Influence of permafrost degradation on piles bearing capacity

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Abstract. The permafrost zone is one of the main natural systems in the Russian Federation that are exposed to global warming. The temperature of permafrost soils changes, the seasonal thaw zone increases, the process of permafrost degradation is started, influencing the strength properties of the soils. The study sought to assess climate change in terms of the impact on the bearing capacity of the soil under buildings and structures built in the 1960s and 1980s on the principle of maintaining the permafrost condition of soils. On the basis of published archival and forecast data on the increase rate in the active layer thickness and the rising trends in the temperature of permafrost soils for four geographical regions of Russia (North of the European part, North of Western Siberia, Middle Siberia, Yakutia) a reduction in the bearing capacity of the standard reinforced concrete pile was determined (35x35 cm section, 10 m long). The study showed that, for most regions, the reduction in the bearing capacity of the pile is currently on average level (10-20 %). However a high (>30%) decrease is expected by 2050.

1. Introduction

International research [1] has documented a continuous increase in the average temperature of the planet, so-called «global warming». Different causes are cited, but the increase in temperature remains indisputable. In addition to finding solutions to slow down the process, it is necessary to adapt to new living and economic conditions. We have to contend with the fact that the life cycle of previously constructed buildings and structures did not take into account long-term climate changes, which are researched relatively recently (early 1990s).

Climate change in Russia as a whole is characterized as a continuing warming, the tendency to slow down warming according to observations is not traced [2]. One of the main natural systems prone to climate change in Russia is the permafrost zone. Together with the increase in average annual temperatures of the surface air and changes in the snow regime, the temperature of the permafrost soils also changes, the seasonal thaw increases, and the degradation of the permafrost begins, accompanied by a change in the boundaries of its distribution. From a geotechnical point of view, these changes are important because they have an impact on the strength of soils and the activation of hazardous cryogenic processes.

Geotechnical construction on permafrost soils imposes increased requirements for the design and further operation of buildings that are not always met. Therefore, emergency situations and building failures are common in the region. In recent decades, the warming of the climate has had an
increasingly negative impact on the state of existing buildings. According to the estimation of J. A. Kronik [3] about a quarter of all deformations of buildings and structures in Russian permafrost zone may be related to the fact that climate change exceeded the design regulatory limits for which the stability was calculated. Attention to the problem was drawn to the recent large-scale technological accident at the Norilsk-Taimyr Company's power plant. One of the preliminary versions of the reason for the resulting decompression of the reservoir (36 years of operation) on the pile foundation was ground subsidence caused by warming in permafrost conditions. The number of deformed objects detected in the Norilsk area over the past 10 years has been significantly higher than in the previous 50 years [4]. There is a common trend for permafrost zone of increasing deformation of objects [5].

In view of the increased deformability and the risk of accidents, this study aims to assess climate change in terms of the impact on the bearing capacity of the soil under operational buildings and structures on permafrost.

2. Research method

More than 75% of all buildings and structures in permafrost zone of Russia are built and operated on the Principle I (maintaining the permafrost state of the soil) or passive approach [6]: the foundations are frozen in the ground and thus provide the required bearing capacity [2]. Most urban buildings are standard panel or brick five to nine storey buildings on piles [6].

Based on the above, the bearing capacity of the soil was estimated for a standard reinforced concrete pile with a 35x35 cm section and 10 m length. This type of pile size was most widely used in the 1970s - 2000s for construction in permafrost areas [5]. The load-bearing capacity of the pile was determined by the method of calculation with the use of permafrost soils according to Principle I, given in SP 25.13330.2012 «Bases and foundations on permafrost soils». According to this method, the bearing capacity of the vertically loaded pile $F_u$ is determined by the equation:

$$F_u = \gamma_t \gamma_c (RA + \sum_{i=1}^{n} R_{af,i} A_{af,i})$$

(1)

where $\gamma_t$ is a temperature coefficient accounting for potential changes in the ground thermal regime; $\gamma_c$ is a production coefficient; $R$ designates normal stresses generated at the base of the pile (kPa); $A$ is bottom area of the bearing pile at its contact with the ground ($m^2$); $R_{af,i}$ represents shear stresses generated along the shaft of the pile at a contact with layer $i$ (kPa); $A_{af,i}$ is the area of the side contact of a pile with frozen ground ($m^2$); $n$ is the number of different layers of permafrost in contact with the pile.

$R$ and $R_{af,i}$ (equation (1)) were determined from the Annex B tables of SP 25.13330.2012 based on equation (2) values $T_z$ - temperature of permafrost soils at depth $z$ and $T_e$ - “equivalent temperature” of permafrost soil, i.e. temperature at the point located halfway between the bottom of the pile and the top of permafrost (homogeneous permafrost ground is considered)

$$T_{z,e} = (T_{0} - T_{bf}) \alpha_{z,e} + (T_{0} - T_{0}^{'}) k_1 + T_{bf},$$

(2)

where $T_{0}^{'}, T_{bf}$ is the calculated mean annual temperature at the top of permafrost under a building, °C; $T_{bf}$ is the temperature at freezing point of the soil, °C; $\alpha_{z,e}$ ($\alpha_z$ and $\alpha_e$) are seasonal temperature coefficients for the soil; $k_1$ is coefficient of thermal impact of a building; $T_0$ is mean annual temperature of permafrost soil outside the building contour.

Climate warming affects the change in two calculated parameters: $d_{th,n}$ - depth of seasonal thaw (equals active-layer thickness (ALT)) and $T_e$ (see equation (2)). $A_{af,i}$ (equation (1)), $k_1$ and $\alpha_{z,e}$ (equation (2)) depends on the value of $d_{th,n}$.

Archival and forecast data was collected from literary sources on the increase rate in the active layer thickness and the rising trends in the temperature of permafrost soils for four geographical
regions of Russia. An increase of $T_o$ (table 1) and in active-layer thickness (ALT) (table 2) were determined for 2020 and 2050, when most of the buildings in question will have reached the end of their operation.

Table 1. Change in mean annual temperature of permafrost soil $T_o$.

| Region                  | $T_o$ trend, °C/year [7] 1965-2010. | $T_o$ increase 1965-2020, °C | $T_o$ trend climate forecast in 21st cent., °C/year | $T_o$ increase by 2050, °C |
|-------------------------|------------------------------------|-----------------------------|----------------------------------------------------|-----------------------------|
| North of the European part | 0.024                              | 1.32                        | 0.03$^a$                                          | 2.22                        |
| North of Western Siberia | 0.031                              | 1.71                        | 0.04$^a$                                          | 2.91                        |
| Middle Siberia          | 0.025                              | 1.38                        | 0.036$^b$                                         | 2.46                        |
| Yakutia                 | 0.033                              | 1.82                        | 0.01$^c$                                          | 2.12                        |

$^a$ As reported by [8].
$^b$ As reported by [9],[10].
$^c$ As reported by [11].

Table 2. Determination of the ALT change during climate warming.

| Region                  | ALT rate increase [12], cm/year | ALT increase by 2020, m | ALT increase rate climate forecast in 21st cent. [13], cm/year | ALT increase by 2050, m |
|-------------------------|---------------------------------|-------------------------|---------------------------------------------------------------|-------------------------|
| North of the European part | 4                               | 0.8                     | 3                                                             | 1.70                    |
| North of Western Siberia | 1                               | 0.2                     | 2                                                             | 0.80                    |
| Middle Siberia          | 2                               | 0.4                     | 1                                                             | 0.70                    |
| Yakutia                 | 1                               | 0.2                     | 1                                                             | 0.50                    |

3. Results and discussion
For each of the four geographical regions of Russia, the bearing capacity of the pile was determined according to equation (1) at the time of construction and by 2020 and 2050 taking into account climate change. The obtained values were compared. The reduction in the bearing capacity of the pile relative to the beginning of the building's operation, compared to the resulting increases in $T_o$ (table 1) and in the ALT, is shown in tables 3, 4. Figures 1 and 2 graphically show the reduction in load-bearing capacity by region.

By 2020, the reduction of the bearing capacity of the pile had reached 25% (North of the European part), but for most regions it remained at the average level (10-20%). The forecast to 2050 showed a high (>30%) decrease with the greatest values for the North of Western Siberia.

It should be noted that climate is not the only one factor influencing the condition of buildings and structures on permafrost. Factors such as technogenic and direct anthropogenic impacts are important and can also have a negative consequences on the reduction of load-bearing capacity, especially in the long term.
Table 3. Reduction in bearing capacity of piles by 2020.

| Region                          | ALT increase by 2020, m | Permafrost temperature 1965-2020, °C | soils temperature increase | Reduction of bearing capacity from 1965 to 2020, % |
|---------------------------------|-------------------------|--------------------------------------|-----------------------------|-------------------------------------------------|
| North of the European part     | 0.8                     | 1.32                                 | 25                          |
| North of Western Siberia       | 0.2                     | 1.71                                 | 14                          |
| Middle Siberia                 | 0.4                     | 1.38                                 | 6                           |
| Yakutia                        | 0.2                     | 1.82                                 | 18                          |

Figure 1. Reduction in bearing capacity of piles by 2020 for four geographical regions of Russia: 1 - North of the European part, 2 - North of Western Siberia, 3 - Middle Siberia, 4 - Yakutia.

Table 4. Reduction in bearing capacity of piles in the forecast for 2050.

| Region                          | ALT increase by 2050, m | Permafrost temperature by 2050, °C | Predicted reduction of bearing capacity by 2050, % |
|---------------------------------|-------------------------|----------------------------------|-------------------------------------------------|
| North of the European part     | 1.70                    | 2.22                             | 44                                              |
| North of Western Siberia       | 0.80                    | 2.91                             | 67                                              |
| Middle Siberia                 | 0.70                    | 2.46                             | 45                                              |
| Yakutia                        | 0.50                    | 2.12                             | 31                                              |

In future studies, as new data become available on the increase rate in the active layer thickness and trends in the temperature of permafrost soils, other geographical regions of Russia which include permafrost zone will be considered: South Siberia, North-East Russia, Pribaikalie and Zabaikalie.
4. Conclusions

The warming of the climate in Russia has a noticeable impact on permafrost region. The permafrost is thawing. As the mean annual temperature of the ground rises and the seasonal thaw depth increases, the bearing capacity of the piles decreases.

Research has shown that for the 60s and 80s buildings (I principle of construction on permafrost soils) the reduction of the bearing capacity of the pile is up to 25%, but for most regions remains at the average level (10-20%).

The calculation of bearing capacity change by 2050, based on existing forecasts of climate change, showed a high reduction. Most of the old building will be unsuitable for operation even before the end of their life cycle. There is a need to monitor the condition of such buildings and to plan measures to ensure their operational safety. Technological and structural solutions include soil thermostabilization systems, including jacking of piles through thawing soil into solid ground [15] to ensure that the foundations of buildings and structures are operational under climate changes.

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