Forecast of Thermal Mode for the Slope Fill-Up Ground, Considering the Operation of Seasonal Cooling Units in Cryolithic Zone Conditions

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Abstract. The article is concerned with the solution of the issue of freezing and stabilization of negative thermal mode for the slopes made of fill-up ground, which are held by a gabion wall in cryolithic zone conditions. To estimate the efficiency of artificial freezing of the slope ground, a mathematical 3D model of heat-exchange processes was worked out, which takes into account the phase change of moisture, freezing temperature, length of cooling devices, their quantity and location, the annual cycle of ambient air temperature and ground bedding. The model takes into account geometrical parameters of the slope and impact of daylight surface. The issue had been solved with numerical technique of finite differences. The calculations indicated the efficiency of implementation of seasonal cooling units for increasing of the fill-up slope stability. Their implementation results in progressive accumulation of cold in its ground. By the end of the fourth year of freezing, the whole mass of the fill-up slope ground turns into a frozen state. When seasonal cooling units were switched off in next years, the frozen area in the fill-up slope remains the same and thermal mode of the slope ground becomes a stable periodic cycle, i.e. expected seasonal temperature oscillations take place.

1. Introduction

The most reliable, long-lasting and effective method of slope ground stabilization is the erection of gabion boxes filled with quarry stones[1-3]. Construction of various facilities in a cryolithic zone is often performed at sites with unstable ground and rugged topography with hillsides and slopes. In such cases, to prevent the ground mass creeping, special landslide prevention works are performed. As per SNIIP 2.02.04-88 [4], during construction on slopes made of cryolithic grounds, one must predominantly apply the principle of ground maintenance in all-year frozen state, provided that negative temperature will be secured during the whole operation period. Besides, one must forecast the thermal mode, and, if necessary, perform special activities on securing designed temperature of frozen ground. As it is known, frozen ground has high strength properties, which allows to maintain all-year stability of engineering structures built on it, as well as those which use it as construction material.

Engineering constructions (area of the Omchak River valley, Magadan Region) are built on fill-up ground on a slope, and a gabion retaining wall was erected to protect against the ground mass creeping (Fig. 1). The retaining wall has a row echelon form, in eight rows. The maximum width of the bottom...
row is 6.0 meters, the top row maximum width is 1.0 m. Retaining wall height is 8.0 meters. After dumping of the slope fill-up thawed ground during a warm season, an extensive thawed zone was formed in it. Calculation of gabion retaining walls demonstrated that it is difficult to ensure their stability under potential dynamics of geocryological and geomechanical processes in the ground without performance of special technical activities, which secure preservation of structural and deformational characteristics of the ground. Under these circumstances the most reliable and comparatively easily implemented method to secure the slope stability can be artificial freezing of thawed fill-up ground, which will result in formation of an ice-rock wall, in which the ground strength will considerably increase due to moisture freezing.

![Figure 1. Gabion retaining wall.](image)

It is recommended that artificial freezing of the ground would be performed with seasonal cooling units (SCU) [5-8]. Development of various engineering and technical solutions for freezing processes as well as countermeasures against thawing with loss of bearing capacity of rock require enhancement of numerical mathematical simulation method, taking into account the actual circumstances of SCU thermal impact on thermal mode of the ground. In this regard, the investigation of the consistent pattern of heat transfer in engineering structure foundations takes a center stage for estimation of their reliability and durability. The work objective is to forecast the temperature of the slope fill-up ground retained by a gabion wall, considering SCU operation.

2. Method of simulation of heat exchange processes in slope fill-up ground, considering seasonal cooling units operation in cryolithic zone conditions

To develop a control method for thermal mode of the slope ground retained by a gabion wall and to secure their stability, a mathematical 3D model of heat-exchange processes was worked out, which takes into account the phase change of moisture, freezing temperature, length of cooling devices, their quantity and location, the annual cycle of ambient air temperature and ground bedding. The model also takes into account such factors as geometrical characteristics of the slope and impact of the day-light surface.

A fill-up ground slope erected on natural slope and retained by a gabion wall is considered. Two rows of SCU located checker wise are installed along the gabion wall in order to increase the slope...
stability by means of ground freezing. The scheme of slope thermal mode calculation with SCU is shown in Fig. 2.

![Diagram of thermal mode calculation with SCU](image)

**Figure 2.** 3D area for slope ground thermal mode calculation with two rows of SCU installed along the gabion wall.

The process of heat expansion in slope ground mass considering the phase change is described by the equation [9,10]:

\[
\left[ C(T) + L_{ph} \cdot \omega \cdot \rho \cdot \delta(T - T^*) \right] \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda(T) \cdot \frac{\partial T}{\partial x} \right] + \\
+ \frac{\partial}{\partial y} \left[ \lambda(T) \cdot \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ \lambda(T) \cdot \frac{\partial T}{\partial z} \right], \quad (x, y, z) \in \Omega,
\]

where \( C \) - volumetric heat capacity of the ground, \( J/(m^3 \cdot K) \); \( T \) - ground temperature, \( ^\circ C \); \( L_{ph} \) - latent heat of phase change of pore moisture, \( J/kg \); \( \omega \) - ground moisture content by weight, decimal quantity; \( \rho \) - ground consistency, \( kg/m^3 \); \( \delta(T - T^*) \) - Dirac delta function, \( 1/K \); \( T^* \) - phase change temperature, \( ^\circ C \); \( t \) - time, \( s \); \( \lambda \) - heat conduction coefficient, \( W/(m \cdot K) \), \( x, y, z \) - coordinates, \( m \).

It is assumed that at area side borders \( \Omega \) there is no heat flow.

**Equation 2:**

\[ \lambda(T) \cdot \frac{\partial T}{\partial z} = 0, \quad z = 0; \]

**Equation 3:**

\[ \lambda(T) \cdot \frac{\partial T}{\partial z} = 0, \quad z = z_1; \]

**Equation 4:**

\[ \lambda(T) \cdot \frac{\partial T}{\partial x} = 0, \quad x = 0, \quad 0 \leq y \leq y_2, \quad 0 \leq z \leq z_1; \]

**Equation 5:**

\[ \lambda(T) \cdot \frac{\partial T}{\partial x} = 0, \quad x = x_4, \quad 0 \leq y \leq y_2, \quad 0 \leq z \leq z_1; \]

Newton’s boundary condition is established on day-light surface:
\[ \lambda \cdot \frac{\partial T}{\partial n_B} = \alpha \cdot (T - T_a), \quad (x, y, z) \in \Gamma_x, \]  

where \( \partial / \partial n_B \) indicates the area \( \Omega \) outer normal line to border \( B \); \( T_a \) – atmospheric air temperature, °C; \( \alpha \) — coefficient of heat transfer from the air to ground mass, W/(m²·K).

Coefficient of heat exchange \( \alpha \) of atmospheric air with the ground mass surface in winter depends on snow cover depth [11] and is determined from the formula:

\[ \alpha = \frac{1}{\frac{1}{\alpha_0} + \frac{\delta_s}{\lambda_s}}, \]  

where \( \delta_s, \lambda_s \) – depth (m) and heat conduction coefficient of the snow cover (W/(m·K)); \( \alpha_0 \) – empirical coefficient of convective heat exchange (W/(m²·K)) calculated from Yurgens formula [12]:

\[ \alpha_0 = \begin{cases} 6.16 + 4.19 \cdot v, & 0 < v < 5; \\ 7.56 \cdot v^{0.78}, & 5 < v < 30; \end{cases} \]

where \( v \) - wind speed, m/s.

For \( \alpha_0 \) calculation, monthly information on snow cover heat conduction coefficient \( (\lambda_s) \) and depth \( (\delta_s) \) is required. Based on large scope of experimental material in work [12], the following averaged correspondences have been obtained for calculation of \( \lambda_s \):

\[ \lambda_s = \begin{cases} 1.165 \cdot \rho_s, & T_s > -10^0 \text{C}; \\ 1.035 \cdot \rho_s, & -10^0 \text{C} \geq T_s \geq -20^0 \text{C}; \\ 0.907 \cdot \rho_s, & T_s < -20^0 \text{C}; \end{cases} \]

where \( T_s, \rho_s \) – accordingly, temperature and density of the snow cover;°C, g/cm³.

Snow density is calculated from the formula [13]:

\[ \rho_s = 0.182 + 0.18 \cdot \delta_s. \]

It must be noted that snow density is not a constant value and it is quickly changed during spring melting: from 0.35 g/cm³ at the beginning, 0.45 g/cm³ in the middle and 0.6 g/cm³ at the end of snow melting.

The heat flow on the border with SCU was calculated taking into account the heat exchange area:

\[ \lambda \cdot \frac{\partial T}{\partial n_{SCU}} = \alpha_2 \cdot (T - T_{SCU}), \quad (x, y, z) \in B_{SCU}, \]

where \( \partial / \partial n_{SCU} \) indicates the area \( \Omega \) outer normal line to border \( B_{SCU}, \alpha_2 \) - coefficient of heat transfer from SCU evaporator to the ground mass, W/(m²·K); \( T_{SCU} \)– cooling temperature, °C. The area of SCU contact with rocks is calculated taking into account the evaporator diameter.

In calculation it is assumed that SCU start operation at air temperature drop beginning from -10°C and cooling temperature is equal to \( T_{SCU} = T_a + 5 \), °C.

In calculation of the heat flow via the inclined surface, a decreasing coefficient was used, which is equal to ratio of physical area of heat exchange to effective one, formed by edges of boundary boxes. In initial time the ground temperature distribution is set.

For numerical solution of the task of ground thawing-freezing, a smoothing method is used, and to solve a 3D task of heat exchange, a cumulative approximation method is used [10, 14], which reduces
the task to a sequence of univariate problems. In this regard, difference schemes meet the requirements of approximation and stability. On each temporary layer a sequence of univariate problems is solved. All systems of difference equations are derived considering the geometry of the area concerned.

Based on calculation results, it is possible to obtain a dynamics of slope ground temperature change for several years, taking SCU operation into account. If required, the results are presented as temperature isolines by set cross-sections.

3. Calculation results
Thermal mode for the slope ground is calculated in the presence of SCU, located in two rows checkerwise near the retaining wall. Diameter of SCU tubes is 57 mm, their length is 10 m and distance between them is 2 m. Calculation starts from October. It is assumed that SCU start operation in two years after embankment filling in October, when air temperature drops to -10°C, i.e. thermal mode of the slope ground during 2 years is calculated without considering SCU operation. In Fig. 3, thermal isolines are shown near the gabion retaining wall in the middle of October before SCU operation start. It is evident from the figure that the slope ground is in thawed state.

![Figure 3](image)

*Figure 3.* Thermal isolines near the gabion retaining wall in the middle of October before SCU operation start.

In Fig. 4, thermal isolines are shown near the gabion retaining wall in the middle of January and October in the first year of facility operation with SCU. It is evident from the figure that between the gabion retaining wall and SCU in January there remains a small area of thawed ground with dimensions approximately 2x1 m. At the beginning of summer, the dumped rocks of the slope are frozen for the whole depth of SCU installation at 10 m distance from the outer border of gabions. By the end of summer, the ground frozen in winter are in frozen state with temperature -2 -1°C.
Fig. 4. Thermal isolines near the gabion retaining wall in the middle of January (a), April (b), July (c) and October (d) in the first year of SCU operation.

Fig. 5 shows the results of thermal mode calculation for the slope in the fourth year of SCU operation. It is evident from the figures that the cold is progressively accumulated in the slope ground, e.g. by the end of summer of the 4th year of SCU operation, the ground temperature drops to -6°C, and zero temperature of the ground remains only at the distance of 15 m from the outer wall of gabions, which indicates the efficiency of SCU application for the slope strengthening.

Fig. 6 shows the dynamics of thermal mode change for the slope ground in subsequent 4 years (after switching SCU off). It is evident from the figures that thermal mode is reaching a stable periodic behavior, i.e. only expected seasonal temperature fluctuations take place. In this case, the slope ground is all the year round in a frozen state.

Fig. 5. Thermal isolines near the gabion retaining wall in the middle of January (a) and October (b) in the fourth year of SCU operation.
Figure 6. Thermal isolines near the gabion retaining wall in the middle of January (a) and October (b) after four years of SCU switching off.

4. Conclusions

After dumping of the slope fill-up thawed ground during a warm season, an extensive thawed zone remains in it. In this situation, in the absence of frozen ground, in case of hydrological regime disturbance, the surface water and downfall can be infiltrated into the mass and excessive humidity can be generated in grounds with the loss of their stability.

Calculations indicated the efficiency of seasonal heat stabilizer implementation in increasing fill-up slope stability by means of freezing. Even in the first year of the ground freezing with SCU application, a zone of negative temperatures is formed in the mass of the slop fill-up ground. In this case, the thawed zone in fill-up slope gradually decreases and after the fourth year of SCU operation it disappears completely.

Calculations indicated that after 4 years of SCU operation, they can be switched off. In this case, thermal mode of slope ground is close to natural thermal mode of the regional frozen ground. The slope is absolutely stable. Only phenomena of surface deformation related to seasonal freezing and thawing of ground can take place.

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