International Journal for Computational Civil and Structural Engineering, 18(1) 141–150 (2022)

DOI:10.22337/2587-9618-2022-18-1-141-150

FORECAST OF THE SOIL DEFORMATIONS AND DECREASE OF THE BEARING CAPACITY OF PILE FOUNDATIONS OPERATING IN THE CRYOLITHOZONE

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Abstract: Currently, permafrost is degrading due to global warming. The destructive impact of cryogenic processes on buildings and structures in the permafrost zone is increasing. The purpose of this study was to predict the decrease in the bearing capacity of pile foundations of existing buildings and the resulting deformations of the permafrost soils due to climate change. Numerical studies of the bearing capacity of pile foundations and deformations of the base of a building erected in the 1980s in Norilsk according to the first principle of construction on permafrost soils were carried out. Modeling showed a decrease in the bearing capacity of the piles of the building up to 50% over 60 years (mesured since 2000). The period after which the building will come into an emergency condition is determined. Article provides an assessment of the effectiveness of the use of seasonally operating cooling devices to ensure its operational reliability.

Keywords: permafrost soils, cryolithozone, pile foundations, thermal stabilizers, bearing capacity of piles, building maintenance.

ПРОГНОЗ ДЕФОРМАЦИЙ ОСНОВАНИЯ И СНИЖЕНИЯ НЕСУЩЕЙ СПОСОБНОСТИ СВАЙНЫХ ФУНДАМЕНТОВ В КРИОЛИТОЗОНЕ

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Аннотация: В настоящее время по причине глобального потепления климата происходит деградация вечной мерзлоты. Усиливается деструктивное воздействие криогенных процессов на здания и сооружения в криолитозоне. Целью данной работы являлось прогнозирование в связи с изменением климата снижения несущей способности свайных фундаментов существующих зданий и вызванных этим деформаций основания из многолетнемерзлых грунтов. Были проведены численные исследования несущей способности свайных фундаментов и деформаций основания здания, возведенного в 80-х годах прошлого века в Норильске по I принципу строительства на многолетнемерзлых грунтах. Моделирование показало снижение несущей способности свай здания до 50% за 60 лет (начиная с 2000 г.). Определен срок, по истечении которого здание придет в аварийное состояние. Дана оценка эффективности применения сезонно-действующих охлаждающих устройств для обеспечения его эксплуатационной надежности.

Ключевые слова: многолетнемерзлые грунты, криолитозона, свайные фундаменты, термостабилизаторы, несущая способность свай, эксплуатация зданий.

INTRODUCTION

The Earth's climate has changed throughout the humanity's existence. The modern warming period began from the mid-70s of the twentieth century and continues up to the present time [1] It is worth noting that in the 30s–40s there was also warming, which was especially evident in the Arctic. This led to its rapid development at that time [2]. The Earth's climate has changed throughout the existence of mankind. The modern period of warming began in the period from the mid-70s of the twentieth century and continues up to the present time [1] It is worth noting that in the 30s–40s there was also warming, which was especially evident in the Arctic, which led to its rapid development at that time [2]. An analysis of modern research allows us to identify five scenarios of climate change, for which the positions of the boundaries of the distribution of permafrost soils (PS) and the depths of seasonal thawing are calculated. The most popular is the scenario in which global warming will occur relatively quickly. By the end of the 21st century, the average temperature of the Earth's surface may increase from 1.1 to 6.4 °C in comparison with 1990. In the northern hemisphere, where the most rapid and significant warming will be observed, the area of distribution of PS will decrease to 40% by 2050 [3].

The degradation of permafrost has a direct impact on the construction sites located there [4]. The destructive impact of cryogenic processes on infrastructure facilities in the area of permafrost has increased as follows: by 61% in Yakutsk, 90% in Amderma, 42% in Norilsk [5]. In the Norilsk region, climate warming should be considered as a significant factor in the occurrence of accidents, which must be taken into account when calculating the bases in the permafrost zone for the entire period of construction and operation of facilities [6].

The observed upward redistribution of permafrost temperatures at the depth of annual zero amplitudes is especially dangerous for existing buildings and structures.

More than 75% of all buildings and structures in the permafrost zone of Russia are built and operated according to the principle of maintaining the frozen state of foundation soils. That is the foundations are frozen into the soil, and this ensures the required bearing capacity [7]. Most urban buildings are typical panel or brick five-nine-story buildings on pile foundations [8].

Thus, the relevant problem is the prediction of deformations of the PS base and the decrease in the bearing capacity of pile foundations due to climate warming.

Analytical forecast of reducing the bearing capacity of pile foundations by the middle of the 21st century [9,10 showed that at the moment for buildings built in the 60-80s (I principle of construction on PS), the reduction in the bearing capacity of the pile foundation reaches 25% (North European parts of Russia). However, it remains at an average level (10-20%) for most regions. By 2050, it's a high (>30%) decrease will be observed.

Khrustalev L.N. determined an increase in the required depth of pile driving to ensure the stability of buildings for the period from 1950 to 2010 for Vorkuta and to 2030 for Yakutsk due to an increase in the temperature of the permafrost caused by climate warming [11].

Kudryavtsev S.A. et al., propose a conceptual basis for the model for determining the bearing capacity of pile foundations based on studies conducted over the past 45 years of observations for the infrastructure facilities of the Eastern Range of the Far Eastern Railway located on the PS. According to this, the bearing capacity of piles decreased by 3 times from 1990 to 2020. [12,13].

The purpose of this article is to predict the decrease in the bearing capacity of pile foundations of existing buildings in the conditions of Norilsk and the resulting deformations of the PS base in relation with climate warming.

RESEARCH METHOD

The determination of the reduction in the bearing capacity of pile foundations and the calculation of deformations of the PS base were

carried out by a numerical method in the Settlement Calculator, which is part of the Frost 3D software package.

In the Frost 3D Settlement Calculator, the calculation of soil settlement and bearing capacity of piles is carried out in accordance with Chapter 7 of Building Code of Russian Federation SP 25.13330.2012 " Soil bases and foundations on permafrost soils". The calculations used the modified method SP 25.13330.2012 embedded in the Calculator, which allows performing calculations on a three-dimensional finite-difference computational grid and taking into account the proportion of unfrozen water in the ground.

Determination of the deformation of the base of the foundations performed using the numerical solution of a stationary differential equation in partial derivatives, which describes small transverse deflections of a thin plate, considering the elastic forces under perpendicular effects of external forces.

The pile foundation of a multi-storey building with dimensions of 12x24 m, built according to the I principle of construction on the PS, was modeled. There was a ventilated underground under the entire volume of the building. The foundation consists of reinforced concrete piles d = 0.35 m, buried in the ground to a depth of 13 m (piles of the extreme row) and 15 m (piles under the middle of the building) and united by a tape or slab grillage. The pressure from the building to the foundation was set in the case of a strip grillage of 204 kPa for a row of piles under the wall in the middle of the building and 149 kPa in the case of an extreme row of piles, for a slab grillage it was 120 kPa.

When calculating the bearing capacity and deformations, the temperature distribution obtained by the authors in the course of previous studies [9,6] at the base of the building in Norilsk, which was erected according to the I principle of construction on PS with a ventilated underground, was used, taking into account climate warming (Figure 1). The bearing capacity of pile foundations was determined by 2000 using the temperature distribution obtained from meteorological data. By 2021 and 2059, it was determined considering the trend of climate warming.

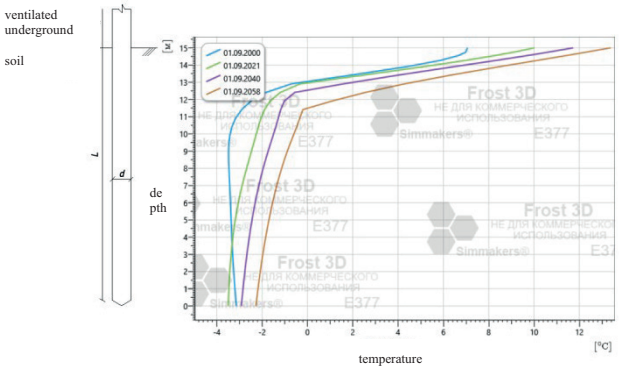


Figure 1. Soil temperature distribution along a pile with a length L = 16 m, d = 0.35 m, located under the middle of the building

RESULTS

By 2021, the calculation condition for the first limit state (ultimate state) is met. The bearing capacity of piles exceeds the calculated load applied to them (Figure 2), despite the decrease by 2021 compared to 2000 of the bearing capacity of piles of the extreme row by 13%, piles under the middle of the building by 11%.

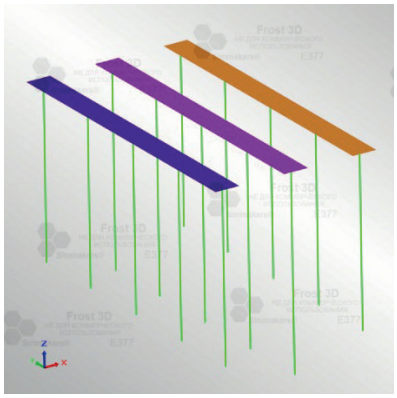
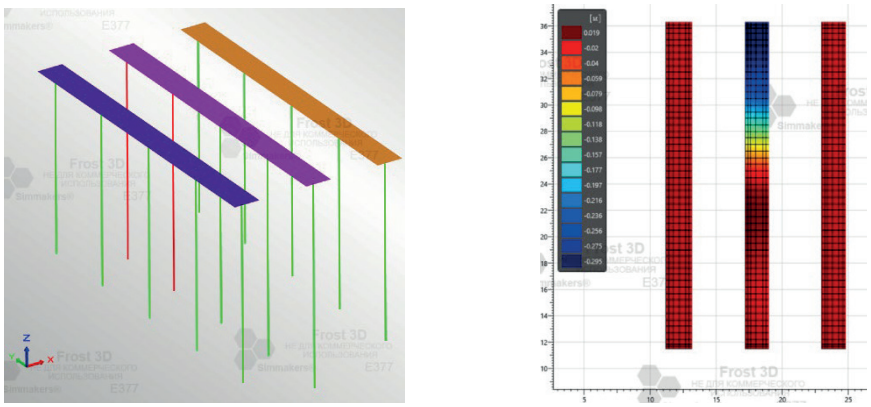


Figure 2. Calculation of the bearing capacity of piles by 2021. Piles are highlighted in green in the model. The calculation condition for the first limit state is met

By 2040, part of the piles is predicted to lose stability due to a decrease in their bearing capacity caused by the predicted increase in the

temperature of permafrost with climate warming (Figure 3a). In comparison with 2000, a decrease in bearing capacity was obtained by 30% and 28% for the piles of the extreme row and piles under the middle of the building, respectively. The calculation of deformations of the building base was made. A settlement of 30 cm was obtained and the relative difference in settlements was 0.047 in the transverse and 0.016 in the longitudinal directions (Figure 3b) due to the loss of bearing capacity by some of the piles for the strip grillage.

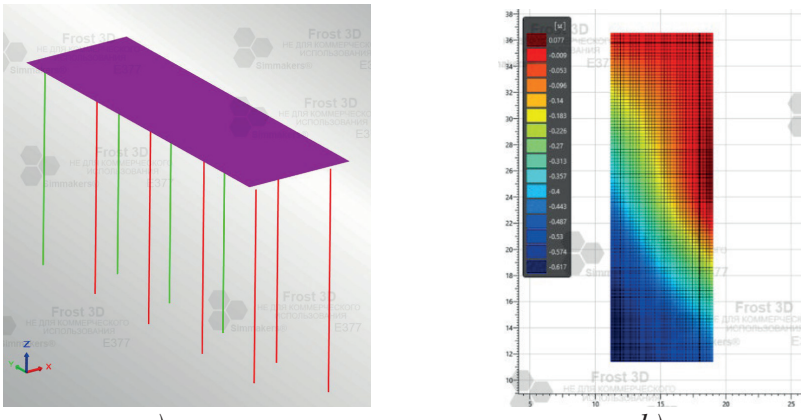
By the end of the simulated time period (2059), the bearing capacity is predicted to decrease by 52% for the piles of the outermost row, by 49% for those located under the middle of the building, and, in the case of a strip grillage, the latter will lose stability.



a) *b)*

Figure 3. Loss of stability by part of the piles, caused by a decrease in their bearing capacity due to the predicted increase in the temperature of the permafrost by 2040: a) calculation model of piles and strip grillage, in red - piles that have lost stability; b) additional sediment received

For a slab grillage, the piles' loss of stability is shown in Figure 4a. Figure 4b presents the results of the settlement calculation. The following values of deformations were obtained: draft 62 cm, relative difference of draft 0.035 in transverse and 0.033 in longitudinal directions. Figure 5 shows the general diagram of the decrease in the bearing capacity of piles by 2059 in relation to 2000 due to an increase in the temperature of the permafrost with a warming climate.



a) *b)*

Figure 4. Loss of stability by part of the piles (red) caused by a decrease in their bearing capacity due to the predicted increase in the temperature of the permafrost by 2059: a) calculation model of piles and slab grillage; b) additional sediment received

As a result, it was found decrease of bearing capacity of the piles of the facilities built in 1981 according to principle I in Norilsk. And by 2040, the building will come into an emergency condition. It is necessary to plan structural and technological measures to ensure operational reliability, as well as the organization of geocryological and geotechnical monitoring of such buildings.

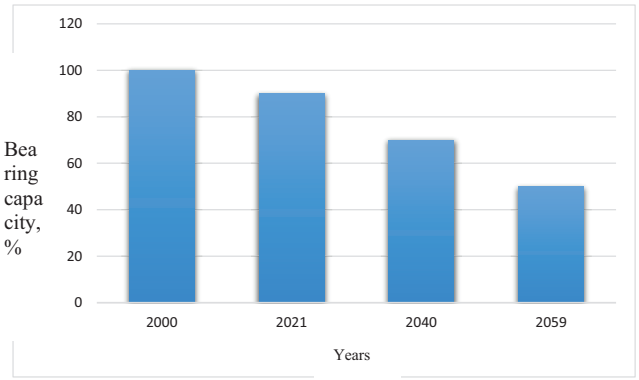


Figure 5. Diagram of the decrease in the bearing capacity of piles by 2059 relative to 2000 due to climate warming

USE OF SEASONAL COOLING DEVICES

The main existing types of structures and technologies used to prevent the degradation of permafrost soils at the base of buildings and structures were identified: ventilated undergrounds (including adjustable ones) [14], enclosing clips arranged in the base using various technologies along the contour of the building [15]; thermal stabilization of soils with the help of seasonally operating cooling devices (SOCD).

Soil thermal stabilizers, otherwise called thermosiphons or seasonal cooling devices, have been successfully used since the 1960s [16, 17, 18]. The operation of such an installation is based on a physical phenomenon - convection. Provided that the outdoor air temperature is lower than the ground temperature, heat exchange takes place with the help of a condenser and a refrigerant.

On the example of the considered model of a building in Norilsk, the problem was solved to assess the effectiveness of the use of the SOCD to prevent a decrease in the bearing capacity of foundation piles and extend the life of the building.

In the Frost 3D software, the use of the SDA with the following characteristics was simulated: the length of the above-ground part is 2 m, the underground isolated section is 3 m, the length of the evaporator part is 10 m, the radius of the evaporator pipe is 16.85 mm, the area of the condenser part is 2.43 m2, the evaporator part - 1.06 m2.

Using the Frost 3D Heat Transfer Conditions Calculator, based on long-term meteorological data on wind speed (Scientific and Applied Handbook on Climate of the USSR, 1990) and the design parameters of the condenser, the heat exchange coefficients of the heat exchanger finned tube with air were calculated for the entire forecast period: 2021-2059. The decrease in wind speed for the SDA located in the ventilated underground was taken into account.

The layout of the JCS is shown in Figure 6. In Frost 3D, only the evaporative part of the condenser is graphically specified in the model.

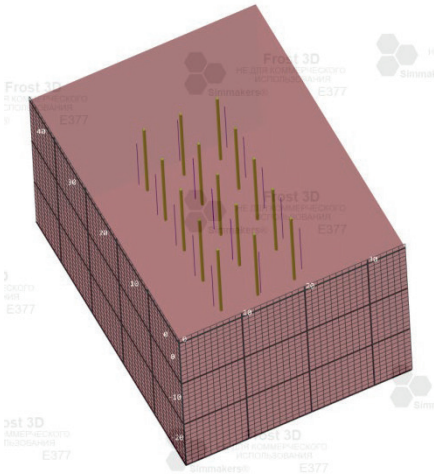


Figure 6. Model of a soil mass containing piles and SOCD

The technique for conducting a numerical study was similar to that given for modeling without a SOCD.

In the Frost 3D program, the temperature distribution in the soil mass was obtained with an interval of one month for the time interval 1981-2059. It was assumed that the SOCD were installed in 2021. Figure 7 shows the base temperature isofields at the end of the simulated time period (on February 2059).

Forecasting the change in the bearing capacity of pile foundations and deformations of the foundation from PS during the construction of the SOCD in connection with climate warming was carried out by a numerical method in the Settlement Calculator of the PC Frost 3D.

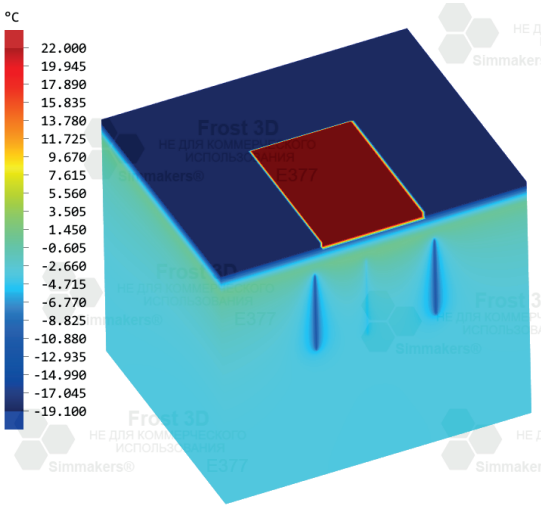


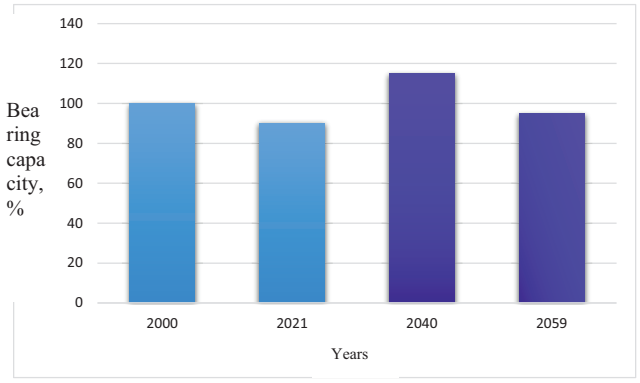
Figure 7. Temperature distribution in the soil mass in February 2059

The bearing capacity of pile foundations was determined after the installation of the SOCD (2021) by 2040 and 2059 using the obtained temperature distribution, considering the trend of climate warming.

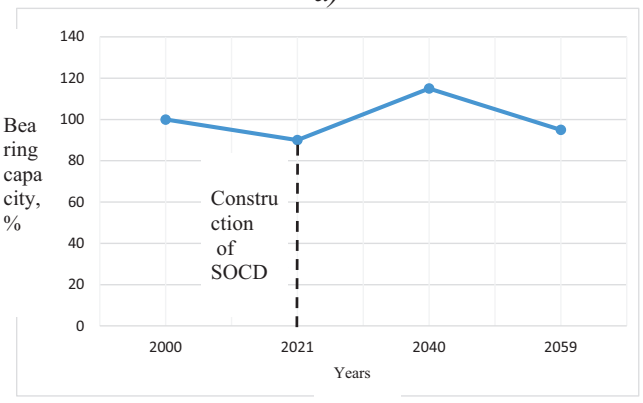
By 2040, the bearing capacity of the piles of the extreme row increases by 12%, the piles under the middle of the building - by 14% in relation to 2000 due to the installation of the SOCD. The calculation condition for the first limit state is fulfilled: the bearing capacity of the piles exceeds that applied to them calculated load.

In the period from 2041 to 2059, a decrease in the bearing capacity of piles is again predicted due to an increase in the temperature of the permafrost due to climate warming. By 2059, a decrease in bearing capacity relative to 2000 was obtained by 7% and 5% for the piles of the outer row and under the middle of the building, respectively. The calculation condition for the first limit state is met. The diagram of changes in the bearing capacity of piles in relation to 2000 before and after the installation of the SOCD is shown in Figure 8.

The use of SOCD guarantees the operational suitability of buildings until the middle of the 21st in the conditions of a predicted increase in air temperature. However, it is necessary to consider the economic costs associated with the limited period of their operation and the need for replacement when making a decision on the construction of the SOCD.



a)



b)

Figure 8. Change in the bearing capacity of piles by 2059 relative to 2000 when installing a SDA in 2021 to prevent the degradation of permafrost due to climate warming: a) diagram; b) schedule

CONCLUSION

1. Numerical modeling in the Frost 3D program showed a decrease in the bearing capacity of piles of a building built in Norilsk in 1981 according to the first principle by 10% by 2021, by 30% by 2040, by 50% by 2059 compared to 2000. The operational suitability of the building in 2021 is ensured (the maximum settlement did not exceed 5 mm), by 2040 the building will be in an emergency condition (the projected settlement will be 30 cm, the relative difference of the settlement is 0.033-0.035).
2. Modeling the use of SOCD to prevent the reduction in the bearing capacity of foundation piles and extend the life of a building with a ventilated underground showed that the bearing capacity of piles first increases by 15% by 2040 compared to 2000, and then there is a slight decrease (5-7%). Thus, the use of SOCD guarantees the operational suitability of buildings until the middle of the 21st in the conditions of a predicted increase in air temperature.
3. It is necessary to continue research aimed at developing scientific foundations for the preservation of soils in the permafrost zone in the permafrost state at the base of existing buildings, communications and highways by controlling the temperature regime of soils using new technologies and constructive measures.

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