Vulnerability of the transport system and infrastructure in the north under changing climate conditions

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Abstract. Ongoing global warming leads to accelerated degradation of permafrost. This creates critical risks for transport and engineering infrastructure in Arctic and subarctic regions. The purpose of this study is to provide a comprehensive analysis of the vulnerability of structures in the North against the background of current climate change. The article summarizes long-term data on increasing air and ground temperatures in Eastern Siberia, particularly Central Yakutia, showing a trend from 0.1 to 0.7°C per decade depending on landscape conditions. Economic estimates of damage to buildings and engineering structures in the Arctic zone of the Russian Federation are presented, reaching up to 5–7 trillion rubles by 2050 if the current trend persists. The paper describes a methodology for comparing data from thermometric boreholes of Lomonosov Moscow State University with the results of mathematical modeling of the thermal state of soils based on the Fourier equation. Special attention is paid to experimental studies of the strength properties of ice and frozen soils carried out in the laboratory of the Faculty of Geography of Moscow State University, which make it possible to predict the behavior of the foundations of engineering structures.

1 Introduction

Current problems associated with climate warming require scientifically grounded approaches to ensuring the sustainable development of northern territories. Regions of permafrost distribution are characterized by extremely low air temperatures, down to –50°C and below, and by the presence of ground ice. Permafrost is a dynamic component of the natural environment that controls the functioning of biotic and abiotic systems. Effective economic activity and reliable operation of engineering structures in these regions are impossible without taking ongoing cryogenic changes into account.

According to the international report State of the Climate in 2025, global warming continues without slowing down: the summer of 2025 in the Northern Hemisphere became one of the hottest in the entire observational record, with a temperature anomaly of 0.68°C relative to the 1991–2020 baseline period. Rising temperatures in northern Russia have

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intensified permafrost thawing, which directly threatens transport routes, pipelines, and buildings [3-6].

The purpose of this study is to assess the vulnerability of the transport system and infrastructure of the North in the context of changing climate based on field data, numerical modeling, and laboratory experiments.

2 Climate change and permafrost response

Monitoring in Yakutia records a steady increase in mean annual air temperature (MAAT). During the period from 1978 to 2020, warming at a number of meteorological stations, including Chulman, Tiksi, Verkhoyansk, Oymyakon, and others, ranged from 1.1 to 3.3°C. In the central part of the region, in the Churapchinsky District, the spatial heterogeneity of the trend reaches 0.1–0.7°C per 10 years depending on geomorphological and landscape conditions. The highest rates of increase are observed for sandy-ridge terrain types and anthropogenically disturbed areas. The active layer thickness (ALT) demonstrates steady growth in the typical tundra of the Lower Lena, Lower Kolyma, and Central Siberia, while the mean annual ground temperature (MAGT) at depths of 3, 5, 10, 20, and 30 m in the mountain tundra of Eastern Siberia is steadily increasing (Fig. 1).

Table1. Changes in mean annual air temperature at selected stations in Yakutia, 1978–2020

Station	Temperature increase, °C
Chulman	1.4
Tiksi	1.9
Verkhoyansk	3.0
Oymyakon	3.0
Chokurdakh	2.5
Sangar	2.2

3 Consequences for engineering structures and economic risks

Permafrost degradation causes the activation of cryogenic processes, including thermokarst, frost heave, and thermal erosion. This leads to widespread deformation and destruction of infrastructure facilities. Field surveys record the heaving of buried main gas pipelines, deformation of high-voltage power transmission line supports, destruction of road surfaces, and damage to the foundations of residential and industrial buildings [7-10].

As part of the analysis of permafrost conditions, trends in its change, and socio-economic consequences, economic damage estimates were obtained. The value of buildings and engineering structures located on permafrost in the Arctic zone of the Russian Federation is approximately 9.6 trillion rubles, including 1.1 trillion rubles for the housing stock. If the current climate trend continues until 2050, according to 24 analyzed scenarios, average losses for residential and industrial facilities may reach 5–7 trillion rubles, while losses for the housing stock alone may amount to approximately 770 billion rubles.

The Meteorological Observatory of Moscow State University also has several thermometric boreholes, which are used to collect data on ground temperature at sites with natural cover and on bare plots. Students and staff process thermometric series as well as drilling materials.

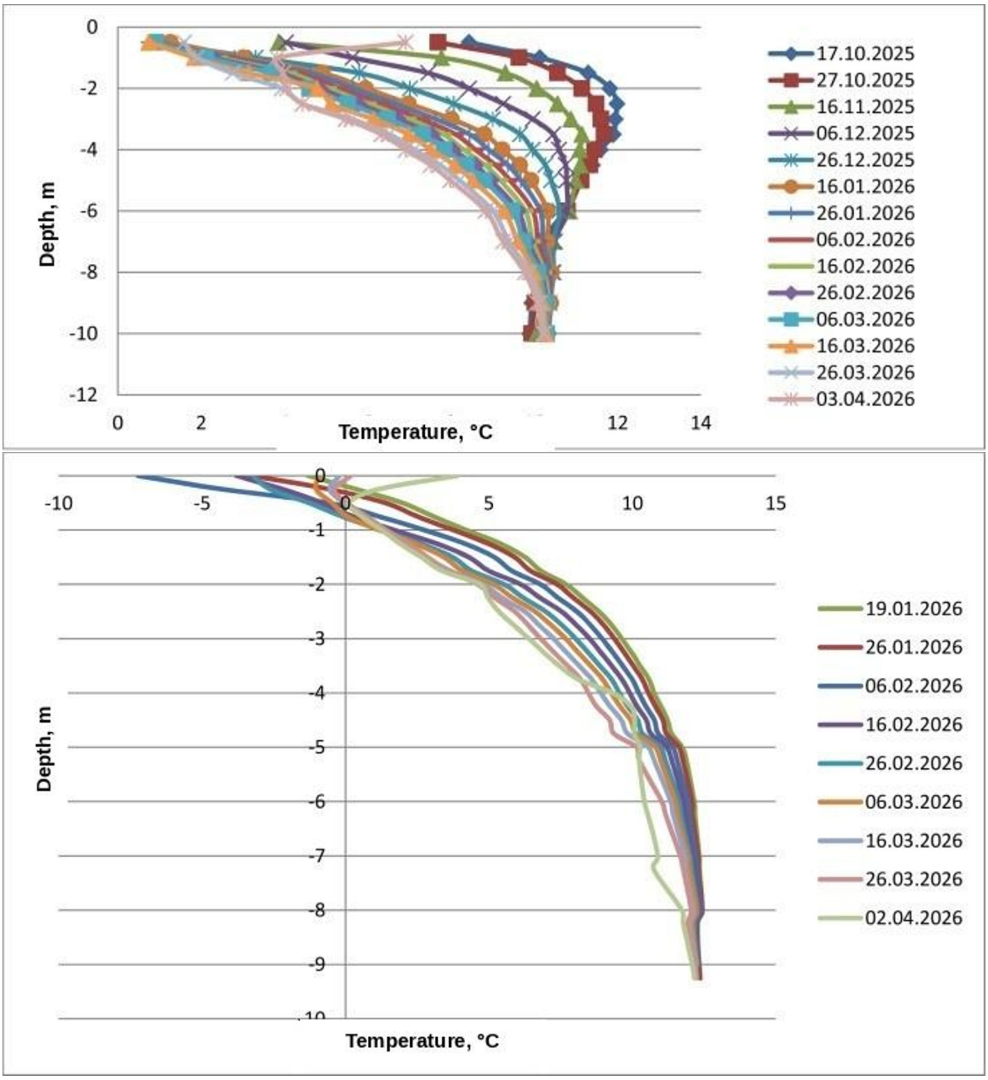

Fig. 1. Thermal state of soils at sites with natural cover and without cover during the winter season of 2025/26 at the Meteorological Observatory of Moscow State University.

Figure 1 shows, in particular, that at the site with natural cover during the winter season of 2025/26 at the MSU Meteorological Observatory, freezing did not occur under the snow, whereas freezing was observed at the site without cover.

4 Mathematical modeling of the thermal state of soils

Of particular value is the comparison of observations with mathematical modeling. The calculations are based on solving the Fourier heat conduction equation. Numerical implementation was carried out using the finite-difference scheme described in the classical work by A. A. Samarskii and A. V. Gulin [1]. To describe the temperature field in the soil layer, the heat conduction equation is solved, while initial data are specified according to temperature measurements near the ground surface.

Comparison of the numerical experiment results with field data showed a high degree of agreement. The model makes it possible to predict the dynamics of the temperature field under various climate change scenarios and to estimate the time required for critical strength values to be reached in the foundations of structures.

5 Experimental studies of the strength of ice and frozen soils

To parameterize physical and mechanical models of soil behavior under changing temperature conditions, short-term strength tests of ice and frozen soils are carried out in a cold chamber at the Faculty of Geography of Moscow State University. The automated measuring system ASIS is used, allowing uniaxial tests of samples lasting from 30 to 150 seconds.

The dependence of ice strength on temperature under uniaxial compression was studied at a loading rate of 2 mm/min. The obtained curves are consistent with the classical data of Schulson (1997) [2], demonstrating an increase in strength limit with decreasing temperature, as well as sensitivity to strain rate. Analysis of structural and textural features, including crystal structure in longitudinal and transverse sections and air-flow lines, makes it possible to explain the anisotropy of strength properties.

For frozen soils of different particle-size composition, including kaolin clay and sand, ultimate deformations under uniaxial compression were experimentally determined. Photographs of samples before and after failure recorded characteristic cracks. These results serve as the basis for calculating the bearing capacity of foundations of transport structures and for determining critical thresholds at which plastic flow of ice-rich soils begins.

6 Conclusion

1. Climate warming in northern latitudes leads to accelerated degradation of permafrost. In Central Yakutia, during the period from 1978 to 2020, air temperature increased by 1.1–3.3°C, while the rate of temperature increase in frozen soils reaches 0.7°C per 10 years.
2. Economic losses for the engineering infrastructure of the Arctic zone of the Russian Federation by 2050 are estimated at trillions of rubles. Roads, pipelines, power transmission lines, and residential buildings are exposed to critical risk.
3. Direct observational data and mathematical modeling will provide the necessary information base for decision-making.
4. Laboratory experiments using the ASIS system will make it possible to refine the dependences of ice and frozen soil strength on temperature, loading rate, and structural characteristics, which is critically important for the bearing capacity of transport structure foundations under climate-related challenges.

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