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Change of the bearing foundation capacity in connection with climate warming in the northwest of Siberia

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Abstract

Considering different physicographical territory under changing climate conditions, a quantitative technique is presented for estimating the changes in bearing capacity of the permafrost foundations. The results showed an increase in the permafrost temperature over 30 years (1960-1990) due to climate warming. This led to a decrease in the bearing capacity foundations in the north of Western Siberia, and in some regions the reduction was up to 45%. The predicted climate warming may lead to a further decrease in the bearing capacity of the foundations built on the principle of permafrost construction, which will lead to an increase in the number of deformations of buildings and structures and may adversely affect the development of the region's infrastructure.

Keywords: Bearing capacity; Permafrost; Northwest of Siberia; Climate change; Geocryological hazards.

1. Introduction

The Arctic has long ceased to be an undeveloped region. This is evidenced by numerous settlements, industrial centers, and developing infrastructure. More than 370 settlements with a total population of about 10 million people are located in the Arctic. Despite the fact that basically these settlements are small enough, in the Russian Arctic there are several large cities with a population of more than 100 thousand people. About 5% of the Russian population living in the Arctic contributes 11% to the country's GDP and approximately two-thirds of its currency earnings (Anisimova and Greenpeace, 2009).

One of the most developed Arctic regions of the Russian sector is Western Siberia, where hydrocarbon fields are actively being developed, a well-developed pipeline network has been built, such cities as Nadym, Novy Urengoy, Pangody and others have been built, thousands of kilometers of roads and power lines for various purposes. The construction and maintenance of infrastructure in the northwestern of Siberia is complicated not only

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by the severity of climatic conditions, and the remoteness of regions from the base cities, but also by the presence of long term permafrost.

The ability of the long term permafrost to provide the required bearing capacity for buildings and structures depends primarily on the temperature and mechanical characteristics of the soil. While the mechanical properties of the soil are relatively conservative in the time scale of construction and operation of most structures, the temperature characteristics of the soil change under the influence of radiation-heat balance on the surface of the earth. At the same time, changes in the heat balance at the surface and in the depth of the soil can be carried as technogenic destruction of the vegetation cover, redistribution of snow, substitution of soil during construction, bogging, etc., and natural character like long-term warming or cooling winters. Therefore, consideration of climatic characteristics and factors of the physical and geographical environment when choosing the bases of buildings and structures is the most important step in calculating the bearing capacity of pile foundations on permafrost (USSR,1985; SNiP, 1990; Grebenets and Rogov, 2000).

According to national normative documents, in the calculation of permafrost characteristics for the determination of bearing capacity of foundations of buildings and structures, information from the relevant SNiP or from climate reference books published earlier every ten years is used. It should be noted that the data on weather stations show from the mid 60's - early 70's, and the last century, a steady increase in average annual air temperatures (ACIA, 2004; ACIA, 2005).

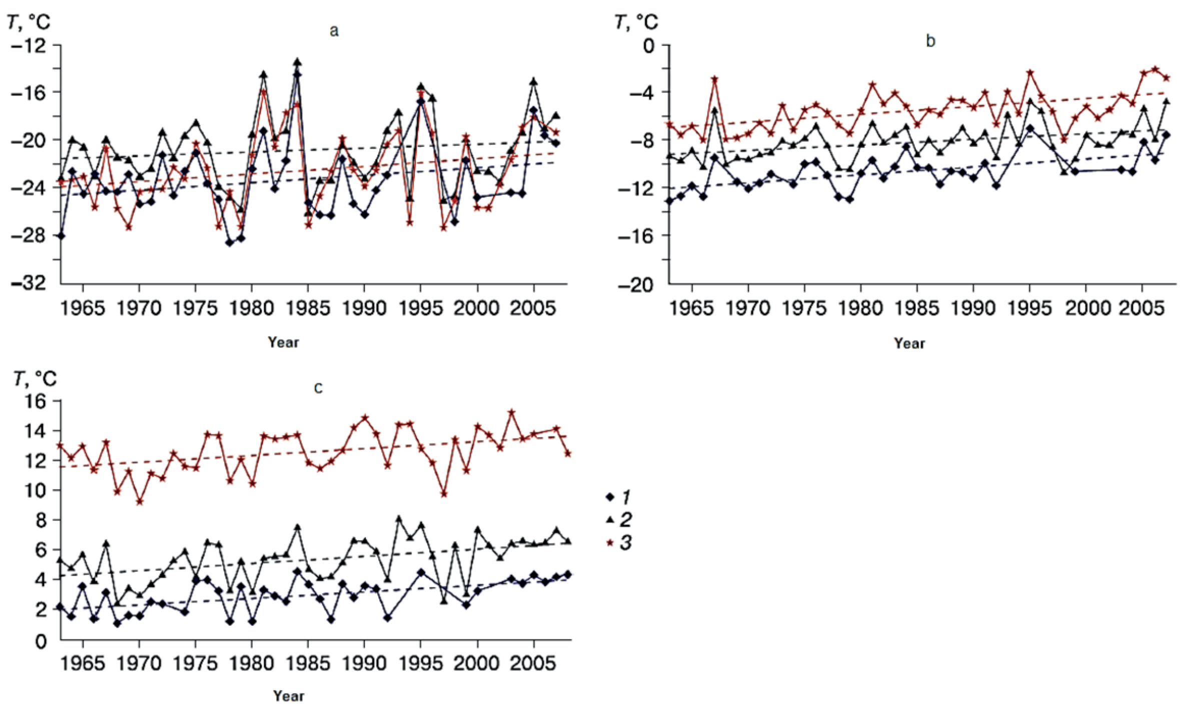

Figure 1. Air temperature curves for three weather stations in the north of West Siberia, located along the north-south profile: 1- Bely Island, 2- Cape Marre-Sale, 3- Nadym; a is the temperature of the coldest month, b is the average annual temperature, and c is the temperature of the warmest month

Climate warming can be traced both in the greater part of the Arctic and in its Russian sector, including in Western Siberia (Pavlov, 2005). The temperature trends constructed at three stations selected along the bioclimatic transect in Western Siberia show an increase in the mean annual air temperature of about 0.06 °C/year for the period 1963-2008. The strongest warming is typical for the winter period, while a small trend is also traced in the summer months (Figure 1). For the last 25 years the duration of the warm period in the tundra zone increased by 5-6 days, in the zone of the northern taiga by 15-17 days (Vasiliev *et al.,* 2008)

The warming of the climate led to an increase in the temperature of the permafrost. According to (Romanovsky and Osterkamp, 1997; Romanovsky *et al.,* 2010), the permafrost temperature at the depth of zero annual fluctuations has increased by 0.5-2.0 ° C over the past 20-30 years in the whole of the Russian Federation's permafrost zone. According to (Pavlov, 2008; Pavlov and Malkova, 2009), the range of changes in soil temperature for the north of Russia is from 0.004 to 0.05 °C/year.

The European North of Russia is characterized by a warming rate of about 0.01-0.04 °C/year in the western part (Malkova, 2008) and 0.01-0.08 ° C / year in the eastern part (Oberman, 2008). The displacement of the permafrost boundary north by 30-40 km in the Pechora lowland and 70-100 km in the Urals occurred in 1970-2005 (Oberman and Shesler, 2009). The highest rate (0.08 °C/year) of warming was found in peat bogs, the slowest (0.01 °C/year) in loamy loams of Mazhitova *et al.,* 2004). A similar situation is typical for the forest-tundra of Western Siberia, where the most intensive warming is observed in peat-lands (0.04 °C/year), and the lowest in marsh landscapes. A noticeable reduction in the long term permafrost area over the last 30 years has been recorded in the southern forest-tundra in the Urengoy gas-condensate field (Vasiliev *et al.,* 2008).

North Yakutia has been warming up to 1.5 °C in the eastern part since 1980, but in the areas located in the western part of the region, there has been no significant warming until recently. Warming of permafrost was also noted in the Baikal area (from 0.025 to 0.04 °C/year).

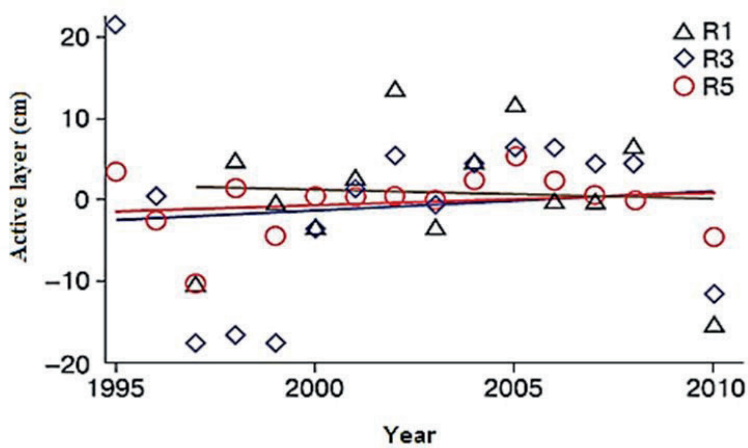

Figure 2. Active layer trends in monitoring Areas contains: Kam: R1, Nadym: R3, Marresale (Yamal Peninsula), R5: Villa Vaska (Yamal Peninsula)

Despite the fact that the increase in average annual temperatures is more pronounced in the cold period of the year with a rather weak warming in the summer months (Pavlov, 2005), the temperature rise of the frozen bed was accompanied by a slight increase in the active layer, including the west of Siberia (Figure 2). The figure shows the active layer anomalies for the period of 1995-2008.

An increase in the temperature of the permafrost and an increase in the depth of the active layer can potentially lead to a decrease in the bearing capacity of frozen foundations below the calculated values adopted in the design and construction by the results there prior to exploration, especially for objects built before the 1980s, since the bearing capacity of the piles was calculated on the basis of other parameters of the permafrost, primarily from the temperature and depth of its roof. According to a number of assessments (Anisimova and Greenpeace, 2009), on the oil fields of the Khanty-Mansiysk Autonomous Okrug, due to deformations of the ground and the melting of permafrost, an average of 1900 accidents occur in a year, and in the whole of Western Siberia is about 7400. To maintain the efficiency of pipelines and eliminate mechanical deformations associated with melting permafrost, with an increase in the depth of the active layer and activation of the tangential forces of frost heaving, each year up to 55 billion rubles are spent. For example, due to the gradual increase in the depths of the active layer and the increase in the tangential forces of the frost heave on the lightly loaded gas pipeline supports, 3000-4000 supports of in-site and main gas pipelines are annually cut off in the Yamburgskoye gas condensate field.

The current situation became a possible cause of mass deformations and, in some cases, collapse of buildings and structures in most settlements of the Russian Arctic, built on permafrost on the first principle (Table 1). The first principle of construction on permafrost is based on the preservation of the frozen state of soils during the whole period of construction and operation of buildings and structures of SNiP (1990). More than 75% of buildings in the permafrost are built on the first principle, with preference given to pile foundations.

The bearing capacity of each pile is determined by calculation or field testing and represents the sum of the forces of normal pressure on the sole of the pile (resistance to compression) and the forces of freezing on the lateral surface (shear resistance). These characteristics, in

Table 1. Deformations of structures in populated areas of Russia's permafrost zone

Locality	Population *, people	Buildings with deformations **,%
Yakutsk	284000	9
Norilsk	205000	10
Tiksi	5600	22
Dixon	600	35
Amderma	500	50
Magadan	99000	55
Vorkuta	71000	80
Chita	307000	60

* According to the Federal State Statistics Service on 01.01.2009

** According to Kronik (2001)

turn, depend on the geometric parameters of the piles, the temperature of the long term permafrost, the soil structure, the ice content, salinity and the amount of unfrozen water. Moreover, it is the temperature of the long term permafrost that is the determining characteristic in the calculation of the bearing capacity. The permafrost temperature during the operation of the objects is a function of the surface temperature of the soil, which depends on the heat exchange on the surface and varies according to the temperature fluctuations of the air, the presence of vegetation and changes in the snow cover.

In the earlier researches (Khrustalev and Shumilishskii, 1997; Khrustalev and Davidova, 2007), it was shown that the change in air temperature and snow accumulation conditions significantly affects the soil temperature, on which their properties depend and, hence, the bearing capacity. At the same time, Khrustalev (2000) analyzed the various coefficients introduced to increase the bearing capacity of foundations and stipulated by SNiPs, established that the margin for bearing capacity is from 1.05 to 1.56. This means that if the bearing capacity of soil base of a building or structure will decrease by 64-95% under the influence of climatic or technogenic factors, then such a building will potentially be subject to deformation and destruction. Further Khrustalev calculated the carrying capacity of typical foundations in Yakutsk and concluded that an increase in the average

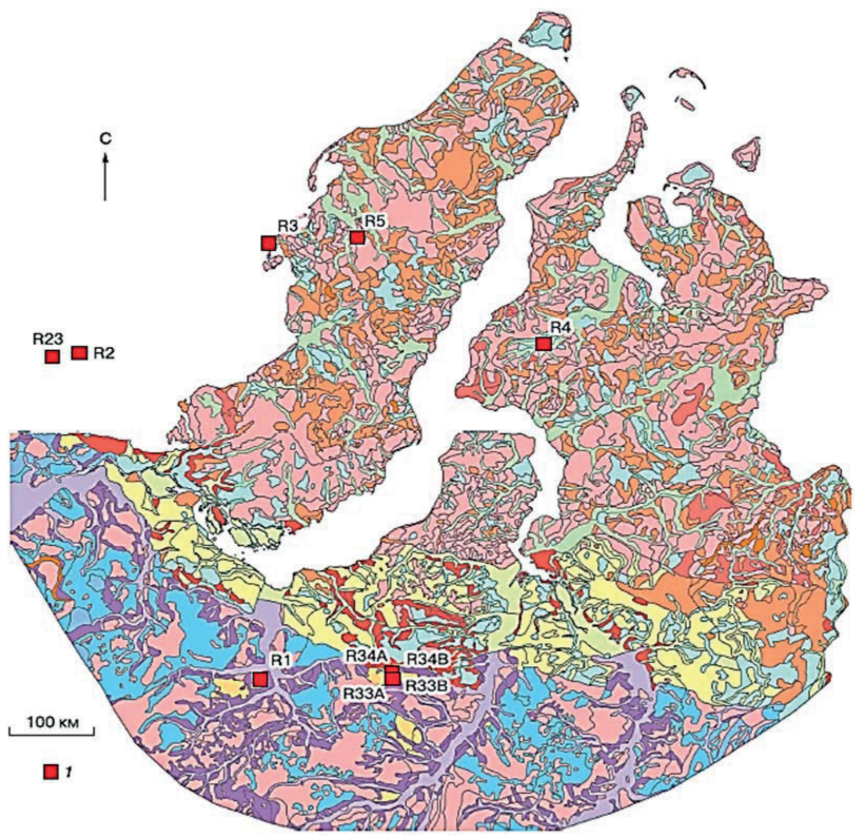

Figure 3. Study Area, Map-Layer of West Siberia based on proceedings of the Institute of Earth's Cryosphere Russian Academy of Sciences, and the location of the CALM monitoring sites (1) in the region

annual air temperature by 1.5 °C could lead to the destruction of almost all foundations in this city.

The purpose of our study was to assess the change in the bearing capacity of soil in the foundations of buildings and structures under the influence of warming climate in the northwestern of Siberia (Figure 3). It was assumed that the bearing capacity of the soil of the foundations of buildings and structures built over the past twenty years was calculated on the basis of climatic averages during the 1960-1990. Within the framework of this goal a number of tasks were set: a) analysis and comparison of widely used climate data on a regional scale; b) creation of a model for calculating the temperature of long-term permafrost and capacity of the active layer, taking into account the physical-geographical features of the region; c) development of a model for calculating the bearing capacity of the foundations of buildings and structures constructed according to the first principle, in a changing climate.

2. Methods and Materials

2.1. Analysis and comparison of climate data of the north of western Siberia

The Arctic as a whole and the north of West Siberia in particular are characterized by a relatively limited network of weather stations. At the same time, any regional climate assessments require knowledge of the climatic characteristics in each domain of the region, adequate to the scale of the work being done. This problem can be solved by interpolating the climatic data to a regular geographic grid, i.e., a grid with a given step. The use of different methods of interpolation and verification of results inevitably leads to differences between the climate fields produced by different authors. Therefore, comparison of climatic data is a necessary condition for modeling permafrost characteristics in the region.

To analyze the climate fields in the area of the north of western Siberia, four widely used climate models were used: Willmott and Matsuura University of Delaware (W&M), UK Climate Research Unit (CRU), the European Center for Medium-Range Weather Forecast 40-year Re-Analysis (ERA40), National Center for Environmental Prediction National Center for Atmospheric Research (NCEP). Each of the four climatic bases contains monthly data on air temperature and the intensity of precipitation on the EASE-grid with a step of 25 km. The boundaries of the north of Western Siberia were adopted as 63-74 ° N. and 63-87 ° E, which corresponds to an area of about 1 million km2. Comparison of the four databases for the region showed that the average annual air temperature here is -6.8 ... -7.5 °C. The average annual temperature calculated by CRU and ERA40 is 0.5 °C higher than W&M and NCEP. This indicates a good coherence of climatic databases in Western Siberia (in the Arctic as a whole, this figure is about 1 °C). However, seasonal differences are most noticeable in the spring and autumn seasons. In winter, W&M and NCEP show the lowest and the highest temperature, respectively. In the spring, W&M values are much lower than the rest of the archives. Summer temperatures are consistent with CRU and ERA40, while W&M and especially NCEP are significantly low. The NCEP model shows lower temperature in autumn by almost 2 °C. The annual rainfall in the region varies from 426 to 564 mm, depending on the database. For the winter season, there is 14-20% of precipitation, for spring 18-21%, for summer 30-40% and for autumn 25-30%. Thus, summer is the wettest season in the north of Western Siberia.

The analysis of temperature trends was limited to the period 1960-2002. Calculations show good consistency between the four databases, all of which point to climate warming in the region. The most significant trend of warming refers to the winter and spring periods, with a slight positive trend in the summer and no trend in the fall (Figure 4).

It is established that for the time estimates of permafrost characteristics the choice of a particular archive is not fundamental, at the same time, absolute values for different archives will be insignificantly different. It is received, that the W&M database is the most "cold", and ERA40 - the most "warm". Accordingly, for conservative estimates, ERA40 seems to be the most profitable database, since the calculated depths of the active layer and permafrost temperatures obtained by it will be overestimated, which will lead to underestimated values of the bearing capacity of the foundations of structures.

2.2. Calculation of temperature of long-term permafrost and depth of active layer considering physiographical features of the region

Despite the rather large volume of accumulated field data on the permafrost characteristics of Western Siberia, regional estimates of these characteristics are heterogeneous and limited,

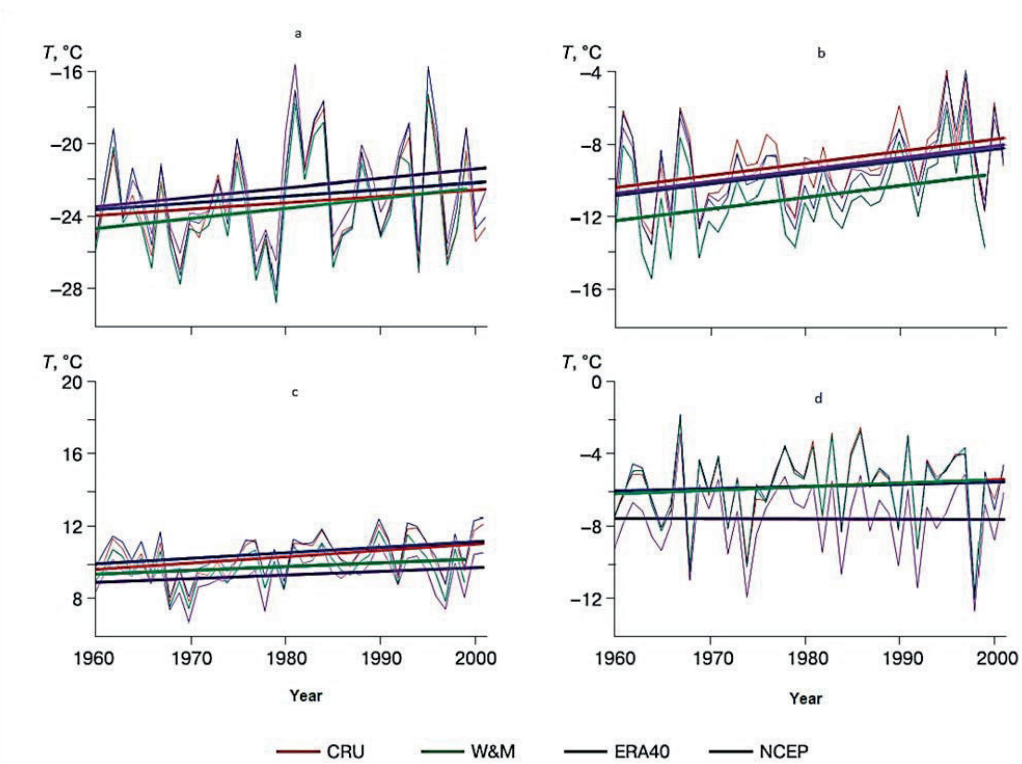

Figure 4. Seasonal changes in air temperature in the north of Western Siberia, calculated on four databases for 1960-2002. (After 2002 there is no data on ERA40): a-winter, b-spring, c-summer, d-autumn.

primarily, by the volume of large-scale field works carried out. In this context, it is very important to model permafrost characteristics for more accessible climatic databases. Geological, geomorphological and landscape maps can provide the minimum possible, but necessary information on soil and its characteristics.

A fairly simple method is the analytical solution of the heat equation for a moving boundary of phase transitions (the so-called Stefan condition), which has found application not only in engineering calculations, but also in a number of fundamental scientific studies. For modern regional permafrost estimates, the modified equations developed by Kudryavtsev et al. (1974). The dependencies obtained take into account the variability of the geological and geographic situation, which together with the use of GIS technologies makes it possible to produce regional small-scale estimates of some geocryological parameters, primarily the average annual temperature at the long-term permafrost roof and the active layer power.

In this paper, a model is used, described in detail in Streletskiy research (2010). This model is based on the equations developed by Kudryavtsev et al. (1974), with additions to the influence of the peat horizon (Anisimov and Nelson, 1997), the volumetric content of peat on the soil (Streletskiy, 2010) and the heat fluxes in the soil-snow system (Sazonova and Romanovsky, 2003).

The results of the simulation were verified by a series of monitoring sites for the Circum- lar monitoring of the active layer (CALM site: www.udel.edu/Geography/calm) in Western Siberia and Alaska (USA). Extremely warm (cold) years lead to overestimated (underestimated) model values of the temperature of long term permafrost and active layer. At the same time, the averaging of the data over a long period eliminates these differences. Therefore, the results showed very good convergence of data on a time scale of more than five years, which corresponds to the task.

"Map of the seasonal layer of Western Siberia", prepared on the basis of the materials of the Russia Akademgorodok ICS SB RAS, used as a basis for verifying model results on a smaller scale (see Figure 3). For this, the vector map "Landscapes of Western Siberia" was translated into a raster format with a resolution of 1 km^2. This scale was chosen as the most appropriate dimension of the landscape level of mapping (Melnikov *et al.,* 1983). Required characteristics for the model, such as soil density, ice capacity, peat thickness and others were taken by Trofimov and Vasil'chuk Yu (1987), and Melnikov *et al.* (1983). When the values of soil characteristics were absence, the soil was taken as an appropriate loam with a density of 1400 kg/m^3.

To assess the changes in permafrost characteristics, the model used data for the periods 1960-1990 and 1990-2010. For each period, the climatic values of the depth of active layer and the average annual temperature of the upper permafrost were calculated.

2.3. Calculation of bearing capacity of soils foundations of buildings and structures built-up by the first principle

The power of the active layer and the temperature of the long term permafrost in the zone of engineering development are the most important characteristics when calculating the bearing capacity of soils' foundation and structure. An analysis of the effect of natural conditions on the forces of freezing frozen soil and foundations in different permafrost geological and geographic conditions was performed for a standard indicator probe, adopted for a kind of "stamp", through which the quantitative parameters of the nature of the freezing in different regions of the cryolithozone are monitored. The fulfilled spatial analysis allows defining more clearly cryolithological factors influencing the character of the freezing. Calculation of the bearing capacity of foundations and structures was made for a standard reinforced concrete pile with a section of 35 × 35 cm and a length of 10 m SNiP 2.02.04-88 (1979), such a pile size was most widely used in 1970-2000. In the north of western Siberia to optimize the process, the Fortran software environment was used.

The bearing capacity was determined according to SNiP (1990):

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

where γ_t is the temperature coefficient taking into account the change in the temperature of soils foundation during the construction and operation of the structure; γ_t = 1, 1 for low-temperature soils (-3 °C and below); γ_t = 1, 0 for other soils; γ_c is coefficient of soil conditions; R is the calculated pressure on the frozen soil below the lower end of the pile, kPa (kgf/cm^2), determined experimentally or according to Table 1 soil temperature (SNiP, 1990); A is the area of pile support on the soil in m^2 (cm^2), taken for solid piles with an equal area of their cross-section (or area of broadening); $R_{af,i}$ is resistance of frozen soil or ground solution to shear along the side surface of basement freezing within the ith soil layer, kPa (kgf /cm^2), determined experimentally or according to SNiP (1990), T_z at the depth of the ith layer; $A_{af,i}$ is the surface area of the surface of the ith layer of soil with the lateral surface of the pile in m^2 (cm^2); n is the number of permafrost soils identified during the calculation.

The distribution of temperature over the depth of pile laying is not stationary (seasonal fluctuations are affected), but in the presence of trends towards an increase in surface temperature (climate warming) is changing towards higher values and the temperature is at the same level depth of zero annual fluctuations, which is not taken into account in traditional calculations using the methodology of national standards, for example in SNiP (1990). Thus, the use of temperature on the upper long term permafrost, instead of the temperature at the depth of pile, gives a slightly understated, but at the same time, conservative value of the bearing capacity. The large amplitude of the oscillations at the depth of the upper permafrost, in comparison with the depth of pile placement, is compensated by an increase in the time series and does not play an important role in long-term assessments.

3. Results and Discussion

3.1. Estimated changes in the bearing capacity of frozen soils for 2010

The analysis of temperature fields over two periods of time showed that the western part of the north of Western Siberia experienced a more serious warming compared to the eastern part. For example, the average annual air temperature on the Yamal Peninsula and the Tazovsky Peninsula increased by 0.8-1.1 °C, and on the Gydan Peninsula, the warming over the same period was 0.1-0.7 °C. In the continental part of the north of Western Siberia, it was from 0.1 °C in the west to 0.8 °C in the east (Figure 5a). The maximum warming is typical for the delta of the river in the southern region of the Tazovsky Peninsula including Tarko-Sale and Urengoy as well as the north of the Yamalo Peninsula and Bely Island.

The bearing capacity of the soils of buildings and structures on average in the region decreased by 17%, and in some areas up to 45% (Figure 5d). Minor changes are due to characteristic of the northern parts of Yamal and Gydan and generally increase from north to south. The decrease in the bearing capacity in the subzone of the arctic tundra was 5-11%, in the northern tundra 9-13%, in southern tundra 12-25%. The multiple increases in the landscape diversity during the transition from the tundra to the forest are reflected in changes in the bearing capacity of the structures' foundations, which ranged from 12 to 45%. The districts of Salekhard, Nadym and Novy Urengoy are characterized by a decrease about 15-25% of bearing ability on the soil. A more favorable situation was

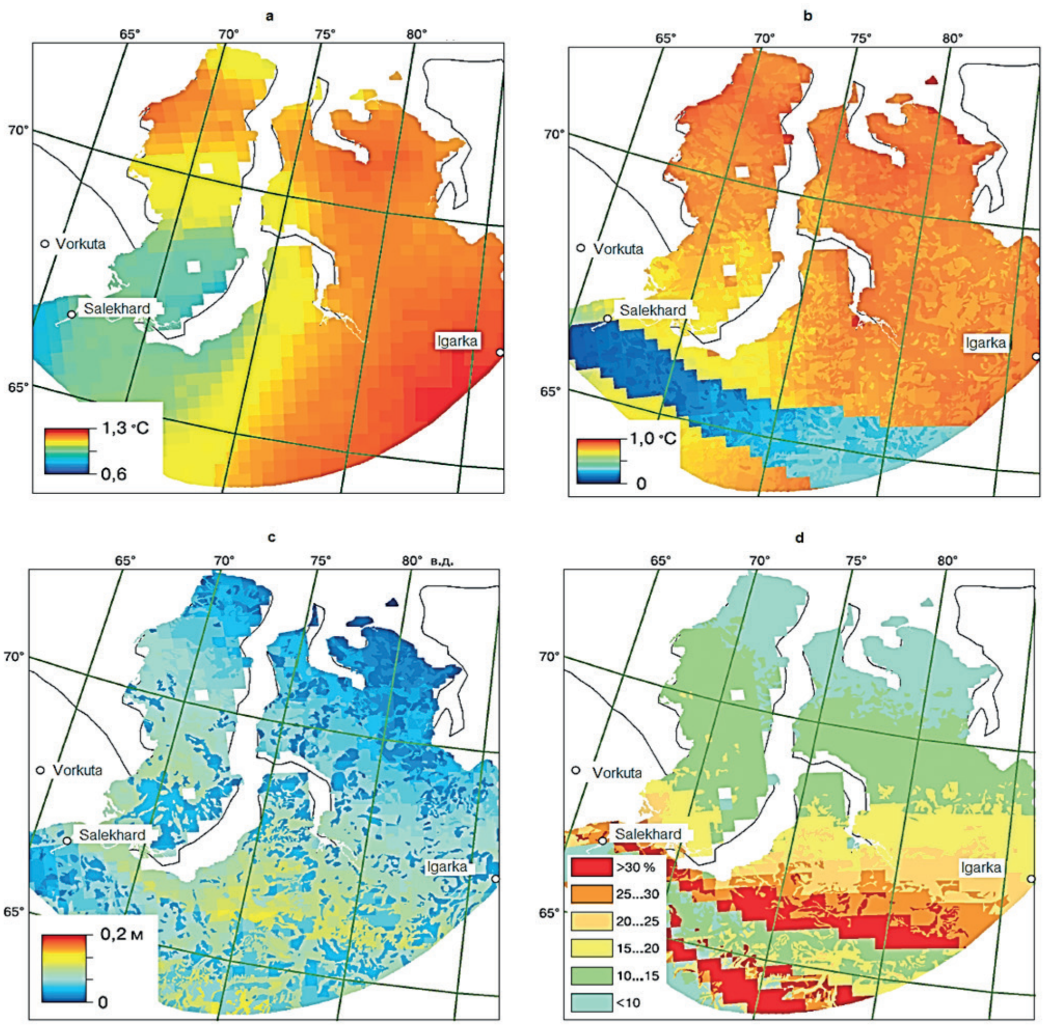

Figure 5. Change in permafrost characteristics (a-c) and bearing capacity of the foundations of structures (d) for 1990-2010. In comparison with the climatic change during 1960-1990: a) is the average annual air temperature; b) average annual temperature of the upper boundary of the permafrost; c) seasonal layer.

observed in the settlements located along the banks of the Yenisei River - in the districts of Igarka and Dudinka (10-15%), as well as in the Vankor oil and gas condensate field. However, field surveys carried out in July-August 2010 showed that more than 80% of buildings and structures were deformed in Igarka, about 35% in the cities of Norilsk industrial area, 3.5 times higher than the figures given by Kronik (2001) for the late 1990s. Analysis of the data of field observations and the dynamics of the temperature fields formed in the base soils showed that more than two thirds of the deformations of objects in these cities are due to the warming of the permafrost: an increase in the depths of the zone thawing (and thus a decrease in the surface of the frozen previously installed piles), the formation of local taliks, an increase in the temperature of soils along the depth of the frozen-in foundation, and the activation of cryogenic weathering of reinforced concrete piles in the increased active layer.

3.2. Estimated changes in the bearing capacity of frozen soils by 2050

Estimation of changes in the bearing capacity of frozen soils by 2050, i.e., during the period of construction and operation of new oil, gas and condensate deposits of the region can be performed only approximately, because such estimations are based on local climate models. These local climate models, firstly, are not developed for Western Siberia; secondly, they are based on scenarios of a continuous increase in the content of CO_2 in the atmosphere. This leads to the fact that model climate estimates give clearly overestimated rates of warming. For example, well-known models predict an

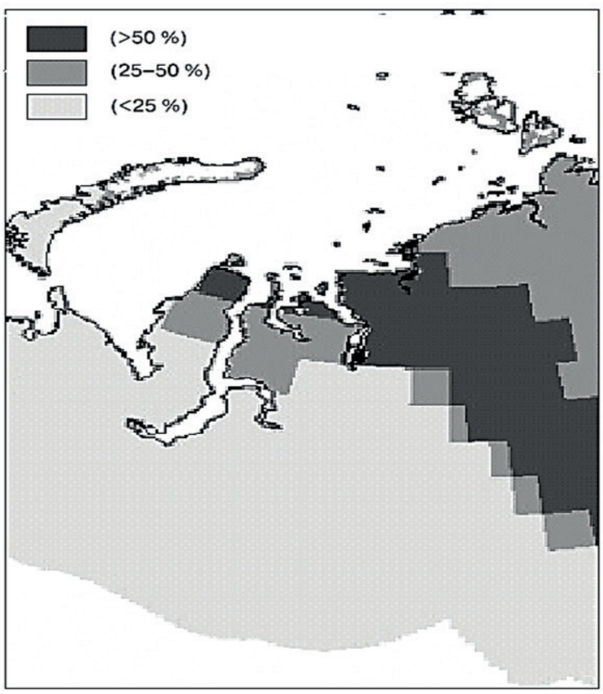

Figure 6. Estimation of the reduction in the bearing capacity of the structures' foundations of by the middle of the 21st century, based on the NCAR CCSM3 climatic model

increase in the average annual air temperature for northern Yamal by about 4-6 ° C, which is a clear exaggeration. Nevertheless, this approach remains the only one for assessing climatic indices and the changes caused by them in the bearing capacity of frozen soils. Figure 6 shows the distribution of the bearing capacity of frozen soils by 2050 compared with 2010. The calculation is based on the scenario A1B of the climate model NCAR CCSM3 with a horizontal resolution of 1.40 ° (Kluzek *et al.,* 1996). Taking into account the critical remarks made to the peculiarities of models, one can speak only about the qualitative spatial distribution of the bearing capacity.

Conclusions

Within the framework of the goal, a method for rapid assessment of geocryological and engineering conditions under climate variations in the north of Western Siberia was developed. The presented method is based on the application of GIS technologies and climate modeling, which integrate field research data, permafrost and landscape maps, as well as climate databases. An integrated data array is used in modeling when calculating the permafrost characteristics and bearing capacity of the foundation of structures. The obtained results indicate an increase in the air temperature in the region, which caused an increase in the temperature of the permafrost and an increase in the active layer, which led to a virtually universal reduction in the bearing capacity of the foundations of the structures. The greatest changes in this regard touched the southern part of the permafrost zone of Western Siberia. In some areas, the reduction in bearing capacity is already outside the limits of the reserve factors adopted in the construction. The situation is aggravated by the intensive man-made weathering of the permafrost soils of the grounds, especially in settlements with developed urban infrastructure, as well as on pipeline routes.

New buildings and structures should be built taking into account medium-term climate forecasts, while monitoring of the existing infrastructure and rapid adoption of engineering solutions aimed at maintaining the temperature of the long term permafrost is mandatory. At present, only qualitative assessments of climatic changes and the dangerous geological processes caused by them and the reduction of the bearing capacity of frozen soils are possible. It is necessary to develop local climate models and scenarios of possible climate changes. On this basis, it is possible to obtain reliable estimates of the change in the geocryological conditions of the permafrost zone of the north of Western Siberia.

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