values below the design ones. For the rock layer in question, the minimum duration of the active rock freezing stage, at which $\Delta E = 0$, is met, is about 130 days or about 4.3 months.

Influence of column spacing on ice wall formation

It is of interest to study the dependence of criterion ΔE on the distance between two adjacent freezing columns. In the present study, such analysis was carried out for the clay layer. Fig. 4 shows the dependences of the criterion ΔE on the distance a between two neighboring freezing columns for active freezing duration of 50, 100, 120, 130 and 150 days for the case of emergency shutdown of one of the freezing columns, as obtained by numerical simulation. Five different distances between the freezing columns were considered: 0.72, 0.96, 1.2, 1.44 and 1.68 m. Analysis of the distances between the freezing columns of 0.7 m and less is meaningless due to the difficulty or impossibility of implementing such distances in practice, taking into account the designed deviations of the positions of the freezing columns from the vertical.

Quite a natural fact follows from Fig. 4: the criterion ΔE is a monotonically increasing function of the distance between neighboring freezing columns. The longer the active freezing period, the stronger the rock mass is cooled and frozen and the lower the value of criterion (10), and the smaller the negative effect of the sudden shutdown of the freezing column. On the whole, the functional form of the criterion $\Delta E(a)$ is significantly non-linear.

For 50 days of active freezing, non-zero reductions in ice wall thickness were observed for all considered freezing column spacing values. For 150 days of active freezing, criterion (10) turned to zero for all the considered distances, except for 1.68 m. For the most common in practice distances between freezing columns (from 1.1 to 1.3 m), the ice wall thickness will decrease if the time of active freezing is less than 130 days.

As noted in [5], the ice wall thickness by the isotherm of actual water freezing (around 0 °C) does not decrease and maintains a positive growth rate throughout the entire period of passive freezing, regardless of the duration of active freezing. At the same time, as can be seen from the calculations produced here, the decrease in ice wall thickness by the −8 °C isotherm is significant, and hence the decrease in the average ice wall temperature is also significant, if the latter is calculated by the isotherm of actual water freezing. This indicated imaginary reliability of

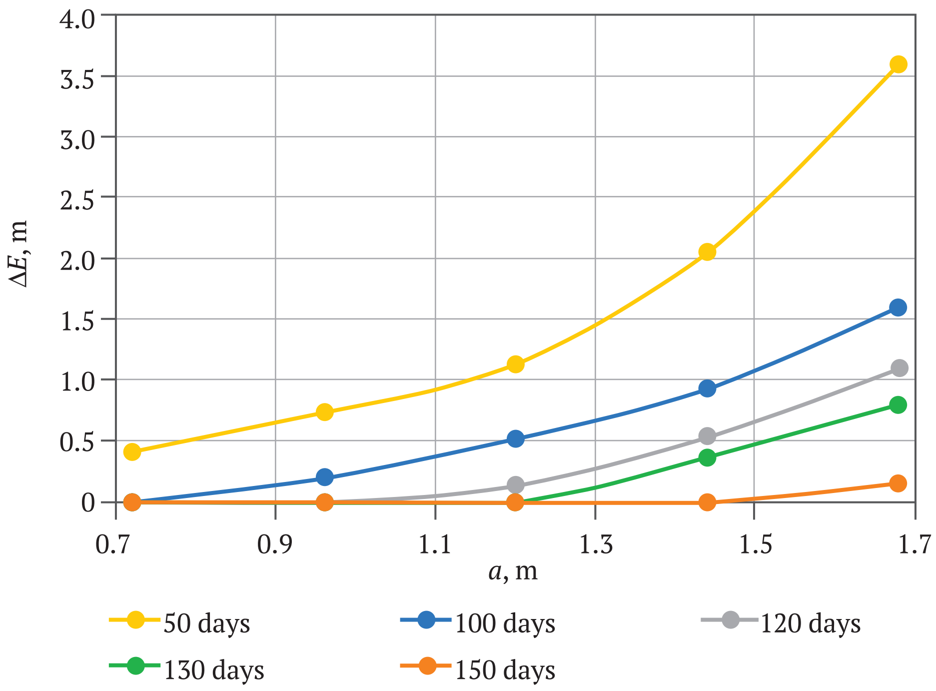

Fig. 4. Maximum ice wall thickness decrease ΔE (m) as a function of the distance between two neighboring freezing columns (m)

ice wall, the thickness of which was determined by the isotherm of actual freezing of water.

The safe distance between the freezing columns, at which no significant decrease in ice wall thickness takes place, depends on the design time of active freezing of the rock mass. Longer active freezing time is more preferable, since in this case it is possible to reduce the decrease in ice wall thickness caused by the transition to the passive freezing mode and the shutdown of one of the freezing columns. If condition $\Delta E = 0$ m, is taken as a safety criterion when selecting the distance a, then for 100 days of active freezing the value of a is about 0.7 m, while for 150 days of active freezing, the value amounts to about 1.5 m. Taking into account that in practice the distances between neighboring freezing columns are usually in the range of 1.1 to 1.3 m, it is sufficient to require that the time of active freezing of the rock mass is not less than 130 days (about 4.3 months). The estimated safe time of active freezing is true only for the considered clay layer.

For larger values of distance a, the time of active freezing should be selected on the basis of Fig. 4 or similar quantitative assessments using criterion (10) or similar criteria. Naturally, selection of the time of active freezing of rocks should also be based on a number of other criteria, for example, the minimum time of freezing of rocks to the design thicknesses. This criterion, together with the proposed criterion ΔE will make it possible to determine the optimal operating mode of a freezing station during the stages of active and passive freezing.

It is important to note that the results obtained in the paper correspond to the case of a fairly sharp increase in the brine temperature during the transition to passive freezing and further maintenance of this value over time throughout the passive freezing stage. There is also an alternative approach to ensuring a given ice wall thickness at the passive freezing stage, involving smooth changing the brine temperature (and flow rate, if necessary) over a long time interval. However, this alternative approach turns out to be not always applicable due to the limited technical capabilities: often the refrigeration equipment used in shaft construction does not allow flexible control of the refrigeration capacity [25].

Conclusion

A theoretical study of changes in the ice wall thickness during the passive freezing stage in normal and emergency operation modes of a freezing station was carried out. As an example, the clay layer from the interval of being frozen rocks as applied to the case of the shafts under construction of a potash mine in the Republic of Belarus was considered. The main findings of the study are given below:

1. When selecting the duration of the active rock freezing stage, it is necessary to take into account the condition of maintaining the design thickness of the ice wall at the passive freezing stage. Fulfillment of this condition strongly depends on the extent to which the rock mass was cooled into the depth. For the clay layer in question, it was found that the minimum duration of the active rock freezing stage, which ensured the design ice wall thickness during passive freezing, was about 4.3 months.

2. When analyzing the changes in ice wall thickness at different distances between the freezing columns, it was found that the most common column spacing in the range from 1.1 to 1.3 m requires observing restrictions on the duration of active freezing to prevent a critical decrease in ice wall thickness during the passive freezing stage or decreasing the distance between the freezing columns. In this case, preservation of positive dynamics of ice wall thickness growth is ensured. For the clay layer considered in the study and the distance between the columns from 1.1 to 1.3 m, the minimum time of active freezing is also about 4.3 months.

The above conclusions are important in view of the current trend to reduce the time of active freezing of rocks in order to accelerate the construction of mine shafts. For example, for the conditions of the shafts under construction at several potash mines in Russia and Belarus the design time of active freezing is from 3 to 4 months. It should be remembered that reducing the active freezing time may not be safe due to a potential decrease in ice wall thickness and loss of its continuity when shifting to passive freezing with possible emergency shutdown of one or more freezing columns.

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