Modeling of Influence of Climate Change Character on the Territory of the Cryolithozone on the Value of Risks for the Road Network

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Abstract—The level of climate risks is proposed to be estimated by the amount of thawing soil settlement in the formation of automobile roads, corresponding to the accepted scenario of the climate change. An updated algorithm is presented, according to which the average risk assessment for a 4-year period is divided into a risk assessment for individual years. Calculations performed for the climatic conditions of Yakutsk and Urengoy establish a significant dependence of the predicted risk on the warming pattern. The level of risk predicted when the average annual air temperature increases by 2 degrees is estimated as average (up to 526 points on a 1000-point scale). The most appropriate method of reducing this risk is to perform timely repairs to bring the road to the standard technical and operational condition without the use of special technologies for regulating the temperature regime of soil.

Keywords—Climate change, Road Network, Cryolithozone, Modeling, Soil Thawing, Climate Risks.

1 Introduction

1.1 Review of literature

In modern conditions, global climate change is a factor that has an apparent effect on the functional suitability of engineering linear objects operated in constant contact with the environment [1]. Regardless of how significant the contribution of man-made activities to the observed climate changes is (the diversity of opinions on this issue is very significant), the fact of such changes, in particular, the continued increase in air temperature in the atmospheric boundary layer, is not in doubt and requires measures to adapt objects to these changes [2]. Territories with permafrost or cryolithic soils are characterized by increased vulnerability to climate change (to the increase in average annual air temperatures) [3]. In these areas, the observed climate changes lead to the degradation of permafrost soils in the formation of linear structures, including the road network. The efficiency of subgrade soils reduction (as a result of intensive thawing of
the upper layer of permafrost) leads to the appearance of additional settlements of the thawing soil and deformation of road structures, which causes deterioration of their technical and operational properties up to destruction. In particular, numerous chaotically located road surface subsidence’s naturally lead to the maximum possible traffic flow speed decrease and the road capacity reduction [4]. Possible empirical methods for evaluating the road surface condition parameters, in particular, its width, are described in [5]. The use of a multi-purpose radio-controlled car for this purpose is shown in [6].

Among the studies devoted to the influence of natural and climatic conditions on the technical and operational state of the road network, the following can be distinguished. In [7] it is shown that the express defect of the road slope (as a result of its erosion by the water flow of the increased intensity) leads to the accelerated pavement and road cross section damage; the road cross section resistance level to such external influence depends on the soil type and the slope angle. A new method for estimating seismic risk for transport networks with bridge structures using probabilistic seismic hazard analysis (seismic risk assessment based on the theorem of total probability) is given in [8]. The survival analysis of light cellular concrete used as part of the subgrade is performed in [9]. The method for survival assessing includes building a multi-level model for evaluating factors that affect the concrete functional performance (analytical hierarchy), building a membership function for each factor, and obtaining the final complex membership function for a parameter that quantitatively describes the survival (fuzzy integral assessment). In [10] a list of climatic and weather factors is formed, that have the most significant impact on the technical and operational condition of the road; and the structure of information-measuring system is proposed that can fix parameters values reflecting these factors in real time, and can forecast the technical and operational road condition on the basis of constantly updated data.

Quantitative forecasting of the subgrade settlement, taking into account the probabilistic nature of the factors affecting it, is performed in [11]. To overcome the weaknesses and limitations of purely probabilistic and purely deterministic models, a combined forecasting model is proposed and numerically implemented, based on an improved analysis of set pairs, and taking into account both stochastic and deterministic impacts on the subgrade soil. As a result, it is possible to quantify the amount of forecasted settlement at different levels of the probability of not exceeding this value. In [12], the development process of loess soil settlement is described quantitatively: its increase over time, starting from the moment of the first subgrade load application.

It should be noted that there are many methods used to forecast the soil settlement amount at the base of engineering constructions, and to provide a sufficiently high results accuracy. Subgrade settlement forecasting based on the regression of the reference vector of least squares and the quantum evolutionary algorithm is performed in [13]. A simplified method for settlement forecasting of pivot rings on reinforced cohesionless soils is given in [14].

In [15], the principles allowing to quantify the risks of road infrastructure objects (including road surface) malfunction in the territories of permafrost soils distribution, depending on the climate warming magnitude, are substantiated. The main parameter that determines the climate risk is thawing soil settlement value (additional settlement
as compared to that occurs in the climate before the warming beginning). Climate changes are described by a spasmodic increase in the average annual air temperature; as these changes have the probabilistic nature, warming is considered a normally distributed random variable with an average value of +2 °C and is described by a sample of several realizations. For each random variable realizations the expected additional soil settlement at the subgrade is determined and the climate risk is assessed; the final risk value is the settlement weighted average for all the considered realizations.

The forecast values of climate risk obtained in [15] are averaged over a sufficiently long period during which an increase in air temperature is simulated, and the realization order in the sample is not taken into account. Accordingly, the purpose of this work is to analyze in more detail the risks distribution within this period, and to obtain climate risk estimates for the most unfavorable dynamics of temperature changes, described using a sequence of random variable realizations that characterize the increase in the average annual air temperature for individual years of the simulated period.

1.2 Climate risk prediction technique

The main climatic parameters that affect the road network functionality decrease as a result of forecasted climate changes are the air temperature $t$, °C, and the wind speed $v$, m/s. The quantitative values of these parameters are modeled at a pitch of $\Delta \tau$ for one full average year, the duration of which is assumed to be 365 days. Then, with the same pitch $\Delta \tau$, the heat exchange is modeled between atmospheric air and soil (the first type), and between individual fragments of the soil mass formed by the road cross section and the formation soil (the second type). Heat transfer of the first type is described by the empirical dependence of Matsumura:

$$Q_1 = 18v^{0.577t}(t_a - t_g)S_g\Delta \tau,$$

where $Q_1$ – the heat energy (J), $v$ – the mean wind speed for the period $\Delta \tau$ (m/s); $t_a$ and $t_g$ – the average temperature of atmospheric air and ground surface, respectively (°C); $S_g$ – square of design element of soil mass in contact with atmospheric air (m$^2$).

The values of $Q_1 > 0$ correspond to the heat flow into the soil, where the second type heat exchange models temperature dynamics in the road cross section and its formation. Then the modeled soil mass is divided into individual elements and the heat exchange of the second type between them is described by the formula:

$$Q_2 = \frac{\lambda_A + \lambda_B}{2\delta_x}(t_A - t_B)\delta_y\delta_z\Delta \tau,$$

where $\lambda_A$ and $\lambda_B$ – the temperature-dependent coefficients of soil thermal conduction for the contiguous design elements A and B (W/(m·°C)); $\delta_x$, $\delta_y$, $\delta_z$ – the designed soil elements dimensions along the x, y, and z axes (m); $t_A$ and $t_B$ – the average temperature of the design elements A and B, respectively (°C).

Based on the dependencies (1) and (2), the soil mass temperature dynamics during the average year is determined as a sequence of the individual design elements temperatures separated by time intervals $\Delta \tau$. Next, the soil state is detected at the maximum
during the one year) thawing depth \( h_{\text{max}} \) (corresponding to the depth of penetration of the temperature isoline \( t = t_{\text{bf}} \) into the soil, where the soil freezing temperature \( t_{\text{bf}} \) depends on soil type and humidity). Thus, the maximum thawing depth of the formation soil can be represented as:

\[
    h_{\text{max}} = M(T, V, G),
\]

where \( M \) – a generalized transformation operator (including, among others, a computational procedure for modeling the temperature dynamics of the formation soil); \( T \) – an array of atmospheric air temperature values throughout the year; \( V \) – an array of wind speed values; \( G \) – a set of geometric, physicomechanical, and thermophysical soil parameters.

The magnitude of the section or road network functionality loss risk expected when climate changes occur is considered to depend on the amount of excess soil thawing in the road formation, and on the additional settlement \( \Delta m \) caused by this thawing in the soil mass. To quantify \( \Delta m \), two climate states are considered: the basic one, characterized by averaged values of \( T \) and \( V \) for the period 1960-1990, and the modified one, in which all values of atmospheric air temperatures are assumed to be increased by the same value of \( n \) (°C), resulting in an array of temperatures \( T^{(n)} \).

The base climate corresponds to the design and construction period of most of the currently operated highways in the cryolithozone of Russia; the changed climate reflects scenario assumptions about the road network operating conditions for the period up to 2030. The value of excess thawing during climate warming at \( n \) °C is defined as:

\[
    \Delta h^{(n)} = M(T^{(n)}, V, G) - M(T, V, G).
\]

After that, taking into account the physicomechanical parameters of the soil, an additional settlement \( \Delta m^{(n)} \) in the thawed soil layer with a thickness of \( \Delta h^{(n)} \) is calculated.

The period during which additional thawing soil settlement is simulated and associated climate risks are determined consists of 4 consecutive years. The parameter \( n \) is considered a random normally distributed value, with an average value of \( n_{\text{med}} = +2 \) °C and a standard deviation of \( \sigma = 0.85 \) in order to take into account the variability of climate conditions for individual years. The climate warming is thus described by a sequence of values \( \{n_1, \ldots, n_4\} \), reflecting the atmospheric air temperature increase (compared to the base climate) for individual years of the modeled period.

The selection \( \{n_1, \ldots, n_4\} \) corresponding to the accepted values of \( n_{\text{med}} \) and \( \sigma \) is determined in sequence (see Fig. 1):

1. The range of possible values of \( n \) is divided into 4 sections with equal probability of getting the random variable realization within each of the sections; adjacent boundaries are determined from the conditions \( F(n) = 0.25, F(n) = 0.5 \) and \( F(n) = 0.75 \), where \( F(n) \) is a function of the normal distribution;
2. Within each \( i \)-th section, the median value of \( n_i \) is determined, which is considered one of the implementations of the random variable \( n \).
The resulting sample of 4 realizations of \( n \), arranged in ascending order, has the form \( \{n_1=0.86; n_2=1.686; n_3=2.316; n_4=3.142\} \) (values in C); the average value and the standard deviation of the sample coincide with \( n_{med} \) and \( \sigma \). At the same time, there may be other implementations sequences in the sample that preserve the specified values of \( n_{med} \) and \( \sigma \); there are 24 different sequences in total. Each sequence of \( n_i \) values reflects a particular variant of the atmospheric temperature dynamics over a 4-year period and, accordingly, one of the possible variations in climate risks during this period. To identify the most dangerous variant with the highest risks, all 24 \( n_i \) sequences are considered, and for each of them, risks are quantified by three indicators.

The first indicator \( R_{1,i} \) reflects the risks expected in the \( i \)-th year of the period, and determined directly from the results of modeling additional formation soil settlement \( \Delta m_i \), expressed in cm:

\[
R_{1,i} = 100 \Delta m_i. \tag{5}
\]

The second indicator \( R_2 \) reflects the weight-average risk across all years of the period under review; considering the same probability for each of the implementations of \( n_i \) and hence the same probability for all values of \( \Delta m_i \), the value of average risk is:

\[
R_2 = 25 \sum_{i=1}^{4} \Delta m_i. \tag{6}
\]

The third risk indicator \( R_{3,i} \) is determined by the value \( \Delta m_i \) gradient: the specific settlement is calculated (corresponding to an increase in air temperature by +1 °C), which increases by the value of the average warming \( n_{med} \):

\[
R_{3,i} = 200 \frac{\Delta m_i}{n_i}. \tag{7}
\]

The \( R_2 \) indicator reflects the most conservative estimation of the climate risk (lower estimate). The maximum value of \( R_{3,i} \) for all years of the period, on the contrary, can be considered as the most pessimistic risk estimation (upper assessment). The indicator \( R_{1,i} \), obviously, in most cases will give a risk forecast value, intermediate between the second and third indicators. The final conclusion about the expected climate risks value is formulated taking into account the values of all three indicators.
2 Results and Discussion

2.1 Numerical simulation results

Quantitative risk estimations performed for Yakutsk climatic conditions are shown in the Table 1, the values highlighted in the table correspond to the highest forecasted risk estimates for each of the three indicators $R_1$, $R_2$, and $R_3$. The road body (soil formation) height was assumed to be 2 m, the width at the top was 10 m, the formation soil was clay, with high humidity.

The forecast risks values for the road network (sections) in the Urengoy climate are shown in the Table 2, the geometric dimensions and physicomechanical parameters of the soil mass were assumed to be the same as for Yakutsk.

When performing all calculations, the modelling interval $\Delta t$ was assumed to be 1800 s; the geometric dimensions of the soil mass designed element were $\delta_y = \delta_z = \delta_x = 0.1$ m. Reducing the values of these modelling parameters did not lead to a significant change in the numerical results thus, the accuracy of the values in the tables 1 and 2 can be considered guaranteed.

Table 1. Forecast risks of the road network functionality decrease when the climate warms by 2 °C in the climatic conditions of Yakutsk

<table>
<thead>
<tr>
<th>The temperature change dynamics by year</th>
<th>Annual risks $R_{1}$</th>
<th>Average risk for the entire period $R_{2}$</th>
<th>Risks defined by the gradient $R_{3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_1$-to-$n_2$</td>
<td>49</td>
<td>239</td>
<td>346</td>
</tr>
<tr>
<td>$n_2$-to-$n_3$</td>
<td>49</td>
<td>373</td>
<td>393</td>
</tr>
<tr>
<td>$n_3$-to-$n_4$</td>
<td>49</td>
<td>325</td>
<td>301</td>
</tr>
<tr>
<td>$n_4$-to-$n_5$</td>
<td>49</td>
<td>325</td>
<td>381</td>
</tr>
<tr>
<td>$n_5$-to-$n_6$</td>
<td>49</td>
<td>442</td>
<td>312</td>
</tr>
<tr>
<td>$n_6$-to-$n_7$</td>
<td>49</td>
<td>415</td>
<td>366</td>
</tr>
<tr>
<td>$n_7$-to-$n_8$</td>
<td>208</td>
<td>182</td>
<td>285</td>
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<td>$n_8$-to-$n_9$</td>
<td>208</td>
<td>182</td>
<td>439</td>
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<td>$n_9$-to-$n_10$</td>
<td>208</td>
<td>335</td>
<td>213</td>
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<td>$n_10$-to-$n_11$</td>
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<td>456</td>
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<td>$n_11$-to-$n_12$</td>
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<td>159</td>
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<td>$n_12$-to-$n_13$</td>
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<td>357</td>
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<td>$n_13$-to-$n_14$</td>
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<td>192</td>
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<td>$n_14$-to-$n_15$</td>
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<td>$n_16$-to-$n_17$</td>
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<td>241</td>
<td>452</td>
</tr>
<tr>
<td>$n_17$-to-$n_18$</td>
<td>241</td>
<td>439</td>
<td>163</td>
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<td>$n_18$-to-$n_19$</td>
<td>241</td>
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<td>244</td>
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<td>$n_19$-to-$n_20$</td>
<td>354</td>
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<td>352</td>
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<tr>
<td>$n_23$-to-$n_24$</td>
<td>354</td>
<td>351</td>
<td>219</td>
</tr>
<tr>
<td>$n_24$-to-$n_25$</td>
<td>354</td>
<td>351</td>
<td>314</td>
</tr>
</tbody>
</table>
2.2 Discussion

For all the considered variants of atmospheric temperature dynamics, high risk variability is forecasted for individual years of the 4-year period (indicators $R_i$ and $R_t$). According to the indicator $R_i$, this variability is slightly higher in Yakutsk conditions (the maximum change in risk over 4 years is 409 units). In Urengoy conditions, the $R_t$ risk value is also high (393 units). Risk estimates based on the gradient of settlement variability is forecasted for individual years of the 4-year period (indicators change in the climatic conditions, the possible values spread is: for $R_i$, the entire period $R_t$ change $R_1$, $R_2$, $R_3$, $R_4$).

\[
\begin{array}{cccc}
\text{The temperature change dynamics by year} & \text{Annual risks } R_{ij} & \text{Average risk for the entire period } R_i & \text{Risks defined by the gradient } R_t \\
1 & 119 & 195 & 312 & 512 & 284 & 276 & 231 & 269 & 326 \\
1 & 119 & 195 & 491 & 409 & 303 & 276 & 231 & 312 & 353 \\
1 & 119 & 343 & 293 & 430 & 296 & 276 & 284 & 347 & 273 \\
1 & 119 & 343 & 429 & 308 & 300 & 276 & 284 & 273 & 365 \\
1 & 119 & 424 & 300 & 397 & 310 & 276 & 270 & 356 & 343 \\
1 & 119 & 424 & 399 & 319 & 315 & 276 & 270 & 344 & 378 \\
1 & 227 & 166 & 374 & 436 & 300 & 269 & 385 & 323 & 277 \\
1 & 227 & 166 & 484 & 408 & 321 & 269 & 385 & 308 & 353 \\
1 & 227 & 360 & 183 & 429 & 300 & 269 & 311 & 426 & 273 \\
1 & 227 & 360 & 505 & 225 & 329 & 269 & 311 & 322 & 522 \\
1 & 227 & 426 & 189 & 391 & 308 & 269 & 271 & 440 & 338 \\
1 & 227 & 426 & 403 & 212 & 317 & 269 & 271 & 348 & 492 \\
1 & 304 & 173 & 286 & 505 & 317 & 263 & 403 & 339 & 321 \\
1 & 304 & 173 & 489 & 329 & 324 & 263 & 403 & 311 & 391 \\
1 & 304 & 286 & 181 & 429 & 300 & 263 & 339 & 421 & 273 \\
1 & 304 & 286 & 501 & 223 & 328 & 263 & 339 & 319 & 517 \\
1 & 304 & 480 & 204 & 299 & 322 & 263 & 306 & 475 & 354 \\
1 & 304 & 480 & 306 & 190 & 320 & 263 & 306 & 365 & 441 \\
1 & 429 & 183 & 290 & 395 & 323 & 269 & 425 & 344 & 341 \\
1 & 429 & 183 & 385 & 306 & 324 & 269 & 425 & 332 & 363 \\
1 & 429 & 296 & 129 & 313 & 290 & 269 & 352 & 300 & 270 \\
1 & 429 & 296 & 395 & 209 & 331 & 269 & 352 & 341 & 486 \\
1 & 429 & 390 & 189 & 242 & 311 & 269 & 337 & 439 & 287 \\
1 & 429 & 390 & 302 & 201 & 327 & 269 & 337 & 359 & 466 \\
\end{array}
\]

The spread of risk values obtained taking into account possible differences in the dynamics of the temperature regime of atmospheric air in the territory of Yakutsk is: for the indicator $R_i$, the entire period $R_t$ (354, $R_{1,\text{max}}=461$), for the indicator $R_t$, the entire period $R_i$ (263, $R_{2,\text{max}}=309$), for the indicator $R_i$, the entire period $R_t$ (298, $R_{3,\text{max}}=526$). In Urengoy climatic conditions, the possible values spread is: for $R_i$, the entire period $R_t$ (424, $R_{1,\text{min}}=424$, $R_{1,\text{max}}=512$), for $R_t$, the entire period $R_i$ (284, $R_{2,\text{max}}=331$), for $R_i$, the entire period $R_t$ (326, $R_{3,\text{max}}=522$).

The high variability of risk estimates corresponding to different variants of possible atmospheric temperature dynamics indicates an underestimated level of climate risk
forecasted on the basis of averaged temperature parameters over the entire period. Only an analysis of all possible variations of temperature changes in the territory can reliably identify the maximum possible risk. It is also necessary to note the impact of the particular territory climatic features on the risk values, which is most noticeable in relation to $R_i$.

The maximum forecasted climate risk level obtained from numerical simulation is $R_3 = 526$ units and corresponds to the climate conditions of Yakutsk; in relation to the climatic features of Urengoy, the upper limit of the expected risk $R_3$ is at the level of 522 units. The qualitative interpretation of the risk values is described in [13]; according to it, the maximum risk, which means the complete functionality loss of the road section, corresponds to the value $R = 1000$. The range of values $301 \leq R < 600$, to which the $R_3$ values belong for both examples considered, corresponds to the upper sublevel of the average risk. The lower risk estimate, based on weighted average values over a 4-year period, is $R_2 = 331$ for Urengoy and $R_2 = 309$ for Yakutsk; these values also allow to classify the risk as the average level one (lower sublevel).

3 Conclusion

The atmospheric air temperature dynamics influence on the risks level for roads sections (network) in the cryolithozone is significant and causes a change in the forecasted risk value from 17% to 77%. Identification of the most unfavorable temperature dynamics, at which the maximum road malfunction risk is forecasted, is an essential condition for obtaining reliable quantitative estimates of climate risks.

The risk level forecasted for road sections (network) in the area of Yakutsk and Urengoy, with the increase in the average annual air temperature as a result of climate warming up to +2 °C and the most dangerous nature of climate change, is estimated as average. This risk level involves constant monitoring of the road surface current state and timely repair works to eliminate defects that occur due to excessive soil formation thawing and settlement. The use of technologies for adaptation of road facilities that regulate the soil temperature regime (thermal insulation coatings, seasonal cooling devices) and prevent the occurrence of excess soil settlement is not mandatory for average risks. However, the final decision on the application of engineering measures to adapt specific roads sections in the regions under consideration should be made on the basis of detailed technical and economic calculations.

4 References


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