Assessment of the road transport infrastructure facility functionality loss risk resulting from climate change

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Abstract. The cause of a road bridge functionality loss risk in the conditions of climate changes in the Arctic is a decrease in its load-bearing capacity as a result of permafrost soil degradation. Modeling of the soil temperature regime of the bridge piling in Yakutsk for 2 years was performed and the minimum load-bearing capacity of the bridge piling was determined for this period. It was assumed that the average annual air temperature increased by 2 degrees Celsius in combination with an increase in the contrast between summer and winter temperatures. The obtained value of the climate risk level (438 units) allows to continue operating the facility without implementing engineering and technical measures aimed at stabilizing the soil temperature regime.

1. Introduction
Climate change significantly increases the risk of dangerous phenomena and events occurrence in all spheres of human activity. The main types of climate risks include [1]: an increase in the severity of emergencies, an increase in the frequency of their occurrence, the spread of these phenomena to new territories where they were not previously observed, as well as a significant acceleration of slow natural processes, which, in particular, include the degradation (thawing) of permafrost. Taking into account the significant distribution of permafrost and cryolitic soils on the territory of Russia (60-65% of its total area), a systematic decrease in the load-bearing capacity of thawing soils in the cryolithozone is particularly dangerous for the road network and transport infrastructure.

Forecasting climate risks for engineering facilities requires the most reliable estimates for the climate parameters values. The main one (but not the only) is the air temperature in the surface layer. Taking into account the natural variability for individual years, climate change can manifest itself in relation to either its individual parameter (as a change in the average value, variance, frequency of occurrence, or probability density), or several parameters simultaneously (multivariate analysis) [2]. In [3], a methodology for recording the values of climate parameters that change over time on the territory of the road network by means of an intelligent information and measurement system is shown.

Methodological approaches to climate forecasting are very diverse. Individual climate parameters forecasting is shown in [4], where the combined use of global and regional models of atmospheric circulation makes it possible to obtain highly accurate data on future atmospheric precipitation in the territory. Forecasting the intensity of solar radiation using the random subspace method [5] allows obtaining a correlation coefficient of 0.98 between the expected and subsequently observed values of
this parameter. The use of a neural network for forecasting future air temperature based on its past values is shown in [6]; the average error is 0.907 °C. Multidimensional climate models used for Central and Eastern European regions showed an expected warming of up to +3 °C by 2050, and up to +5 °C by 2100 [7].

Modeling of climate systems on the territory of the cryolithozone has additional features. Accounting for heat transfer in frozen soils (including permafrost soil thawing), as a necessary condition for effective modeling of changes in the atmosphere climate parameters, is justified in [8]. The high sensitivity of discontinuous permafrost to long-term warming is shown in [9]; the expected rate of its degradation increases on steep slopes facing the South. The rate of increase in air temperature in the Arctic is expected to be 1.5-2 times higher than in the rest of the world [10]; the increase in permafrost temperature by 2026 will be +2 °C. Forecast estimates of the road network settlement due to permafrost thawing at its base range from 1 to 3 cm (with scenario assumptions of air warming by +2 °C), while clay soils with high humidity are the most vulnerable [11].

A quantitative assessment of a facility operational suitability measure reducing (which occurs as a result of certain changes that are unfavourable for the facility operation) is the amount of risk. For complex facilities, the risk is determined by taking into account the probability of malfunction of individual elements (individual risk) and the joint influence of all elements on the facility functioning as a whole (system risk) [12]. The technology of risk assessment using expert analysis of the road bridges state (based on the classification of identified defects for each facility under consideration) is shown in [13].

The reasons for the increase in accidents and reduced safety of buildings and structures built on permafrost are systematically considered in [14]. The most dangerous is the melting of permafrost soils of high humidity, for which a number of methods for calculating strength and settlement are not applicable, which are effectively used for soils with low humidity [15]. To quantify the risk to a transport infrastructure facility in the cryolithozone, it is mandatory to take into account the ice content in the soil; as a result, it is possible to forecast climate risks for the roadbed with a correlation coefficient for predicted and subsequently observed damage levels of about 0.74 [16]. Using the response surface to speed up the computational procedure allows obtaining forecasted estimates of climate risks for large areas. In [17], the backbone road network on the territory of the Magadan region (within the boundaries of the 300x400 km section) is considered; the forecasted risk of +2 °C warming ranged from 78 points on a 1000-point scale (dry sandy soils on the continental territories of the region) to 360 points (aqueous clay soils in the coastal zone of the sea of Okhotsk).

Reducing climate risks to an acceptable level for newly constructed facilities is achieved by enlarging the bearing part of the foundations by an amount determined by the solution of the probabilistic and economic problem [18]. For existing facilities, risk reduction is possible due to engineering and technical measures that counteract the impact of climate change and maintain the temperature regime of permafrost soil within the design conditions.

2. Research methods
The quantitative assessment of climate risk $R$ includes the following steps:

- identification of the climatic conditions taken into account during the facility designing and determination of the climate parameters values separated by the modeling interval $\Delta t$ for at least one year (the base climate represented as the $C_0$ data array);
- formulation of scenario assumptions about the changed climate and determination of the corresponding climate parameters combined in the $C$ array;
- recording of the soil conditions $G$ (type of soil, humidity, permafrost layer temperature at the depth of seasonal temperature fluctuations, etc.);
- performing simulations of heat transfer in the soil during the period reflected in the $C_0$ and $C$ arrays, with determination of the soil temperature dynamics (represented by the $D_0$ and $D$ arrays – for the base and modified climate, respectively);
- determining the values of the facility condition criterion indicator $K$ (reflecting the load-bearing capacity of the soil) throughout the entire modeling period, identifying its minimum values in the conditions of the basic and modified climate;
- based on the decrease value in $K$ in the changed climate (compared to the base climate), the facility functionality indicator $U$ in the new climate conditions is determined, as well as the associated risk $R$.

In this paper, the climate risk in relation to the road bridge pile foundation is assessed that occurs when the average annual air temperature increases by a value of $\Delta T = 2^\circ C$ in combination with an increase in climate contrast $\Delta T^+ = 2^\circ C$ in the absence of risk reducing engineering and technical measures. Contrast refers to an additional increase in temperatures during the summer period (the duration of which was determined by the condition $T \geq 0^\circ C$), with a simultaneous decrease in temperatures during the rest of the year; the value of this decrease was assigned so that the average annual air temperature as a whole increased by $2^\circ C$.

The cross-section of the pile is 40x40 cm, the depth of immersion is 6 m. The location of the bridge, which determines the climatic conditions of its operation, is Yakutsk. Indicators of the base climate state, determined by the results of long-term instrumental observations, are shown in table 1.

| Ordinal number | Number of days | Maximum $T_{\text{max}}$ | Minimum $T_{\text{min}}$ | Average $T_{\text{mid}}$ | The average wind speed $v$, m/s |
|----------------|----------------|--------------------------|--------------------------|--------------------------|-------------------------------|
| 1              | 31             | -37.7                    | -46.6                    | -42.6                    | 1.1                           |
| 2              | 28             | -30.4                    | -41.7                    | -35.9                    | 1.1                           |
| 3              | 31             | -14.4                    | -30.1                    | -22.2                    | 1.7                           |
| 4              | 30             | -0.2                     | -14.6                    | -7.2                     | 2.6                           |
| 5              | 31             | 12.0                     | -0.5                     | 5.8                      | 3.1                           |
| 6              | 30             | 21.7                     | 8.1                      | 15.4                     | 2.9                           |
| 7              | 31             | 25.2                     | 11.7                     | 18.7                     | 2.6                           |
| 8              | 31             | 21.7                     | 8.6                      | 14.9                     | 2.5                           |
| 9              | 30             | 12.1                     | 0.7                      | 6.2                      | 2.4                           |
| 10             | 31             | -3.6                     | -12.4                    | -8.0                     | 2.2                           |
| 11             | 30             | -24.1                    | -32.9                    | -28.3                    | 1.6                           |
| 12             | 31             | -35.3                    | -43.5                    | -39.5                    | 1.1                           |

The air temperature increase by the value of $\Delta T$ for the forecast climate state was assumed to be the same for all days of the year. The contrast increase suggested that the temperature during the period of positive temperatures was increased by $\Delta T^+$, and during the period of negative temperatures – decreased by $\Delta T^-$; the value of this decrease was determined from the condition that the average annual air temperature remained unchanged. Both parameters of the changed climate were represented as random variables $\Delta \bar{T}$ and $\Delta \bar{T}^+$, distributed according to the normal law, with average values of $+2^\circ C$. The variability of the normal distribution of these parameters was determined from the condition of temperature deviation from the average value by the value $\varepsilon = \pm 2^\circ C$ no more than 1 time in 50 years, which corresponded to the probability $p = 0.01$ (figure 1, a).

For a normal distribution where $\mu = 2$ and $\sigma = 0.02$:

$$
\int_{-\infty}^{\infty} \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(\Delta T - \mu)^2}{2\sigma^2}} d(\Delta T) = 0.98
$$

(1)

Solving equation (1) with respect to the standard deviation, we get $\sigma = 0.86$. Thus, the normal distribution law of a random variable $\Delta \bar{T}$ is characterized by the parameters $\Delta \bar{T} = +2^\circ C$ and $\sigma_{\Delta \bar{T}} = 0.86^\circ C$.
\[ f(\Delta T) = \frac{1}{0.86\sqrt{2\pi}} e^{-\frac{(\Delta T-2)^2}{2(0.86)^2}} \]

For the three implementations used, the probabilities of their occurrence are (figure 1, b):

\[ p_1 = \int_{-\infty}^{1.5} f(\Delta T)d(\Delta T) = 0.2805, \]
\[ p_2 = \int_{1.5}^{2.5} f(\Delta T)d(\Delta T) = 0.439, \]
\[ p_3 = \int_{2.5}^{\infty} f(\Delta T)d(\Delta T) = 0.2805. \]  

### Figure 1

Accounting for the climate change probabilistic nature:

a) – determination of the standard deviation \( \Delta T \) for the normal distribution law,

b) – determination of the \( \Delta T \) realizations probability.

### 3. The results of climate risk modeling

The computation process parameters were adopted as follows:

- the design soil elements dimensions when modeling the dynamics of the temperature regime were \( \delta_x=\delta_y=0.1 \) m;
- simulation quantum (the time interval during which the simulated parameters were considered unchanged) was \( \Delta t=900 \) s;
- the simulation period duration was two full years, which corresponded to \( t_{\text{max}}=63,072,000 \) s, or \( N_{\Delta t}=70,080 \) simulation quanta.
Three implementations of interrelated random variables $\Delta \tilde{T}$ and $\Delta \tilde{T}^+$ were considered, combined as $\tilde{X}_1(\Delta \tilde{T}, \Delta \tilde{T}^+) = \{+1\text{°C}, +1\text{°C}\}$, $\tilde{X}_2 = \{+2\text{°C}, +2\text{°C}\}$ and $\tilde{X}_3 = \{+3\text{°C}, +3\text{°C}\}$. For each of the three combinations, the changed climate temperature indicators were determined (table 2). The average monthly wind speeds values for all three variants of climate change were taken from table 1.

| Month $i$ | $\Delta T_{\text{max}}$ | $\Delta T_{\text{min}}$ | $\Delta T_{\text{mid}}$ | $\Delta T_{\text{max}}$ | $\Delta T_{\text{min}}$ | $\Delta T_{\text{mid}}$ | $\Delta T_{\text{max}}$ | $\Delta T_{\text{min}}$ | $\Delta T_{\text{mid}}$ |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1         | -37.4           | -45.8           | -29.3           | -37.3           | -45.0           | -41.4           | -37.3           | -44.3           | -41.0           |
| 2         | -30.1           | -45.8           | -31.6           | -30.0           | -40.1           | -34.7           | -30.0           | -39.4           | -34.3           |
| 3         | -14.1           | -29.3           | -21.6           | -14.0           | -28.5           | -21.0           | -14.0           | -27.8           | -20.6           |
| 4         | 1.8             | -13.8           | 3.8             | -13.0           | -6.0            | 5.8             | -12.3           | -5.6            |                 |
| 5         | 14.0            | 1.5             | 7.8             | 16.0            | 9.8             | 18.0            | 5.5             | 11.8            |                 |
| 6         | 23.7            | 10.1            | 17.4            | 25.7            | 12.1            | 19.4            | 27.7            | 14.1            | 21.4            |
| 7         | 27.2            | 13.7            | 20.7            | 29.2            | 15.7            | 22.7            | 31.2            | 17.7            | 24.7            |
| 8         | 23.7            | 10.6            | 16.9            | 19.6            | 12.6            | 18.9            | 27.7            | 14.6            | 20.9            |
| 9         | 14.1            | 2.7             | 8.2             | 16.1            | 4.7             | 10.2            | 18.1            | 6.7             | 12.2            |
| 10        | -3.3            | -11.6           | -7.4            | -3.2            | -10.8           | -6.8            | -3.2            | -10.1           | -6.4            |
| 11        | -23.8           | -32.1           | -27.7           | -23.7           | -31.3           | -27.1           | -23.7           | -30.6           | -26.7           |
| 12        | -35.0           | -42.7           | -38.9           | -34.9           | -41.9           | -38.3           | -34.9           | -41.2           | -37.9           |

To determine air temperatures and wind speeds at random times, interpolation was used, the base points for which were the values of $T_{\text{max}}, T_{\text{min}}, T_{\text{mid}}$ and $\nu$, assigned to the midpoints of the corresponding months. As a result, based on the data in table 2, for each simulation quantum $0<\nu \leq N_M$, $T_{\text{max}}, T_{\text{min}}, T_{\text{mid}}$, and $\nu$ were determined. Than the air temperature $T_i$ corresponding to this time quantum was determined.

Soil temperature dynamics modeling was performed for three variants of climate changes, as well as for the basic state of the climate. For each soil mass temperature state, the value of the criterion indicator $K$ was calculated, which reflected the maximum possible load on an individual pile. Based on the analysis of changes in $K$ values during the modeling period, the minimum values for each of the four climate states were determined (table 3).

| Climate state | Criterion indicator $K$ | Day | Functionality indicator $U$ |
|---------------|-------------------------|-----|-----------------------------|
| Base climate  | 2,602                   | 640 | 1,000                       |
| $\tilde{X}_1$ | 2,461                   | 650 | 0,765                       |
| $\tilde{X}_2$ | 2,331                   | 650 | 0,548                       |
| $\tilde{X}_3$ | 2,231                   | 650 | 0,382                       |

For each variant of climate change, the functionality indicator values $U$ were determined, corresponding to the worst, during the average year, criterion indicator $K$. The dependence $U(K)$ was assumed to be linear on the section $0<U(K)<1$. The value of the criterion indicator for the basic climate state $K_0=2.602$ was considered a point on the border of the transition area; the used reserve value was $\Delta=1.3$. Accordingly, the other extreme point of the transition area was characterized by the value $K_0=2.602$ (figure 2).

For all three variants of climate change, the point corresponding to the functionality indicator is located on the transition section of the graph shown in Fig. 2. Values of the functionality indicator determined by linear interpolation between points $U(2,002)=0$ and $U(2,602)=1$ are shown in the last column of table 3.
Climate risk $R$ was calculated as the weighted average value of negative consequences (due to reduced facility functionality) for all variants of climate change (table 3), determined taking into account the probabilities of their occurrence ($3$) and normalized to the range $[0; 1000]$:

$$R = 1000 \sum_{i=1}^{3} p_i (1 - U_i) = 438$$  \hspace{1cm} (4)

4. Discussion and conclusions
When interpreting a quantitative risk assessment, the following should be considered. The minimum possible risk (within the range used $[0; 1000]$) $R_{\text{min}}=0$ occurs in climatic operating conditions that fully correspond to the facility design. Under these conditions, the safety margin for the base bearing capacity is maximum, based on the rich experience of operating similar facilities, there is no reason to doubt its safe operation. The maximum possible risk $R_{\text{max}}=1000$ means that this safety margin is completely depleted. At the same time, even the value $R=1000$ cannot be interpreted as an immediate destruction of the object due to insufficient load-bearing capacity of its base. Physical destruction in this case is possible if a number of operational factors are combined unfavorably (for example, when several types of loads, each of which has its own safety margin, simultaneously reach their calculated values), which is very unlikely. However, the safety of a facility when there is no safety margin of the base bearing capacity at $R=1000$ obviously cannot be considered sufficient, and the continuation of its operation in its current state should be immediately stopped – despite the continued integrity of the facility shape.

With an allowance for the abovementioned, the climate risk $R=438$ should be considered average. The operation of the facility in the changed climatic conditions may continue, but in the medium term it is necessary to develop and implement engineering and technical measures aimed at risk reducing. These measures should be aimed on adjusting the soil temperature regime and bringing it to the design characteristics corresponding to the base climate conditions.

It should also be noted that the scenario assumptions used in the simulation about the changed climate (warming by $+2$ °C) are very cautious. As it was shown in this article earlier, the expected warming in Europe in a number of scenarios is up to $+3$ °C by 2050, and the increase in air temperatures in the Arctic is expected to be 1.5-2 times more significant. Accordingly, in relation to the facility under consideration, it is necessary to systematically monitor the climatic parameters on the territory of its operation. If a higher rate of warming is recorded than was taken into account in determining the climate risk in this paper, it is necessary to re-evaluate the risk in accordance with the new scenario assumptions about the climate.

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