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Research of Reliability Criteria of Ice Wall in Monitoring and Control of Artificial Freezing of Rocks

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Исследование критериев надежности ледопородного ограждения при контроле и управлении искусственным замораживанием горных пород

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artificial freezing, rock, ice wall, thermometric control, temperature field, isotherm, criterion, freezing mode, control.

Three thermodynamic criteria of ice wall reliability are investigated, which determine and combine its thickness and temperature in different ways. Boundary isotherms for different criteria are determined based on 1) the freezing temperature of rock water; 2) the temperature for which the ice wall thicknesses were calculated based on strength and creep conditions, and 3) a floating temperature value determined based on ensuring a specified average temperature in the ice wall volume. The considered criteria are used in the process of thermometric monitoring of the ice wall condition when assessing its bearing capacity. Each criterion was described in detail, the sufficient conditions for the reliability of the ice wall associated with it were presented, and the problem of optimal control of the coolant temperature increase mode, which could be solved with its use, was presented. A comparative analysis of the criteria was carried out from the standpoint of optimal control of the artificial freezing mode, ensuring the minimum possible energy costs for maintaining the ice wall during its life cycle while maintaining the required safety of mining operations. The "optimal" mode of operation of the freezing station within each criterion was determined by a series of numerical calculations of the thermophysical problem in the specialized software product FrozenWall. Based on the results of the study, the third, most flexible criterion with a floating temperature value determining the boundary isotherms of the ice wall from the condition of constancy of the average temperature in the volume of frozen rocks was recommended for practical application. For the other two criteria, the temperatures of the ice wall boundaries are rigidly fixed, which significantly limits the upper limit of the increase in the temperature of the coolant in the brine network and leads to lower energy efficiency of the freezing system as a whole. The results of the work will be useful to specialists in the field of thermometric control in the construction of mine workings using the method of artificial freezing of rocks.

Ключевые слова:
искусственное замораживание, горная порода, ледопородное ограждение, термометрический контроль, поле температур, изотерма, критерий, режим замораживания, управление.

Исследуются три термодинамических критерия надежности ледопородного ограждения (ЛПО), различным образом определяющие и сочетающие его толщину и температуру. Граничные изотермы для различных критериев определяются, исходя из 1) температуры замерзания породной воды; 2) температуры, для которой рассчитывались толщины ЛПО по условиям прочности и ползучести, а также 3) плавающего значения температуры, определяемого исходя из обеспечения заданной средней температуры в объеме ЛПО. Рассматриваемые критерии используются в процессе термометрического мониторинга состояния ледопородного ограждения при оценке его несущей способности. Каждый из критериев детально описан, приведены связанные с ним достаточные условия надежности ледопородного ограждения и задача оптимального регулирования режима повышения температуры хладоносителя, которую возможно решить с его применением. Проведен сравнительный анализ критериев с позиций оптимального управления режимом искусственного замораживания, обеспечивающим минимально возможные энергетические затраты на поддержание ЛПО в течение его жизненного цикла при сохранении требуемой безопасности ведения горных работ. Определение «оптимального» режима работы замораживающей станции в рамках каждого критерия осуществлялось посредством серии численных расчетов теплофизической задачи в специализированном программном продукте FrozenWall. По результатам исследования к практическому применению рекомендован третий, наиболее гибкий критерий с плавающим значением температуры, определяющей граничные изотермы ЛПО из условия постоянства средней температуры в объеме замороженных пород. Для двух других критериев температуры границ ЛПО жестко фиксированы, что существенно ограничивает верхний предел повышения температуры хладоносителя в рассольной сети и приводит к меньшей энергоэффективности системы замораживания в целом. Результаты работы будут полезны специалистам в области термометрического контроля при строительстве горных выработок с применением способа искусственного замораживания горных пород.

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Introduction

The sinking of vertical mine shafts with preliminary artificial freezing of soils is used in difficult hydrogeological conditions in the presence of watered unstable (loose or weakly cemented) rocks in the section, less often – in watered stable rocks when water suppression by other methods is impossible. The method of artificial freezing is one of the most effective methods for strengthening watercut soils and is widely used in the construction of mine shafts and mines, horizontal workings and tunnels [1–8].

The ice wall (IW) formed during freezing plays the role of a temporary support and is designed to solve two main tasks: 1) hydraulic (anti-filtration) – preventing the filtration of groundwater into the mine under construction and 2) mechanical - maintaining the integrity of the walls of the mine until the completion of work on its fastening [9–10].

The required waterproofing properties of IW are provided by reducing the pore and fracture permeability of the rock to a value which does not allow groundwater filtration at a given hydraulic head.

The required mechanical characteristics of IW are ensured by achieving the required rock strength and its low creep for a given time under the influence of external load in the form of the sum of rock and hydrostatic pressure.

When modelling in the process of studying various aspects of the behaviour of the massif of soils under the influence of artificial freezing or defrosting, the vast majority of modern researchers consider the problem in the most complete thermohydromechanical formulation [11–17].

In practice, it is difficult to control the two tasks of mechanical and hydraulic control during artificial freezing, so an indirect assessment is made on the basis of the relationship between physical and mechanical parameters and thermodynamic parameters, i.e. temperature and volume of frozen rock. Thus, when controlling the formation and condition of IW in the process of mine shaft construction, thermodynamic criteria come to the forefront and serve as a basis for other criterion assessments. Their observance is a priority and sufficient condition for simultaneous solution of mechanical and hydraulic problems and judgement on IW reliability [18].

In formalised form, the analysis of the thermodynamic state of the ice wall is usually reduced to a comparison of its actual minimum thickness and average temperature with the required values determined for each rock layer at the design stage, where the thickness is determined along a given radial direction from the centre of the shaft through the IW body. The thermometric method is the main method, supplying initial data for continuous monitoring and providing feedback between the artificial freezing effect and the response of the environment to it.

Assessment of IW thickness and temperature, let us call them performance characteristics, are based on mathematical (thermophysical) modelling, which makes it possible to reconstruct the temperature field in the rock massif with a certain accuracy from discrete measurements. In this case, the IW configuration is determined by isotherms of the temperature field and can be studied in any plane cutting the frozen rock volume [19].

In general, the mechanical task imposes more stringent requirements to the IW condition than the hydraulic one. It is traditionally considered that to prevent subjacent filtering it is necessary to freeze water in the pore-crack space of the rock, to "lock" it in some part of the massif. Whereas, to ensure the criteria of IW non-destruction and small deformations of the unfixed shaft wall during sinking, it is necessary to freeze the rock in a certain volume to a certain negative temperature. The latter simultaneously ensures the solution of the hydraulic problem, i.e. (1) reduction of rock permeability and (2) prevention of its destruction during sinking with formation of through cracks and secondary permeability, since in the latter case groundwater penetration into the workings under construction is inevitable. Therefore, in this study, compliance with thermodynamic criteria is considered in connection with ensuring mechanical conditions of IW reliability during operation, and they are compared in terms of their applicability to solving the problem of optimal control of artificial freezing during the IW maintenance period.

Flexible control of the freezing complex operation mode depending on the construction process and actual situation development is called "freezing on demand concept" [20, 21] or Freezing on Demand (FoD) [22, 23]. [20, 21]. The application of this concept became possible with the development of means of automatic monitoring of physical processes occurring in the rock massif under anthropogenic load. It is based not only on new means of automation of measurements, but also on a powerful tool of mathematical modelling with the development of a detailed thermophysical model which takes into account the thermal influence of all kinds of natural and anthropogenic sources. In general, freezing in the "on-demand" concept makes it possible to significantly reduce operating costs at the stage of IW formation and maintenance and to increase the safety of mining operations under its protection, as it allows not only to monitor in advance the precursors of possible negative development of the process, but also to promptly perform prediction calculations, develop on their basis and implement compensating measures.

Technology of brine freezing of rocks, monitoring of IW condition and control of artificial freezing mode

The technology of artificial freezing of rocks by brine method is sufficiently described in the literature [10, 24–26]. The area of the rock massif, which needs to be strengthened and made waterproof, is "pierced" by special freezing boreholes. Each borehole is equipped with a freezing column in which a coolant – aqueous salt solution (brine) circulates, which does not freeze at low subzero temperatures.

The freezing columns are combined into a closed brine network with circular brine lines located in the freezing gallery around the mine shaft mouth and above-ground main brine lines supplying brine to the refrigeration equipment. Pumps built into the above-ground part of the brine network ensure circulation of the coolant in the brine pipelines and freezing columns, and the refrigeration equipment ensures its constant cooling to the required temperature. Together with the control unit, they form a single freezing station complex.

Artificial freezing is controlled through the control of the freezing complex operating mode and is expressed in the possibility of regulating two determining parameters: temperature *Tc* and flow rate *Vc* of the coolant in the brine network. Changing the coolant flow rate determines to a lesser extent the intensity of the freezing process while maintaining fluid flow regime in the freezing columns (laminar or turbulent), gives less economic effect of reducing the cost of pumping equipment operation. Besides, the permissible variations of the coolant flow rate are limited by the limits imposed by the refrigeration equipment, which requires minimum coolant flow through the heat exchanger unit.

The main regulation of the operation mode of the freezing complex is carried out by changing the temperature of the coolant. Depending on the capabilities of refrigeration machines, the temperature increase can be smooth and carried out by changing the setpoints or stepwise – by taking the refrigeration unit out of operation. In any case, it is the control of the coolant temperature that allows to influencing the freezing process most effectively and reducing economic costs. Further in this paper, the control of artificial freezing will be understood as a change in the temperature of the coolant at a constant flow rate in the brine network.

Control is impossible without feedback on the change in thermodynamic parameters of the rock mass in response to freezing action [27]. Modern engineering science makesit possible to deploy an intelligent system of thermometric control the IW condition at the site of the mine under construction [28], the general principle scheme of interaction of its elements is presented in Fig. 1.

At the mine shaft construction site, several control-thermal (CT) boreholes are installed to monitor the temperatures of the frozen massif, usually one borehole for every 10 freezing columns. Temperatures are measured by means of fibre optic cable lowered into thermometric columns of CT wells filled with heat-conducting liquid, most often coolant circulating in the freezing columns.

Data from CT wells are processed on the information-analytical server, where all necessary calculations are made, on the basis of which recommendations are developed to maintain or change the current mode of operation of the freezing station with subsequent control of the medium response to the applied impact.

Procedure of calculating IW parameters in the process of thermometric control

In order to understand how useful each of the criteria described below is in practical application, it is firstly necessary to describe the procedure for calculating the IW parameters in thermometric control of artificial freezing. The process is based on mathematical modelling, for which a detailed thermophysical model of the medium is developed, capable to consider all influencing thermal factors of natural and anthropogenic genesis [29, 30].

Modelling is carried out by numerical methods of calculation in the FrozenWall software package [31]. Due to the significant labour intensity and time constraints imposed by the applied nature of the problem (reports on the state of the IW must be generated daily), the restoration of the temperature field in the rock massif

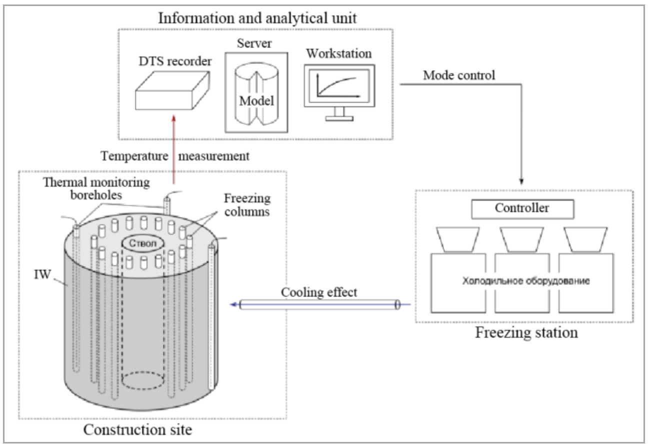

Fig. 1. Schematic diagram of the thermometric control and control of artificial freezing of rocks at the shaft construction site

surrounding the future mine shaft is usually performed in a two-dimensional formulation, i.e. in the *Oxy* horizontal plane. The geological section is represented as a system of enlarged horizontal layers with a thickness of more than 5 m, with the calculated depth mark referring to the middle of each layer.

With the help of mathematical modeling using the developed thermophysical model, the temperature field at a given point in time and is presented in the form of a map of isotherms (Fig. 2).

The minimum thickness of the IW is defined as the minimum distance between the isotherms with a given temperature value running inside and outside the contour of the freezing columns [18, 32]. The calculation is automated by a special algorithm, as well as the procedure for determining the average temperature of the IW for a given profile, for example, for the OA profile, as shown in Fig. 2.

Three thermodynamic criteria of IWs Reliability

Before proceeding directly to the criteria for the reliability of IW, let us consider the difference between the theoretical formulation of the problem of static calculation of its thickness and the real situation observed in the process of artificial freezing. Let us consider the relative location of the center of the mine shaft under construction, defined at point O, and the freezing columns located at points A and B, in the projection on the earth's surface (view from above) and determine the necessary names of vertical cutting planes (Fig. 3). The plane passing along the *AB* line through two adjacent freezing columns is usually called the axial plane; along the *OB* line, i.e. through the center of the shaft and any freezing column, – main one; along the line *OP* through the centre of the shaft and the middle of the segment *AB* – lock one [10].

Let us assume the case when all freezing columns operate in normal mode, i.e. there are no columns switched out of use or not providing normal heat flow for any reason, for example, if the coolant flow rate in a column is significantly reduced relative to the others. Physical-mechanical and thermophysical properties of the medium are isotropic, and the medium itself is homogeneous. In such a case the IW will have the smallest thickness in the lock plane. Hereinafter *OP* direction will be taken as providing the minimum IW thickness. It is for this plane that the main conclusions will be drawn.

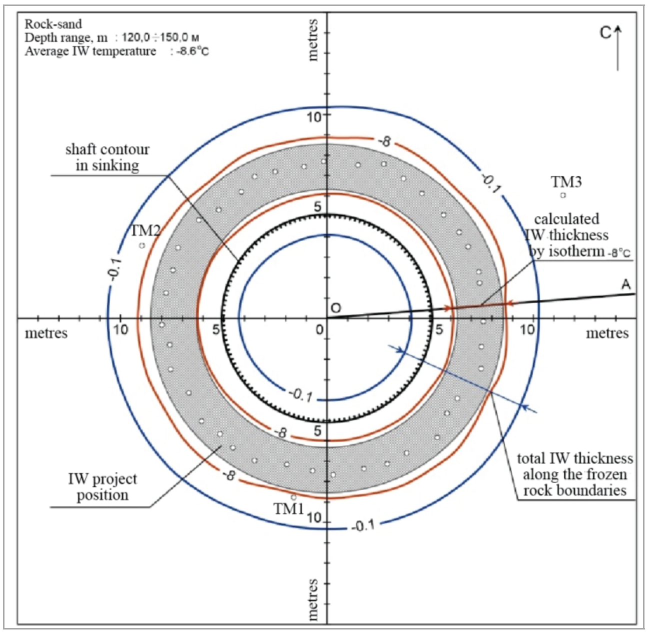

Fig. 2. Main elements of IW on the isotherm map

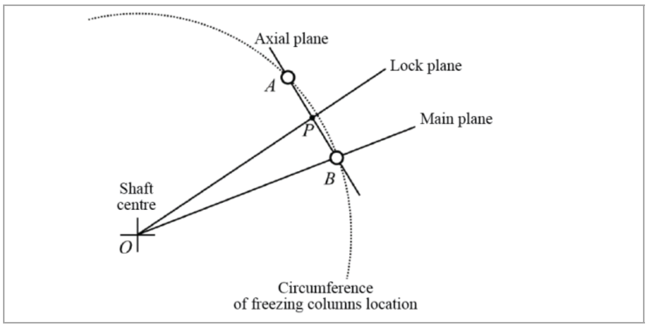

Fig. 3. Schematic location of freezing columns relative to the centre of the shaft in projection on the ground surface with marking of projections of secant planes

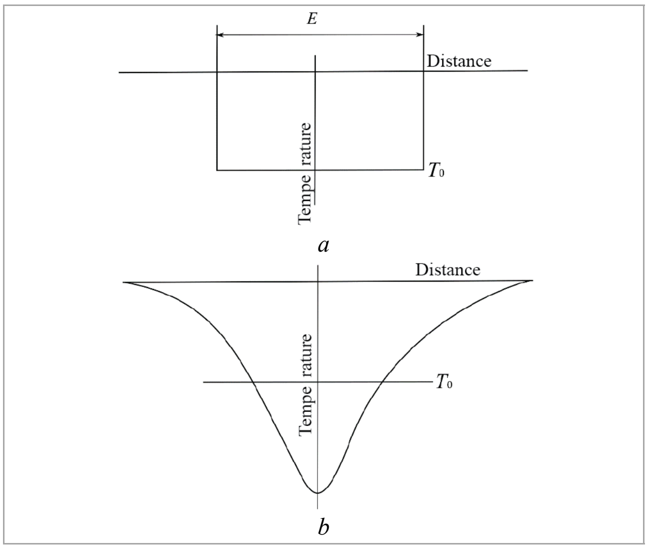

Fig. 4. Rock temperature distribution in the lock plane: idealized theoretical (*a*) and real smooth (*b*)

Fig. 4 schematically illustrates the temperature distribution along the radial profile from the centre of the shaft in the lock plane in two variants corresponding (see Fig. 4, *a*) to the mathematical formulation of the problem of static calculation of IW for strength and creep, and (see Fig. 4, *b*) to the real situation. The vertical axis passes through the point P, where in the case (see Fig. 4, *b*) the minimum of non-uniform temperature distribution is located. In the case of the mathematical formulation, the temperature distribution inside the IW is assumed to be uniform with some given temperature of the solid rock T_0 and its discontinuity at the transition to the unfrozen rock. The external load is applied to this boundary. Formulas for static calculation of IW thickness, for example, the formulas of Läme, Domke [33, 34], Vyalov [9], which do not account for the non-uniform character of temperature distribution inside it, are derived for the mathematical formulation according to the type shown in Fig. 4, *a* [35].

At present, attempts have been made to bring the existing formulas of static calculation closer to reality [36], to take into account the uneven distribution of temperatures in the frozen rock mass [37, 38]. However, the latter requires detailed information about the relationship between the strength and deformation characteristics of frozen rock and temperature.

From a practical point of view, this means performing laboratory core strength and creep tests for each lithological difference in the freezing interval at the mine shaft construction site. Moreover, the tests of each frozen rock sample must be carried out at a series of negative temperature values.

Such studies are very resource-intensive and therefore are rarely performed at the pre-project stage of the survey. Usually all laboratory tests of rocks are carried out at one single value of negative temperature, chosen empirically – it should: a) be below the freezing point of water in all present lithological differences; b) provide a high percentage of water freezing in pores but at the same time c) not be too low.

Since the mechanical (strength and deformation) characteristics of the frozen rock are directly related to its temperature [39–41], the uneven temperature distribution in case (*b*) entails the uneven distribution of mechanical parameters within IW [42]. In this case, there is no sharp contact between the frozen solid rock with a temperature of T_0 and the unfrozen part of the massif, as in the case of (*a*). It should be noted that the temperature of frozen rock T_0 in practical calculations corresponds to the temperature at which laboratory geomechanical tests of frozen soils are carried out with the determination of their strength and deformation characteristics.

In the temperature distribution by type (*b*), the part of the frozen rock adjacent to the non-frozen mass will have a temperature above T_0, the other part adjacent to the freezing columns will have a temperature below T_0. Accordingly, the mechanical characteristics of the rock composing these parts of the IW will be lower and higher than similar values determined in the temperature T_0 tests.

As a result of the differences in the theoretical and practical formulation of the problem, there is uncertainty in the choice of practical criteria for assessing the IW reliability in the thermometric method of monitoring its condition. For example, laboratory soil tests have been performed on core samples with a temperature of T_0, and the calculated value of the minimum required thickness E_0 according to the strength and creep criteria is calculated based on the characteristics obtained from these tests. Let's designate T_0 as the temperature of frozen solid rock. The T_0 and

E_0 values act as design criteria for the reliability of the IW, compliance with which ensures its non-destruction under the influence of external load and the permissible value of deformation of the shaft rock wall until the moment of its consolidation.

There are three possible combinations of thickness E and temperature T parameters that can be used as criteria for determining the IW reliability:

1) the IW thickness E is determined by the temperature of the beginning of water freezing in the rock (let us call it the temperature boundary of frozen rock), while its average temperature in the lock plane should correspond to the temperature of solid rock T_0, i.e. the condition $\overline{T} \le T_0$;

2) IW thickness E is determined by the minimum distance between isotherms with solid rock temperature T_0, average IW temperature in this case is not monitored;

3) inside the IW a zone with average rock temperature is specially selected, then the IW thickness E is determined by the boundaries of this zone.

Let us consider each of the criteria separately from the point of view of convenience of their use in controlling the freezing mode.

Criterion 1

In practice, there is no stepped distribution of temperatures with sharp boundaries (Fig. 5, *a*), which is characteristic of the mathematical formulation of the problem of static calculation of the IW for strength and creep. When determining the boundaries of IW by the temperature of the beginning of water freezing in its pores inside the wall, two zones can be distinguished: <1> – the frozen rock here has a temperature above the required average value equal to the temperature of the solid rock T_0, which means that it has a strength deficit and greater creep relative to it; <2> – he frozen rock here has a temperature below the required average value, and therefore has a reserve in strength and deformation characteristics

Are the formulations presented in Fig. 5 equivalent from the point of view of the stress-strain state of a frozen rock massif? Obviously, no. What is the degree of their inconsistency, in particular, was indicated in [42]. Without focusing on the geomechanical aspect of criterion 1 let us consider the expediency of its application from the point of view of rocks artificial freezing control.

Let A be the IW reliability condition, otherwise – if A is met, then the IW fully meets the conditions of safe sinking. Let us write down the sufficient condition for the truth of statement A from the point of view of the criterion 1:

$$B := \left(E \ge E_0\right),\quad C := \left(\overline{T} \le T_0\right),\quad B \wedge C \Rightarrow A. \tag{1}$$

From the position of mathematical logic, the implication is not equivalent, since there are other states A in terms of LPO thickness and frozen rock temperature that meet the conditions of safe sinking.

Let's assume that at some moment of time t_0 the IW state has become minimally satisfying criterion 1, i.e. the IW thickness E along the frozen rock boundaries has

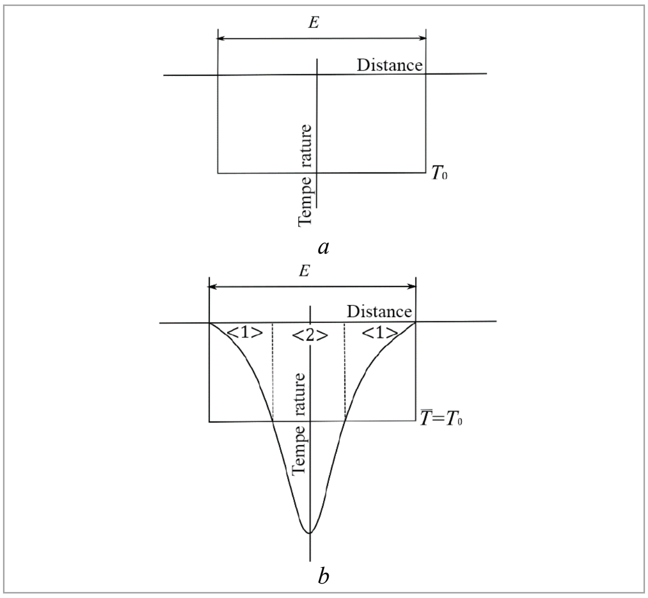

Fig. 5. Determination of the degree of reliability of IW in the idealized theoretical formulation (*a*) and in practice using criterion 1 (*b*)

reached the minimum required value E_0, and at the same time its average temperature in the lock plane is equal to the solid rock temperature T_0. This fact is the basis for transferring the freezing complex to the less energy-consuming passive freezing mode.

Finding the optimal schedule for increasing the temperature of the coolant $T_c = T_c(t)$ in freezing columns when solving the optimization problem should simultaneously ensure the preservation of IW reliability according to criterion 1 and the prevention of expansion of its boundaries, that is, maintain the minimum permissible state of IW within the framework of criterion 1, which can be mathematically written as:

$$T_c = T_c\left(t\right):\ A_t\left(E,T\right) \to \min_{t>t_0} B_t \wedge \max_{t>t_0} C_t. \tag{2}$$

In connection with the problem of optimizing the freezing mode let us consider the problem of determining the boundaries of IW in the projection on the Cartesian plane Oxy (view from above), considering their position unchanged in the vertical coordinate z. Let S_{in} and S_{out} are projections of the inner and outer boundaries of IW on the specified plane determined by the temperature of the beginning of water freezing in the rock, and the points of $M \in S_{in}$ and $N \in S_{out}$ are located in such a way that $d\left(M,N\right) = \min_{Oxy} d\left(S_{in},S_{out}\right)$, where $d\left(M,N\right)$ – Euclidean distance in the lock plane in the direction $\overrightarrow{MN}$ of the least thickness Suppose that at the moment of time t_0 $d\left(M,N\right) = E$, but at constant coolant temperature T_c at the moment of time $t_0 + dt$ distance $d\left(M,N\right) = E + dE$, which violates the condition of non-proliferation of IW boundaries to the outside. Recall that excessive growth of IW leads to unproductive energy consumption.

As a first approximation, the temperature distribution inside the LPO in the lock plane can be represented as a downward directed triangle, i.e., a function of the following form $T = a\left|r - b\right| - T_l$ (Fig. 6), where a – coefficient determining the angle of inclination; r – distance to the calculated point from the centre of the shaft; b – distance from the centre of the shaft to the point of intersection of the lock and axial planes; T_l – the temperature of the beginning of water crystallisation in the rock.

In this case, the average temperature of the rock inside the IW will be determined by the integral expression $\overline{T} = \frac{1}{E_\tau}\int_{r_M}^{r_N} T dr$, in which the value of the integral with the account of the sign, can be defined through the area of the triangle bounded by the specified function, i.e. $\int_{r_M}^{r_N} T dr = \frac{1}{2} E_\tau (T_P - T_l)$, where E_τ – IW thickness along the frozen rock boundaries at the moment of time τ; r_M and r_N – distances to the inner and outer boundaries of the IW from the centre of the shaft in the lock plane; T_P – the minimum temperature of the rock in the lock plane within given limits, which is usually observed at the point P of intersection of the lock and axial planes or its vicinity (see Fig. 3). Combining these two expressions, we obtain that the average temperature of frozen rock $\overline{T} = \frac{1}{2}(T_P - T_l)$ in the lock plane is determined not by the IW dimensions, but by the minimum rock temperature T_P at a fixed value T_l.

Maintaining the minimum temperature of the frozen rock at point P or its junction after the minimum required IW thickness E has been reached is directly dependent on maintaining a certain rock temperature $T_{\min}$ in the junction of the freezing columns which, in turn, is included in the heat transfer equation for the freezing columns:

$$\Delta Q_f = \frac{T_{\min} - T_c}{R}, \tag{3}$$

where ΔQ_f – is the heat flux through the wall of a single freezing column, J/sec; R – thermal resistance of the freezing column.

Knowing this, let's try at the moment of time t_0 to raise the temperature T_c so that at the moment of time $t_0 + dt$ to preserve $d(M,N) = E$. As a result of the reaction of the environment, we will inevitably get $\overline{T} > T_0$, which violates condition C within the framework of criterion 1, and therefore, if condition B is met, it takes the state of IW reliability A beyond the permissible limits.

A legitimate question arises: if it is necessary, for example, to maintain the average temperature of the IW $\overline{T} = -8$ °C in the locking plane, it is necessary to keep the minimum temperature of the rock for this purpose $T_{\min} = -16$ °C, and the actual size of the IW does not determine the possibility of freezing control? This statement is incorrect.

The external boundary of the IW is affected by the earth's heat inflows, and since its thickness is constantly increasing, the temperature gradient near the phase transition boundary declines and the value of the earth's heat inflows to the freezing columns lows down [43]. Let us consider the heat balance equation of the system "freezing columns – rock massif" (Fig. 7):

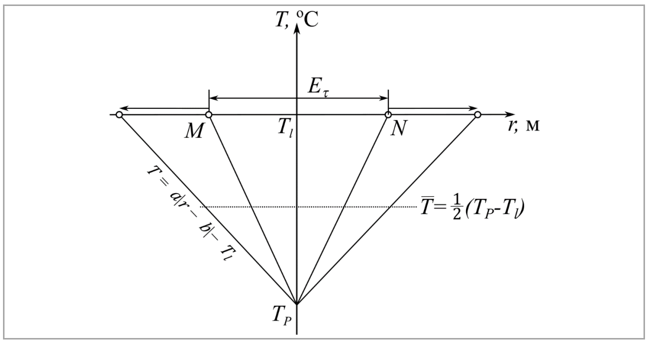

Fig. 6. Simplified representation of the temperature field in the lock plane

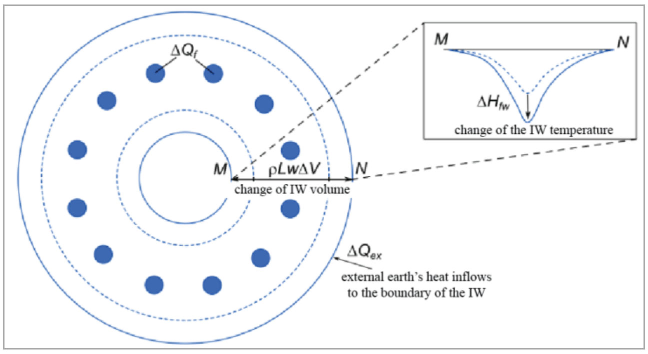

Fig. 7. Schematic representation of elements of heat balance equation

$$\Delta Q_{\Sigma f} = \Delta Q_{ex} + \Delta H_{fw} + \rho L w \Delta V, \tag{4}$$

where $\Delta Q_{\Sigma f} = n\Delta Q_f$ – the total heat inflow provided by freezing columns in the number of n units, W; ΔQ_{ex} – value of the earth's heat inflows, W; ΔH_{fw} – the change in heat content of the rock inside the IW as a result of its temperature change, without phase transition, W; ρ – rock density, kg/m^3; L – specific heat of phase transition, J/kg; w – weight amount of water in the rock capable of freezing in the used temperature range, kg/kg; ΔV – change of IW volume, m^3.

Thus, the first summand in the right part of equation (4) is responsible for the external earth's heat inflows to the LPO boundary; the second summand is responsible for the change in the frozen rock temperature inside the IW without changing its volume; the third summand is responsible for the change in the IW volume.

Let us assume that the last two summands in the right part of equation (4) can be physically nullified, i.e. after the required IW parameters are reached, the operation mode of the freezing station is adjusted so that the ice-rock enclosure no longer increases in size and the temperature of the rock inside it does not change. Then the total heat flux to the freezing columns should be adjusted so as to fully compensate only external earth's heat inflows:

$$\frac{T_{\min} - T_c}{R} = \frac{1}{n}\Delta Q_{ex}. \tag{5}$$

Provided that the temperature $T_{\min}$, linearly related to T_P, must remain constant in order to keep constant the average temperature $\overline{T}$, temperature of coolant in freezing columns T_c must be raised to the value:

$$T_c = T_{\min} - \frac{R}{n}\Delta Q_{ex}, \qquad (6)$$

after which it cannot be increased further.

In such an ideal case, the limit value of the temperature T_c, determined by equation (6), will be high enough. In practice, fulfilment of the minimum condition $C := \left(\overline{T} = T_0\right)$ requires a sufficiently low value of $\overline{T}$ and the corresponding T_P, $T_{\min}$ and T_c. The heat flux provided by the freezing columns exceeds the external heat inflows, and the difference is spent on further growth of IW and lowering its temperature. It is practically impossible to reduce the last two summands in equation (4) to zero while maintaining the IW bearing capacity according to criterion 1.

In view of the mentioned above, the growth of the coolant temperature of the coolant T_c is feasible while simultaneously moving the IW boundaries outwards. Theoretically, at time step $t_0 + dt$ at $d(M,N) = E + dE$ it is possible to adjust the temperature $T_c + \delta T$ so that to keep on the condition $\max\limits_{t>t_0} C_t := \left(\overline{T} = T_0\right)$, but the condition $\min\limits_{t>t_0} B_t := (E = E_0)$ is impossible. The task of increasing the temperature of the coolant within the framework of criterion 1 from the point of view of the maximum permissible reduction of unproductive energy costs can be optimized only under the condition *C*:

$$T_c = T_c(t):\ A_t(E,T) \to B_t \wedge \max_{t>t_0} C_t. \qquad (7)$$

The problem is solved only in case of maintaining the average temperature of the frozen rock. Containment of IW growth, as well as reduction of the associated energy overconsumption, remains unfeasible.

Criterion 2

Let us again consider the problem of determining the IW boundaries in projection on the Cartesian plane *Oxy* (top view), considering their position unchanged along the vertical coordinate *z*.. Let S_{in} and S_{out} are the projections of the inner and outer boundaries of the LPO on the specified plane, determined by isotherms with the temperature value equal to the temperature of the solid frozen rock T_0, and points $M \in S_{in}$ and $N \in S_{out}$ are arranged so that $d(M,N) = \min\limits_{Oxy} d(S_{in}, S_{out})$, where $d(M,N)$ – Euclidean distance in the lock plane along the direction $\overrightarrow{MN}$ of the least thickness.

When defining IW boundaries by isotherm with solid frozen rock temperature T_0 as in the case of criterion 1, two zones can be distinguished within the IW: <1> – The frozen rock here has a temperature higher than the required T_0 value, and thus has a strength deficit and greater creep relative to it; <2> – The frozen rock here has a temperature lower than the required T_0 value, and therefore has a reserve in terms of strength and deformation characteristics. Let's call the zone <1> "buffering", and <2> – "zone of durable IW". The boundaries between the zones are conditional and defined only by the isotherm with some temperature value.

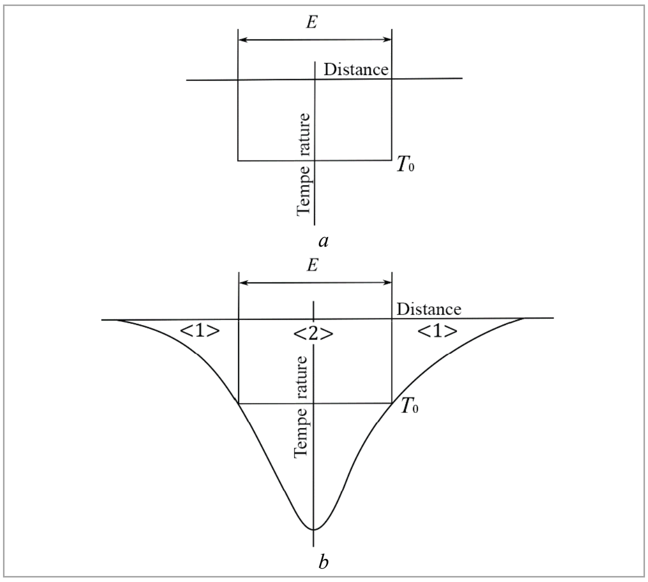

Fig. 8. Determination of IW reliability in idealized theoretical formulation (*a*) and in practice with the use of criterion 2 (*b*)

In the problem formulation for criterion 2, the external load is not applied directly to the IW boundaries. It is absorbed by the "buffer zone" composed of frozen but "more pliable" rock and, damping it, transfers it further to the boundaries of the "durable IW zone".

In accordance with the conditions of criterion 2, the actual IW thickness *E*, compared to the minimum required value E_0, is taken to be the distance $d(M,N)$, and the average temperature of the frozen rock is not controlled, since in this setting between the points *M* and *N*, in the zone <2> a priori there is a frozen rock formationa with an average temperature of $\overline{T} < T_0$ (Fig. 8), which is a guarantee of IW reliability. Mathematically, criterion 2 is written simply:

$$\begin{gathered} B := (E \ge E_0), \\ C := \left(T\big|_{\Gamma} = T_0\right), \\ B \wedge C \Rightarrow A, \end{gathered} \qquad (8)$$

where Γ – IW boundaries by isotherms with temperature value T_0.

From the point of view of freezing mode control the task of optimal increase of the coolant temperature $T_c = T_c(t)$ after reaching the minimum required thickness of IW E_0 fairly clear and relatively easy to implement:

$$T_c = T_c(t):\ A_t(E,T) \to \min_{t>t_0} B_t \wedge C_t. \qquad (9)$$

Fixing the position of isotherms with temperature T_0 in the points *M* and *N*, it is necessary to select such a temperature rise mode $T_c = T_c(t)$, to keep their position constant (Fig. 9). At the same time, along the frozen rock boundaries, the IW continues to increase in size, as in the case of criterion 1. Points *C* and *D* are being displaced. he temperature of the frozen rock at point *P* rises with the temperature of the coolant. Average temperature of the whole IW $\overline{T}$, i.e. between the points *C* and *D*, as stated above, with the use of this criterion is not controlled and may be higher from a certain point in time T_0.

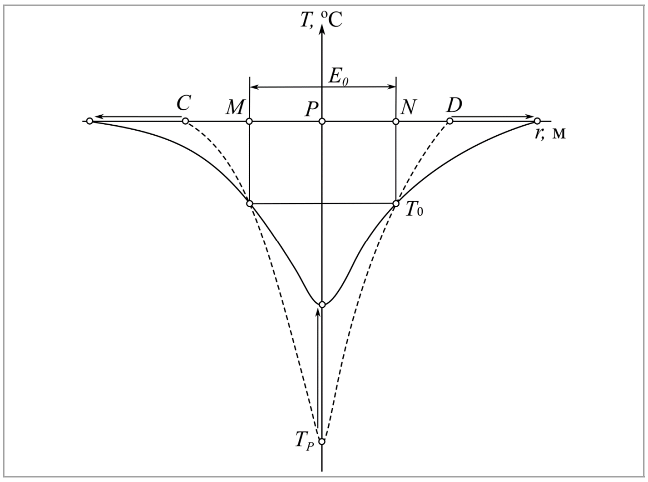

Fig. 9. Conservation of LPO thickness according to criterion 2 with increasing temperature of the coolant and subsequent change in the rock temperature followed by a change in the rock temperature

And again possibilities of increasing the temperature of the coolant T_c are determined by the heat balance in the system "freezing columns – rock massif" and the amount of the earth's heat inflows that reaches the freezing columns depending on the IW thickness growth. It should be noted that the task of completely stopping the expansion of the IW boundaries (we mean the boundaries of frozen rock at the temperature of the beginning of water freezing) as physically unfeasible is not set here also. Indirectly, the IW expansion within criterion 2 is minimized by fixing its fictitious boundaries by isotherms with the temperature of T_0.

Criterion 2 raises the limit of the coolant temperature rise defined by criterion 1, since the average temperature of the entire IW along the minimum thickness direction over a large time interval is higher than T_0 and average rock temperature in the zone $<2>$. Correspondingly temperatures T_P, $T_{\min}$ and T_c will also be higher than when criterion 1 is used. Freezing mode control by criterion 2 is easy to algorithmise, as shown by the authors of [44], at that IW reliability is preserved.

Criterion 3

This criterion is the most ambiguous of the three and is somewhat more difficult to apply. Within the IW, a "zone of strong IW" is identified with an average rock temperature of $\overline{T}=T_0$. Control of actual IW thickness E is made by the boundaries of this zone, which are conditional in physical terms, as they are expressed not by a change in the physical state of matter (e.g., phase transition), but only by some value of the rock temperature. The criterion is based on the assumption that if inside the LPO there is a zone of frozen rock with an average temperature of at least T_0, then this zone meets the required criteria for static strength and creep calculation of IW. Similarly to criterion 2, the external load is applied to the boundaries of the zone indirectly, through the "buffer" thickness of frozen rock with higher temperature, and at the boundaries of the zone itself its value is reduced [18] (Fig. 10). There is a certain arbitrariness in finding the boundaries of the "zone of strong IW", allowing several variants. Let the points M and N, as previously define these boundaries in the lock plane. In the first variant their position can be found from the symmetry condition with respect to the point P, i.e., at an equal distance $d(M,P)=d(P,N)$ from it in both directions, towards and away from the shaft. But since the IW itself has a known asymmetry relative to the circumference of the freezing columns, the temperatures at the boundaries of the zone will not be equal, i.e. $T_M \neq T_N$ (see Fig. 10, *a*).

The second option is possible when the inner and outer boundaries of the "zone of strong LPO" are defined by isotherms with equal temperature value inside (in the direction of the borehole) T_M and outside T_N from the circumference of the freezing columns to the profile:

$$\begin{cases} \overline{T}=\int\limits_M^N T dr, \\ \sup T_{hsz}=T_M=T_N, \end{cases} \qquad (10)$$

where $\sup T_{hsz}$ – is the upper temperature limit of the IW strength zone, $\overline{T}$ – necessary average rock temperature (see Fig. 10, *b*).

The second variant of criterion 3 is similar to criterion 2 with the difference that the thickness of the IW E is determined not by isotherms with fixed temperature T_0, but with a "floating" $\sup T_{hsz}$. Let in the first approximation the temperature distribution inside the IW in the lock plane corresponds to a downward directed triangle (Fig. 11). Then the average temperature of the rock in the "zone of solid IW will be determined by the integral expression $\overline{T}=\frac{1}{E_\tau}\int\limits_{r_M}^{r_N} T dr$, in which the value of the integral, taking into account the sign, can be defined through the corresponding areas of the rectangle and triangle indicated by the grey fill as

$$\int\limits_{r_M}^{r_N} T dr = E_\tau\left(T_M - T_I\right)+\frac{1}{2}E_\tau\left(T_P - T_M - T_I\right),$$

where E_τ – IW thickness along the frozen rock boundaries at the moment of time τ; r_M and r_N – distances to the inner and outer boundaries of the "strong IW zone" from the centre of the shaft in the lock plane; T_P – the minimum temperature of the rock in the lock plane within the given limits, which is usually observed at the point P of the intersection of the lock and axial planes or its vicinity (see Fig. 3). Combining both expressions, we obtain that the average temperature of the "zone of strong IW" in the lock plane is equal to

$\overline{T}_z=\frac{1}{2}\left(T_P+T_M\right)-T_I$. Hence $\sup T_{hsz}=2\overline{T}_z-T_P+T_I$.

Assuming the condition $\overline{T}_z=T_0$, we obtain $\sup T_{hsz}=2T_0-T_P+T_I$.

In case when $T_P \le 2T_0$, "zone of solid IW" is defined along the boundaries of frozen rock, and criterion 3 corresponds to criterion 1. In other cases, when

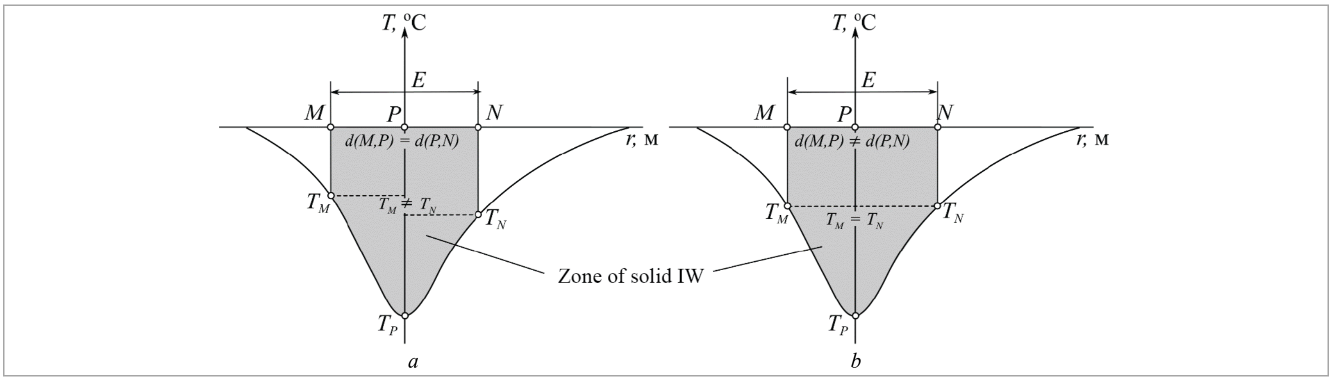

Fig. 10. Determination of the boundaries of the "zone of solid IW" for criterion 3 from the condition of equal distances (*a*) and temperatures (*b*)

controlling the operation mode of the freezing complex, the upper limit of temperature T_P can theoretically be located in the interval $T_0 < T_P < 2T_0$ and depends on the total thickness of the LPO. In general, to assert the reliability of the IW under criterion 3, it is only necessary to show that inside it there is a zone with an average temperature $\overline{T}_z = T_0$, having the dimensions $E \geq E_0$.

Mathematically, criterion 3 is written in the form of the expression

$$B := \left(E \geq E_0\right),\quad C := \left(\overline{T}_{hsz} = T_0\right),\quad B \wedge C \Rightarrow A. \tag{11}$$

From the point of view of freezing mode control the task of optimal increase of the coolant temperature $T_c = T_c\left(t\right)$ after the minimum required LPO thickness E_0 has been reached for criterion 3 will be written similarly to the expression (9) for criterion 2:

$$T_c = T_c\left(t\right):\ A_t\left(E\right) \to \min_{t>t_0} B_t \wedge C_t. \tag{12}$$

Criterion 3 raises the limit for the increase of the coolant temperature determined by criteria 1 and 2, since the average temperature of the entire IW $\overline{T}$ in the direction of the minimum thickness over a long time interval above the average rock temperature $\overline{T}_{hsz}$ in “zone of strong IW”, and the value $\sup T_{hsz} > T_0$. Corresponingly temperatures T_P, $T_{\min}$ and T_c will also be higher than when using criteria 1 and 2. As for the previous criteria, the control of the freezing station mode according to criterion 3 does not completely stop the expansion of the frozen rock boundaries, but only restrains its speed within certain limits.

Comparative analysis of the applicability of criteria on a model example

As shown above, the problem statements that meet each of the criteria differ to varying degrees from the mathematical one (for which the basic formulas for static strength and creep are derived) in terms of temperature distribution and determination of the boundaries of IW. Therefore, in fact, the assessment of the reliability of IW for each of the criteria has a different degree of margin. In criteria 2 and 3, it is associated with the "buffer zone" of frozen rock, which has a temperature above the minimum required value, which creates a thickness reserve, absorbs the external load and, "damping", transmits it further to the "conditional" boundaries of the IW. The rock in the "strong IW zone" has a lower temperature T_0, which also creates a margin.

In criterion 1, the safety margin is related to the fact that the IW thickness along the frozen rock boundaries, after reaching the minimum required value, inevitably continues to increase throughout the artificial freezing, or in other words, during the entire period while the required average IW temperature is maintained. In this case, the reserve of strength and creep resistance with respect to the predetermined minimum required value is implied, based on the homogeneity and isotropy of physical-mechanical and thermophysical properties of the massif. Local inhomogeneities in the rock mass (inclusions, cracks, caverns, etc.) can reduce strength, deformation and imperviousness properties of IW, but their consideration is beyond the scope of this paper.

Let us determine the most rational schedule for increasing the temperature of the coolant according to each of the criteria and demonstrate the calculations on a modelling example. Let's set a layer of rock – sand – having characteristics according to the table below.

We solve the artificial freezing problem in two-dimensional formulation in the Oxy plane in the FrozenWall software [31]. A sectoral fragment of the computational domain with the mapped network nodes and the position of freezing columns is shown in Fig. 12. The calculations in FrozenWall software are performed by the finite difference method, and the problem itself is solved in the enthalpy formulation. An adaptive radial grid with densification in the boundary region of the shaft support (if available in the model) and heat sources ("cold"). The mathematical model and calculation algorithms are described in more detail in the works [29, 30, 45, 46].

To calculate cooling capacity of freezing columns it was required to specify their working, length, so the thickness of the model layer was assumed to be 100 m. The value of minimum permissible thickness of IW is determined as E = 2,0 m, calculated for the temperature of solid rock $T_0 = -8$ °C. The flow rate of coolant in the brine network is assumed at the rate of 6 m³/h per one freezing column, which corresponds to the practice of artificial freezing. The minimum temperature of the coolant in the process of IW formation is limited to –30 °C.

Thermophysical model parameters

Serial number	Parameter	Symbolic representation of a value	Value
	Characteristics of the frozen rock		
1	Natural temperature of the rock, °C	T_∞	10.0
2	Crystallisation onset temperature of water in the rock, °C	T_l	–0.1
3	Temperature of complete crystallisation of water in the rock, °C	T_s	–1.0
4	Heat transfer coefficient of unfrozen rock, W/(m ·°C)	λ_1	2.5
5	Heat transfer coefficient of frozen rock, W /(m·°C)	λ_2	3.5
6	Specific heat capacity of unfrozen rock, J/(kg ·°C)	c_1	1200
7	Specific heat capacity of frozen rock, J/(kg ·°C)	c_2	900
8	Amount of freezing water in the rock, kg/kg	w	0.15
9	Rock density, kg/ m^3	ρ	2000
	Technological parameters		
№	Parameter		Value
	Freezing system parameters		
1	Contour radius of freezing columns, m		7.0
2	Distance between neighbouring freezing columns, m		1.22
3	Number of freezing columns, units.		36
	Shaft parameters		
4	Radius in sinking, m		5.0
	Coolant properties ($CaCl_2$)		
5	Density, kg/m^3		1280
6	Specific heat capacity, J/(kg ·°C)		2659
7	Heat transfer coefficient, W/(m ·°C)		0.49
8	Dynamic viscosity, 10^4 Pa·s		212.8

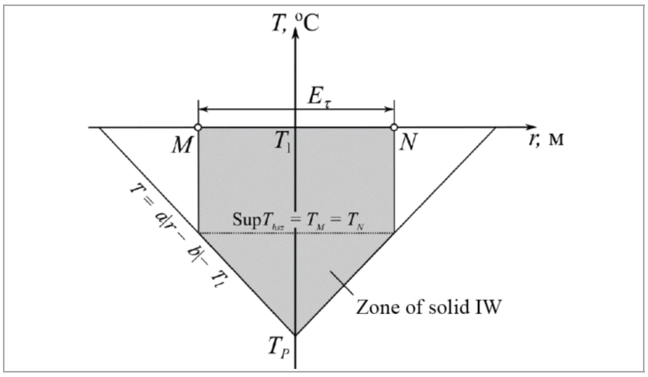

Fig. 11. Simplified representation temperature field in the lock plane with the applied "zone of strong IW"

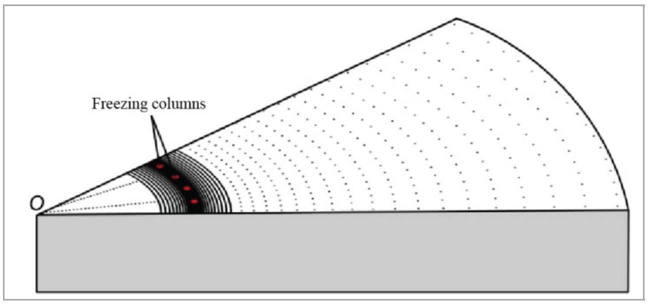

Fig. 12. Sectoral fragment of the computational domain with the mapped node grid and the position of the freezing columns (red colour)

The results of multivariate modelling with determination of the most rational modes of IW maintenance after reaching its required parameters according to all three criteria are illustrated in Fig. 13 in the form of graphs of change in of the coolant temperature, freezing column cooling capacity, minimum IW thickness along the frozen rock boundaries and its average temperature.

It is necessary to pay special attention to the selection of the freezing mode for criterion 1. Two variants of this criterion have been calculated for the following reason: with the limitation of the lower temperature of the coolant –30 °C it is impossible to simultaneously achieve the average temperature of IW at any time $\overline{T} = -8$ °C and its thickness along the frozen rock boundaries E = 2.0 m. Thus, for example, on the 63rd day from the beginning of freezing, the average IW temperature will reach the value of $\overline{T} = -8$ °C, but its thickness E at the frozen rock boundaries will be 3.7 m, i.e. will be obviously more than the minimum required 2 m. This variant of calculation is labelled as "criterion 1.v2" in the diagrams.

In case of strict compliance with the conditions of criterion 1, the variant labelled "criterion 1.v1" was calculated, in which the temperature of the coolant during the period of IW formation was reduced to –47 °C. Thus, the average temperature of IW on the 29th day from the beginning of freezing was achieved as $\overline{T} = -8$ °C simultaneously with its thickness along the frozen rock boundaries E = 2.0 m. However, as calculations have shown, the cooling power expenditures for this are on average 1.4 times higher than in the previous variant.

Analysis of the graphs shows that the most economical in terms of reduction of cooling power expenditures is criterion 3, and at the same time it fully meets the conditions of safe operation of IW. The graphs corresponding to it are highlighted in red colour. It is quite convenient in application, because the search for the upper temperature limit, as well as the determination of the boundaries of the "IW solid zone", is easy to algorithmise. Of all three criteria criterion 3 ensures IW reliability at its lowest average temperature, as well as the minimum expansion rate of frozen rock boundaries outwards, including inside the shaft sinking contour. The correlation of the IW boundaries determined by the three reliability criteria will be demonstrated clearly. The temperature distribution along the radial profile from the centre of the shaft in the lock plane on the 73rd day from the beginning of freezing is illustrated in Fig. 14. The operation mode of the freezing station corresponded to the one presented in Fig. 13 for criterion 3.

According to the temperature distribution shown in Fig. 14, the thickness of the "zone of solid IW" with an average rock temperature of -8 °C is 2.0 m, which corresponds to the condition of its reliability for criterion 3. While the other two criteria are not fulfilled, because the distance between the isotherms with the temperature value of -8 °C on both sides from the point of P is only 1.2 m and at the frozen rock boundaries, although it is 4.1 m, which is more than the minimum required value of 2.0 m, but at the average temperature of the entire IW $\overline{T} = -5.3$ °C, which is higher than the accepted value of the solid rock temperature of -8 °C, and therefore unacceptable.

The temperature of the frozen rock at point P is only –9.9 °C. If the other two criteria were met, it would have to be significantly lower (about –16 °C to fulfil the conditions under criterion 1), since both of them "limit" themselves by a more stringent temperature setting condition.

This means that the temperature of the coolant and the cooling power expenditures are lower at application of criterion 3 with a "floating" upper temperature limit than when using the other two criteria.

Conclusion

In this paper the authors consider three main criteria for assessing the reliability of IW during thermometric control of its condition in the process of artificial freezing of rocks during the construction of vertical mine shafts.

Calculations and practical experience show that it is impossible to select an optimal mode of operation of the freezing station with increase of the coolant temperature during the IW maintenance period, which would provide a complete stop of its boundaries expansion at the temperature of the beginning of water freezing in the rock.

Regarding the criteria: the first one is the least flexible for artificial freezing control. The parameter of IW thickness along the frozen rock boundaries, which is included in it, plays the role of a critical mark, below which it is inadmissible to go below. But, as shown above, it is impossible to use it as one of the conditions of the optimisation problem. The second condition for maintaining the average IW temperature significantly limits the gradient and the upper limit of the coolant temperature rise.

The second criterion is friendly in use. The search for the minimum distance between isotherms with a given temperature value is easy to algorithmise, and the position of the selected isotherms can be easily fixed by appropriate selection of the coolant temperature rise mode. Simplicity and cost-effectiveness of the criterion allow us to recommend it as the second main criterion to be used in practice in the process of thermometric control of IW condition.

Despite the apparent complexity of criterion 3, the search for the upper temperature limit, as well as the definition of the boundaries of the "zone of solid IW", is also easy to algorithmise. And since the upper limit is "floating" in time, and not fixed by rigidly set temperature values, as in criteria 1 and 2, the third of them is the most economical in terms of cooling power of the freezing complex. As the calculations showed, its application makes it possible to select the IW maintenance mode providing the smallest thickness growth at the lowest average temperature value. Based on the results of the study, the criterion is recommended for use as the main criterion for thermometric control of the IW condition and flexible control of the freezing complex operation mode.

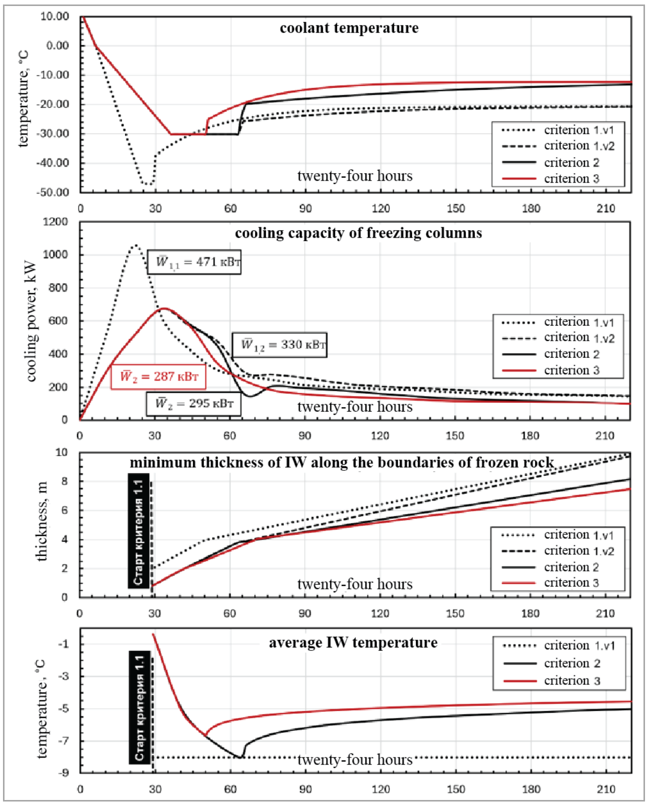

Fig. 13: Results of mathematical modeling for determining the most rational mode of IW maintenance according to three criteria

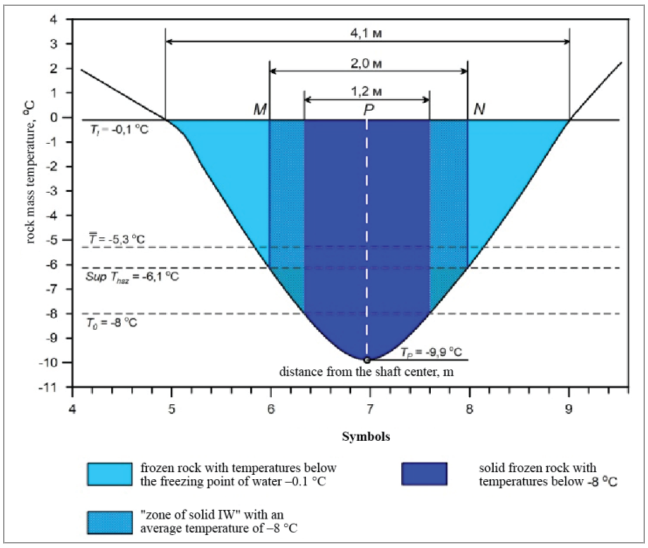

Fig. 14. Ratio of IW dimensions determined by three criteria of reliability

References

1. Akagawa S. Artificially frozen ground and related engineering technology in Japan. *Sciences in Cold and Arid Regions*, 2021, vol. 13, no. 2, pp. 77-86. DOI: 10.3724/SP.J.1226.2021.20046
2. Mauro A., Normino G., Cavuoto F., Marotta P., Massarotti N. Modeling Artificial Ground Freezing for Construction of Two Tunnels of a Metro Station in Napoli (Italy). *Energies*, 2020, vol. 13, no. 5, 1272. DOI: 10.3390/en13051272
3. Pimentel E., Papakonstantinou S., Anagnostou G. Numerical interpretation of temperature distributions from three ground freezing applications in urban tunneling. *Tunnelling and Underground Space Technology*, 2012, vol. 28, pp. 57-69. DOI: 10.1016/j.tust.2011.09.005
4. Russo G., Corbo A., Cavuoto F., Autuori S. Artificial Ground Freezing to excavate a tunnel in sandy soil. Measurements and back analysis. *Tunneling and Underground Space Technology*, 2015, vol. 50, pp. 226-238. DOI: 10.1016/j.tust.2015.07.008
5. Xiang H., Zhang G., Cheng P., Hu J., Wang Z., Zeng D. Analyses of the Ground Surface Displacement under Reinforcement Construction in the Shield Tunnel End Using the Artificial Ground Freezing Method. *Applied Sciences*, 2023, vol. 13, no. 14, 8508. DOI: 10.3390/app13148508
6. Yan Q., Wu W., Zhang C., Ma S., Li Yu. Monitoring and Evaluation of Artificial Ground Freezing in Metro Tunnel Construction-A Case Study. *KSCE Journal of Civil Engineering*, 2019, vol. 23, pp. 2359-2370. DOI: 10.1007/s12205-019-1478-z
7. Yang Yu., Lei D., Cai H., Wang S., Mu Ya. Analysis of moisture and temperature fields coupling process in freezing shaft. *Thermal Science*, 2019, vol. 23, pp. 1329-1335. DOI: 10.2298/TSCI180519130Y
8. Yao Z., Cai H., Xue W., Wang X., Wang Z. Numerical simulation and measurement analysis of the temperature field of artificial freezing shaft sinking in Cretaceous strata. *AIP Advances*, 2019, vol. 9, no. 2, 025209. DOI: 10.1063/1.5085806

9. Vialov S.S. Prochnost' i polzuchest' merzlykh gruntov, i raschety ledogruntovykh ograzhdenii [Strength and creep of frozen soils, and calculations of ice-soil barriers]. Moscow: Akademiia nauk SSSR, 1962, 253 p.
10. Trupak N.G. Zamorazhivanie gruntov v podzemnom stroitel'stve gornykh vyrabotok [Freezing of soils in underground construction of mine workings]. Moscow: Nedra, 1974, 281 p.
11. Alzoubi M.A., Xu M., Hassani F.P., Poncet S., Sasmito A.P. Artificial ground freezing: A review of thermal and hydraulic aspects. *Tunneling and Underground Space Technology*, 2020, vol. 104, 103534. DOI: 10.1016/j.tust.2020.103534
12. Lai Yu., Wansheng P., Zhang M., Zhou J. Study on theory model of hydro-thermal-mechanical interaction process in saturated freezing silty soil. *International Journal of Heat and Mass Transfer*, 2014, vol. 78, pp. 805-819. DOI: 10.1016/j.ijheatmasstransfer.2014.07.035
13. Sweidan A.H., Heider Yo., Markert B. A unified water/ice kinematics approach for phase-field thermos-hydro-mechanical modeling of frost action in porous media. *Computer Methods in Applied Mechanics and Engineering*, 2020, vol. 372, 113358. DOI: 10.1016/j.cma.2020.113358
14. Tounsi H., Rouabhi A., Jahangir E. Thermo-hydro-mechanical modeling of artificial ground freezing taking into account the salinity of the saturating fluid. *Computers and Geotechnics*, 2020, vol. 119, 103382. DOI: 10.1016/j.compgeo.2019.103382
15. Zhelnin M., Kostina A., Prokhorov A., Plekhov O., Levin L.Coupled thermo-hydro-mechanical modeling of frost heave and water migration during artificial ground freezing of soils for mineshaft sinking. *Journal of Rock Mechanics and Geotechnical Engineering*, 2022, vol. 14, no. 2, pp. 537-559. DOI: 10.1016/j.jrmge.2021.07.015
16. Zueter A., Nie-Rouquette A., Alzoubi M.A., Sasmito A. Thermal and hydraulic analysis of selective artificial ground freezing using air insulation: Experiment and modeling. *Computers and Geotechnics*, 2020, vol. 120, 103416. DOI: 10.1016/j.compgeo.2019.103416
17. Zhou M.M., Meschke G. A three thermos-hydro-mechanical finite element model for freezing soils. *International Journal for Numerical and Analytical Methods in Geomechanics*, 2013, vol. 37, pp. 3173-3193. DOI: 10.1002/nag.2184
18. Pugin A.V., Ogloblina A.A., Bogomiagkov A.V. Analiz sostoianiia ledoporodnogo ograzhdeniia v usloviiakh asimmetrichnogo raspredeleniia temperatur v zamorazhivaemom massive gornykh porod [Analysis of the state of the ice wall under conditions of asymmetric temperature distribution in a frozen rock mass]. *Gornoe ekho*, 2022, no. 2, pp. 133-139. DOI: 10.7242/echo.2022.2.22
19. Semin M.A., Bogomiagkov A.V., Levin L.Iu. Teoreticheskii analiz dinamiki ledoporodnogo ograzhdeniia pri perekhode na passivnyi rezhim zamorazhivaniia [Theoretical analysis of frozen wall dynamics during transition to ice holding stage]. *Zapiski gornogo instituta*, 2020, no. 243, pp. 319-328. DOI: 10.31897/PMI.2020.3.319
20. Golovatyi I.I., Levin L.Iu., Semin M.A., Pugin A.V. Realizatsiia printsipov zamorazhivaniia “po trebovaniiu” pri stroitel'stve stvolov Darasinskogo rudnika [Implementation of freezing-on-demand concept in shaft construction in Belaruskali's Darasinsky mine]. *Gornyi zhurnal*, 2023, no. 8, pp. 34-39. DOI: 10.17580/gzh.2023.08.05
21. Semin M., Golovatyi I., Levin L., Pugin A. Enhancing efficiency in the control of artificial ground freezing for shaft construction: A case study of the Darasinsky potash mine. *Cleaner Engineering and Technology*, 2024, vol. 18, 100710. DOI: 10.1016/j.clet.2023.100710
22. Alzoubi M.A., Sasmito A.P., Madiseh A., Hassani F.P. Freezing on Demand (FoD): An Energy Saving Technique for Artificial Ground Freezing. *Energy Procedia*, 2019, vol. 158, pp. 4992-4997. DOI: 10.1016/j.egypro.2019.01.667
23. Alzoubi M.A., Zueter A., Nie-Rouquette A., Sasmito A.P. Freezing on demand: A new concept for mine safety and energy savings in wet underground mines. *International Journal of mining Science and Technology*, 2019, vol. 29, no. 4, pp. 621-627. DOI: 10.1016/j.ijmst.2019.06.015
24. Dorman Ia.A. Iskusstvennoe zamorazhivanie gruntov pri stroitel'stve metropolitenov [Artificial freezing of soils during the construction of subways]. Moscow: Transport, 1971, 302 p.
25. Dorman Ia.A. Spetsial'nye sposoby rabot pri stroitel'stve metropolitenov [Special methods of work in the construction of subways]. Moscow: Transport, 1981, 302 p.
26. Andersland O.B., Ladanyi B. An introduction to frozen ground engineering. Springer Science & Business Media, 1994, 352 p.
27. Golovatyi I.I., Levin L.Iu., Parshakov O.S., Diulin D.A. Optimizatsiia protsessov formirovaniia ledoporodnogo ograzhdeniia pri sooruzhenii shakhtnykh stolov [Optimization of ice wall formation processes during construction of mine tables]. *Gornyi zhurnal*, 2018, no. 8, pp. 48-53. DOI: 10.17580/gzh.2018.08.06
28. Parshakov O.S. Razrabotka avtomatizirovannoi sistemy termometricheskogo kontrolia ledoporodnykh ograzhdenii [Development of an automated system for thermometric control of ice barriers]. Ph D. thesis. Perm', 2020, 140 p.
29. Levin L.Iu., Semin M.A., Bogomiagkov A.V., Parshakov O.S. Primenenie programmnogo kompleksa “FrozenWall” dlia rascheta iskusstvennogo zamorazhivaniia porod [The application of "FrozenWall" software in simulation of artificial ground freezing]. *Izvestiia Tul'skogo gosudarstvennogo universiteta. Nauki o Zemle*, 2019, no. 4, pp. 269-282.
30. Bogomiagkov A.V., Pugin A.V. Sovershenstvovanie matematicheskoi modeli teplomassoperenosa v zamorazhivaemom porodnom massive, realizovannoi v programme FrozenWall [Improvement of the mathematical model of heat and mass transfer in frozen soils implemented in the FrozenWall program]. *Izvestiia Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov*, 2023, vol. 334, no. 2, pp. 164-174. DOI: 10.18799/24131830/2023/2/3808
31. Bogomiagkov A.V., Zaitsev A.V., Kliukin Iu.A., Levin L.Iu., Parshakov O.S., Pugin A.V., Semin M.A. FrozenWall. Svidetel'stvo o gosudarstvennoi registratsii programmy dlia EVM no. 2018666337 (2018).
32. Instruktsiia po raschetu parametrov, kontroliu i upravleniiu iskusstvennym zamorazhivaniem gornykh porod pri stroitel'stve shakhtnykh stvolov na territorii Respubliki Belarus' [Instructions for calculating parameters, monitoring and managing artificial freezing of rocks during the construction of mine shafts in the Republic of Belarus]. Minsk; Soligorsk: OAO “Belarus'kalii”, 2019, 67 p.
33. VSN 189-78. Vedomstvennye stroitel'nye normy. Instruktsiia po proektirovaniiu i proizvodstvu rabot po iskusstvennomu zamorazhivaniiu gruntov pri stroitel'stve metropolitenov i tonnelei [VSN 189-78. Departmental building codes. Instructions for design and execution of works on artificial freezing of soils during construction of subways and tunnels]. Moscow: TsNIIS, 1978, 68 p.
34. Vremennoe rukovodstvo po proektirovaniiu protsessa zamorazhivaniia porod dlia prokhodki vertikal'nykh stvolov shakht [Interim Guidelines for the Design of Rock Freezing Processes for Sinking Vertical Mine Shafts]. Khar'kov: VNIIOMShS, 1971, 103 p.
35. Levin L.Iu., Semin M.A., Plekhov O.A. Sravnitel'nyi analiz sushchestvuiushchikh metodov rascheta tolshchiny ledoporodnogo ograzhdeniia stroiashchikhsia shakhtnykh stvolov [Comparative analysis of existing methods for calculating frozen wall thickness for mine shafts under construction]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Stroitel'stvo i arkhitektura*, 2018, no. 4, pp. 93-103. DOI: 10.15593/2224-9826/2018.4.09
36. Kostina A., Zhelnin M., Plekhov O., Panteleev I., Levin L., Semin M. An Applicability of Vyalov's equations to ice wall strength estimation. *Frattura Ed Integrità Strutturale*, 2020, vol. 14, no, 53, pp. 394-405. DOI: 10.3221/IGF-ESIS.53.30
37. Semin M.A., Levin L.Iu. Metody rascheta iskusstvennogo zamorazhivaniia porod pri stroitel'stve shakhtnykh stvolov [Methods of calculating artificial freezing of rocks during the construction of mine shafts]. Moscow: Nauchnyi mir, 2021, 152 p.
38. Hu C., Yang Z., Han T., Yang W. Calculation method of the design Thickness of a Frozen Wall with Its Inner Edge Radially Incompletely Unloaded. *Applied Sciences*, 2023, vol. 13, 12650. DOI: 10.3390/app132312650
39. Tsytovich N.A. Mekhanika merzlykh gruntov [Mechanics of frozen soils]. Moscow: Vysshaia shkola, 1973, 448 p.
40. Tsytovich N.A. Mekhanika gruntov (kratkii kurs) [Soil Mechanics (short course)]. Moscow: Vysshaia shkola, 1983, 288 p.
41. Anderson D.M., Morgenstern N.R. Physics, chemistry and mechanics of frozen ground. *2nd International Conference on Permafrost*, 1973, pp. 257-288.
42. Semin M.A., Brovka G.P., Pugin A.V., Bublik S.A., Zhelnin M.S. Issledovanie vliianiia neodnorodnosti polia temperatur na prochnost' ledoporodnykh ograzhdenii stvolov shakht [Effects of temperature field nonuniformity on strength of frozen wall in mine shafts]. *Gornyi informatsionno-analiticheskii biulleten'*, 2021, no. 9, pp. 79-93. DOI: 10.25018/0236_1493_2021_9_0_79
43. Semin M.A., Levin L.Iu., Pugin A.V. Raschet zemnykh teplopritokov pri iskusstvennom zamorazhivanii porodnogo massiva [Analysis of earth's heat flow in artificial ground freezing]. *Fiziko-tekhnicheskie problemy razrabotki poleznykh iskopaemykh*, 2020, no. 1, pp. 162-171. DOI: 10.15372/FTPRPI20200118
44. Zhelnin M.S., Plekhov O.A., Levin L.Y. Optimization of the Passive Regime of Artificial Freezing of a Water-Saturated Rock Mass. *Journal of Engineering Physics and Thermophysics*, 2020, vol. 93, pp. 685-692. DOI: 10.1007/s10891-020-02167-8
45. Levin L.Iu., Semin M.A., Parshakov O.S. Sovershenstvovanie metodov prognozirovaniia sostoianiia ledoporodnogo ograzhdeniia stroiashchikhsia shakhtnykh stvolov s ispol'zovaniem raspredelennykh izmerenii temperatury v kontrol'nykh skvazhinakh [Improving Methods of Frozen Wall State Prediction for Mine Shafts under Construction Using Distributed Temperature Measurements in Test Wells]. *Zapiski Gornogo instituta*, 2019, vol. 237, pp. 268-274. DOI: 10.31897/PMI.2019.3.274
46. Levin L., Golovatyi I., Zaitsev A., Pugin A., Semin M. Thermal monitoring of frozen wall thawing after artificial ground freezing: Case study of Petrikov Potash Mine. *Tunneling and Underground Space Technology*, 2021, vol. 107, 103685. DOI: 10.1016/j.tust.2020.103685

Библиографический список

1. Akagawa, S. Artificially frozen ground and related engineering technology in Japan / S. Akagawa // Sciences in Cold and Arid Regions. – 2021. – Vol. 13, № 2. – P. 77–86. DOI: 10.3724/SP.J.1226.2021.20046
2. Modeling Artificial Ground Freezing for Construction of Two Tunnels of a Metro Station in Napoli (Italy) / A. Mauro, G. Normino, F. Cavuoto, P. Marotta, N. Massarotti // Energies. – 2020. – Vol. 13, № 5. – 1272. DOI: 10.3390/en13051272
3. Pimentel, E. Numerical interpretation of temperature distributions from three ground freezing applications in urban tunnelling / E. Pimentel, S. Papakonstantinou, G. Anagnostou // Tunnelling and Underground Space Technology. – 2012. – Vol. 28. – P. 57–69. DOI: 10.1016/j.tust.2011.09.005
4. Artificial Ground Freezing to excavate a tunnel in sandy soil. Measurements and back analysis / G. Russo, A. Corbo, F. Cavuoto, S. Autuori // Tunneling and Underground Space Technology. – 2015. – Vol. 50. – P. 226–238. DOI: 10.1016/j.tust.2015.07.008
5. Analyses of the Ground Surface Displacement under Reinforcement Construction in the Shield Tunnel End Using the Artificial Ground Freezing Method / H. Xiang, G. Zhang, P. Cheng, J. Hu, Z. Wang, D. Zeng // Applied Sciences. – 2023 – Vol. 13, № 14. – 8508. DOI: 10.3390/app13148508
6. Monitoring and Evaluation of Artificial Ground Freezing in Metro Tunnel Construction-A Case Study / Q. Yan, W. Wu, C. Zhang, S. Ma, Yu. Li // KSCE Journal of Civil Engineering. – 2019. – Vol. 23. – P. 2359–2370. DOI: 10.1007/s12205-019-1478-z
7. Analysis of moisture and temperature fields coupling process in freezing shaft / Yu. Yang, D. Lei, H. Cai, S. Wang, Ya. Mu // Thermal Science. – 2019. – Vol. 23. – P. 1329–1335. DOI: 10.2298/TSCI180519130Y
8. Numerical simulation and measurement analysis of the temperature field of artificial freezing shaft sinking in Cretaceous strata / Z. Yao, H. Cai, W. Xue, X. Wang, Z. Wang // AIP Advances. – 2019. – Vol. 9, № 2. – 025209. DOI: 10.1063/1.5085806
9. Вялов, С.С. Прочность и ползучесть мерзлых грунтов, и расчеты ледогрунтовых ограждений / С.С. Вялов. – М.: Изд-во Академии наук СССР, 1962. – 253 с.

10. Трупак, Н.Г. Замораживание грунтов в подземном строительстве горных выработок / Н.Г. Трупак. – М.: Недра, 1974. – 281 с.
11. Artificial ground freezing: A review of thermal and hydraulic aspects / M.A. Alzoubi, M. Xu, F.P. Hassani, S. Poncet, A.P. Sasmito // Tunneling and Underground Space Technology. – 2020. – Vol. 104. – 103534. DOI: 10.1016/j.tust.2020.103534
12. Study on theory model of hydro-thermal-mechanical interaction process in saturated freezing silty soil / Yu. Lai, P. Wansheng, M. Zhang, J. Zhou // International Journal of Heat and Mass Transfer. – 2014. – Vol. 78. – P. 805–819. DOI: 10.1016/j.ijheatmasstransfer.2014.07.035
13. Sweidan, A.H. A unified water/ice kinematics approach for phase-field thermos-hydro-mechanical modeling of frost action in porous media / A.H. Sweidan, Yo. Heider, B. Markert // Computer Methods in Applied Mechanics and Engineering. – 2020. – Vol. 372. – 113358. DOI: 10.1016/j.cma.2020.113358
14. Tounsi, H. Thermo-hydro-mechanical modeling of artificial ground freezing taking into account the salinity of the saturating fluid / H. Tounsi, A. Rouabhi, E. Jahangir // Computers and Geotechnics. – 2020. – Vol. 119. – 103382. DOI: 10.1016/j.compgeo.2019.103382
15. Coupled thermo-hydro-mechanical modeling of frost heave and water migration during artificial ground freezing of soils for mineshaft sinking / M. Zhelnin, A. Kostina, A. Prokhorov, O. Plekhov, L. Levin // Journal of Rock Mechanics and Geotechnical Engineering. – 2022. – Vol. 14, № 2. – P. 537–559. DOI: 10.1016/j.jrmge.2021.07.015
16. Thermal and hydraulic analysis of selective artificial ground freezing using air insulation: Experiment and modeling / A. Zueter, A. Nie-Rouquette, M.A. Alzoubi, A. Sasmito // Computers and Geotechnics. – 2020. – Vol. 120. – 103416. DOI: 10.1016/j.compgeo.2019.103416
17. Zhou, M.M. A three thermos-hydro-mechanical finite element model for freezing soils / M.M. Zhou, G. Meschke // International Journal for Numerical and Analytical Methods in Geomechanics. – 2013. – Vol. 37. – P. 3173–3193. DOI: 10.1002/nag.2184
18. Пугин, А.В. Анализ состояния ледопородного ограждения в условиях асимметричного распределения температур в замораживаемом массиве горных пород / А.В. Пугин, А.А. Оглоблина, А.В. Богомягков // Горное эхо. – 2022. – № 2. – С. 133–139. DOI: 10.7242/echo.2022.2.22
19. Семин, М.А. Теоретический анализ динамики ледопородного ограждения при переходе на пассивный режим замораживания / М.А. Семин, А.В. Богомягков, Л.Ю. Левин // Записки горного института. – 2020. – № 243. – С. 319–328. DOI: 10.31897/PMI.2020.3.319
20. Реализация принципов замораживания "по требованию" при строительстве стволов Дарасинского рудника / И.И. Головатый, Л.Ю. Левин, М.А. Семин, А.В. Пугин // Горный журнал. – 2023. – № 8. – С. 34–39. DOI: 10.17580/gzh.2023.08.05
21. Enhancing efficiency in the control of artificial ground freezing for shaft construction: A case study of the Darasinsky potash mine / M. Semin, I. Golovatyi, L. Levin, A. Pugin // Cleaner Engineering and Technology. – 2024. – Vol. 18. – 100710. DOI: 10.1016/j.clet.2023.100710
22. Freezing on Demand (FoD): An Energy Saving Technique for Artificial Ground Freezing / M.A. Alzoubi, A.P. Sasmito, A. Madiseh, F.P. Hassani // Energy Procedia. – 2019. – Vol. 158. – P. 4992–4997. DOI: 10.1016/j.egypro.2019.01.667
23. Freezing on demand: A new concept for mine safety and energy savings in wet underground mines / M.A. Alzoubi, A. Zueter, A. Nie-Rouquette, A.P. Sasmito // International Journal of mining Science and Technology. – 2019. – Vol. 29, № 4. – P. 621–627. DOI: 10.1016/j.ijmst.2019.06.015
24. Дорман, Я.А. Искусственное замораживание грунтов при строительстве метрополитенов / Я.А. Дорман. – М.: Транспорт, 1971. – 302 с.
25. Дорман, Я.А. Специальные способы работ при строительстве метрополитенов / Я.А. Дорман. – М.: Транспорт, 1981. – 302 с.
26. Andersland, O.B. An introduction to frozen ground engineering / O.B. Andersland, B. Ladanyi. – Springer Science & Business Media, 1994. – 352 p.
27. Оптимизация процессов формирования ледопородного ограждения при сооружении шахтных столов / И.И. Головатый, Л.Ю. Левин, О.С. Паршаков, Д.А. Диулин // Горный журнал. – 2018. – № 8. – С. 48–53. DOI: 10.17580/gzh.2018.08.06
28. Паршаков, О.С. Разработка автоматизированной системы термометрического контроля ледопородных ограждений: дис. … канд. техн. наук / О.С. Паршаков. – Пермь, 2020. – 140 с.
29. Применение программного комплекса "FrozenWall" для расчета искусственного замораживания пород / Л.Ю. Левин, М.А. Семин, А.В. Богомягков, О.С. Паршаков // Известия Тульского государственного университета. Науки о Земле. – 2019. – № 4. – С. 269–282.
30. Богомягков, А.В. Совершенствование математической модели тепломассопереноса в замораживаемом породном массиве, реализованной в программе FrozenWall / А.В. Богомягков, А.В. Пугин // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2023. – Т. 334, № 2. – С. 164–174. DOI: 10.18799/24131830/2023/2/3808
31. Свидетельство о государственной регистрации программы для ЭВМ №2018666337. FrozenWall / Богомягков А.В., Зайцев А.В., Клюкин Ю.А., Левин Л.Ю., Паршаков О.С., Пугин А.В., Семин М.А.; заявитель и правообладатель: ПФИЦ УрО РАН. – № 2018663501 заявл. 28.11.2018. опубл. 17.12.2018. Реестр программ для ЭВМ – 1 с.
32. Инструкция по расчету параметров, контролю и управлению искусственным замораживанием горных пород при строительстве шахтных стволов на территории Республики Беларусь. – Минск; Солигорск: ОАО «Беларуськалий», 2019. – 67 с.
33. ВСН 189-78. Ведомственные строительные нормы. Инструкция по проектированию и производству работ по искусственному замораживанию грунтов при строительстве метрополитенов и тоннелей. – М.: ЦНИИС, 1978. – 68 с.
34. Временное руководство по проектированию процесса замораживания пород для проходки вертикальных стволов шахт / ВНИИОМШС. – Харьков, 1971. – 103 с.
35. Левин, Л.Ю. Сравнительный анализ существующих методов расчета толщины ледопородного ограждения строящихся шахтных стволов / Л.Ю. Левин, М.А. Семин, О.А. Плехов // Вестник Пермского национального исследовательского политехнического университета. Строительство и архитектура. – 2018. – № 4. – С. 93–103. DOI: 10.15593/2224-9826/2018.4.09
36. An Applicability of Vyalov's equations to ice wall strength estimation / A. Kostina, M. Zhelnin, O. Plekhov, I. Panteleev, L. Levin, M. Semin // Frattura Ed Integrità Strutturale. – 2020. – Vol. 14, № 53. – P. 394–405. DOI: 10.3221/IGF-ESIS.53.30
37. Семин, М.А. Методы расчета искусственного замораживания пород при строительстве шахтных стволов / М.А. Семин, Л.Ю. Левин. – М.: Научный мир, 2021. – 152 с.
38. Calculation method of the design Thickness of a Frozen Wall with Its Inner Edge Radially Incompletely Unloaded / C. Hu, Z. Yang, T. Han, W. Yang // Applied Sciences. – 2023. – Vol. 13. – 12650. DOI: 10.3390/app132312650
39. Цытович, Н.А. Механика мерзлых грунтов: учебн. пособие. / Н.А. Цытович. – М.: Высшая школа, 1973. – 448 с.
40. Цытович, Н.А. Механика грунтов (краткий курс): учебник для строит. вузов / Н.А. Цытович. – М.: Высшая школа, 1983. – 288 с.
41. Anderson, D.M. Physics, chemistry and mechanics of frozen ground / D.M. Anderson, N.R. Morgenstern // 2nd International Conference on Permafrost. – 1973. – P. 257–288.
42. Исследование влияния неоднородности поля температур на прочность ледопородных ограждений стволов шахт / М.А. Семин, Г.П. Бровка, А.В. Пугин, С.А. Бублик, М.С. Желнин // Горный информационно-аналитический бюллетень. – 2021. – № 9. – С. 79–93. DOI: 10.25018/0236_1493_2021_9_0_79
43. Семин, М.А. Расчет земных теплопритоков при искусственном замораживании породного массива / М.А. Семин, Л.Ю. Левин, А.В. Пугин // Физико-технические проблемы разработки полезных ископаемых. – 2020. – № 1. – С. 162–171. DOI: 10.15372/FTPRPI20200118
44. Zhelnin, M.S. Optimization of the Passive Regime of Artificial Freezing of a Water-Saturated Rock Mass / M.S. Zhelnin, O.A. Plekhov, L.Y. Levin // Journal of Engineering Physics and Thermophysics. – 2020. – Vol. 93. – P. 685–692. DOI: 10.1007/s10891-020-02167-8
45. Левин, Л.Ю. Совершенствование методов прогнозирования состояния ледопородного ограждения строящихся шахтных стволов с использованием распределенных измерений температуры в контрольных скважинах / Л.Ю. Левин, М.А. Семин, О.С. Паршаков // Записки Горного института. – 2019. – Т. 237. – С. 268–274. DOI: 10.31897/PMI.2019.3.274
46. Thermal monitoring of frozen wall thawing after artificial ground freezing: Case study of Petrikov Potash Mine / L. Levin, I. Golovatyi, A. Zaitsev, A. Pugin, M. Semin // Tunneling and Underground Space Technology. – 2021. – Vol. 107. – 103685. DOI: 10.1016/j.tust.2020.103685

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