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CONTROL OF GROUND TEMPERATURES UNDER HEADFRAMES AND COLLARS OF VERTICAL SHAFTS: A CASE STUDY OF THE UDACHNY DIAMOND MINE (YAKUTIA)

A.S. Kurilko[1], Yu.A. Khokholov[1], A.V. Drozdov[2], D.E. Solovev[1]

[1] *Chersky Mining Institute of the North, SB RAS, 43, Lenina ave., Yakutsk, 677980, Russia; Solovjevde@igds.ysn.ru*
[2] *Institute of the Earth's Crust, SB RAS, 128, Lermontova str., Irkutsk, 664033, Russia; drosdovav@list.ru*

The paper presents data on ground temperatures and salinity of groundwater and soil under headframes and collars of vertical shafts at the ALROSA underground diamond mine of Udachny. The ground temperature pattern for the headframe pile foundation is reconstructed using 3D modeling of heat transfer in soil. Numerical experiments allow predictions for the rate of 0 °C isotherm propagation in soil during operation-suspension cycles of a freezing system, with implications for the optimal schedule of temperature logging.

Permafrost, mine, temperature regime, geothermal monitoring, pile foundation, headframe, vertical shaft, ground freezing system

INTRODUCTION

Diamond production from the Yakutian kimberlites in Russia was run as surface open-pit mining for about fifty years before the ALROSA company proceeded to underground mining at large deposits. Kimberlites are recovered through vertical shafts at several mines (Internatsionalny, Mir, and Udachny), and two sloping shafts are used additionally at the Aikhal mine. The stability of headframes above the shafts is important for general work safety to avoid accidents during skip and cage rides associated with headframe tilting which pose health and life risks and lead to prolonged suspension of mining, shutting down of processing, and require expensive repair works.

Headframes are most often installed upon ice-rich fine-grained soils which loose mechanic strength upon thawing. Shaft placement and operation warm up the space around the supports. For instance, the thaw area around the cage shaft of the Internatsionalny mine reached a radius of 20 m and covered the whole pile framework. The conventional methods are inapplicable to ensure the stability of headframes above vertical shafts in deep diamond mines, which are heavily loading structures upon soils with complex temperature patterns. Freeze back of soil beneath headframes may cause heaving and deformation of shaft supports. Thus, it is important to manage the ground freezing process to provide the required bearing capacity of foundations without disturbing the support stability.

Monitoring the thermal and mechanic processes associated with thawing and freezing of soil under headframes requires creating systems for ground temperature measurements and development of related modeling methods for predicting the thermal behavior of soils during the headframe lifespan. The respective theoretical and practical issues are of special importance as no experience is yet available in creating such systems for mining.

PERMAFROST TEMPERATURE AND SALINITY UNDER HEADFRAMES AT THE UDACHNY MINE SITE

The territory of the Yakutian diamond province belongs to the northern permafrost zone of Siberia (northern continental subzone) [*Fotiev et al., 1974*], with up to 1500 m thick continuous low-temperature permafrost. Mean annual ground temperature at 20 m below the surface varies from −7.5 to −3.0 °C and from −4 to −1 °C or warmer in the northern and southern parts of the territory, respectively [*Balobaev and Devyatkin, 1983*]. The climate is strongly continental, with temperature contrasts exceeding 100 °C. According to records of weather stations, low mean annual air temperatures and negative annual radiation budget (879–1130 MJ/m^2 [*Pivovarova, 1977*]) maintain the temperature stability and local changes of permafrost exposed to effects from diamond mining.

Engineering-geological surveys show uneven salinity distribution of groundwaters and soils at all ALROSA underground mining sites. According to analyses of soil samples, strongly saline groundwaters

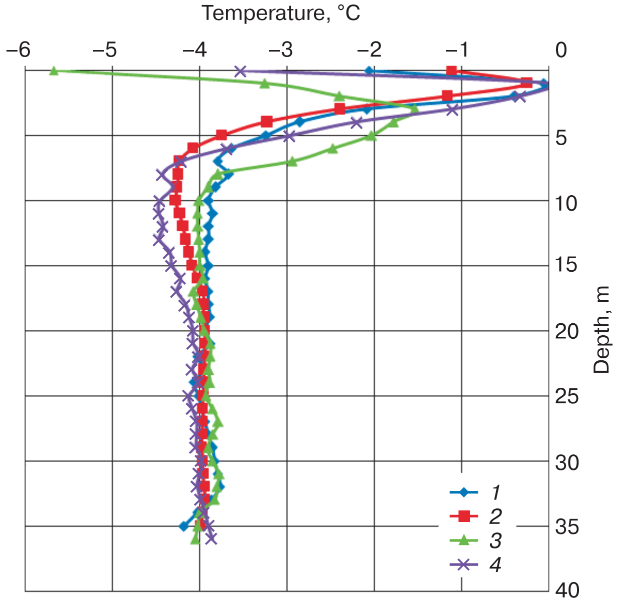

Fig. 1. Depth-dependent ground temperature in boreholes near a cage shaft of Udachny mine.

1 – borehole 9 (04.10.2012); *2* – borehole 10 (03.10.2012); *3* – borehole 11 (16.10.2012); *4* – borehole 12 (05.10.2012).

(brines) contaminate shaft collars, as well as the surrounding frozen ground, during drilling and mining. Brines percolated into permafrost are known to decrease the melting point of pore ice, and its melting reduces the bearing capacity of foundation soils. Furthermore, highly aggressive saline waste waters cause corrosion of concrete and thus deteriorate the stability of headframes, which are essential elements of utility systems.

Geophysical surveys and studies of soils at the Udachnyi mine revealed a man-caused talik with saline waters in the northern part of the site, at depths of 11 to 30 m. Meanwhile, the normal seasonal frost and thaw depth (active layer thickness) is from 2.7 to 5.5 m depending on lithology and thermal properties of soils. Engineering-geological boreholes tapped active layer waters at the depths 1.0–4.0 m. As shown by chemical analyses, water in boreholes has mainly calcium-chloride chemistry and varies in salinity from brackish (1.5–2.0 g/L) to weak metamorphic brine (60–70 g/L).

Shallow groundwaters collected at the site from 2003 through 2010 varied in salinity from fresh to strongly brackish, but the current concentrations of salts rather correspond to saline waters or brines. The salinity increased obviously during the construction of vertical shafts. The negative effect on the shallow permafrost-groundwater system mainly results from discharge of natural brines (up to 400 g/L) from pilot holes, temporal storage of wet rocks from shafts during drilling, and pad filling with saline soil.

Judging by data on the construction technology of vertical shafts and on the actual state of rocks under the surface-mounted mine structures, water contents within the active layer have changed notably for the period of development. When loosened wet ground recovered from the holes was dumped on a concrete baseplate while drilling, some highly saline water spilled off into the unshielded active layer. The saline water melted pore ice in permafrost, increased the permeability of soil, and migrated downward. Thereby the original salinity of natural waters reduced to the equilibrium with the surrounding soils which are relatively cold but heterogeneous. This inference is supported by the presence of groundwater venting in skip and ventilation shafts.

Monitoring in November–December 2007 within the mine site showed up to 0.5 m^3/hr water influx to the shaft at depths from 12 to 30 m. The sampled water was a transparent liquid that tasted bitter and salty, had a typical brine smell, and froze at −15 °C.

The water flowing into the vertical shaft had a salinity of 58.3 g/L and thus may come from the man-caused talik. Thus, field observations in the skip and ventilation shafts and related comprehensive studies (drilling, geophysical surveys, etc.) at the Udachny mining site reveal taliks with diluted natural brines at shallow depths under the headframes of vertical shafts. Therefore, good freezing cohesion of pile foundation elements under permanent headframes requires cooling the soils around piles to lower temperatures than it was previously expected (−3 to −5 °C) according to the natural thermal conditions (Fig. 1). The amount of required cooling and its difference from the designed values can be estimated by simulation (see below).

3D MODELING OF HEAT TRANSFER IN SOILS UNDER HEADFRAMES OF VERTICAL SHAFTS

Installation of freezing systems is envisaged for each shaft to keep the soil frozen and to maintain its capacity to bear headframes at diamond mines. It is a nontrivial task to manage the process of soil freezing with the proper trade-off between providing sufficient bearing capacity of piles and avoiding deformation of tubbing or concrete supports by freezing-related stress.

Interaction between saline waters and rocks is an important issue for diamond mining in Yakutia. It is necessary to estimate the temperatures, water contents, and salinity of permafrost in natural conditions and under mining loads. There are various techniques for predicting the temperature patterns of saline frozen ground that provide quite a good idea of processes in it [*Sleptsov et al., 1996; Permyakov and Ammosov, 2003*]. The main problem is to choose input model parameters, especially, the temperature of freezing onset and the phase state of pore water.

A team of the Mining Thermophysics Laboratory at the Mining Institute of the North (Yakutsk) designed a 3D forward model of heat transfer in rocks with an embedded vertical shaft and its headframe upon a pile foundation, as a basis for ground temperature control. The model takes into account the temperature of freezing liquid, the lengths, number, and placement of freezing holes, annual air temperature variations, air temperature in the shaft, as well as stratification and salinity of rocks.

Modeling for prediction of thermal conditions is performed for the domain Ω (Fig. 2) by solving a multidimensional Stefan problem. Such solutions are most often found numerically by smoothing [*Samarsky and Moiseenko, 1965*], which corresponds in our case to the assumption that the water-ice phase change occurs within some temperature range controlled by the smoothing parameter, rather than at some specific T_0 value. In numerical experiments, the T_0 values are commonly allowed to vary and the temperature range varies correspondingly. The source of heat spent on phase transition has constant power and average temperature but its density distribution function is variable. It is known, however, that some pore water in fine-grained materials, such as the simulated soil, can remain liquid at negative temperatures, and the amount of unfrozen water increases with salinity. Free water commonly freezes at $T_0 = T_{bf}$, while residual bound water crystallizes as the matrix temperature decreases. In this case, bound water undergoes phase transition within a certain temperature range [T_1, T_2], which leads to the formation of a freezing zone. We use the natural smoothing method [*Permyakov and Ammosov, 2003*] in which equations represent the real process of permafrost pore water freezing and thawing within the respective temperature range. The approach is advantageous as no choice of smoothing parameter is needed. It allows finite-difference modeling with smoothed coefficients, i.e., the problem is reduced to the ordinary one for thermal conductivity. The nonlinear solution is sought by iterative Godunov's method, which largely simplifies the solution of multidimensional problems for heat and mass transfer in frozen ground due to the use of low-cost locally one-dimensional additive finite-difference schemes.

The thermal conductivity problem is solved by natural smoothing using the unfrozen water function [*Samarsky and Moiseenko, 1965*]:

$$\left[C(T)+L\rho\frac{\partial W_1}{\partial T}\right]\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[\lambda(T)\frac{\partial T}{\partial x}\right]+$$
$$+\frac{\partial}{\partial y}\left[\lambda(T)\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[\lambda(T)\frac{\partial T}{\partial z}\right],\quad (x,y,z)\in\Omega,\quad (1)$$

where C is the volumetric heat capacity of ground, J/(m^3·K); T is the ground temperature, °C; L is the heat of water phase transitions, J/kg; W_1 is the amount

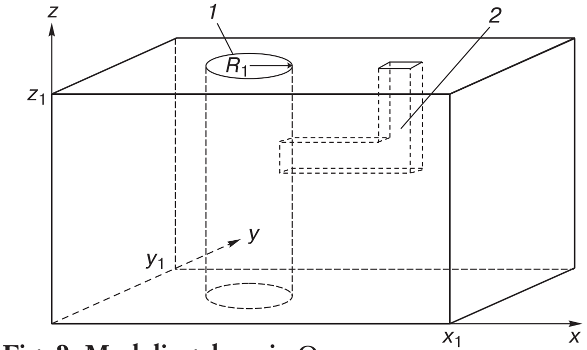

Fig. 2. Modeling domain Ω:

x_1, y_1, z_1 are the coordinates of modeling domain limits; R_1 is the shaft radius; *1* – main vertical shaft; *2* – ventilation shaft.

of unfrozen water, unit fraction (u.f.); ρ is the ground density, kg/m^3; t is the time, s; λ is the ground thermal conductivity, W/(m·K).

Heat flux through the sides and base of the domain Ω is assumed to be zero (boundary condition of the second kind):

$$\lambda(T)\frac{\partial T}{\partial x}=0,\quad x=0,\quad 0\le y\le y_1,\quad 0\le z\le z_1;$$
$$\lambda(T)\frac{\partial T}{\partial x}=0,\quad x=x_1,\quad 0\le y\le y_1,\quad 0\le z\le z_1;$$
$$\lambda(T)\frac{\partial T}{\partial y}=0,\quad 0\le x\le x_1,\quad y=0,\quad 0\le z\le z_1;$$
$$\lambda(T)\frac{\partial T}{\partial y}=0,\quad 0\le x\le x_1,\quad y=y_1,\quad 0\le z\le z_1;$$
$$\lambda(T)\frac{\partial T}{\partial z}=0,\quad 0\le x\le x_1,\quad 0\le y\le y_1,\quad z=0,$$

where x_1, y_1, z_1 are the domain limit coordinates, m.

The boundary condition on the ground surface is set with regard to air temperatures:

$$\lambda(T)\frac{\partial T}{\partial z}=\alpha\left(T-T_3\right),\quad 0\le x\le x_1,\quad 0\le y\le y_1,\quad z=z_1,$$

where α is the heat transfer across the ground-air interface, W/(m^2·K); T_3 is the air temperature, °C.

The third kind boundary conditions on the inner surfaces of the skip and ventilation shafts are

$$\lambda\left.\frac{\partial T}{\partial n}\right|_{\Gamma_1}=\alpha_1\left(T-T_4\right),\quad (x,y,z)\in\Gamma_1;$$
$$\lambda\left.\frac{\partial T}{\partial n}\right|_{\Gamma_2}=\alpha_2\left(T-T_5\right),\quad (x,y,z)\in\Gamma_2,$$

where $\partial/\partial n|_{\Gamma_1}$ and $\partial/\partial n|_{\Gamma_2}$ are the outer normals to the boundaries of the skip (Γ_1) and ventilation (Γ_2) shafts, respectively; T_4 and T_5 are the air temperatures in the two shafts, respectively, °C; α_1, α_2 are the coefficients of heat loss through the shaft walls, W/(m^2·K).

The starting ground and air temperatures in both shafts are specified for the time t_0. The convective heat transfer across the ground-air interface is found as [*Kurtener and Chudnovsky, 1969*]

$$\alpha = \begin{cases} 6.16 + 4.19v, & 0 < v < 5; \\ 7.56v^{0.78}, & 5 < v < 30, \end{cases}$$

where v is the wind speed, m/s.

The heat loss α_1 is found using the equation from the theory of turbulent air flow heat transfer [*Shcherban et al., 1977*]:

$$\mathrm{Nu} = 0.0195\,\varepsilon \mathrm{Re}^{0.8},$$

where Nu is the Nusselt number, $\mathrm{Nu} = \alpha_1 R_1/\lambda_0$; ε is the roughness of mine walls; Re is the Reynolds number, $\mathrm{Re} = \rho_0 v_0 R_1/\mu$; λ_0 is the air thermal conductivity, W/(m·K); μ is the air dynamic viscosity, Pa·s; v_0 is the air stream speed, m/s; ρ_0 is the air density, kg/m^3; R_1 is the shaft radius, m.

The heat loss α_2 is calculated in the same way.

The presence of ground freezing systems is taken into account by specifying the required cooling temperature in the respective coordinates.

The unfrozen pore water curve can be approximated using many different equations, among which that of *Anderson and Morgenstern* [*1973*] is the most commonly used:

$$W_1(T) = \begin{cases} W_2, & T \le T_1; \\ \left(W - W_2\right)\left(\dfrac{T - T_1}{T_2 - T_1}\right)^n + W_2, & T_1 < T < T_2; \\ W, & T \ge T_2, \end{cases}$$

where W is the total water content, u.f.; W_2 is the bound water content, u.f.; T_2 is the freezing point of pore water, °C; T_1 is the temperature of complete pore water freezing, °C; n is the empirical parameter.

The phase transition temperatures of brines depend on the concentration of salt and are found as [*Iwata, 1974; Popov and Kurilko, 2006*]:

$$T_2 = \frac{273.15}{L}\left(273.15R\ln\left(\frac{1-\kappa C'}{1-C'}\right) + \Psi_1 - \Psi_2\right),$$

where R is the gas constant, $8.314\cdot10^3$ J/(K·kmol); κ is the coefficient of salt uptake by the ice surface, u.f.; C' is the salt concentration in pore water, mol/L; Ψ_1, Ψ_2 are the potentials of ground surface interactions with ice and water, respectively, MPa.

The volumetric heat capacity and thermal conductivity of ground are estimated with regard to the unfrozen water curve as:

$$C(T) = \begin{cases} \left(C_1 + 2260\left(W - W_2\right) + 4212W_2\right)\rho, & T \le T_1; \\ \left(C_1 + 2260(W - W_1) + 4212W_1 + L\dfrac{\partial W_1}{\partial T}\right)\rho, & T_1 < T < T_2; \\ \left(C_1 + 4212W\right)\rho, & T \ge T_2; \end{cases}$$

$$\lambda(T) = \begin{cases} \lambda_1, & T \le T_1; \\ \left(\lambda_1 + \dfrac{\left(\lambda_2 - \lambda_1\right)\left(T - T_1\right)}{T_2 - T_1}\right), & T_1 < T < T_2; \\ \lambda_2, & T \ge T_2, \end{cases}$$

where C_1 is the specific heat of the rock matrix, J/(kg·K); λ_1 is the thermal conductivity of frozen ground, W/(m·K); λ_2 is the thermal conductivity of unfrozen ground, W/(m·K).

The 1D freezing-thawing problem formulated as in (1) is commonly solved using Godunov's scheme [*Samarsky and Moiseenko, 1965; Samarsky, 1983; Samarsky and Vabishchevich, 2003*].

The solution to the 3D heat transfer problem was obtained by the sum approximation method [*Yanenko, 1967; Samarsky and Vabishchevich, 2003*] which reduces the initial problem to a sequence of 1D problems. Note that finite-difference schemes satisfy the approximation and stability conditions only in the final result. The sequence of 1D problems is solved for each time layer. All systems of difference equations are derived with regard to the modeling domain geometry.

SYSTEMS FOR GROUND FREEZING AT PILE FOUNDATIONS OF HEADFRAMES AND MODELING RESULTS

Ground temperature stabilization for providing the required bearing capacity of pile foundations and the durability of engineering structures is the basic problem for construction in permafrost. The vitality of this issue is evident at all ALROSA mining sites. Special soil stabilization measures are crucial for surface-mounted mining structures and especially cage and skip shafts, as their pile foundations and collars are exposed to warming during drilling, construction, and production. The warming and thawing of permafrost have several causes: inputs of ventilation air to the mine which has a positive temperature all year round; heat inputs from heated buildings; high salinity of soils; effect of warm atmospheric air in the summer season.

The thermal field of ground around a shaft is controlled by interaction of heat flows from the shaft and the effect of the ground surface. Clean air is supplied to underground mines, through main and ventilation shafts, in all seasons, to maintain positive temperatures with air heating systems, which heats up the surrounding frozen ground and deteriorates its stability. According to the practical experience, the use of passive thermal insulation alone cannot cancel the prolonged warming effect from the shaft, and soil stabilization requires installing freezing systems around the shaft.

The surface-mounted structures at mining sites include large headframes with pile foundations (16 m long bore piles, 650 mm in diameter) placed around the shafts which experience heavy loads. Thus, the headframes can be stable only if the ground is kept frozen all year round at negative temperatures sufficient to overcome the warming effect of the shaft. This is possible with systems of forced freezing consisting of a station, a gallery of brine ducts, and freezing pipes. The total number of pipes in a gallery depends on the shaft diameter and varies from 12 to 56 m, at the length 15–40 m. The freezing station is operated for the whole mine lifespan and is set on and off according to temperature logs from geothermal boreholes.

The designed forward model was used to choose the operation regime of the freezing system to keep frozen the ground under headframes and shaft collars at ALROSA diamond mines [*Khokholov et al., 2016*].

As the freezing system starts working, the ground around the shaft and the sub-headframe piles cools down gradually and then freezes up. However, complete freezing is forbidden as it is known from practice to cause shear stress and deformation of the concrete support. The stress and deformation can be damped by a ring-shaped unfrozen zone around the shaft, at least 0.5 to 1.0 m wide [*Sleptsov et al., 1996; Kramskov, 2004*]. Therefore, the freezing station should be operated in a way to keep unfrozen the damping ring but freeze the soil near the piles, in order to ensure the designed bearing capacity of the headframe.

Modeling was performed for different operation regimes of the freezing system, with two refrigerant temperatures (−15, −20 °C) and three air temperatures in the shaft (+5, +10 and +15 °C). The numerical experiments allowed choosing the optimal cooling regime to provide the formation of a damping unfrozen ring, at least 0.5 m in diameter, around the shaft.

The inferred optimal regime for a ventilation shaft at the Udachny mine site is: +10 °C shaft air temperature; −15 °C refrigerant temperature; operation in 5 month cycles with 1 month breaks. Operation in this regime can produce a ring-shaped frozen zone (−6 to −8 °C) around the ventilation shaft in four years, as shown by calculations (see temperature contour lines in Fig. 3: a horizontal section at the depth 27 m in panel *a* and a vertical section in panel *b*). The ventilation shaft causes a significant thermal effect on the surrounding rocks, but calculations of the bearing capacity of piles show that freezing boreholes placed near the piles, as designed, can keep the soil frozen and maintain its stability. The size of the thaw ring around the ventilation shaft (Fig. 4) changes notably as the freezing system is turned on/off.

Therefore, a system of automated thermal control consisting of vertical and horizontal boreholes is required for temperature stabilization of soils in zones of headframe pile foundations and at shaft collars.

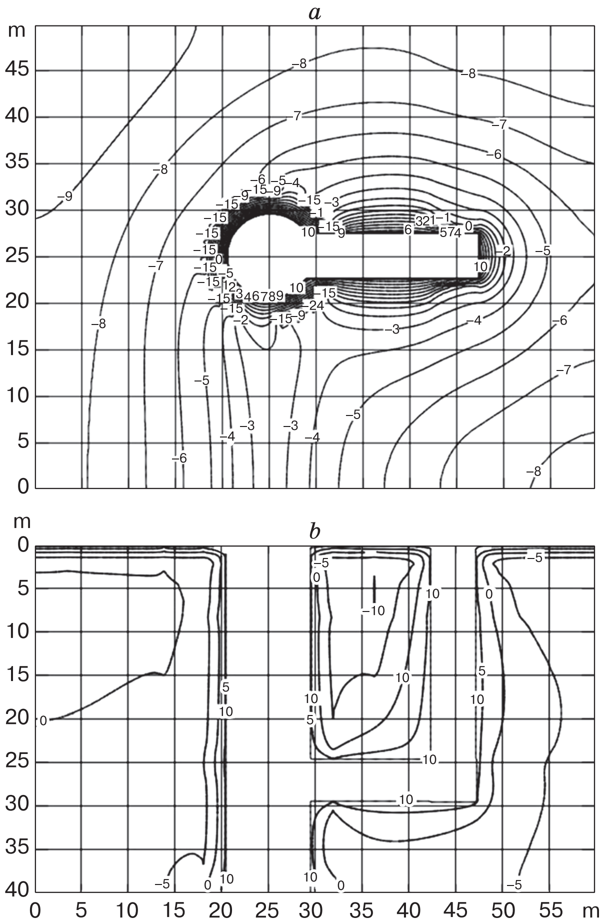

Fig. 3. Temperature field (°C) around a ventilation shaft after four years of operation of the freezing system.

a – section at depth 27 m; *b* – section across the vertical shaft axis along the ventilation shaft axis.

The vertical geothermal boreholes, with their depth commensurate to the pile length, should be placed proceeding from their calculated capacity of providing control for each pile cluster (two holes per cluster). Temperature is logged by several thermistors: the first one at the ground surface level and the others at every 1 m all the way downhole. Additional boreholes should be placed for ground temperature monitoring between the shaft supports and the freezing columns, and within the damping unfrozen ring around the shafts which prevents support deformation and failure by freezing-related stress. The placement of horizontal boreholes should base on numerical results with regard to temperature, water content, and salinity of soils at the site and to the freezing system features.

Consider, as an example, size variations of the thaw ring around a ventilation shaft at the Udachny site and placement of horizontal geothermal bore-

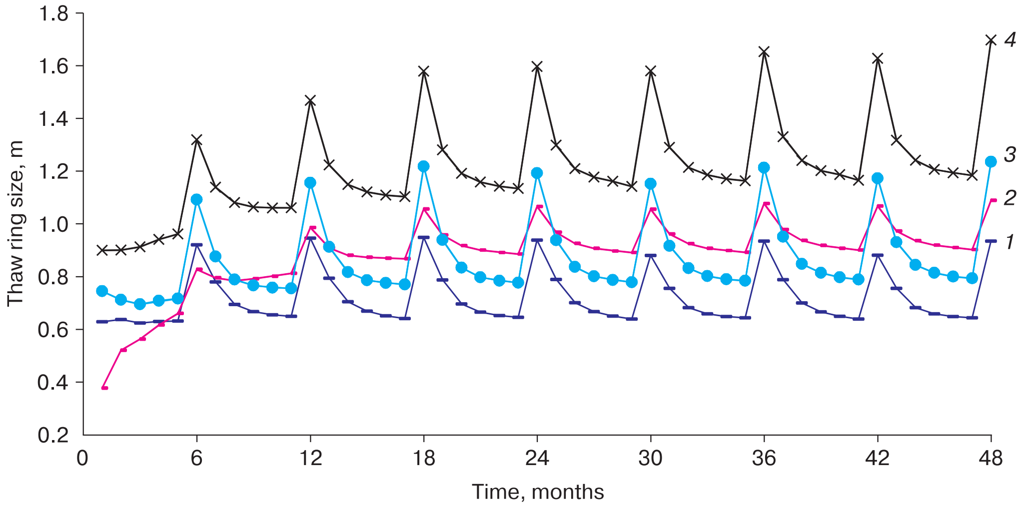

Fig. 4. Temperature dynamics in thaw rings around a ventilation shaft.

The freezing system operated for five months, with a 1 month break; air temperature in the shaft is +10 °C; freezing temperature –15 °C. Depths: *1* – 14 m; *2* – 27 m; *3* – 30 m; *4* – 37 m.

holes during suspension of the freezing station. The calculations were performed for +15 °C air temperature in the shaft, –20 °C refrigerant temperature, and 1 month breaks at every 5 months of operation. The thaw ring (0 °C) propagates off the shaft through the soil (Fig. 5) almost parallel to the fixed shaft surface, except for the lower part where the unfrozen zone is located below the freezing pipes and their effect on heat flow from the shaft attenuates.

According to the modeling results, the system for automated ground temperature control at the ventilation shaft collar should include 2.5 m long horizontal geothermal boreholes placed at the depths 8, 18 and 35 m below the ground surface (above and below the ventilation shaft). The holes should have metal casing of high mechanic strength, which is important for both installation and operation. Temperature logging is performed by multi-bead ground temperature cables, with eight thermistors: two at interfaces of the support with air (0 m, thermistor 1) and soil (0.5 m below the surface, thermistor 2), and the others downhole at the depths 0.75 m (3), 1.0 m (4), 1.25 m (5), 1.5 m (6), 2.0 m (7), and 2.5 m (8).

Automated temperature control systems at mines allow temperature logging and recalculation of logs at different sampling intervals. Heat transfer in rocks is known to have rather high inertia and the temperatures to change quite slowly. Therefore, special numerical experiments were performed to predict the 0 °C isotherm propagation rate during operation-suspension cycles of the freezing system and thus to choose the optimal time for temperature logging.

The input parameters for the modeling were: +10 °C temperature of air supplied to the shaft and –20 °C refrigerant temperature; 2 month operation cycles with 2 month breaks. The thaw ring was predicted to change smoothly in size for a month (Fig. 6), without abrupt ground temperature changes. The thaw ring reduced from 1.34 to 0.88 m for a month of the freezing system operation, i.e., 0.11 m per week on average. When the cooling station was off, the 0 °C isotherm propagated more slowly; it became stable in

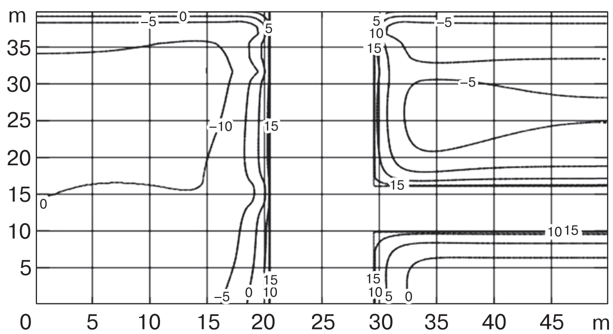

Fig. 5. Temperature field (°C) around a ventilation shaft, after 30 day suspension of the freezing system.

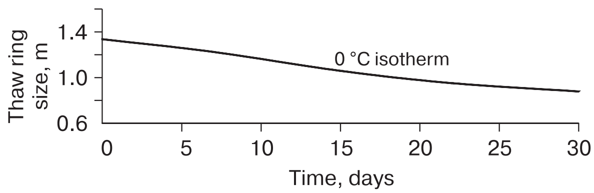

Fig. 6. Size changes of thaw ring around a ventilation shaft at Udachny mine while the freezing system is on.

the following few days and then began to increase gradually.

Thus, the numerically estimated rates of 0 °C isotherm propagation suggest that weekly logging is sufficient for rapid ground temperature monitoring at shaft collars. The same monitoring frequency is applicable to soil under headframes (though these zones are free from powerful heat sources), in order to obtain the complete temperature pattern of the whole monitored site.

CONCLUSIONS

Engineering geological surveys at the ALROSA mining sites revealed brackish to brine pore water salinity variations in soils under headframes of vertical shafts. According to analytical data, the pore waters mainly have calcium-chloride chemistry. Therefore, shallow permafrost became contaminated by mine drainage spilled off and infiltrating into soil at the site.

The designed 3D forward model of heat transfer in sub-headframe soil, with regard to its salinity, freezing system parameters (refrigerant temperature, as well as the number, length, and positions of freezing boreholes), air temperature in the shaft, etc., simulates freezing and thawing of pore water in permafrost within the temperature range corresponding to depth-dependent variations of thermal properties and salinity.

The optimal operation regimes of the freezing system were chosen from multi-variant modeling results to provide the required negative temperatures of saline soils under headframes and to maintain the existence of a damping thaw ring around the shaft, at least 0.5 m in diameter.

A special numerical experiment predicted the rate of the 0 °C isotherm propagation in soils around each shaft collar during operation-suspension cycles of the freezing system and thus to choose the optimal time for temperature logging. On this basis, recommendations have been issued for operation of ground temperature control systems at pile foundations and shaft collars during mining.

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