Influence of Groundwater in the Base of the Gas Pipeline During the Formation of Aufeis

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Abstract. Pipelines with a large length in permafrost areas pass through various water passages. In winter, due to various types of waters – underground, river, and lake (often ice has mixed nutrition) – we observe the formation of aufeis. When they repeatedly pour out onto the surface and layer by layer freezing, plane-convex ice bodies are formed – aufeis. The heat and mass transfer interaction of a gas pipeline with a frozen ground base is considered during the filtration of permafrost groundwaters. Numerical modelling was carried out taking into account the real thawing process – freezing of the pore solution in the temperature spectrum at various temperature regimes of filtration of permafrost groundwater. As a result of a numerical experiment, it was established that aufeis formation occurs in the second half of winter and has a warming effect. In the first half of the summer period, intensive thawing of aufeis is observed, and the dynamics of the depth of seasonal thawing occurs with some delay, but at the beginning of the winter period, it is restored, as in ordinary soil. Long-term seasonal filtration of groundwater with a natural temperature of the environment has a warming effect on the temperature regime of frozen rocks. Warming and increased water saturation of the frozen soil base are accompanied by negative seasonal permafrost processes.

1. Introduction

Long-distance trunk pipelines in permafrost areas pass through various water passages and undergo various exogenous processes, such as heaving, thermal subsidence, aufeis formation, etc. In Yakutia, with a harsh climate and widespread development of permafrost, the processes of aufeis formation are mainly concentrated in river basins with mountainous terrain. It is not known how the main pipelines interact with permafrost in the winter, especially in mountainous areas, in the presence of aufeis. The outflow and freezing of groundwater in the river valleys of the permafrost zone creates specific conditions for heat and mass transfer, as a result of which a system of aufeis coating and ground complexes is formed.

In this paper, we consider how aufeis formation affects the heat and mass transfer regime of the soil base of the gas pipeline. Aufeis that occurs and grows only in the frosty season, is formed due to various waters: underground, river and lake (often aufeis has mixed feeding) [1-3]. When they repeatedly pour out onto the surface and layer by layer freezing, plane-convex ice bodies are formed –
aufeis. These aufeis deposits affect the redistribution of surface runoff, affect the terrain and cause the formation of specific deposits ("aufeis alluvium"), which harm engineering structures. The interaction of pipelines with aufeis is not well understood. The purpose of this work is the numerical simulation of the heat and moisture regime of the soil base of a gas pipeline during aufeis formation.

2. Water crossings
The construction of pipeline crossings through water barriers is envisaged by the trench method (figure 1). In this case, the depth value is set taking into account channel deformations of the watercourse and is not less than 0.5 m below the predicted level of channel erosion from the top of the pipeline ballast, but not less than 1 m from the natural marks of the watercourse bottom and not less than 0.5 m, counting from the top of the pipeline ballast to the bottom of the reservoir when passing in the underflow part on rocky soils.

The stability of pipelines against ascent is provided by ballasting. On channel and floodplain sections of underwater crossings, the use of ring weighting materials from cast iron or reinforced concrete, as well as mounted reinforced concrete weighting agents are provided (figure 1). Outside these areas, the use of weighting agents of a predominantly container type is envisaged.
Iron Ring Weight Material

**Figure 1.** Methods for laying pipes.

Gas pipelines during the passage of water barriers are subjected to the cryogenic movement of soils, among which the leading place is occupied by the hydrodynamic movement of soils - heaving, thermokarst, thermal subsidence and thermal erosion. To predict the influence of groundwater, the following mathematical formulation of the heat and mass transfer problem is formulated.

### 3. Problem statement

The mathematical model of the moisture transfer process taking into account the phase pore solution in the temperature range in rocks is described by the following system of equations [4]:

\[
c \frac{\partial \tau}{\partial \tau} = \text{div}(\lambda \text{grad} \tau) - (c_w V \text{grad} \tau) + L \frac{\partial \theta_i}{\partial \tau}, \tag{1}
\]

\[
\frac{\partial \theta_w}{\partial \tau} = \text{div}(k_p \text{grad} \theta) - \frac{\partial \theta_i}{\partial \tau}, \tag{2}
\]

\[
\frac{\partial W_w}{\partial \tau} = \text{div}(k \text{grad} W_w) - \frac{\partial W_i}{\partial \tau} \tag{2'}
\]

\((x, z) \in \Omega, \ \tau > 0, \ \Omega = [0, R] \cup [0, l]\)

The system of equations (1) – (2) is closed by the equation of the amount of unfrozen water:

\[
W_{wb} = W_{wb}(T, W) \tag{3}
\]

The area of numerical modelling is a vertical section of the soil with coordinates \((x, z)\) (figure 2).

On the soil surface AB (at the upper boundary), boundary conditions of the second kind for temperature and the condition of atmospheric precipitation or evaporation are set:

\[
(-\lambda \text{grad} \tau + c_w V \text{grad} \tau)_n = q_T(\tau)
\]

\[
(-k \text{grad} \theta)_n = q_\theta(\tau), \ \text{at} \ z = 0, \ 0 < \tau, \tag{4}
\]

\[
(-k \text{grad} W_w)_n = q_\theta(\tau) \tag{4'}
\]

On the left border of FA in the summer, depending on the depth of thawing and water retention, suprapermafrost groundwater flows with pressure \(H = z\). The aquifer is rocky soil.
Figure 2. Area of numerical simulation.

On the right border in section BC, the condition for the removal of permafrost groundwater is fulfilled. The boundary condition of seepage is defined by two boundary conditions since they are used to determine the position of the free boundary border seepage – point C for the portion BC:

\[
\frac{\partial H}{\partial x} > 0 \quad \text{and} \quad P = 0.
\]

If \( P < 0 \), then the CD sucking area is not missing at the right border.

In the remaining sections, CDEF is the boundary non-leakage condition for temperature and moisture.

On the wall of the pipeline, the condition of heat transfer of the second kind is fulfilled:

\[
-\lambda \frac{\partial \tau}{\partial n} = Q(\tau)
\]  

(6)

The heat transfer through the walls of the pipe during forced turbulent movement of the transported product is described as follows:

\[
Q(\tau) = \alpha(T_2 - T),
\]  

(7)

where \( \alpha = Nu \lambda_{ic}/d \) is the heat transfer coefficient on the surface of the pipeline.

Here \( c, c_w \) are the volumetric heat capacity of soil and water, J/(m\(^3\)-K); \( T \) is temperature, K; \( \tau \) – time, s; \( \lambda \) is soil thermal conductivity, W/(m-K); \( r, z \) are spatial coordinates (\( z \) is spatial coordinate directed down), m; \( L \) is volumetric heat of the phase transition, J/m\(^3\); \( W_i, W_{iw} \) are total moisture content, in the form of ice and water, \%; \( V = (V_x, V_z) \) is filtration rate, m/s; \( k \) is diffusion coefficient, m/s; \( H = P - z \) is pressure, m; \( P \) is suction pressure, m; \( k_f \) is filtration coefficient, m/s; \( \theta = \theta_i + \theta_w \) is total volumetric moisture, the content of volumetric ice and water; \( n \) is external normal; \( q_f(\tau) \) – is heat flow, W/m\(^2\); \( q_\theta(\tau) \) – is humidity flow, m/c; \( R, l \) are width and depth of the considered area, m; \( \lambda_{ic} \) is the thermal conductivity of the transported product, W/(m-K); \( d \) is pipe diameter, m; \( Nu \) is the Nusselt number.

Equation (1) describes the process of freezing and thawing of the soil, taking into account heat transfer by moisture. Water movement and ice generation are taken into account by expressions (2) and (3). To predict the moisture regime, one can use any of these equations, usually, Richards equation (2) is used in saturated and unsaturated soils, and equation (2\( * \)) in unsaturated soils [5].
The system of nonlinear equations (1)-(2) in the two-dimensional region (figure 2) splits into one-dimensional equations. The heat equation (1) contains convective terms and, when solving numerically, the main attention is paid to the approximation of convective terms. It should be noted that schemes with directional differences are widely used in practice for convective terms, taking into account the sign of the filtration rate [6-7].

4. Results of numerical research

4.1. For numerical modelling, 2 sites were taken (control and with aufeis) in Yakutia’s highlands [1-3]. The initial parameters for the computational experiment on heat and moisture transfer at the base of the gas pipeline are determined in relation to the climatic conditions of Yakutia (table). A gas pipeline with a diameter of 1400 mm was laid at a depth of 2.4 m. The temperature of the transported gas depends on the operating conditions and at the beginning of construction it is equal to the temperature of the adjacent soil, and then it gradually switches to a positive mode of operation.

| Soil type           | Depth layer, m | Skeleton bulk density $\rho, kg/m^3$ | Thermal conductivity, W/(m$^\cdot$C) | Specific heat, J/(kg$^\cdot$K) | Porosity |
|---------------------|----------------|--------------------------------------|-------------------------------------|-------------------------------|----------|
| Coarse sand         | 0.0–0.4        | 1500                                 | 1.19, 1.39                          | 690                           | 0.24     |
| Low strength granite| 0.4–3.4        | 2050                                 | 1.99, 2.20                          | 660                           | 0.23     |
| Strong granite      | 3.4–…          | 2500                                 | 2.15, 2.50                          | 790                           | 0.15     |

On the surface of the soil, the second kind of boundary condition is specified. In the calculation, we used the restored heat flux densities [10], which take into account the thickness of the ice massif. The maximum height of aufeis reaches two meters, but every year its height varies depending on the external temperature and the volume of groundwater. Approximately from October to December, the site is covered with snow, and from January to July with aufeis (figure 3). To identify the parameters of the heat flux, we used the method of Alifanov O.M. [11] for solutions of boundary inverse heat conduction problems. With the onset of a warm period, we observe the thawing of aufeis. The results of a numerical study show that the thawing intensity depends on the external temperature and ice area, and sometimes ends in late July or does not thaw completely. The depth of seasonal thawing is delayed compared to the control site (figure 4). Ice thawing occurs simultaneously with the ingress of permafrost groundwater, which enhances the thawing process.
The formation of aufeis in the mountains is associated with the influx of precipitation and groundwater. In this regard, a numerical experiment was conducted with the admission of permafrost groundwater with a temperature of 1 °C (figure 4). As can be seen from the figure, the total soil moisture at higher horizons rises and has a warming effect. A gas pipe, crossing a water barrier, acts as a barrier and changes the course of the flow of groundwater.
4.2. Permafrost groundwater flows in the warm season and stops in the winter when the water source freezes. The intensity of which depends on many factors such as ambient temperature, groundwater, etc. In this case, the hydrophysical characteristics of the rocks are selected taking into account the works [12-15]. Figure 5 shows the distribution of temperature and pressure of the groundwater in August. Groundwater with ambient temperature flows to the left, and the pressure depends on the depth of thawing and reaches the rock, which is water-resistant (b).

Figure 6 shows the distribution of temperature and volumetric moisture in December. The soil base of the gas pipeline is in a frozen state. As can be seen from the figure, the flow of groundwater has an insulating effect and increases the water saturation of the base. An increase in water saturation in winter is accompanied by a negative permafrost heaving process.

Figure 4. Distribution of Temperature and Total Moisture Upon Admission of Permafrost Groundwater (June and September) After 1 Year with a Positive Operating Mode.
Figure 5. Distribution of Temperature (a) and Groundwater Pressure (b) when Filtering Groundwater (August).
Figure 6. Distribution of Temperature (a) and Volumetric Moisture (b) when Filtering Groundwater (December).

The long-term supply of groundwater with ambient temperature increases the average annual temperature and moisture of the soil base of the pipeline (figure 7). Temperature warming is accompanied by degradation of permafrost, which enhances the process of thermal subsidence, which usually transforms the system of aufeis ground complexes. The annual formation and destruction of aufeis and underground ice are accompanied by particularly dangerous geodynamic phenomena, among which the leading place is occupied by the hydrothermal movement of soils – heaving, thermokarst and thermoerosion. The many years of cyclic freezing and thawing of the soil base cause seasonal swelling and subsidence, i.e. “Seasonal Loosening” causes low-cycle fatigue failure of the pipeline.

Figure 7. Distribution of Temperature (a) and Volumetric Moisture (b) Initial Distribution and After 10 Years.
5. Conclusion
As a result of a numerical experiment, it was established that aufeis formation occurs in the second half of winter and has a warming effect. In the first half of the summer period, intensive thawing of aufeis is observed, and the dynamics of the depth of seasonal thawing occurs with some delay, but at the beginning of the winter period, it is restored, as in ordinary soil.

Numerical modelling was carried out taking into account the inflow and removal of permafrost groundwater. Long-term filtration of groundwater with a natural temperature of the external environment has a warming effect on the temperature regime of frozen rocks.

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Acknowledgements
This article was written with the help of RFBR grants: 18-41-140008 r_a., 20-55-53036 GFEN a.