Concerning the Bottom Erosion and Frost Heaving on the Section of the Underwater Crossing Route of MGL Across the River Lena

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Abstract. The uneven nature of the planned-high-altitude positions (PHAP) of the gas pipelines in the floodplain of the river Lena is affected by the hydrological, natural environment, and climatic processes and such permafrost processes as heaving, thawing, and freezing. The effects of hydrodynamic and permafrost processes, heaving phenomena on floodplain areas and shore slopes together increase the non-functional loads on the underwater gas pipeline. Due to these factors, high longitudinal tensile stress arises in the welded joints of siphon pipes and facilitates accidents and incidents at the underwater crossing of MGL. A numerical experiment was performed with the initial data on the river Lena in the area of the underwater crossing of the main gas pipeline (MGL) using hydrometeorological data. The dynamics of erosion over time is presented. A change in the profile of bottom sediments negatively affects the state of the pipeline. Dangerous exogenous processes: seasonal heaving, frost cracking, thermal subsidence, thermokarst, and coastal erosion, intensify when the natural conditions are disturbed (underwater crossings).

1. Introduction
Ensuring the operational reliability and safety of underwater crossings of the main gas pipelines (MGL) in the North is of particular importance. The route of the underwater crossing of MGL across the river Lena undergoes negative geocryological processes that affect both nature and the pipeline.

Denudation of the main gas pipeline and loss of stability occur during its operation. The underwater section of the gas pipeline is subjected to hydrodynamic effects of a water stream and shock impact of ice masses in the spring. They lead to accidents and a decrease in the operational reliability of the pipeline [1].

The interaction of the main gas pipeline with the surrounding soil and reconstruction of the main gas pipeline system [2, 3], as well as the formation of ice jams during an ice drift on the river Lena, are the technogenic factors that cause an increase in soil temperature and thawing depth, activation of thermal erosion and thermokarst processes. Moreover, the formation of ice jams is followed by flooding of lower sections of the river valley [4].

To increase the operational reliability of the underwater crossing of MGL, to prevent, and eliminate possible emergencies during its operation, it is imperative to conduct a predictive estimate of the bottom erosion of the river Lena [5]. In this regard, a numerical prediction of the bottom of the underwa-
ter crossing section of the main gas pipeline was accomplished taking into account sediment loads at various initial hydrometeorological data [6].

2. Research materials and method

The problem statement for riverbed erosion consists in constructing a mathematical model that describes the motion of a thin homogeneous two-phase layer of a water-soil mixture (streamflow) with a constant density, bounded by a stationary loose medium (watercourse bottom) from below and by fluid flow from above.

The position of the upper and lower boundaries of the moving layer should be determined from the problem solution. However, the position of the upper boundary of the moving layer can be considered set due to the significant difference in the characteristic times of the hydrodynamic flow and streamflow. The normal and shear stresses, which can be obtained from solving the hydrodynamic equations for the river flow, are determined on the upper surface of the streamflow. Considering that the depth $h$ of the streamflow is much less than its estimated size $L$, a well-known shallow water model can be used to describe its movement [7]:

\[
\begin{align*}
\frac{\partial h u_i}{\partial t} + \nabla_k (u_k u_i h) + g h \nabla_i (h + z) - \nabla_k (\mu h \nabla_k u_i) - h (\tau_i - \tau_i^0) &= 0 
\end{align*}
\]

(1.1)

\[
\begin{align*}
\frac{\partial h}{\partial t} + \nabla_i (h u_i) &= -R, \quad i, k = 1, 2, \quad \vec{x} \in \Omega,
\end{align*}
\]

(1.2)

\[
\begin{align*}
u_i(\vec{x}, t) &= u_i^0(\vec{x}, t), \quad \vec{x} \in \partial \Omega \quad (1.3)
\end{align*}
\]

\[
\begin{align*}
u_i(\vec{x}, 0) &= u_i^0, \quad h(\vec{x}, 0) = h^0 \quad \vec{x} \in \partial \Omega \quad (1.4)
\end{align*}
\]

where $u_i$ are the components of the required velocity field, which is averaged over the depth $h$ of the channel flow; $t$ is the time; $R$ is the intensity of bottom erosion; $\nabla_i$ is Hamilton operator; $g, \mu = \text{const} > 0$; $\vec{x} = \{x_1, x_2\}$; $\tau_i^0$ are the shear stresses acting from the hydrodynamic flow side; $\tau_i = \alpha u_i$ are the shear stresses determined from the linear law of resistance to the streamflow; $u_i^0, h^0, u_i^0$ are the initial and boundary values of the required functions; $Z$ is a lower boundary of the moving layer.

The obtained mathematical model of the riverbed erosion (in $h, z$ variables) is difficult to use for practical calculation. Therefore, a new variable $\xi = h + z$ was introduced to overcome this difficulty. The function $\xi$ determines the free surface of the streamflow, which can be relatively easily recorded in experiments [7]. To close the model (1.1) - (1.4), an additional equation that determines the formation of the bottom surface (Exner's equation) is introduced:

\[
\frac{\partial \xi}{\partial t} = R
\]

The formula for the function of the bottom erosion $R$ is an important issue in formulating the problem on the streamflow. The work [7] offers the formula of bottom erosion and provides its experimental support:

\[
R = \frac{1}{B} (|u_i| - q_s)
\]

(1.5)

Considering that $q = |u_i|h, q_s = |u_i|h_s$, we obtain:

\[
R = \frac{1}{B} (h - h_s)
\]

(1.6)

where $B$ is the width of the channel; $q$ is the flow rate of the channel stream; $q_s$ is the local transporting ability of the streamflow; $h_s$ is the depth of the transporting ability of the water-soil flow determined by the transportability of the hydrodynamic flow.

Eliminating the speed, we obtain the relation for the function $R$ [7]:

\[
R = \frac{1}{aB} |\tau_i^0 - g \nabla_i \frac{\partial \xi}{\partial x}(h - h_s) | (1.7)
\]

An analysis of the erosion function (1.7) shows that two significant terms of the equation for the bottom erosion characterize two opposite mechanisms for changing the bottom shape:

- a mechanism of the riverbed deepening owing to the drag force of the hydrodynamic flow, which entrains the bottom material $\tau_i^0$;
- a mechanism of smoothing - shallowing of the riverbed due to bank subsidence, smoothing of meander and braid bars, and others, which is determined by the term \( q \nabla_i \xi \).

As mentioned above, the flow level increases in the area located above the formation of an ice jam, and the shear stress of the riverbed deepening \( \tau_i \) increases in the zone of the ice jam \( h \to 0 \).

A numerical experiment was accomplished with the initial data of the river Lena in the area of the underwater crossing of the main gas pipeline using hydrometeorological data. Figure 1 shows the calculations at an average flow velocity of 2 m/sec for two heads of the ice jam \( H = 10 \) and \( H = 14 \ m \).

![Figure 1](image1)

Figure 1. Change in the position of the riverbed level:
- \( t_1 = H = 10 \ m \);
- \( t_2 = H = 14 \ m \).

The process of erosion intensifies with increasing pressure. For example, alluvium of 1.5 m in height is observed on the left bank at a pressure of \( H = 14 \ m \), and erosion of 1.5 m in depth is observed in the middle at a pressure of \( H = 14 \ m \).

Figure 2 demonstrates the erosion dynamics in time. The profile of bottom sediments changes over time and negatively affects the state of the main gas pipeline.

![Figure 2](image2)

Figure 2. Dynamics of the position of the riverbed level (at \( U = 3U_0 \)):
- \( t_1 = 1 \);
- \( t_2 = 3 \);
- \( t_3 = 10 \ days \).
3. Results
The results of a numerical experiment confirm that there is a restructuring of the forms of bottom sediments, a significant change in hydraulic resistance, and sediment discharge during ice clogging. In turn, a change in alluvium leads to a restructuring of the profile of bottom sediments.

Long-term operation of the above structures in the Far North is accompanied by various undesirable permafrost processes: heaving, thermal subsidence, thermokarst, soliflux, and others. [8, 9].

In this regard, the work presents a mathematical model of heaving and thermal subsidence in frozen soils and the results of a numerical experiment for predicting exogenous processes at the base of an oil and gas pipeline.

The mathematical model of heaving is based on the assumption that the expansion of the soil volume occurs in height (towards the soil surface) since the pore matter increases due to the transformation of water into ice, i.e. without the possibility of lateral expansion, as is accepted in the problem of compression compaction of soils.

The amount of heaving can be described as follows using the total volumetric water content $\theta$ [8]:

$$S_1 = \int_0^l (\theta - n) \, dz, \quad m$$ (1.8)

The mathematical model of the thermal subsidence (compaction) of frozen soil is derived similarly taking into account the thawing depth, compressibility, and load on frozen soil [10]:

$$S_2 = k_o \xi + \alpha (P + 0.5 \rho_{ck} (1 + W) \xi) \xi \, m$$ (1.9)

where $\xi$ is the thaw halo of the soil at the base of the pipeline, m;
$k$ is the thawing coefficient of frozen soils (relative subsidence without load);
$\alpha$ is the compressibility factor, MPa$^{-1}$;
$P$ is the pressure on thawed soil, MPa;
$\rho_{ck}$ is the bulk density of the skeleton, kg/m$^3$;
$W$ is the weight total moisture content ($W = W_i + W_w$, d.e.);
$W_i, W_w$ are the moisture content due to ice and water.

The remaining initial parameters $k, P, n, \alpha$ are set taking into account the physical-mechanical properties of the soil. The total volumetric moisture content is expressed in terms of weight humidity as follows:

$$\theta = \frac{\rho_{ck} W}{\rho_h \rho_h} \left( \rho_h + (\rho_h - \rho_h) \cdot i(T) \right).$$

4. Discussion
The study of the stress-strain state of the oil and gas pipeline gives an example of the dynamics of gas pipeline heaving. The distributions of temperature and total moisture content over 50 years are considered in the profile of a two-dimensional area with a gas pipeline. The depth and width of the section are 14 and 48 m, respectively. In the lower right corner at a depth of 14 m, groundwater enters with a positive temperature of 0.2°C (open system). Above is the usual cyclical seasonal freezing and thawing of the soil with atmospheric precipitation and evaporation taken into account. The presence of groundwater has an insulating effect on the temperature regime of the massif.

Cyclic freezing-thawing causes the migration of groundwater from the surface, and the injection ice forms at a depth of 8–12 m. This process is known as heaving mound in geocryology (bulgunnyakh in Yakut language).

Figure 3 presents the dynamics of heaving at the right end of the gas pipeline over 50 years in the observed region. Depending on the soil filtration coefficient, heaving increases as follows: 2.0; 3.4; 4.7 m. If the difference between the maximum and minimum values of heaving is more than 0.5 m, then the soil is considered as highly susceptible to heaving and creates adverse conditions for the stability of engineering structures.
3. Dynamics of changes in the heaving dimensions at various values of the filtration coefficient.

«Seasonal loosening» of the main gas pipeline proceeds slowly compared to the soil surface. The amplitude of the seasonal variation is 3.8 cm. The maximum values of «loosening» are observed at the end of May, and the minimum is observed at the beginning of November. Repeated thawing-freezing processes reinforce the heaving of the gas pipeline. The general course of this numerical experiment coordinates with the field observation data.

5. Conclusions
Thus:
- when laying the underwater crossing in winter, an ice shell forms around the gas pipeline;
- the thermal regime changes insignificantly during underground installation. The humidity regime changes strongly and is followed by the heaving of the gas pipeline;
- the total heaving increases during the repeated freezing-thawing cycle, which can lead to an emergency rupture.

To prevent the destruction of the gas pipeline during its operation on the border of heaving and non-frost susceptible soils, it is necessary to perform activities that reduce the negative impact of heaving soils.

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