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CHANGES IN THE BACKGROUND PERMAFROST TEMPERATURE IN YAKUTSK DURING CURRENT PERIOD OF CLIMATE WARMING IN SIBERIA (1976–2011)

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This paper presents results of the statistical analysis of borehole temperatures data obtained in Yakutsk during the observed global warming period (1976–2011) against the period with no warming (1930–1940). A comparative analysis of the data sets revealed climate warming effects on the background temperatures of permafrost as a 4.0 °C increase at the depths of 10–15 m in the downtown area and a 1.2 °C increase in the suburbs, at a rate of 0.056 and 0.017 °C/year, respectively. The difference in the temperature rise is attributed to different inputs of some anthropogenic factors that control ground surface shadowing and cooling. Despite the persistent climate warming which began in the mid-1960s, the permafrost temperatures did not reach critically high values (–0.1 to –0.5 °C) at a depth of 10–15 m in the period between 1976 and 2011 and varied from –1.0 to –6.0 °C with 80–85 % probability for Yakutsk. These temperatures are sufficiently low for foundation soils composed of ice-poor, non-saline sands at the pile embedment depth, to maintain their mechanical strength.

Yakutsk, borehole temperature measurements, permafrost, temperature, background values, climate warming, probability

INTRODUCTION

Permafrost strata response to global climate changes has been research focus of many scientists since early days of the permafrost science [*Konishchev, 2009*]. The renewed interest to this phenomenon in the second half of the twentieth century was associated with another global warming activity, when the applied problems of studying the climate warming-induced changes in the thermal state of permanently frozen sediments during their interaction with engineering structures came to the forefront. The purpose of this article is to show climate warming effects on permafrost deposits (henceforward alternatively termed as frozen soils) which serve as bases of pile foundations of engineering structures in Yakutsk. Achieving this goal requires solving several problems of statistical and comparative analyses, using borehole thermometry data obtained before 1930–1940 and during the 1976–2011 climate warming.These data provided a basis for calculation and comparison of the background values of frozen soils temperature within the 10–15 m[1] depth interval (interpreted as the most important for engineering structures construction and operations), which is also the depth of zero annual amplitude layer ZAAL (i.e. the lower part of layer of annual heat exchange cycles), for two major functional parts of the city of Yakutsk designated as the central part and its vicinities.

It is worth mentioning that although the term "background temperature value" is often used in Earth Sciences, it has no unambiguous definition. When applied to the temperature field study from the perspective of probability theory and mathematical statistics, this notion does not imply any average value, but only the arithmetic mean of temperatures derived from sufficiently large amount of data whose probability distribution is effectively or theoretically described by a Gaussian (normal) distribution law. Using this definition, the background temperature value, given certain generality and accuracy, is regarded as a selective representative mathematical expectation estimate of the true average temperature value in a general population in reality consisting of a very large number of data (in this case, borehole thermometry data for the area of Yakutsk) and is therefore impracticable.

OBJECT OF RESEARCH

The known historical facts recount that Yakutsk was founded in 1632 by Peter Beketov in the expanded left-bank Lena river valley (indigenous name: Tui-

[1] As a rule, geotechnical boreholes were drill to this depth, inasmuch as it coincides with the pile foundation depth for engineering structures.

maada). The valley stretched between the Tabagin cape (in the south) and Kangalass cape (in the north) to almost 70 km, with its width reaching 11–15 km. From the standpoint of geomorphology, Yakutsk resides on two above-floodplain terraces of Holocene age [*Korzhuev, 1959; Soloviev, 1959; Grinenko et al., 1995*]. The historical and modern city center resides on the 1st terrace (Yakutskaya), while vicinities of the central part on a higher, 2nd terrace (Sergellyakhskaya).

This scheme of geomorphological zoning is traditionally used by geologists. However, results of the studies of alluvial stratigraphy of the Tuimaada valley in greater detail [*Spektor et al., 2008*] indicate that Yakutsk is located on a single high-altitude Dryas-Holocene terrace whose denudation-accumulative surface has a complex microrelief structure and hydrographic network (ox bows, river arrms, lakes).

The floodplain sector of the Tuimaada valley remains largely undeveloped to this day, except two experimental construction sites (housing blocks 202 and 203) using alluvial sands as building pad fill soil. Despite the diversity of geomorphologists' opinions about the Tuimaada valley structure, however, some facts are generally recognized: the thickness of frozen alluvial and lacustrine-boggy deposits increasing in the direction from the Lena riverbed towards the bedrock composed of Jurassic sedimentary rocks (sandstones, siltstones, siltstones) where it outcrops on the day surface[2]. According to the drilling and geophysical data, within the area of Yakutsk, these rocks occur mainly at a depth of 16–23 m.

The thickness of underlying permafrost in Yakutsk is 250–300 m. The temperature in the lower part of layer of zero annual amplitude (ZAAL) at a depth of 10–15 m is extremely variable in the horizontal direction. Thus, ground temperature may change by several degrees within a distance of first tens of meters, which does provide additional challenges in analyzing the frozen soils temperature dynamics across the entire area of Yakutsk. As such, the adversary facing the decision makers both in engineering and management can be hardly caused by natural diversity of heat exchange between frozen soils and the ground surface, but rather by effects of a complex system of engineering structures and utilities (houses, roads, power cable trays, sewers systems, etc.).

According to the data provided by Yakut geotechnical surveys company YakutTISIZ, the structure of the generalized engineering and geological section of Yakutsk includes:

1) *cultural layer* (bricks, lime, manure, sawdust, and other debris of the past and present times) varying from 0.4 to 3.7 m (on average 1.5 m) in thickness; the probability of encountering the layer in the cross-section is 25 %;

2) *layer of clayey soils of varying salinity* (silts and clayey silts), 1.2–4.1 m (on average, 2.6 m) in thickness; the layer occurrence is limited by depths of 0.6–3.2 m; the probability of encountering the layer in the cross-section is 86 %;

3) *layer of dry sands* (zero ice content) with massive cryotexture; its thickness is 8.7–16.2 m (on average 14.7 m); the layer occurrence is delimited by depths of 3.7–18.4 m. The layer may contain slightly saline silty sands with inclusions of plant residues and detritus, as well as fine-grained dominantly non-saline sands rarely interspersed with plant residues (probability: 31 and 37 %), while non-saline pure (with no organic admixtures) and homogeneous medium- to coarse-grained sands are encountered with probability of 92 and 70 %, respectively;

4) *layer of coarse-grained soils* (gravel and pebbles): its thickness is from 0.7 to 4.2 m (on average 2.7 m); the occurrence depth is 17.3–20.0 m; the probability of its encountering in the cross-section is 100 %;

5) *layer of sedimentary bedrocks*: depth of the layer limits is 11.0–28.9 m, averaging 21.5 m; the probability of encountering the layer in the cross-section is 100 %.

Thus, starting from a depth of about 4 m, pile foundations of engineering structures in Yakutsk are dominantly based on a solid lithogenic base – non-icy and non-saline medium-coarse grained frozen sands.

Let's briefly outline the history of construction in Yakutsk. Back in 1911, the first brick house was built with crawl space foundation design which incorporated ribbon footers by the project of architect K.A. Leshevich. After that, other houses were built on foundations of the same type, however using rubble stone instead of brick. The successful construction of a thermal power plant by the *Yakutstroy Building Trust* in 1936 has given impetus to construction of houses on piles with concrete shoes deepened into the ground to the permafrost table depth (not deeper than 3 m). A subsequent technological breakthrough (in terms of efficiency and reliability) in the mid-1970s was the mass construction of stone houses in the NE part of the Arctic and subarctic zones of Russia (Norilsk, Vorkuta, and Igarka).The pile foundation used in the construction technology was installed by drilling into permafrost (frozen ground or dispersed soils) [*Rastegaev et al., 2009*]. In Yakutsk, the pile end was driven into the lower part of ZAAL (zone of thermal quiescence), mainly to a depth of 10–15 m, the interval, except in rare cases, is characterized by occurrence of coherent, hard-frozen, non-icy, non-saline sands.

[2] In the form of erosional bench of the Lena plateau with a height of 100–120 m above the Tuimaada valley.

FACTUAL MATERIAL

The data pool was collected in the YakutTISIZ archive[3] primarily from geotechnical surveys reports performed for 282 construction and operation sites of engineering structures during the period of 1976–2011.

The material contains borehole temperature measurements for 1123 wells with single measurements in different places of Yakutsk and at different times the temperature of frozen soils measured in the lower part of ZAAL at a depth of 10–15 m (t_{10-15}), the depth, as mentioned above, to which pile foundations of engineering structures were most often installed.

Until the 1980s, borehole temperatures were measured in Yakutsk using exhaust mercury-filled thermometers[4] accurate to about 0.1 °C, which was succeeded by a more accurate, environmentally friendly and practical method consisting in conversion of the electrical resistivity values of semiconductor sensors (thermistors) into temperature values according to calibration tables which were readily available on the computer for each thermistor. The thermistor calibration technology was developed at Melnikov Permafrost Institute of the Siberian Branch Russian Academy of Sciences [*Balobaev et al., 1985*] for regional geothermy of deep wells drilled in permafrost, and measuring borehole temperature (to an accuracy of 0.01 °C). Presently, thermistor resistance measurements are automatically converted into temperature values using loggers at the same or lesser accuracy, with subsequent recording of results in the computer memory. The procedure and works performed during borehole thermometry were generally based on direct temperature measurement with mercury thermometers or indirect temperature estimation from thermistor resistance in compliance with the rules and requirements of Working document GOST 25358-2012 [*2013*].

Locations of single temperature measurements t_{10-15} in clusters of 3–5 or more boreholes drilled in 1976–2011 in the objects of geotechnical surveys in Yakutsk are shown in Fig. 1. Despite the uneven distribution, the areas of investigations involving borehole thermometry cover the entire area of Yakutsk bracketed between the floodplain (named Zelyonyi

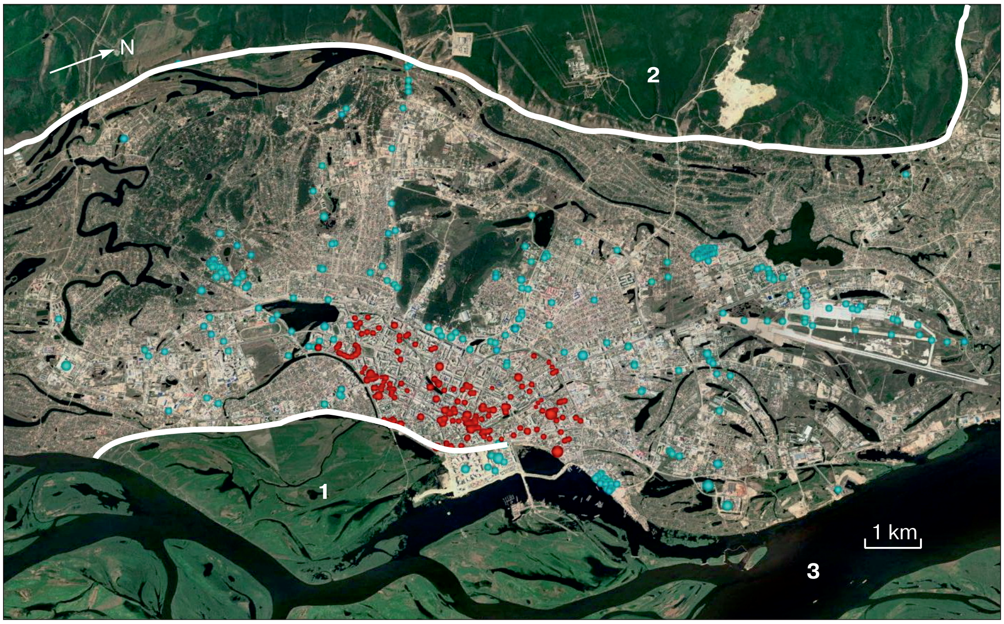


Fig. 1. Location of objects of the 1976–2011 geotechnical surveys involving borehole thermometry for the central part (*red dots*) and the vicinities (*blue dots*) of Yakutsk.

1 – Zelyony Lug floodplain; 2 – high bank of Lena plateau; 3 – Lena River and its arms.

[3] YakutTISIZ was the main organization of "Stroyizyskaniya" with Gosstroy of the RSFSR for most of the 20th century and performed geotecnical surveys in the area of Yakutia. The YakutTISIZ archive held a huge amount of engineering-geological and other valuable information, including borehole thermometry data for the city of Yakutsk. At the end of 2014 YakutTISIZ was declared bankrupt and ceased its operations. Unfortunately, present location of the archive remains unknown.

[4] The thermometers are placed in a duralumin casing, sealed with compressed shavings from wine corks. The top and bottom of the thermometers were filled with liquid wax. This design strongly amplified thermal inertia of the thermometer and allowed measuring the temperature without fear that it will change considerably while the thermometer is being removed from the borehole.

Lug) and the high bank of Lena valley. The survey objects distribution over the entire area of Yakutsk allowed to perform a correct statistical analysis of the area temperature variability (t_{10-15}), taking into account all possible combinations of the construction and operation conditions of engineering structures over the period of 1976–2011.

Uneven distribution of the collected data (Fig. 2) is a drawback which is almost impossible to eliminate, since it was caused by objective factors and, in part, by subjective reasons hindering accumulation of the data pool in the YakutTISIZ archive. Objective factors may turn out advantageous as those related to the years of 1987–1999 and 2005–2010, when the volume of geotechnical surveys involving drilling operations and borehole thermometry was unexpectedly very large in Yakutsk.

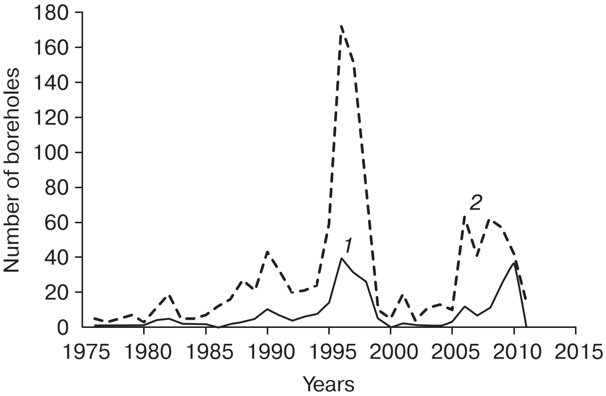


Fig. 2. Time-dependent changes in the number of objects (*1*) of geotechnical surveys and the number of boreholes (*2*) for single thermometric measurements at these objects.

AIR TEMPERATURE ANALYSIS

The analysis was performed for the average annual surface air temperature (t_w) during the mid-century climate warming in Yakutsk [*Skachkov, 2000*]. Since that time, the interannual variability of (t_w) has been tending to increase which is approximated by linear regression equations (linear trends). Results of the time series of (t_w) values [*Weather and Climate Data portal, 2020*], smoothed by the robust Huber estimator method with implementation of Epanechnikov kernel[5] revealed several stages of the climate warming process evolution in Yakutsk with different growth rates (linear trend coefficients) t_w and a measure of determination (multiple correlation coefficients). These are: *inception stage* (1965–1975) – growth rate 0.045 °C/year, temperature from –10.5 to –10.0 °C; *second stage* (1975–1990) – growth rate 0.082 °C/year, temperature from –10.0 to –8.9 °C; *third stage* (1990–2000) – growth rate 0.033 °C/year and a slight change in temperature –8.9... –8.6 °C; *fourth stage* (2000–2009) – growth rate 0.091 °C/year, temperature from –8.6 to –7.7 °C; *fifth stage* (2009–2019) – growth rate of 0.064 °C/year, temperature from –7.7 to –7.1 °C.

Thus, the climate warming, which began in 1965, as a process, which developed unevenly, having a pulsating, cyclical pattern with stages alternating on average in 12 years[6] and exerting a greater or lesser thermal impact on frozen soils (permafrost) in Yakutsk. During 26 years (1975–1990 and 2000–2011), the impact was relatively strong and was indirectly expressed by the growth rate of t_w from 0.082 to 0.091 °C/year. During 33 years, the force of the impact decreased essentially (by 42–85 %) with t_w growing at a rate from 0.033 to 0.059 °C/year.

In the period 1976–2011, the weighted average growth of t_w was 0.077 °C/year.

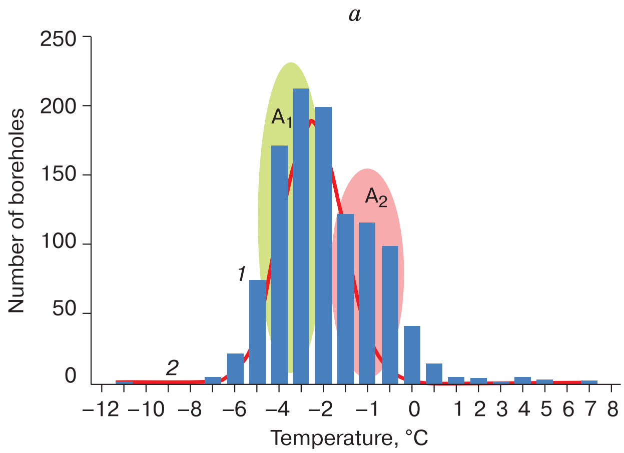
STATISTICAL ANALYSIS OF BOREHOLE THERMOMETRY DATA

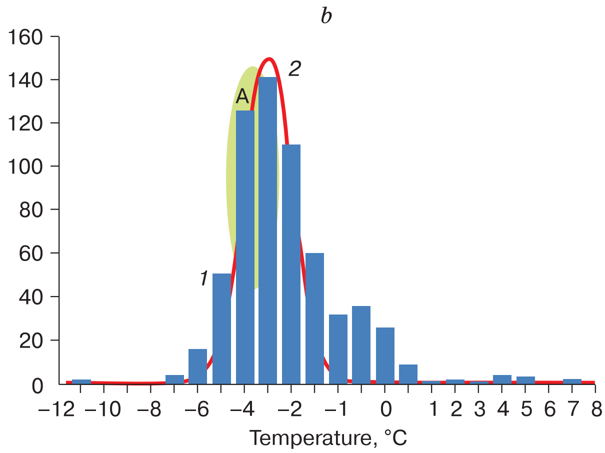
The statistical analysis was conducted to study the law and characteristics of the probability distribution of t_{10-15} values measured in 1976–2011 in whole area of Yakutsk and in its major functional parts (featured by industrial and civil infrastructure), i.e. in the central part and its surroundings. Achieving this goal and solving associated problems required using probability theory and mathematical statistics, coupled with the Microsoft Excel statistical analysis package and the STADIA software [*Kulaichev, 2006*].

Statistical analysis was performed in two steps: first, variability of t_{10-15} over the entire Yakutsk city area was analyzed involving the whole actual material represented by thermometry data from 1123 boreholes; secondly, the actual material was divided into two groups: Group 1 (626 boreholes) for analysis of variability of t_{10-15} was analyzed for the city's central part; Group 2 (497 boreholes) for analysis of variability of t_{10-15} around the city center. In mathematical statistics, such numerical groups are considered as universal and specific sample populations, which are derived from the general population using different schemes, methods and techniques. In a particular case, the general population theoretically represents a very large number of t_{10-15} values at any point in the city of Yakutsk over the entire history of its existence.

The testing based on the three criteria (Kolmogorov, omega-square, chi-square tests) showed that the null hypothesis is not confirmed in the universal and specific sample populations, neither in the whole city of Yakutsk, nor in its central part and its surroundings. Formally, this means that the multi-time probability distribution of t_{10-15} values across

[5] The smoothing of interannual variations of t_w values was performed using the STADIA software [*Kulaichev, 2006*].
[6] Based on the Fourier spectral analysis performed using STADIA software [*Kulaichev, 2006*].





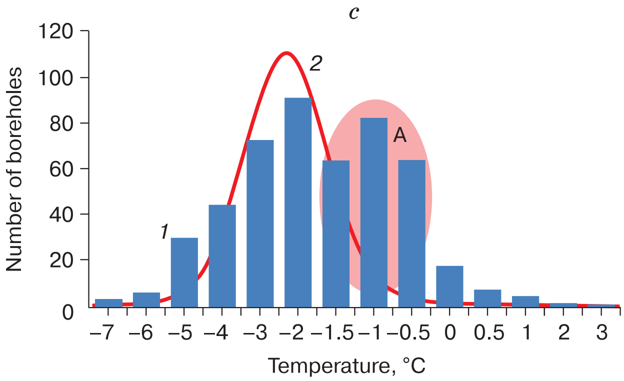


Fig. 3. Actual (*1*) and theoretical variograms (*2*) of the probability distribution of frozen ground temperature values at a depth of 10–15 m:

a – in Yakutsk in a total sample of 1123 thermometric boreholes, A_1, A_2 – low-and high-temperature anomalies, respectively; *b* – in the central part of Yakutsk in a disparate sample of 626 boreholes, A – low-temperature anomaly; *c* – in the vicinities of Yakutsk in disparate sample of a total of 497 wells, A – high-temperature anomaly.

the area of Yakutsk cannot be exactly described by a normal (Gaussian) law. However, it does not follow that the actual material completely lacks the probability distribution of t_{10-15}values formed in accordance with this fundamental law, which explicitly or implicitly exists as a substrate in any uneven distribution of any physical quantity. With regard to the actual material under consideration, the normal law describes the probability distribution of t_{10-15} values as symmetric graphs of theoretical variograms constructed from universal (Fig. 3, *a*) and particular (Fig. 3, *b*, *c*) sample populations.

Table 1. **Descriptive statistics of the probability distribution of permafrost temperatures at a depth of 10–15 m**

Descriptive characteristics	t_{10-15}, °C		
	Entire city of Yakutsk	Central part	Vicinities
Arithmetic mean (*AR*)	–2.7	–3.0	–2.3
Sandard error of *AR*	0.06	0.08	0.10
Average median	–2.6	–3.2	–2.0
Average modal	–2.3	–4.3	–1.2
Standard deviation	1.8	1.9	1.6
Coefficient of variation, %	68.4	65.3	70.6
Minimum value	–11.9	–11.9	–7.3
Maximum value	6.8	6.8	2.8
Number of boreholes	1123	626	497
AR error (95 %)	±0.108	±0.152	±0.146

Asymmetric graphs of histograms describe the part of the probability distribution of t_{10-15} values that partially violates and weakens the normal law counterbalancing effects of many combinations of multidirectional climatic, permafrost and soil characteristics, anthropogenic and technogenic factors (that are organizationally and technically impossible to control) on the studied temperature field of frozen soils at a depth of 10–15 m.

Geophysical fields (among them the temperature field) of the Earth's are known to include normal (background) and local (anomalous) components. Regarding the material under consideration, the arithmetic mean and modal values t_{10-15} (Table 1), which accordingly display the maxima at variograms and histograms, characterize the background and anomalous components of the temperature field formed in frozen soils at a depth of 10–15 m in Yakutsk during the period 1976–2011.

The anomalous component of the temperature field can be interpreted as a downward or upward trend in the background values of t_{10-15}. As such, the trends for the area of Yakutsk reveal themselves in the general histogram with two maxima on the left and on the right of the variogram maximum (Fig. 3, *a*). Unfortunately, the trend development during climate warming is beyond control and understanding, as well as their timing and place[7].

According to the detailed histogram analysis results, the presence of an anomalous component of the temperature field with a decreasing trend for its background value t_{10-15} to −4.3 °C was revealed in the central part of Yakutsk (Fig. 3, *b*, Table 1). In a statistical sense, this means that among the characteristic values of t_{10-15} distributed according to the normal law (which constitute the general background of the temperature field equal to −3.0 °C), there appears a group of frequently occurring abnormally distributed values concentrated closely near the mean modal value of −4.3 °C. The maximum peak of histogram corresponding to this value ascertains that in the central part of Yakutsk, the bases and foundations of structures at a depth of 10–15 m are most often in a low-temperature frozen state. The same reasoning is applicable to the vicinities of Yakutsk city center with background t_{10-15} values being equal to −2.3 °C, where a clearly expressed peak in the right part of the histogram with an average modal value of −1.2 °C (Fig. 3, *c*, Table 1) is attributed to a growing trend for t_{10-15} values. Here, permafrost is in a state close to high-temperature, which is not the case in the central part of the city.

DISCUSSION OF RESULTS

In the period 1976–2011, t_{10-15} values generally varied from −11.9 to 6.8 °C for the city of Yakutsk and its central part (Table 1). In the vicinities, the spread of t_{10-15} values narrows to −7.3 and 2.8 °C. A smaller spread implies that in the vicinities, where auxiliary industries and services are based, along with suburban settlements, and plots of land, the underlying frozen soils, on the one hand, are less affected by abnormally high man-made heat loads, on the other hand, they have warmer natural temperatures.

A detailed analysis of the probability distribution of t_{10-15} values (sampling rate: 1.0 and 0.5 °C) in the region adjacent to the ice-to-water phase transitions (Table 2) shows that in 1976–2011, the temperature conditions for construction and operation of engineering structures at a depth of 10–15 m varied

Table 2. **Statistical characteristics of temperature conditions of construction and operation of engineering structures in Yakutsk at a depth of 10–15 m in 1976–2011**

Construction and operation conditions	Category of temperature values	Ground temperature, °C	Probability of an encounter of temperature values, %			
			Central part of the city		Vicinities	
Favorable	Very low	−12...−11	0.3		0.0	
		−11...−10	0.0		0.0	
		−10...−9	0.0	**0.9**	0.0	**0.8**
		−9...−8	0.0		0.0	
		−8...−7	0.6		0.8	
	Low	−7...−6	2.6		1.4	
		−6...−5	8.1	**30.8**	6.2	**16.7**
		−5...−4	20.1		9.1	
	Moderate	−4...−3	22.5	**40.1**	14.7	**33.2**
		−3...−2	17.6		18.5	
Admissible	Slightly high	−2.0...−1.5	9.6	**14.7**	12.9	**29.6**
		−1.5...−1.0	5.1		16.7	
Unfavorably critical	Borderline	−1.0...−0.5	5.8	**10.0**	12.9	**16.5**
		−0.5...0.0	4.2		3.6	
Unacceptably hazardous	High	0.0...0.5	1.4		1.6	
		+0.5...+1.0	0.2		1.0	
	Very high	+1...+2	0.3		0.4	
		+2...+3	0.2	**3.5**	0.2	**3.2**
		+3...+4	0.6		0.0	
		+4...+5	0.5		0.0	
		+5...+6	0.0		0.0	
		+6...+7	0.3		0.0	

Note. The conditions relate to construction and operation of engineering structures on the first principle based the preservation of frozen soils at the base of pile foundations.

[7] The actual material used herewith is disparate (with respect to area and time) borehole thermometry data which does not allow constructing a map of the temperature field divided into the background and anomalous components, which would be helpful.

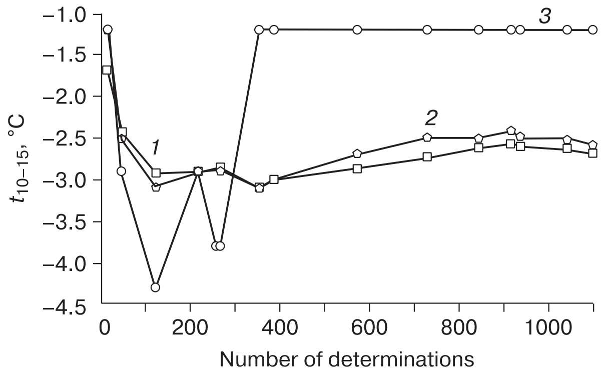


Fig. 4. Probabilistic distribution of sample average values of frozen ground temperature at a depth of 10–15 m (t_{10-15}) in a total sample of 1123 thermometric boreholes in the area of Yakutsk.

1 – arithmetic mean, *2* – median mean, *3* – modal mean.

essentially within the area of Yakutsk. In the central part of Yakutsk and its vicinities, the probability of encountering thawed soils at this depth with the values t_{10-15} = 0.5–7.0 °C is 3.2–3.5 %.

Encountering frozen soils with a very low temperature t_{10-15} = –7.0 °C and below, which was observed in Yakutsk in the 17–19th centuries has become a less frequent event (probability not more than 1 %) in these parts. In the 20th and 21st centuries, low values t_{10-15} = –7.0...–4.0 °C are still found in the central part of the city (*p*-value 30.8 %), and in the vicinities of the city (*p*-value 16.7 %), while moderate values t_{10-15} = –4.0...–2.0 °C are found with higher probability (40.1 and 33.2 %) in these parts of the city. Elevated values t_{10-15} = –2.0...–1.0 °C occur with a probability of 14.7 and 29.6 %. For boundary values t_{10-15} = –1.0...0.0 °C, close to the phase transitions of ice to water in frozen dispersed soils, the probability of an encounter is 9.4 and 15.7 %. In general, as it follows from Table 2, the values t_{10-15} = = –6.0...–1.0 °C are encountered in Yakutsk with *p*-value from 85.5 to 79.5 %.

Thus, despite the felt and documented climate warming, the temperature of frozen soils retained in the period 1976–2011 at the depth of installation of pile foundations was sufficient to continue the construction and operation of engineering structures on the first principle, i.e., with the preservation of permafrost at the base of pile foundations. The case in hand is the temperature at which mechanically strong frozen state of frozen soils is preserved. Without going into detail on this nonetheless important issue, we note that according to the working documents of the state standards [*GOST 25100–2011, 2013*] and building code and regulations [*SP 25.13330.2012, 2012*], frozen sands[8] are sustained in a frozen state at a temperature not higher than –0.1...–0.3 °C.

The sequential analysis-based testing [*Wald, 1960*] showed the sample reliability estimates for the average values of t_{10-15}. Figure 4 shows that the total sample set of 1123 borehole thermometry measurements meets the confidence criterion, according to which the sample estimates of the average values t_{10-15} are either constant or slightly variable in the increasing number of random in time/place repeated samples of thermometric boreholes from a sufficiently large sample set.

In this case, the sample estimates distribution of the average t_{10-15} values acquires the features of stability when the number of thermometric boreholes is >300–350. Beyond this limit, a random change in the sample estimates of the modal mean values t_{10-15} changes dramatically and becomes constant with a value of –1.2 °C. Such specificity, which is rarely observed in the probability distributions of physical quantities, confirms the histogram analysis data for the vicinities of Yakutsk (Fig. 3, *c*).

A different dynamics is observed with the sample estimates of the arithmetic mean and median values t_{10-15} (Fig. 4). While they do not change essentially at small sample sizes, they become asymptotically stabilized at large sample sizes.

The invariance of the average sample estimates of t_{10-15} in the range –2.5...–2.6 °C takes place when the number of thermometric boreholes exceeds 843 in repeated samples. With this amount, according to the law of large numbers [*Paskhaver, 1974*], the sample estimates of the arithmetic mean t_{10-15} are close to the estimate of the mathematical expectation of the average value in the general population for an infinitely large number of boreholes.

The measure of proximity of sample estimates of the mean to the theoretical estimate of the unknown true average can be easily calculated using the well-known formula [*General Theory..., 1974*]. Let's set a 95 % confidence level for solving this problem. With such a high level of confidence and a large number (1123) of thermometric boreholes, the error of sample estimates of the arithmetic mean t_{10-15} for the whole Yakutsk area is ±0.107 °C, while for the central part and its vicinities with the number of boreholes 626 and 497 the errors are ±0.152 and ±0.146 °C, respectively.

In order to understand how much and in what direction the background values of t_{10-15} for Yakutsk have changed during the 1976–2011 climate warming, it is necessary to compare them with similar estimates obtained before the onset of climate warming. The only information appropriate for such comparison is the borehole regime thermometry data ob-

[8] Non-icy and non-saline fine-, medium-to coarse-grained sands. In the vast majority of cases, such sands occur at the depth of the installation of pile foundations of buildings and structures, i.e. 10–15 m.

Table 3. **Comparative analysis of background temperature variability in frozen soils (permafrost) of Yakutsk at a depth of 10–15 m**

Thermometry object	Age of urban development, years	t_{10-15}, °C		Differences in values	
		1930–1940 [*Soloviev, 1958*]	1976–2011 (YakutTISIZ)	°C	%
Central part of the city	200–300	–7.0	–3.0	4.0	80.0
Vicinities of central part	<20	–3.5	–2.3	1.2	41.4

tained in 1930–1940, which was systematized and generalized owing to a fundamental effort made by P.A. Soloviev [*1958*]. Unfortunately, this work, which has already become a bibliographic rarity, does not provide additional information that would be valued for comparative analysis and help bridge existing gaps in the knowledge of past technologies. This includes the type of mercury thermometers used, accuracy of the temperature measurements, number of seasonal cycles included in the monitoring observations of the temperature field, number of boreholes and calculation method[9] used to derive the mean annual temperature values for frozen soils at a depth of 10–15 m.

As such, the uncertainty did not allow to properly compare the 1930–1940 borehole thermometry monitoring data with the single thermometric measurements in 1976–2011. Despite this serious drawback, the comparison procedure was anyway performed. This was justified by the need not only in more extensive borehole thermometry data, but also in reliability and high accuracy of sample estimates of the background t_{10-15} values obtained during 1976–2011, and in more representative estimates of t_{10-15} values collected and analyzed in 1930–1940 by the well-known Russian permafrost scientist P.A. Soloviev. The average annual values of frozen soils (permafrost) temperature obtained from mass-scale measurements during this period are interpreted as background values of the temperature field at a depth of 10–15 m.

The comparison results (Table 3) indicate permafrost response to climate warming at a depth of 10–15 m as an increase in the background values of t_{10-15}. In respect to 1930–1940, these values show an increase both for the central part of Yakutsk (4.0 °C), and for its vicinities (1.2 °C). The growth rate of t_{10-15} background values in these parts of the city in the span of 72 years (1940–2011) was 0.056 and 0.017 °C/year, respectively.

How can we explain the uneven growth of the background temperature t_{10-15} of frozen soils in different parts of Yakutsk which were equally affected by climate warming with a weighted average growth rate of the mean annual temperature of 0.077 °C/year?

The differentiated temperature response is explained by different impacts of some technogenic and anthropogenic factors protecting the day surface of the urban area from the effect of heating by sunlight and thereby cooling the permafrost. I.D. Belokrylov [*Belokrylov, Efimov, 1960*], S.V. Shimanovskii [*1942*], N.I. Saltykov [*1946*], P.I. Melnikov [*1951*], and other researchers studied the extraordinary influence of anthropogenic and technogenic factors capable of lowering the temperature of frozen lacustrine-boggy and alluvial deposits in the city of Yakutsk and in Central Yakut lowland.

Among the anthropogenic factors interpreted as major controls that prime both daytime surface the frozen soils for cooling in the lower part of ZAAL, I.D. Belokrylov and N.I. Saltykov considered the cultural layer, while P.I. Melnikov viewed this phenomenon mainly as the action of salt-containing fecal waters circulating in the active layer. Other scientists provided compelling arguments in favor of other factors, however these somehow were reduced to the conclusion formulated by P.A. Soloviev [*1958*]: "*One of the main factors that contribute to higher cooling of frozen soils in the settlement*[10]*, is most likely the shading, which largely precludes their heating by direct rays of the Sun. Alternatively, this factor is the most universal and is effective in settlements of any type and age*" (*p. 188*).

Given the universality of the shading factor[11] which also acts in natural conditions, P.A. Soloviev concludes that cooling of the day surface is stronger in longer inhabited localities, i.e. this depends on the duration of their development.

Bearing in mind the first principle of construction and operation, i.e. based on the preservation of frozen soil in the bases of engineering structures, the pattern traced there consists in the following. The more buildings and structures in the localities and the closer they are located to each other, the greater the area of shading of the day surface. Therefore, in combination with other factors, the effect of reducing frozen soils temperature in the lower part of ZAAL becomes stronger.

[9] The calculations are likely to have been made using the arithmetic mean method which was common at that time and acknowledged by most permafrost scientists.

[10] i.e. Yakutsk.

[11] It would be more accurate to call the shading factor the shading process, since specifically this notion most fully reflects result of cumulative action (interplay) of natural and man-made factors.

In his work, P.A. Soloviev provided a table showing a correlation between the age of Yakutsk development and the average annual temperature of frozen soils in the lower part of ZAAL at a depth of 10 m (t_{10}) [*Soloviev, 1958, p. 186*].

In 1930–1940, in the then undeveloped city's vicinities the t_{10} value was about –2 °C[12] with no anthropogenic cooling of the earth's surface. In the vicinities of the city center with its development age amounting to 20–30 years in 1940 (the period of development spanned 1910–1920) the anthropogenic cooling caused by the day surface shading from buildings and structures, as well as thermal insulation with a cultural layer, lowered t_{10} to –3...–4 °C. The day surface cooling effect by the anthropogenic process aggravated by influence of other man-made factors essentially lowered t_{10} in the inhabited central part of the city whose age of development was 200–300 years in 1940 (the city development period 1640–1740). In this part of the city, the t_{10} value had become as low as –6...–8 °C by 1930–1940 (Table 3).

In the central part of Yakutsk, the anthropogenically induced process of shading the surface causing therefore a decrease in frozen soils temperature in the lower part of ZAAL which only intensified in the period 1976–2011 due to a multiple growth of the extent of the urban area shading because of the multitude of closely spaced buildings and structures. The permafrost temperature lowering was largely contributed by impact of buildings and structures with ventilated crawl spaces and artificial cooling systems of frozen soils (thermosyphons). The thermal insulation of permafrost provided by the cultural layer also increased with addition of the layer of technogenic deposits whose total thickness has increased by more than 3.7 m[13] on average since 1932 [*Makarov, Torgovkin, 2018*].

All these factors taken together, as well as the forecast for climate warming gradual transition into a long period of cooling, not only in the city of Yakutsk, but also in the whole area of Yakutia [*Balobaev et al., 2009; Neradovskii, Skachkov, 2011*], allow an inference that the temperature t_{10-15} in Yakutsk will not exceed –1 °C, i.e. the borderline (critical) value, beyond which a rapid loss of mechanical strength of frozen sandy soils begins.

This affords an objective reason to expect that within a few decades the foundations of engineering structures will be based on a mechanically strong lithogenic base represented by hard-frozen, non-icy, non-saline sands. Of course, provided that the rules of design and survey investigations are observed and comply with Russian standards and regulations of engineering structures construction and operation on permafrost.

CONCLUSION

Climate warming onset in Yakutsk in 1965 marked by an increase in the average annual surface air temperature t_w, led to an increase in the background temperature of frozen soils in the lower part of zero annual amplitude layer (ZAAL) at a depth of 10–15 m (t_{10-15}). At this depth, within the interval of installation of pile foundations of engineering structures during the 1976–2011 climate warming accompanied by growth rate of t_w values (0.077 °C/year), the background values t_{10-15} in the central part of Yakutsk and its vicinities were equal to –3.0 and –2.3 °C. In comparison with the background values t_{10-15} obtained in 1930–1940 which were –7.0 and 3.5 °C, the growth of the background temperature field of permafrost at a depth of 10–15 m was 4.0 and 1.2 °C with an annual growth rate of 0.056 and 0.017 °C/year. This difference between the central part and vicinities of Yakutsk can be explained by the unequal influence of anthropogenic and technogenic factors controlling the process of shading the day surface from the urban area, thereby decreasing the temperature of frozen soils in the lower part of ZAAL.

The degree of day surface shading depends on the habitation of the urban area and the degree of its development. In the well-developed and densely built-up central part of the city, with development age of 271–371 years (as of 2011), the process of day surface shading transpires most expressly, thereby reducing the background temperature of frozen soils to –4.3 °C in as much as 28 % of the cases. In the less habitable and sparsely built-up neighborhood of the city's central part, whose age is about 100 years (as of 2011), the effect of the day surface shading tends to weaken. The resulting warming trend for an increase in the background temperature of frozen soils to –1.2 °C in 33 %.

Despite the recent climate warming, frozen soils in Yakutsk at a depth of 10–15 m have a temperature of –1...–6 °C with a probability of 80–85 %. Such temperatures are fairly sufficient to maintain the mechanical strength of soils composed of non-icy, non-saline frozen sands at the depth of the installation of pile foundations of buildings and structures.

The anticipated decline in climate warming in Yakutia in the coming years and its transition to a long phase of cooling and favorable temperature conditions at a depth of 10–15 m give hope that the lithogenic base of the frozen foundations of engineering structures in Yakutsk will retain its mechanical strength in the next few decades.

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[12] As compared to this value, the background value of t_{10-15} in the vicinities of Yakutsk has almost not changed (–2.3 °C in 1976–2011).

[13] The exact value for the total thickness in 1976–2011 and currently is unknown.

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