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Improving Methods of Frozen Wall State Prediction for Mine Shafts under Construction Using Distributed Temperature Measurements in Test Wells

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Development of mineral deposits under complex geological and hydrogeological conditions is often associated with the need to utilize specific approaches to mine shaft construction. The most reliable and universally applicable method of shaft sinking is artificial rock freezing – creation of a frozen wall around the designed mine shaft. Protected by this artificial construction, further mining operations take place. Notably, mining operations are permitted only after a closed-loop frozen section of specified thickness is formed. Beside that, online monitoring over the state of frozen rock mass must be organized. The practice of mine construction under complex hydrogeological conditions by means of artificial freezing demonstrates that modern technologies of point-by-point and distributed temperature measurements in test wells do not detect actual frozen wall parameters. Neither do current theoretical models and calculation methods of rock mass thermal behavior under artificial freezing provide an adequate forecast of frozen wall characteristics, if the input data has poor accuracy. The study proposes a monitoring system, which combines test measurements and theoretical calculations of frozen wall parameters. This approach allows to compare experimentally obtained and theoretically calculated rock mass temperatures in test wells and to assess the difference. Basing on this temperature difference, parameters of the mathematical model get adjusted by stating an inverse Stefan problem, its regularization and subsequent numerical solution.

Key words: frozen wall; rock mass; artificial ground freezing; temperature field; mine shaft; fiber optic cable; test wells; freezing columns; monitoring system; Stefan problem

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Introduction. Complex engineering, geological and hydrogeological conditions of mine construction require specific approaches to mining, particularly artificial ground freezing (Branch Construction Norms 189-78 «Design and Operations Guidelines on Artificial Ground Freezing in the Construction of Subways and Tunnels». Mintransstroi. M., 1978. 68 p.). In the context of mine shaft construction, artificial ground freezing is utilized to create a frozen wall around the designed mine working (Fig.1) [2, 10, 11, 14].

Construction of a frozen wall in the process of artificial ground freezing is carried out as follows [10]: designed shaft is contoured by the wells, into which freezing columns are sunk. The operation of freezing stations ensures circulation of the cooling agent (brine). As a result of cooling brine circulation in the freezing column, the temperature of the surrounding rock mass gradually declines and the contained water crystallizes. After some time, separate ice-rock cylinders formed around the freezing columns close in and form a frozen wall. Subsequent mining operations are carried out under its protection [3, 7].

Mining operations are permitted only after a closed-loop frozen section of specified thickness is formed. The thickness of the frozen layer is based on strength condition [17, 19] in such a way as to prevent ground water from entering the working throughout the entire period of mine shaft construction.

The use of fiber optic thermometry to monitor formation and state of a frozen wall.

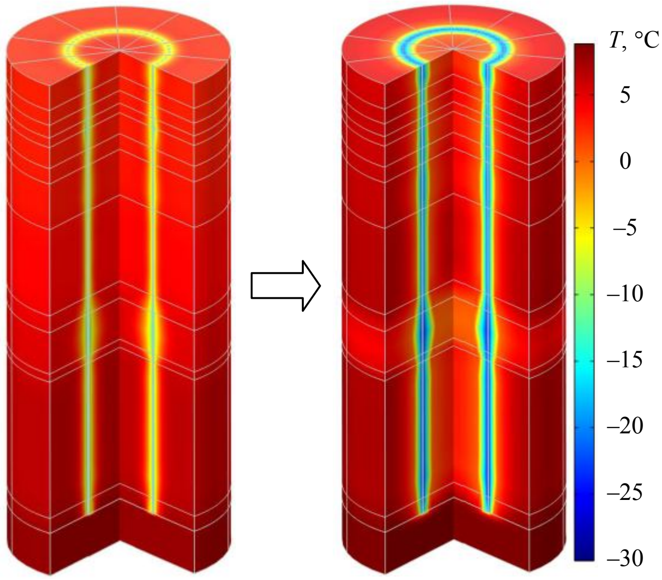

Fig.1. Formation of a frozen wall under artificial freezing conditions

In the process of mining operations, on-line monitoring of the frozen wall state must be organized (Safety Regulations 03-428-02 «Safety Regulations for Underground Construction», affirmed by the Decree of Russian State Mining and Engineering Inspection from 02.11.2001, N 49). Monitoring of frozen wall formation is usually performed using thermal and water monitoring wells, hypersonic devices and computer equipment [1]. The Monitoring provides data on frozen wall integrity and allows to calculate its thickness. Notably, the practice of mine construction under complex hydrogeological conditions by means of artificial freezing demonstrates that modern technologies of point-by-point and distributed temperature measurements in test wells do not detect actual frozen wall parameters [8, 18].

Inability of existing methods to control frozen wall formation, as well as insufficient accuracy of parameter assessment led to problems with frozen wall sealing capacity in cases of high water content of the deposits: e.g., Gremyachinsky mining and processing plant run by a mineral-chemical company Eurochem, Garlyksky plant belonging to a national concern «Türkmenhimiya», mine group of Verkhnekamsk deposit of potash-magnesium salts. Occurring construction accidents reduce the safety of mining operations and incur additional costs [9]. To solve the problem of insufficiently accurate theoretical methods of frozen wall state prediction and to organize operational supervision of its parameters, Mine Ventilation and Thermal Physics Department of the Mining Institute of the Ural Branch of the RAS developed a monitoring system to analyze frozen wall formation and state for mine shafts under construction, which is based on the application of fiber optic thermometry.

The main distinction of the proposed monitoring system is that its structural elements allow to store all the information on geological and thermophysical properties of the rock mass, to obtain parameters of freezing columns operation and to process experimental measurements of rock temperature in varying moments (Fig.2). Using this system, a mathematical interpretation of well thermometry has been obtained, basing on which temperature field of the rock mass is determined under artificial freezing conditions. Proposed monitoring system has been tested and implemented in the mine shaft construction of Petrikovsky mining and processing plant run by JSC «Belaruskali».

In this method, frozen wall monitoring is based on experimental fiber optic measurements of rock mass temperature throughout the entire depth of thermal test wells [9]. The main elements of the system are fiber optic recorder and fiber optic cable that perform distributed temperature measurement. The recorder is responsible for the generation of the optical signal, spectral filtration of backscatter light, conversion of backscatter light into electric signals, as well its intensification and digital processing. Fiber optic cable is used as a full-hole linear sensor located in test wells.

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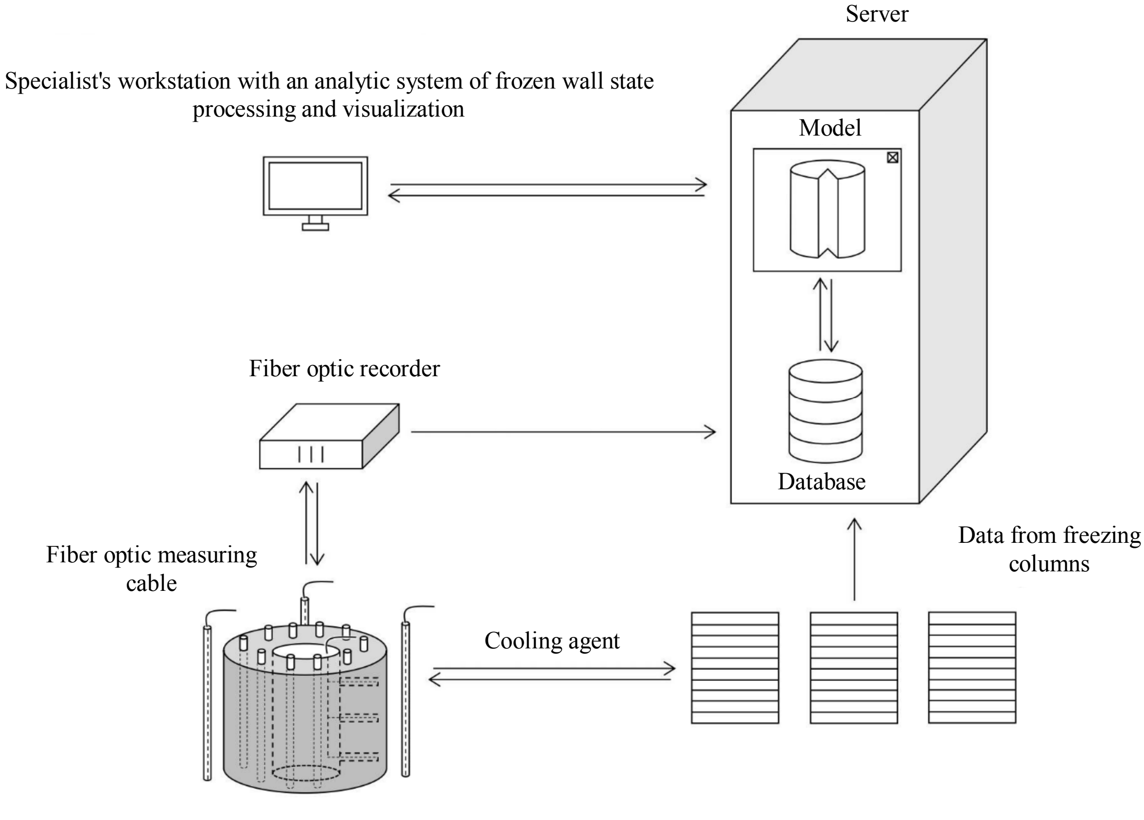

Fig.2. General architecture of frozen wall monitoring system

Thermal impact of freezing columns leads to uneven distribution of rock temperature along the depth of test wells. This temperature unsteadiness causes intramolecular vibrations of the fiber optic grid and, as a result, initiates changes in light transmission characteristics along the cable length. Thus, the principle of distributed temperature measurement centers around the comparison between spectra and intensities of initial laser radiation and backscatter radiation after the fiber optic transition. Processing and interpretation of backward Raman scattering a llow to estimate temperature along the fiber optic cable with space resolution 25 cm and measuring precision 0.1 °C. Notably, the interval of distributed temperature measurement in test wells is only several minutes long. Based on fiber optic technology, temporal and spatial dynamics of rock temperature measurements are estimated in the test wells (Fig.3).

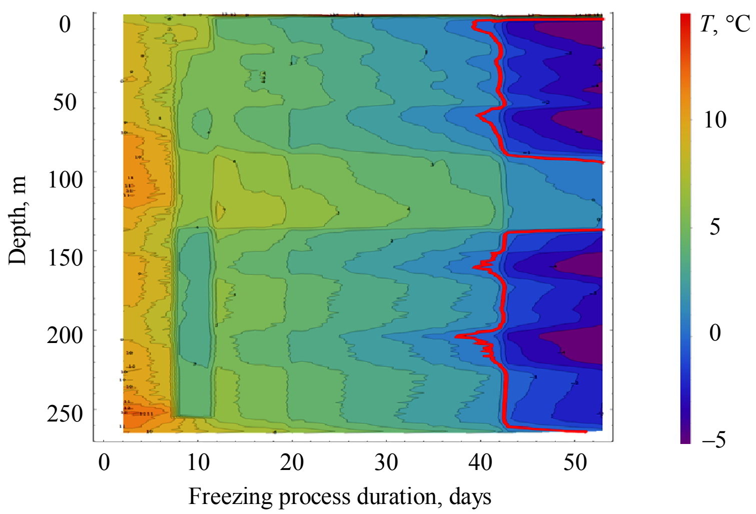

Fig.3. Dynamics of rock mass temperature dependency on test well depth, mine shaft 1, Petrikovsky deposit

Beside that, monitoring system of frozen wall formation and state automatically collects data on freezing columns operation, temperature of direct and reverse flows of the cooling agent and its consumption in the freezing columns.

Mathematical forecast of temperature field in the rock mass. Temperature field forecast in the rock mass under artificial freezing conditions is performed using engineering and geological data (filtration, strength, thermophysical properties of rock layers), as well as data on the freezing system (collar and bottom location of each freezing well, time charts of temperature and brine consumption).

Within the scope of the study, authors have developed a mathematical model of heat transfer processes, occurring in a water-saturated rock mass with isotropic and homogenous properties under artificial freezing. The model implies that heat exchange in the vertical direction is negligible compared to the horizontal one [17] – it allows to reduce the problem to two dimensions and to review each rock layer separately. Fluid migration under the influence of pressure and temperature gradients is not taken into account. Another assumption states that phase transition occurs in a specified temperature interval according to a linear law, described by the following dependency between specific enthalpy H and temperature T:

$$H(T)=\begin{cases}\rho_{th}c_{th}(T-T_{p2})+\rho_{th}wL \; at \; T_{p2}<T;\\ \rho_{th}wL\varphi_{ice} \quad at \quad T_{p1}<T<T_{p2};\\ \rho_{fr}c_{fr}(T-T_{p1}) \quad at \quad T<T_{p1},\end{cases} \tag{1}$$

where ρ – density, kg/m^3; c – mass heat capacity of the ground, J/(°C·kg); w – water content of the ground, m^3/m^3; L – specific heat capacity of the phase transition, J/kg; T_{p1} – initial temperature of crystallization, °C; T_{p2} – end temperature of crystallization, °C; φ_{ice} – concentration of ground water solid phase; «th» index stands for thawed ground, «fr» index – for frozen one.

According to (1), the authors consider the enthalpy formulation of the Stefan problem (or the problem of heat transfer with a moving boundary of phase transition) [4]:

$$\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left[\lambda(\phi_{ice})\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda(\phi_{ice})\frac{\partial T}{\partial y}\right]; \tag{2}$$

$$\left[\lambda(\phi_{ice})\frac{\partial T}{\partial n}-\alpha\left(T_F-T\right)\right]\Bigg|_{\Omega_F}=0; \tag{3}$$

$$T\big|_{\Omega_{out}}=T_0; \tag{4}$$

$$T\big|_{t=0}=T_0; \tag{5}$$

$$\varphi_{ice}(H)=\begin{cases}1 \quad at \quad H<0;\\ 1-H/\left(\rho_{th}wL\right) \quad at \quad 0<H<\rho_{th}wL;\\ 0 \quad at \quad \rho_{th}wL<H.\end{cases} \tag{6}$$

Here $\lambda(\varphi_{ice})=\varphi_{ice}\lambda_{fr}+(1-\varphi_{ice})\lambda_{th}$ – a function of rock mass heat transfer from ice phase concentration, W/(°C·m); t – physical time, s; α – heat exchange factor on the boundary between the rock mass and the freezing columns, W/(°C·m^2); x, y – physical coordinates, m; $\Omega_F=\bigcup\Omega_{Fi}$ – boundaries with all freezing columns i = 1,…,N; Ω_{out} – outer boundary of the computational domain; n – coordinate along the normal line to Ω_F, m.

Experimentally measured temperature distribution along the depth of thermal monitoring wells is used to adjust thermophysical parameters of the problem (1)-(6): thermal conductivity λ_{fr} and λ_{th}, heat capacity c_{fr} and c_{th}, water content w. Adjustment of thermophysical parameters of the problem (1)-(6) represents a solution of the inverse Stefan problem [5, 6, 12, 13].

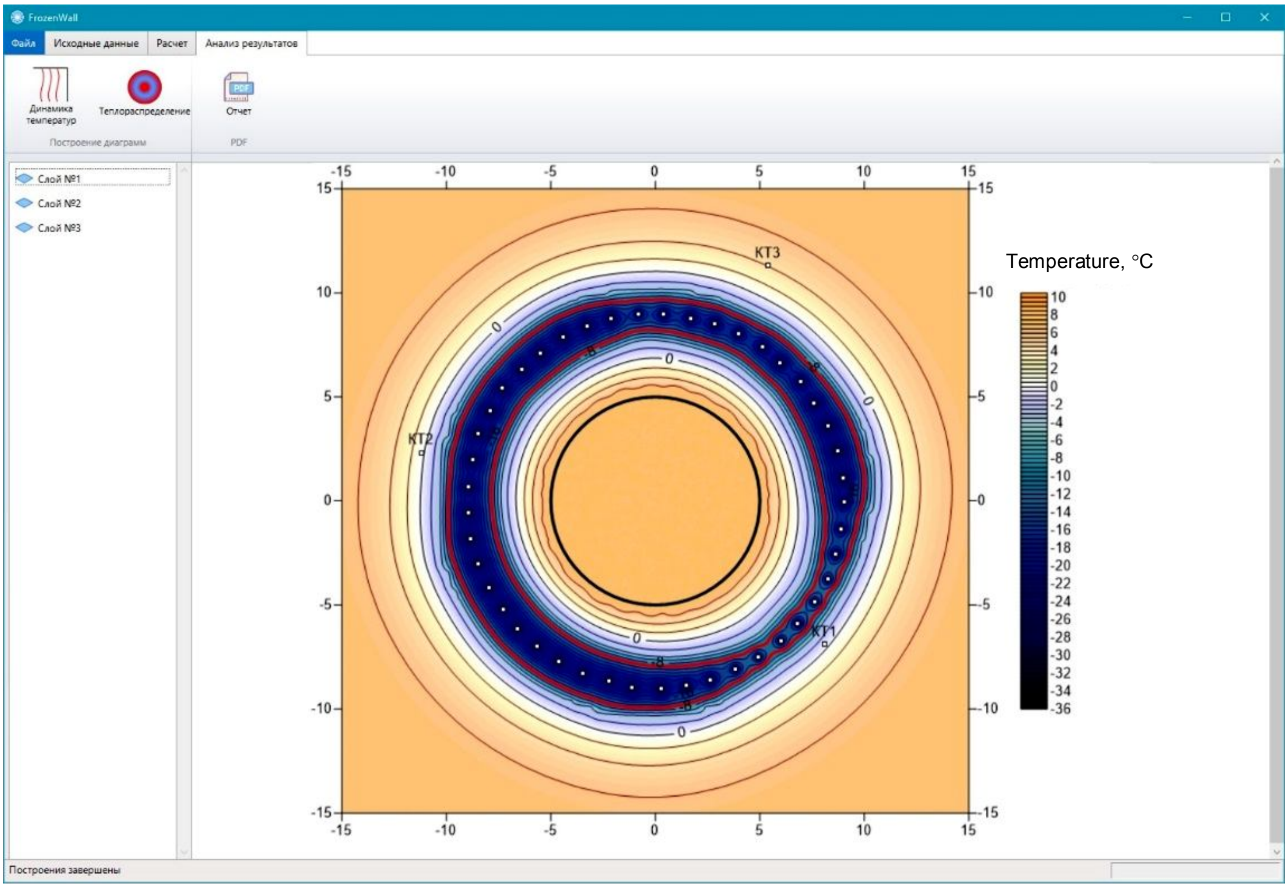

Fig.4. Run screen of analytical system "Frozen Wall"

In order to formulate an inverse Stefan problem, it is needed to overdetermine the direct problem (1)-(6) by including experimentally measured data on temperature $T_i^{(c)}(t)$ in the location (x_t, y_i) of each test well *i*:

$$T(t,x,y) = T_i^{(c)}(t) \quad \text{at} \quad i = 1,\dots,N_C, \tag{7}$$

where N_C – number of test wells.

The location of each test well N *i* is set by coordinates (x_t, y_i) of the point, where the test well intersects with the central horizontal section of rock mass layer under examination.

Hence, the solution of the inverse Stefan problem lies in the estimation of a temperature field $T(t,x,y)$ and the values of thermophysical rock mass parameters, satisfying the set of equations (1)-(7).

Current paper instead of a strict condition (7) focused on the following functional of the mismatch between theoretical and experimentally measured temperatures in the test wells:

$$I = \sum_{i=1}^{N_C} \int_0^{t_\Sigma} \left(T_i^{(e)} - T_i^{(m)}\right)^2 dt\,, \tag{8}$$

where t_Σ – freezing time, days; $T_i^{(m)}$ – model temperature in the i^{th} well, °C.

In the latter case, solution to inverse Stefan problem lies in minimization of functional (8) taking into account conditions (1)-(6). Minimization parameters: thermal conductivities λ_{fr} and λ_{th}, heat capacities c_{fr} and c_{th}, water content *w*.

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Numerical minimization of functional (8) is achieved using modified method of gradient descent [15], which includes proportional-integral derivative control and is performed in iterations. Each iteration involves numerical solution of the direct Stefan problem (1)-(6) for current values of optimization parameters and their minor variations. Numerical solution of the problem (1)-(6) is obtained using finite difference method on a regular non-uniform grid with increasing density near freezing columns.

Numerical algorithm of problem solution (1)-(8) is realized in Visual Studio environment and is included in the analytical system «Frozen Wall», developed in the Mining Institute of the Ural Branch of the Russian Academy of Sciences to process and visualize the processes of frozen wall formation and state control (Fig.4). Analytical system «Frozen Wall» is an element of the monitoring system of frozen wall formation (Fig.2).

Based on estimated temperature fields and performed complex analysis, frozen wall thickness has been predicted for newly constructed mine shafts of the Petrikovsky mining and processing plant run by JSC «Belaruskali».

Conclusion. Proposed monitoring system of frozen wall formation and state control for the shafts is based on the application of fiber optic thermometry. Basing on experimentally measured temperature in the test wells and operating parameters of freezing stations, a method of mathematical processing and interpretation of thermometric results has been developed by means of solving direct and inverse Stefan problems. As a result, the mathematical method allows to restore temperature field in the entire rock mass using engineering-geological data on distributed temperature measurements in the test wells.

Proposed monitoring system has been tested and implemented in the mine shaft construction of Petrikovsky mining and processing plant run by JSC «Belaruskali».

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