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SPECIFITY OF THE PRESENT-DAY SOIL TEMPERATURE REGIME IN A PEAT PLATEAU (SOUTHERN PART OF BOLSHEZEMELSKAYA TUNDRA) AT LOCATIONS CROSSED BY REGIONAL HIGHWAY

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The study investigates characteristics of the present-day temperature regime of anthropogenically transformed and virgin permafrost-affected soils of the peat plateau at a location crossed by the Usinsk–Khar'yaga higway with its concrete surface partially destroyed. To assess the specifics of soil temperature regime, the research was conducted in 2015–2018 at the southern limit of permafrost in the Bolshezemelskaya tundra during periods of relatively high air temperatures. Soil temperatures of the peat plateau and a roadside hollow were measured in two 10-meter thermal boreholes. To study the temperature dynamics of the road embankment, a 5-meter high sandfill pad with stockpiled sand with fairly similar basic characteristics, was used as its model. Results of the study revealed that construction of a road embankment on the southern permafrost limit in the Russian European Northeast entails a significant temperature differentiation of anthropogenically transformed soils. Violations of building codes and further road operation under ongoing climate warming have led to a significant soil temperature increase and partial destruction of roadbed.

Soil temperature regime, road, peat plateau, climate change, permafrost

INTRODUCTION

Effects of roads and highways on thermal regime of permafrost have been fairly well studied [*Tsytovich, 1973; Ershov, 1988*]. The standards and requirements prescribed in Russian Construction Norms VSN 84-89 [*1990*] are unfailingly observed during geotechnical site investigations prior to and in the course of road construction on permafrost. Nevertheless, the construction and exploitation of causeway (a road built on top of an embankment) entail changes in the natural freeze-thaw regime [*Smith et al., 2005*] and, ultimately, alter topsoils causing their significant horizontal and vertical displacements [*Brown, 1967; Hinkel et al., 2003*]. A decrease in roadbed stability and its degradation is largely prompted by increased temperature in the base soils, thereby triggering their thawing. Analysis of the causeway deformations in the context of high-temperature ("warm") permafrost is highly topical in contemporary engineering and geocryological studies [*Kondratiev, Soboleva, 2009; Drozdov, Shaburov, 2015*].

Climate changes taken place in recent decades have largely contributed to temperature warming in anthropogenically transformed soils leading to activation of the thermokarst processes and, as a result, to roadbed deformation [*Fortier et al., 2011*].

The subarctic zone of the Russian European Northeast with high-temperature permafrost distribution is ranked among the regions wich are most susceptible to climate changes in Russia [*Pavlov, Malkova, 2010*]. Construction of roads of different categories in advance of and during the hydrocarbon field development operations is one of the major anthropogenic impacts on the tundra ecosystems and permafrost in the European North [*Ananyeva (Malkova), 1997; Grebenets, Isakov, 2016*]. In the case of incomplete compliance with the technological requirements for road construction in areas of high-temperature permafrost distribution affected by current climate warming, the processes of roadbed deformation receive additional impetus. Besides, insufficient financing of regional transport infrastructure is often a factor limiting the possibility of the timely road maintenance works which often causes bad road conditions.

Evaluation of the thermal state of roadbed soils in the permafrost regions requires conducting geothermal measurements in adequately equipped boreholes [http://transportrussia.ru/avtomobilnye-dorogi/doroga-na-merzlote.html]. Despite the studies of soil temperature field of the causeway embankments in the Bolshezemelskaya tundra involved modeling, they failed to be corroborated by sufficient field data [*Isakov, 2014*]. The model calculations results revealed the potential for shallow closed taliks to develop at the base of road embankment slopes.

This study aims to analyze specific conditions of the temperature regime differentiation in soils of permafrost peat plateau at a location crossed by causeway embankment with its concrete surface partially destroyed, which is largely caused by effects of recent climate warming at the southern limit of the high-temperature permafrost zone in the Russian European North. We consider the temperature regimes of anthropogenically transformed (roadside hollow and causeway embankment) and undisturbed (virgin) sites (peat plateau).

This research seeks to solve practical problems of roads functioning at the southern permafrost limit with account of impacts they exert on permafrost. Its results are highly topical in present-day geocryological studies and geotechnical site investigations. This work is a continuation of earlier GPR studies conducted in this area which revealed a significant lowering of permafrost table induced by construction and exploitation of highways with solid concrete surface constructed on peat plateau in the southernmost permafrost limit, where permafrost thawing and lowering of permafrost table was detected in a roadside (width: up to 50 m) with the maximum (up to 8 m) reported from a roadside hollows [*Kaverin et al., 2018*].

OBJECTS OF RESEARCH

The study area being part of the Kolva river basin (Nenets Autonomous Okrug) is located on the boundary between the southern tundra and forest tundra (tree-line) characterized by massive-island distribution of permafrost with a thickness of 0–100 m and soil temperatures in the range of +1...–1 °C [*Ershov, 1996*]. The study site is located in the area underlain by permafrost ubiquitously thawing from the surface downward [*Oberman, Shesler, 2009*]. According to the road-climatic zoning scheme

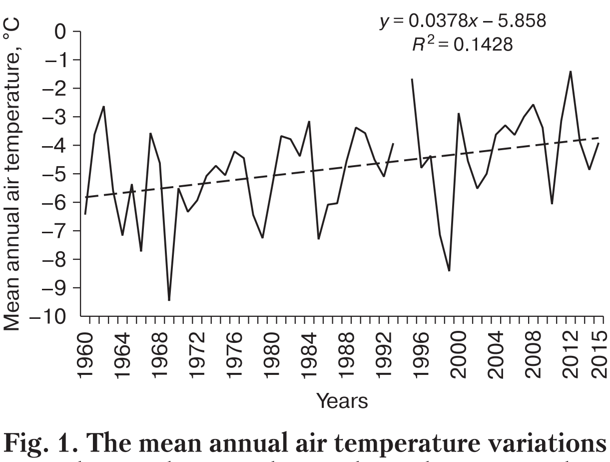

Fig. 1. The mean annual air temperature variations according to the Hoseda-Hard weather station data over the period 1960–2015.

of the cryolithozone, the study site is subsumed into the southern region of high-temperature permafrost-affected soils within the island and partially continuous permafrost distribution [*Davydov, 1979*]. Given that this site belongs to the terrain type 3 of with soils of subsidence categories 3 and 4, it is ranked as particularly complicated in terms of complexity of the permafrost and ground ice conditions [*Construction Norms..., 1990*]. Its microrelief is well expressed, with widely developed bare peat circles, fens and lakes on the surface of peat plateau soils.

The study site is characterized by a moderately continental climate. The mean annual precipitation in the study area was 475 ± 98 mm in the period 2000–2016 (according to the nearby Hoseda-Hard weather station). The mean annual air temperature (MAAT) has increased significantly over the past 50 years which is inferred from its statistically significant ($p < 0.01$) variations (Fig. 1). At this, the MAAT was –5.1 ± 1.5 °C for the so-called background period (1960–1990), whereas in the period 2000–2018 this indicator increased to –3.6 ± 1.2 °C (the Hoseda-Hard weather station data). In the 2017/18 hydrological year, the MAAT for the study site was –1.4 °C according to the measurements of the installed therein digital temperature logger, while sum of degree days of thaw (DDT) was 1156 °C·days, and sum of freezing degree days (FDD) –2067 °C·days.

The soil temperature regime (STR) was studied in 2015–2018 using three boreholes (Fig. 2, Table 1), specifically: boreholes 1 and 2 drilled within a large massif of permafrost peat plateau at a location crossed by the Usinsk-Khar'yaga highway. The peat layer thickness in virgin peat plateau is about 3.5 m

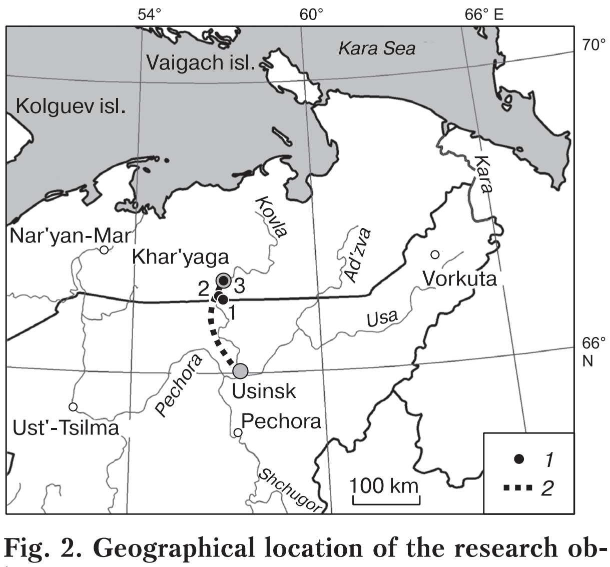

Fig. 2. Geographical location of the research objects.

1 – borehole and its number; *2* – highway.

Table 1. **Characteristics of the research objects**

Borehole number	Topography element	Coordinates	Landscape characteristics	Maximal plant height, cm	Permafrost table depth, m	Average snow cover depth, m	Volumetric water content of the topmost horizon (10 cm) *, %	Name of the soil profile**
1	Peat plateau	67°01′ N, 56°54′ E	Summit of peat mound. Crowberry-grass-moss community (30–40 cm): *Betula nana*, *Ledum* sp., *Rubus chamaemorus*, *Vaccinium vitis-idaea*, *Cladonia*	27 ± 15	0.4	0.2	18	Permafrost-affected oligotrophic peat soil (peat decomposition: 35–40 %)
2	Roadside hollow	67°01′ N, 56°54′ E	Grass-crowberry willow: *Salix glauca*, *Chamerion* sp., *Trifólium* sp., *Equisetum arvense*	65 ± 21	9.0	1.3	35	Embryozem, layered, gleyed, atop sandy-loam infill soils (physical clay content: 12 %)
3	Sandfill pad, an analog of road embankment	67°09′ N, 56°47′ E	Sparse vegetation cover: *Chamerion* sp., *Equisetum arvense*	15 ± 10	3.0–4.0	0.2	10	Sandy infill soils (physical clay content: up to 10 %)

* As of the date: 23.08.2018.
** According to: [*Shishov et al., 2004; Gerasimova et al., 2019*].

(Fig. 3). The road having the status of a regional highway is used primarily by oil production companies for transportation purposes. Presently, it is included in the construction project of the Syktyvkar–Naryan-Mar federal highway [https://regnum.ru/news/2423624.html]. The highway totals 164 km in length, most of which is paved with concrete slabs.

To drill thermal boreholes (boreholes with heat exchangers) 1 and 2 for temperature monitoring the Institute of Biology of Komi Science Centre of the Ural Branch of the Russian Academy of Sciences (IB FRC Komi SC UB RAS) obtained permission No. 4571/07 (25.11.2014) with the “Archangelsk-avtodor”, the Office of the Controller General of the

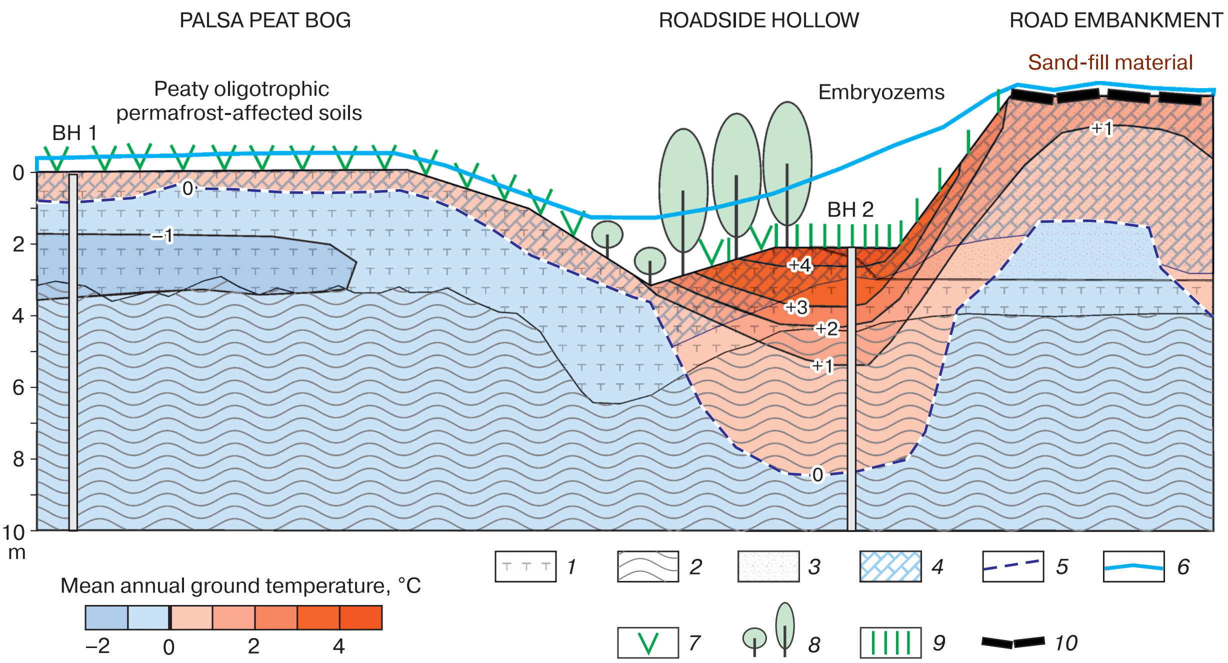

Fig. 3. Complex physical and geographical profile along the “peat plateau – road embankment” line:
1 – peat; *2* – clay loams; *3* – fill material; *4* – active layer; *5* – permafrost table; *6* – snow cover; *7* – moss-lichen-shrub vegetation; *8* – grass-moss willows; *9* – sparse grass vegetation; *10* – concrete slabs.

Arkhangelsk region, for the ongoing scientific projects. Borehole 3 drilled earlier into the body of sandfill pad (Fig. 2, Table 1) was used for temperature measurements within the road embankment thickness (where drilling was prohibited). The 4-meter borehole drilled in the oil field area near Khar'yaga shift camp, 18 km northwest of boreholes 1, 2. The parameters allowing for the sandfill pad to be likened to the Usinsk–Khar'yaga highway embankment are: 5-meter sandy soil layer; sparse (fragmentary) vegetation cover; the absence of topmost organogenic horizon; the snow cover is plowed away in winter. The sandfill pad served as a road embankment model, while the temperature conditions in borehole 3 were taken for the comparative analysis.

Peat plateau (which is a combination of palsa and peat plateau bog) is characterized by the predominance of peat oligotrophic permafrost-affected soils [*Shishov et al., 2004; Field indexing..., 2008*]. Embryozems are widespread in a roadside hollow [*Gerasimova et al., 2019*]. Both the sandfill pad and the road embankment are composed of sand.

RESEACH METHODS USED IN THE STUDY OF SOILS TEMPERATURE REGIME

Soil names and horizon indices are given according to the classification of anthropogenic soils [*Gerasimova et al., 2019*], "Russian Soils Classification and Diagnostics" [*Shishov et al., 2004*], "Field Indexing of Soils in Russia" [*2008*]. The term "soils" used here refers to a unified soil horizon and underlying sediments with total thickness of 2–10 m [*Parmuzin, Karpov, 1994*]. Soil temperature was measured using HOBO U-12-008 digital loggers programmed for 8 measurements per day, with different logger sensors placed at different depths, accordingly: TMC6-HD (depth: 0, 0.2, 0.5, 1.0 m) within the soil profiles; TMC20-HD (depth: 2.0, 3.0, 5.0, and 10.0 m) in the underlying sediments. The logger sensors measuring temperature in the sandfill pad soils were installed at depths of 0, 0.2, 1.0, 2.0, and 3.0 m. The measurement accuracy of HOBO temperature logger sensors is ±0.1 °C. For soil measurements, the logger sensors were mounted on a wooden rod which was placed in a micro-borehole (hole) 2 cm in diameter to a depth of 100 cm. In the case of the underlying sediments, the logger sensors were placed in holes drilled to a depth of 10 m (BH 1, 2) and 3.0 m (BH 3) and fixed by steel tubes 7 cm in diameter, with a steel head attached to the top of each one for placing the temperature logger. The air temperature was measured in 2017–2018 using a HOBO Water Pro digital logger installed 40 m to the west of the borehole 1 at elevation 2 m.

Measurements of the active layer thickness (ALT) (in the third decade of August) and snow cover depth (in the third decade of March) were performed using a graduated metal probe. In August 2018, the volumetric moisture content of the topmost soil horizon (0–10 cm) was determined at the study sites using the HH2 Delta-T hand-held moisture meter with the ML3 Theta Probe sensor (measurement accuracy: up to 0.1 %).

The rate of attenuation of seasonal temperature fluctuations in soils was estimated based on variations of the standard deviation values from the temperature data massifs for different depths. An exponential function written as

$$y = a \exp(bx), \tag{1}$$

and utilized as an approximating function for the changing standard deviation values is a simplified solution of the Fourier's heat conduction equation which is a partial differential equation that describes the change in temperature (T) as a function of time (t) and position (x) [*Polyakova, Kasharin, 2004*]. Here a is the initial value of the standard deviation at a depth of 0 cm, °C; b is the rate of change in the standard deviation values with depth, %/cm; x is the depth of the temperature sensor placement, cm.

RESULTS AND DISCUSSION

Winter soil-temperature regime. Seasonal freezing of the topmost soil horizon begins in October which is associated with the arrival of steady sub-zero temperatures (Fig. 4). Soils of both the peat plateau and sandfill pad are characterized by significant winter freeze-through because of thin snow cover depth (i.e. the snow is blown off from the plateau and plowed away from the sandfill pad). Deep seasonal soil freezing in these sites is largely facilitated by increased thermal conductivity of frozen sediments [*Aleksyutina, Motenko, 2017*] which include: ice-rich permafrost peat horizons (peat plateau) and sandy layer (sandfill pad). The zero or negligibly thin snow cover depth promotes significant winter cooling of road surface soils [*M-Lepage et al., 2012*]. The soils of the sandfill pad are affected by deep winter freezing; furthermore, the seasonal freeze tends to merge with the permafrost at a depth of 3 m.

Soils of the roadside hollow with its thick snow cover (up to 1.5 m and more) differ greatly in winter temperature regime from the soils of other sites. Soils of the roadside hollow freeze very slowly, with negative temperatures reported in late December (depth: 20 cm), and in late January (depth: 50 cm). Near-zero negative temperatures were observed only between February and May at a depth of 100 cm. In general, sub-zero temperatures (0...–2 °C) were recorded in the topmost 1.5-meter soil horizon of the roadside hollow. The underlying sediments horizons are found to be in a permanently unfrozen state within the 1.5–8 m depth interval to the extent that they form a deep closed talik. The zero isotherm in the soils of roadside hollows is significantly lower, than the calculated val-

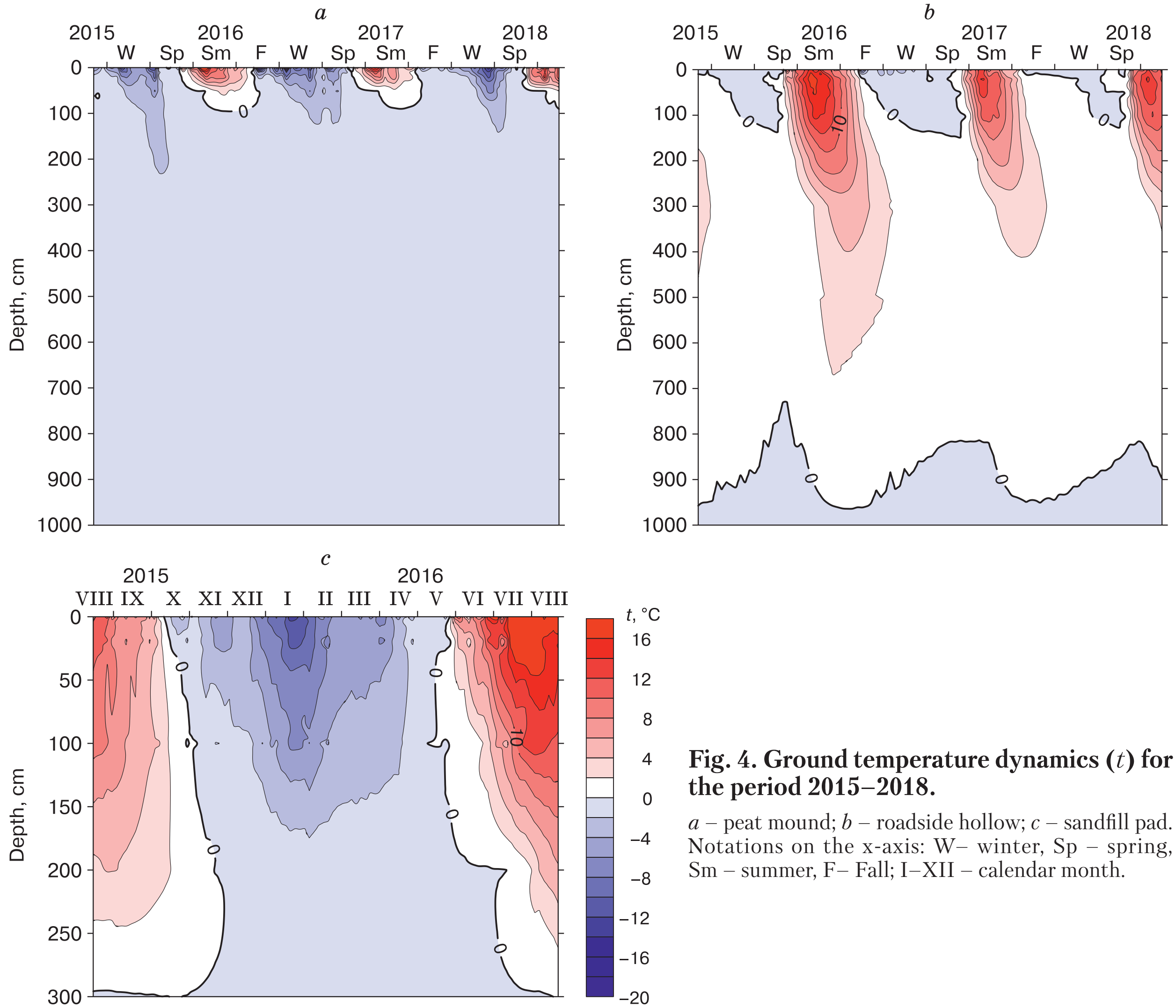

Fig. 4. Ground temperature dynamics (t) for the period 2015–2018.

a – peat mound; *b* – roadside hollow; *c* – sandfill pad. Notations on the x-axis: W– winter, Sp – spring, Sm – summer, F– Fall; I–XII – calendar month.

ues determined for the Bolshezemelskaya tundra area [*Isakov, 2014*]. This stems from underestimated snow accumulation effect in the base of the road embankment and the mitigation of climate conditions in recent decades. Excessive snow accumulation near the road base occurs as a result of blowing and drifting snow activities and snow clearing in the highway. The winter cooling of infill soil thickness of hollows does not compensate for summer warming and results in a significant lowering of permafrost table. The sum of freezing degree days in the topmost soil horizon (depth: 0–1 m) in the peat plateau and in infill material thickness are significantly higher, than in the roadside hollow (Table 2).

The lowest temperatures of seasonally frozen horizons were reported in January–March (depth: 0–50 cm) from peat plateau soils; in March–April (depth: 1–2 m) from the underlying permafrost sediments; in April–June (depth: 3–5 m) (Fig. 4). The temperature minima were observed in January in the topmost soil horizons (0–20 cm) of the roadside hollow embryozems, which tend to shift to February–April at depths of 50–100 cm, while in the underlying sediments (deeper than 1 m) they are usually observed in May. A significant shift in the temperature minima with depth in soils of the roadside hollows is associated with the thermal insulation effect of a thick snow cover. The period of minimum temperatures falls in with January–February on the sandfill pad, across the entire thickness of the investigated soils.

Summer soil-temperature regime. Active seasonal thawing of the studied soils begins in May. Late in May the thawing processes encompass the 20 cm topsoil horizon of the peat plateau, the topmost 50 cm of the sandfill pad, and the uppermost 1-meter horizon of embryozems in the roadside hollow. Unlike during the winter season, soils of roadside hollow and sandfill pad show similarity in the temperature regime during summer. They are characterized by rapid

Table 2. **Main temperature parameters of the studied soils during the hydrological year**

Hydrological year	Parameter	Depth, cm							
		0	20	50	100	200	300	500	1000
1. Peat plateau									
2015/16	*FDD*	−1006	−542	−338	−258	−349	−352	−309	−286
	DDT	1520	731	100	0	0	0	0	0
	T_{yr}	1.4	0.5	−0.7	−0.7	−1.0	−1.0	−0.8	−0.8
2016/17	*FDD*	−1493	−733	−449	−268	−315	−322	−286	−274
	DDT	1583	717	108	0	0	0	0	0
	T_{yr}	0.2	−0.3	−1.1	−0.8	−0.9	−0.9	−0.8	−0.7
2017/18	*FDD*	−1111	−563	−338	−213	−271	−297	−280	−280
	DDT	1355	1126	77	0	0	0	0	0
	T_{yr}	0.7	1.5	−0.7	−0.6	−0.7	−0.8	−0.8	−0.8
2. Roadside hollow									
2015/16	*FDD*	−101	−35	−9	−7	0	0	0	−55
	DDT	1851	1646	1530	1416	1070	632	0	0
	T_{yr}	4.8	4.4	4.2	3.9	2.9	1.7	indefined	−0.2
2016/17	*FDD*	−337	−143	−74	−28	0	0	0	−56
	DDT	1454	1330	1236	1145	1018	755	5	0
	T_{yr}	2.8	3.0	2.9	2.7	2.4	1.8	0.5	−0.2
2017/18	*FDD*	−108	−19	−2	−4	0	0	0	−46
	DDT	1307	1308	1244	1162	892	541	244	0
	T_{yr}	3.3	3.5	3.4	3.2	2.4	1.5	0.7	−0.1
3. Backfilled site									
2015/16	*FDD*	−1097	−942	indefined	−552	−83	−30	indefined	indefined
	DDT	1468	1330	indefined	830	292	0	indefined	indefined
	T_{yr}	1.0	1.1	indefined	0.8	0.6	−0.1	indefined	indefined

N o t e. *FDD* – freezing degree days, °C·day; *DDT* – degree days of thaw, °C·day; T_{yr} – mean annual temperatures, °C.

and deep-propagating summer warming, whereas soils of peat plateau thaw slowly and at a shallow depth (Fig. 4).

On soil surface, the sums of DDT for the studied sites are consistent, while the differences increase significantly with depth (Table 2). Soils of roadside hollow are characterized by maximum sums of DDT (Table 2). Given that the sandfill pad site is warmed up to a lesser degree, the DDT sums sharply decrease with depth towards the permafrost table. The DDT sums in soils largely depend on their lithological composition, the landscape position of the site and the type of soil and vegetation cover [*Bertoldi et al., 2010*].

The highest soil surface temperatures were reported in June–July, with the maximum temperature period shifting with depth (Fig. 4). The temperatures maxima (in the negative range) were observed during December at a depth of 1–3 m in perennially frozen sediments composing the peat plateau, while at a depth of 5 m the period of lowest soil temperatures which is inherently longer, falls on winter months.

The highest temperatures in the 1-meter topsoil horizon of the roadside hollow and sandfill pad were reported in July and August. Soil temperatures in roadside hollow have maxima: in August–September (depth: 2 m) and in September–October (depth: 5 m), while of maximum soil temperature in the sandfill pad more or less persisted within one period (August–September) at a depth of 2–3 m.

The factors that favor the deep warming of the roadside hollow soils include: relatively weak overwinter soil freezing (Table 2); accumulation of soil moisture from highway runoff water (Table 1); coarse texture composition of infill sediments (content of physical clay: 15 ± 2 %); the absence of a pronounced upper organogenic horizon (thickness: 1 cm).

When slope surfaces of the road embankment are exposed to warming, the soils occurring at the bases of road embankments (where the infill soil thickness is minimal) are heated to the maximum [*Isakov, 2014*]. At this, material thawing in the road embankment base will increase the risk of reducing the roadbed stability, thereby causing its nonuniform deformations [*Drozdov, Shaburov, 2015*].

The absence of vegetation cover and upper organogenic horizon, which improves the infill sand drainage, are liable for deeper warming of sandfill pad soils. Alternatively, concrete slabs lying atop the highway provide additional heating to the surface soils of road embankment, as compared to the sandfill

Table 3. **Exponential model parameters describing the depth-dependent standard deviation of temperature**

Site	Coefficient in formula (1)		R^2	F
	a	*b*		
Peat plateau	9.186**	–2.9**	0.992	747.1
Roadside hollow	6.709**	–0.5**	0.984	378.2
Sandfill pad	9.769**	–0.8*	0.977	127.8

* Significance level of the coefficient is at $p < 0.01$.

**At the level of $p < 0.001$.

Note: *a* is initial value of exponential curve, °C; *b* is rate of seasonal temperature fluctuations attenuation with depth, %/cm; R^2 – coefficient of determination (total percentage of variance explained by the model); *F* – the Fischer criteria value of the model consistency.

pad soils. The resulting heat "accumulation" effect in roadside hollows and contrasting temperature regime of road embankments, the permafrost table configuration tends to have W-shape beneath the road.

Deep penetration of thawing during construction of a road embankment occurs in areas where permafrost is preserved mainly on the contours of peat plateau bogs. This is largely accounted for destruction of the soil and vegetation cover of peat plateaus, i.e. violation of the ecosystem's capability to preserve permafrost [*Shur, Jorgenson, 2007*]. As such, these alterations leave the permafrost table "unprotected" against the relatively warm present-day climatic conditions interpreted as unfavorable for the permafrost preservation outside the peat plateau ecosystems.

Annual indicators of soil temperature regime. Statistical analysis indicated that seasonal temperature fluctuations attenuate down the soil profile, reaching zero values within the 2.5–10 m depth interval. The most rapid attenuation of temperature fluctuations is observed in the peat plateau soils, reaching 2.9 %/cm according to model (1), which is 3–5 times faster against soils of anthropogenically transformed sites (Table 3, Fig. 5). As such, the rapid attenuation of temperature fluctuations in peat plateau soils is associated with the presence of thick peat sediments acting as an effective thermal insulator in the warm season [*Ershov, 1988*]. The slowest attenuation of temperature fluctuations in the talik beneath the roadside hollow (Table 3, Fig. 5) is associated with an increase in thermal conductivity of its infill soils. In these conditions, the deep-buried (1.6–3.0 m) peaty horizons fail to function as effective thermal insulator.

Cumulatively, the mean annual ground temperatures (MAGT) in the active layer (AL) of the peat plateau site range between +1.5 and –1.1 °C (Table 2) and typify permafrost-affected soils that develop and function in the southern permafrost zone of the region [*Mazhitova, 2008*], where positive MAGT values in the AL of permafrost-affected soils are indicative of

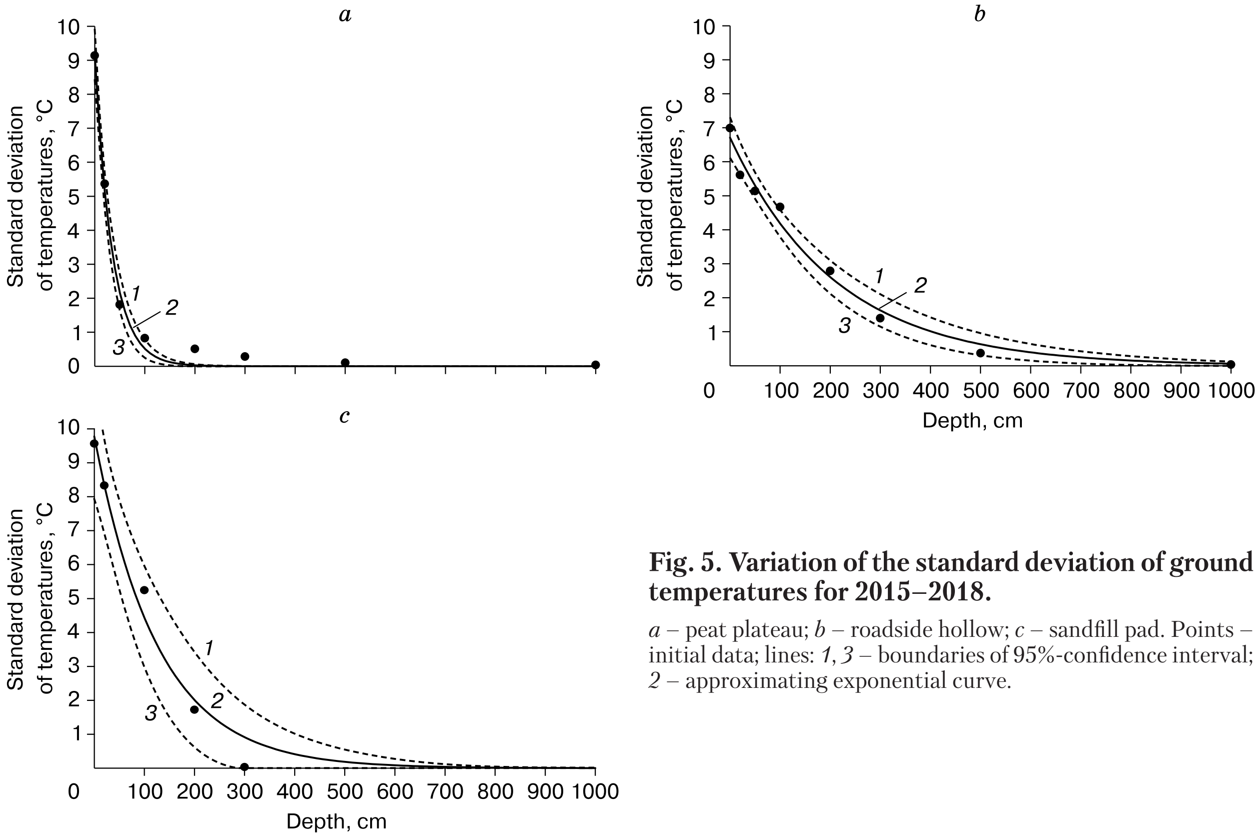

Fig. 5. Variation of the standard deviation of ground temperatures for 2015–2018.

a – peat plateau; *b* – roadside hollow; *c* – sandfill pad. Points – initial data; lines: *1, 3* – boundaries of 95%-confidence interval; *2* – approximating exponential curve.

the processes of permafrost degradation [*Burn, 2004*], and the underlying permafrost is characterized by relatively high MAGT values (–0.6...–1.0 °C). High-temperature permafrost in the southern part of the cryolithzone is highly susceptible to climate warming. According to the GIPL2 regional model developed at the University of Alaska, Fairbanks, by mid of the 21st century, soils with the mean annual temperature of 0...+0.5 °C are anticipated to be prevailing in the study sites [*Stendel et al., 2011*]. Permafrost with average annual temperatures (–0.5...0 °C) in the zero annual amplitude layer will be preserved only in isolated conditions, beneath undisturbed peat plateaus [*Rivkin et al., 2017*].

Soils of the roadside hollow display the highest, mostly positive MAGT (Table 2) prompted by a temperature rise throughout the year. The study area is envisaged to be consumed into the zone of sporadic permafrost distribution in the second half of the 21st century, according to the estimates of the permafrost thaw potential (PTP) concept [*Stendel et al., 2011*]. Given such conditions, permafrost will be completely thawed in the causeway influence zone, while the existing thaw bulbs beneath roads will convert to through taliks. Presently, a similar situation takes place in peat plateaus of the northernmost taiga in the Russian European NE, where permafrost persists in bases of peat mounds (palsas) alone, whereas waterlogged fens are completely thawed [*Kaverin, Pastukhov, 2018*].

According to the mean annual temperature parameters, soils of the sandfill are ranked between the soils of the peat plateau and the roadside hollow (Table 2). Against the backdrop of contrasting annual STR cycle, positive MAGTs of the road embankment suggest that the summer warming tend to outweigh the winter cooling. In the context of natural tundra landscapes, there practically no soils with identical temperature characteristics. Undisturbed deep-buried soils of frozen sand mounds on lakeside terraces display temperature parameters closest to soils composing the sandfill pad. However, seasonal freeze-thaw depth is found to be considerably lower in natural soils (1.0–1.2 m).

The odds are that degradation of the concrete-paved roadbed is associated with nonuniform permafrost thawing and contrasting STR cycle of the road embankment along with the formation of deep high-temperature taliks in roadside hollows. Among other factors liable for roadbed deformations is incomplete removal of peat deposits during road construction. Major deformations of the road surface are expressed at locations crossed by the Usinsk–Khar'yaga highway. The road design must therefore comply with the principle of complete removal of palsa mounds down to the depth of peat layer bottom in the adjacent fens in sites where large palsa mounds occur (height: >1.5 m, diameter: >6 m) [*Construction Norms..., 1990*].

CONCLUSION

Construction and subsequent operations of causeways built on top of an embankment laid across the tundra landscapes in the southern part of the Russian European NE permafrost zone entail a significant differentiation of temperature regime in the anthropogenically transformed soils. The peat plateau soils are characterized by shallow seasonal thawing, rapid attenuation of temperature fluctuations with depth and exposure to low-temperature conditions throughout the year. Results of the studies allow the following inferences: soils of the roadside hollows are characterized by a milder temperature regime during the year (shallow and weak overwinter cooling, deep penetrating considerable summer warming and slow attenuation of temperature fluctuations with depth); soils of the sandfill pad used as a road embankment model are distinguished by a contrasting annual temperature regime, involving both strong cooling in winter and essential warming in summer.

A partial degradation of the concrete road-surface within the studied site of the road embankment built in the Bolshezemelskaya tundra is caused by a combination of factors (anthropogenic, landscape and climatic) leading to nonuniform soil warming and lowering of permafrost table. Incomplete removal of the lower layers of peat deposits at the location of peat plateau crossed by highway has caused soil surface subsidence in the road base. An intensive snow accumulation due to the bush overgrowth and snow cleaning off the road embankment provoked a significant increase in winter soil temperatures in roadside hollows. Summer warming penetrating deep into soils is favored by coarse texture composition and enhanced moisture content of the infill sediments.

In addition, susceptibility of permafrost with near-zero temperatures to ongoing climate warming is exacerbated by anthropogenic disturbances in the subarctic sector of the Russian European NE region.

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