Temperature effects on stress–strain behavior of underground openings in permafrost zone

VD Baryshnikov* and LN Gakhova**
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: *vbar@misd.nsc.ru; **gahoval@mail.ru

Abstract. The authors describe the research results on the temperature effects on the stress–strain behavior of rock mass around single openings driven in permafrost beyond the influence zone of stoping. The variation patterns of stresses and displacements in rock mass and at the boundary of an underground opening are found depending on its operating life and ventilation air temperature. In terms of the Aikhal mine of ALROSA, it is shown that in an opening at a depth of 350 m, given its ventilation temperature is 20 deg for 3 years, the vertical convergence is comparable with elastic displacements caused by the opening driving. An approach is proposed to determining rock stability category based on expected displacements of an opening during its ventilation. The research results are meant for guidelines and regulatory documents on justification of mine support designs in permafrost zone.

1. Introduction
An essential stage of planning and design of mine support is stability estimation of exposed surfaces [1]. For horizontal and inclined openings driven beyond the influence zone of stoping in solid sedimentary rocks (sandstone, siltstone, argillite, limestone, etc.) and abyssal rocks (granite, diorite, porphyrite, etc.), the stability criterion is the absolute value of the displacement $U$ (mm) of the underground opening boundaries (floor, roof, sidewalls). According to the construction code of the Russian Federation [2], rocks can belong to four categories of stability: stable, mid-stable, unstable and very unstable [1, 2].

As a rule, calculations of $U$ disregard the induced change in the initial temperature of rock mass (in particular, under the action of air fed for ventilation of stoping area). Of specific concern is the influence of this factor on the displacements in rocks under thawing in the conditions of permafrost.

2. Experimental results
In single development entries with cross section $5\times4$ m and their intersections with cross drifts (equivalent span $6.1\times4$ m) drive at a depth of 350 m and ventilated, in terms of the Aikhal mine of ALROSA, extra displacements due to rock mass thaw during ventilation are estimated.

At the depth of mining, in non-ventilated openings under the temperature of $-1.5^\circ$C, brines occur in the thawed state [3]. For this reason, the phase transition from solid to liquid state was disregarded for the brines.

During ventilation of underground excavations, the air temperature can change from $+5^\circ$C to $+20^\circ$C. Aimed to estimate extra displacements due to rock thawing, the thermoelastic calculations were carried out using the input data from Table 1.
For the interface of immobile medium (solid) and flowing medium (air), the conditions are set in terms of the coefficient of heat transfer of air: \( \alpha_1 = 6 \text{ W/(m}^2 \cdot \text{deg)} \). The heat exchange coefficient between air and dolomite is \( h_1 = \alpha_1 / k_d = 3.43 \text{ l/m} \).

**Table 1. Physical and mechanical properties of dolomite.**

| Description                        | Dolomite |
|------------------------------------|----------|
| Specific weight \( \gamma \), kN/m\(^3\) | 25.1     |
| Coefficients:                       |          |
| linear heat expansion \( \alpha_1 \), 1/deg | 7.65·10\(^{-6}\) |
| heat conductivity \( k \), W/(m·deg)  | 1.75     |
| diffusivity \( \varepsilon \), m\(^2\)/s | 0.7·10\(^{-6}\) |
| heat transfer \( \alpha_1 \), W/(m\(^2\)·deg) | 3.51     |

The plane quasi-static thermoelastic problem was solved using the method of boundary integral equations. The initial stress state of rock mass was assumed as [5]: \( \sigma_y^0 = -\gamma H; \sigma_z^0 = -\lambda y H \), where \( \gamma \) is the specific weight of rocks, kN/m\(^3\); \( \sigma_x^0, \sigma_y^0 \) are the initial stresses at the depth \( H \); \( \lambda = 0.5 \) is the coefficient of the lateral earth pressure. The elasticity modulus \( E = 10 \text{ GPa} \); Poisson’s ratio \( \nu = 0.25 \).

Figure 1 shows the horizontal \( \sigma_x \) (Figure 1a) and vertical component \( \sigma_y \) (Figure 1b) of stress tensor (MPa) in the vicinity of single development entry 5×4 m after driving without airing. Figure 2 demonstrates the plots of the incremental displacement \( \Delta U_k \), mm, between the roof and floor in the development entry (Figure 2a) and in its intersection with cross cut (equivalent span 6.1×4 m, Figure 2b under different ventilation temperatures \( t \), deg, depending on the ventilation duration \( T \), year.

**Figure 1.** Horizontal (a) and vertical component (b) of stress tensor.
Figure 2. Plots of the incremental displacement $\Delta U_k$ between the roof and floor in the development entry (a) and in its intersection with cross cut (b) under different ventilation temperatures depending on the ventilation duration.

Tables 2 and 3 give the values of incremental stresses in the roof (point A in Figure 1a) and in the sidewall (point B in Figure 1b) of the development entry and intersection depending on the duration and temperature of ventilation.

Table 2. Incremental stresses $\Delta \sigma_x$ in the roof of development entry 5×4 m and its intersection with cross cut (equivalent span 6.1×4 m) during ventilation.

| Ventilation temperature, deg | $\Delta \sigma_x$, MPa | 0.5 year | 1 year | 2 year | 3 year |
|-----------------------------|------------------------|----------|--------|--------|--------|
| 5°C                         |                        | 5×4 m    | 5×6 m  | 5×4 m  | 5×6 m  | 5×4 m  | 5×6 m  | 5×4 m  | 5×6 m  | 5×4 m  | 5×6 m  |
| 5°C                         | -0.3                   | -0.3     | -0.5   | -0.5   | -0.7   | -0.7   | -0.7   | -0.7   | -0.7   |
| 10°C                        | -0.5                   | -0.6     | -1.0   | -1.0   | -1.2   | -1.35  | -1.4   | -1.4   |
| 15°C                        | -0.9                   | -1.0     | -1.4   | -1.6   | -1.9   | -2.1   | -2.0   | -2.2   |
| 20°C                        | -1.3                   | -1.5     | -2.0   | -2.3   | -2.5   | -2.8   | -2.8   | -3.0   |

Table 3. Incremental stresses $\Delta \sigma_y$ in the roof of development entry 5×4 m and its intersection with cross cut (equivalent span 6.1×4 m) during ventilation.

| Ventilation temperature, deg | $\Delta \sigma_y$, MPa | 0.5 year | 1 year | 2 year | 3 year |
|-----------------------------|------------------------|----------|--------|--------|--------|
| 5°C                         |                        | 5×4 m    | 5×6 m  | 5×4 m  | 5×6 m  | 5×4 m  | 5×6 m  | 5×4 m  | 5×6 m  | 5×4 m  | 5×6 m  |
| 5°C                         | -1.3                   | -1.4     | -1.9   | -2.0   | -2.5   | -2.6   | -2.5   | -2.7   |
| 10°C                        | -2.2                   | -2.2     | -3.6   | -3.8   | -4.9   | -5.1   | -5.4   | -5.5   |
| 15°C                        | -3.4                   | -3.3     | -5.5   | -6.0   | -7.5   | -7.6   | -8.3   | -8.4   |
| 20°C                        | -5.0                   | -5.0     | -7.5   | -7.7   | -9.9   | -10.2  | -11.0  | -11.3  |

The calculated data prove considerable influence of airing on stress–strain behavior of walls in the development entry and its intersection with cross cut. It is found that in terms of the Aikhal Mine, ventilation of single development entry and its intersection with cross cut at the depth of 350 m and under the air temperature of 20ºС for 3 years results in the increase of the vertical compressive stresses in the entry sidewall and in the equivalent span by 75–80% (from 13.7 to 24.7 MPa in the sidewall and from 15.9 to 27.2 MPa in the intersection); the incremental convergence $\Delta U_k$ reaches 22 and 25.5 mm, respectively. The increments in the horizontal compressive stresses change from 0.2 to -2.8 MPa (in the roof of the development entry) and from -0.3 to -3 MPa (in the intersection). Depending on the
ventilation temperature $t$, the largest incremental displacements $\Delta U_k$ are observed in the first year of airing and stabilize at $t = 5^\circ C$ by the end of the first year and at $t = 20^\circ C$ in three years.

In order to take into account extra displacements due to rock thawing when determining stability category of an underground opening, the maximum displacements $U_k$ of the opening boundary, found separately in the roof, floor and sidewalls of the opening and its intersection [6], are summed up with extra displacements $\Delta U_k$.

3. Conclusions
From the thermoelastic calculations of the stress–strain behavior of development entries and intersections in mines (with regard to equivalent span) using the method of boundary integral equations, the incremental displacements of boundaries are determined as function of temperature and duration of ventilation. It is found that in terms of the Aikhal Mine, ventilation of a single entry and its intersection with cross cut at the depth of 350 m under the air temperature of $20^\circ C$ for 3 years increases the vertical compressive stresses in the sidewalls of the openings by 75–80%, and the increment in $\sigma_y$ reaches 11–11.3 MPa. The increment in the horizontal stresses in the roof is not higher than -2.7 MPa in the entry and -3 MPa in the intersection. The maximum roof–floor convergence in the development entry is observed in three years of ventilation and reaches 22–25.5 mm, which is comparable with the convergence during driving.

The obtained estimates can be used in determination of the stability category of enclosing rock mass when selecting support designs with regard to basic strength characteristics of rocks and the maximum displacements of the boundary of underground openings.

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