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METHODS OF PERMAFROST STUDIES

ELECTROMAGNETIC INDUCTION SURVEYS FOR THERMAL MONITORING OF PERMAFROST UNDER THE *AMUR* FEDERAL ROAD (CHITA TO KHABAROVSK)

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The applicability of electromagnetic induction (EMI) surveys for thermal monitoring of permafrost beneath operated linear structures is substantiated by theoretical calculations and field experiments along *Amur* motor road. The results support the hypothesis that induction responses of permafrost (active layer and frozen ground) decay with depth at rates correlated with temperatures. The quality of ground temperature estimates inferred from the decay rates of magnetic field components is evaluated by statistical modeling and checked against reference temperature logs. The patterns of correlated temperature and EMI data are regionally consistent and demonstrate that induction decay rates can be used as a proxy of permafrost temperature changes, both in natural ground and in subgrades of roads.

Motor road, soil, subgrade, temperature logging, electromagnetic induction survey, decay rate

INTRODUCTION

Electromagnetic (EM) induction surveys[1] have been used for subsurface studies in Russia since the mid-1920s. Major contribution to the development of the method belongs to A.A. Petrovskiy, V.R. Bursian, V.A. Fok, A.P. Kraev and A.I. Zaborovskiy. Induction resistivity surveys originally were intended for mineral exploration. Among engineering applications, permafrost has been the main focus, which is the subject of the present consideration.

Propagation of electromagnetic waves in the permafrost active layer was first studied in the 1940s near Igarka town using ondometry with circular transmitters and receivers, 50 cm in diameter, at frequencies 300–400 and 800–1000 Hz[2] [*Petrovskiy and Dostovalov, 1947*]. The EM induction (EMI) method has progressed and expanded after a relatively straightforward way to convert the magnetic field parameters to resistivity of rocks was suggested in 1962 [*Veshev et al., 1971*]. EMI dipole profiling at 32, 128, 512, and 2048 kHz with a DEMP-3 system run by the Research and Development Institute of Engineering for Construction (PNIIIS) was used to study geocryological conditions before laying gas pipelines in West Siberia [*Krasovskiy, 1971, 1973*]. In the area of Tiksi town, EMI surveys with a DEMP-2 system provided constraints on the lateral and depth extent of ice-rich permafrost [*Veshev et al., 1971*]. The applicability of the method increased further after medium-frequency instruments were designed in 1991 by *Sibtsvetmetavtomatika* R&D company, which allowed various survey groups to collect large amounts of profiles for temperature monitoring of permafrost foundations in Yakutia and other cold regions. Transient electromagnetic (TEM) soundings[3] were applied to contour taliks and cryopegs and to estimate their thicknesses [*Nim et al., 1994; Stognii, 2003*].

The procedures reported in the cited publications were restricted to mere discrimination between frozen and unfrozen rocks from their responses but left overlooked all intermediate states. Such approach obviously was poorly informative as to the permafrost temperature dynamics, which required the knowledge of correlation between temperature and EM field decay patterns. Research in this line has been undertaken neither in laboratory nor in the field for

[1] Methods for studying the subsurface from induction responses to controlled-source harmonic, stepwise, or pulse electric currents, which are recorded on the surface, in boreholes or in mines.

[2] We used circular antennas of 32 cm in diameter operated at one of four frequencies (281.25, 562.50, 1125, or 2250 kHz).

[3] TEM is an induction resistivity method as well, though it does not measure induction directly. It was designed by Yu.V. Yakubovskiy and F.M. Kamenetskiy et al. from the Moscow Institute of Geological Surveys; instruments and data processing techniques have been developed at the Russian Institute of Procedure and Technology of Exploration (St. Petersburg) since 1960.

the whole history of induction surveys in Russia[4]. The practical use of resistivity methods in this respect was limited to a few cases of permafrost temperatures in the Chukchi Peninsula, first estimated by geocryologists and geophysicists from Lomonosov Moscow University. They applied vertical electric soundings (VES) and DC profiling to estimate (accurate to 16 %) and map the temperatures of frozen ore-bearing soft sediments at the depth of bedrock stripped in mines [*Afanasenko et al., 1991*]. A few years ago, high-resolution resistivity surveys in the Krasnoyarsk region [*Emelyanov and Bondarenko, 2013*][5] were used to obtain the temperatures (accurate to 6 %) and a geothermal cross section of frozen soft sediments and bedrock dolerites in the active layer.

Strong resistivity-temperature correlation in permafrost was revealed in the course of logging in Canada. Thus it was suggested to derive rock temperatures from resistivity logs where conventional temperature logging is hard or impossible [*Seguin, 1978*]. The practically acceptable correlation at $r = 0.6$–0.7 between electrical resistivity and temperature was also obtained for frozen silt and sand in different landscapes of Canada by the surface electrical tomography [*Lewkowicz et al., 2011*].

Since 2006, the temperature dependence of EMI and radar (GPR) decay patterns in permafrost of Yakutia was studied at the Melnikov Institute of Permafrost (Yakutsk). Field experiments confirm the existence of correlation within the active layer. Studies at the Department of geophysics of the Transbaikalian University and at the Transbaikalian laboratory for engineering geocryology of the Melnikov Institute of Permafrost have provided scientific and methodological background for using VES and early-time induced polarization responses as indicators of the thermal behavior of permafrost in the zone of intense pore ice-water-gas phase changes [*Shesternev et al., 2003*].

Synthesis of worldwide laboratory and field data was used to describe the temperature dependence for a broad span of electrical and seismoacoustic properties of frozen fine-grained sediments, half-rocks and bedrocks in the zone of Russian permafrost with a regression equation in terms of a generalized model [*Neradovskiy, 2013*].

The cryo-petrophysical application of resistivity surveys to studies of temperature, structure, and properties of frozen soils is consistent with the current state of research and development in permafrost regions. In terms of theory, it is necessary to revise the existing theoretical views and to systematize the wealth of geocryological knowledge on the basis of a holistic approach, in order to bring geocryology to a higher scientific and philosophical level, that of cryosophy [*Melnikov et al., 2013*]. As for practice, geophysics is indispensable for exploration, production, processing, and transportation of mineral resources in East Siberian, Russian Far East, Arctic and Subarctic regions. Long-term industrial development of these regions requires new environment-friendly, cheap and high-performance technologies for permafrost studies, including those that can reduce risks of thermal, mechanical, and chemical disturbance of permafrost by interaction with buildings and utility structures. Medium-frequency EMI surveys comply with all these requirements.

We discuss the case of using the method to monitor the stability of the *Amur* federal motor road between the cities of Chita and Khabarovsk. Testing the method in surveys along the road, as well as other experimental results[6], contribute to the national research program for the top-priority issue of sustainable nature management[7].

GOAL AND OBJECTIVES

EMI surveys made part of geocryological studies performed by Melnikov Institute of Permafrost (Yakutsk), as scientific support to engineering-geological surveys, in order to explain the causes of deformations along the *Amur* motor road in Transbakalia and Amur region. Induction surveys were tested to justify their applicability to prospecting and monitoring of temperature dynamics in foundations of motor roads. The related objectives were:

(1) running test EMI surveys at sites of temperature logging in boreholes drilled in the subgrade;

(2) running explorative EMI surveys in natural ground beneath the subgrade;

(3) estimating decay rates of magnetic field components to depths of 6–10 m in the active layer;

[4] There are very few publications on this matter. Geophysics is the subject of only 5.6 % out of 250 papers in the IPA journal *Permafrost and Periglacial Process* of 2003 through 2010.

[5] The authors do not provide details of their method.

[6] Experiments were performed at Laboratory of engineering geocryology of Melnikov Institute of Permafrost, as part of SB RAS programs, including Program VIII.77.2 *Cryogenic, Geological, and Physicochemical Processes and their Role in the Evolution of Natural and Manmade Cryospheric Systems* and Project VIII.77.2.3 *Effect of Cryogenic, Geological, and Physicochemical Processes on Natural and Manmade Cryospheric Systems in a Changing Climate*.

[7] The Program includes research, design, and implementation of Technology No. 19 (monitoring and prediction of the state of environment and pollution prevention and mitigation) and Technology No. 21 (prevention and mitigation of natural and man-caused emergency). The technologies are numbered according to the list of key technologies (approved by Decree No. 899 of the President of the Russian Federation of 7 July of 2011).

(4) building a matrix of pairwise decay rates and temperatures at the depths 6, 7, 8, 9, and 10 m;

(5) obtaining a regression equation that relates decay rate and temperature values;

(6) using the obtained regression equation to infer temperatures at sites of EMI surveys;

(7) evaluating the quality (statistic of errors) of temperature estimates inferred from EMI data.

OBJECTS AND SITES

We studied induction responses of soils in the active layer of permafrost within the Chita and Amur segments of the *Amur* motor road. The Chita segment is located in the Mogocha area in northeastern Transbaikalia, in a hilly terrain with elevations about 1300 m asl in mountains and 500–700 m in basins between them (Fig. 1). The road traverses the periphery of the Dauria arch uplift and a narrow strip of the East Transbaikalian basin, extends into the Shilka basin-and-range province, returns to the boundary of the Dauria uplift, passes along it near Mogocha railway station, and reaches the uplift for the third time having crossed the Amazar River.

The subsurface in the road area consists of Middle Archean and Lower-Middle Paleozoic granites, Lower-Middle Jurassic granitoids, and remnant sedimentary rocks. The igneous and sedimentary rocks are mineralogically and petrographically diverse and vary in thermal and other physical properties correspondingly. The variability of bedrock properties still increases due to a rugged terrain and heterogeneous moisture patterns (amount of rainfall in summer and snow thickness in winter). Therefore, the permafrost of Transbaikalia has variable thickness and temperature patterns in both lateral and vertical dimensions.

The road within the Chita segment lies on a 1.2–3.7 m high embankment with natural ground beneath it frozen to a depth of 5 m. According to our data, ground temperatures at the 6–9 m depths range from –0.3 to –1.3 °C (–0.8 ± 0.2 °C on average).

The Amur segment, 419 km long (Fig. 2), is located in the Amur region, in the southern Russian Far East, in the forested steppes of the Amur-Zeya and Zeya-Bureya plains. The embankment height is 2.0–5.0 m; the natural ground under the road is mainly unfrozen, while permafrost occurs sporadically at a depth of 8–9 m. Our estimates of temperatures at the 5–8 m depths give a range of +3.9 to –0.8 °C.

The Amur segment of the road falls within the Mesozoic Amur basin composed of sedimentary, metamorphic, and igneous rocks. The foundation soils belong to eluvial, slope-wash, and fluvial facies, as well as to 3–5 m to 10–15 m thick alluvium of floodplains and low terraces. The eluvium and slope wash facies consist of debris and land waste with a cement of different grain sizes. Near-surface sediments are locally peat-bearing clay silt and silt with very high moisture contents. Alluvium is highly variable in composition, both laterally and with depth, but mainly has coarse grain sizes. Quaternary sediments lie over bedrocks of Upper Paleozoic and Middle Jurassic granites, Jurassic sandstones, and Upper Neogene-Lower Quaternary sandstones, mudstones, and siltstones.

Preliminary analysis of natural conditions and their changes in the course of road construction and operation allowed us to distinguish 10 and 8 key sites within the Chita and Amur segments, respectively, where we set up stations of ground temperature monitoring to the 10 m depth (Figs. 1, 2).

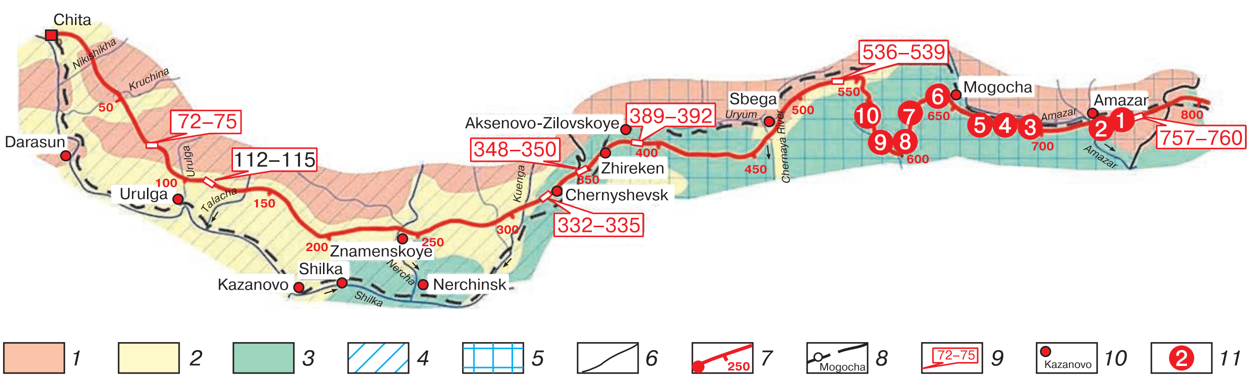

Fig. 1. Geocryological and geomorphic setting along the *Amur* federal motor road in Transbaikalia [*Kondratiev et al., 2010*].

Geomorphological units: 1 – Dauria uplift, *2* – East Transbaikalian basin, *3* – Shilka basin and range province; *permafrost units*: *4* – discontinuous permafrost, *5* – continuous permafrost; *6* – conventional boundaries between permafrost zones; *7* – motor road; *8* – Trans-Siberian Railway; *9* – key segments at some distances along the road; *10* – population centers; *11* – key sites selected and run by Institute of Permafrost (Yakutsk).

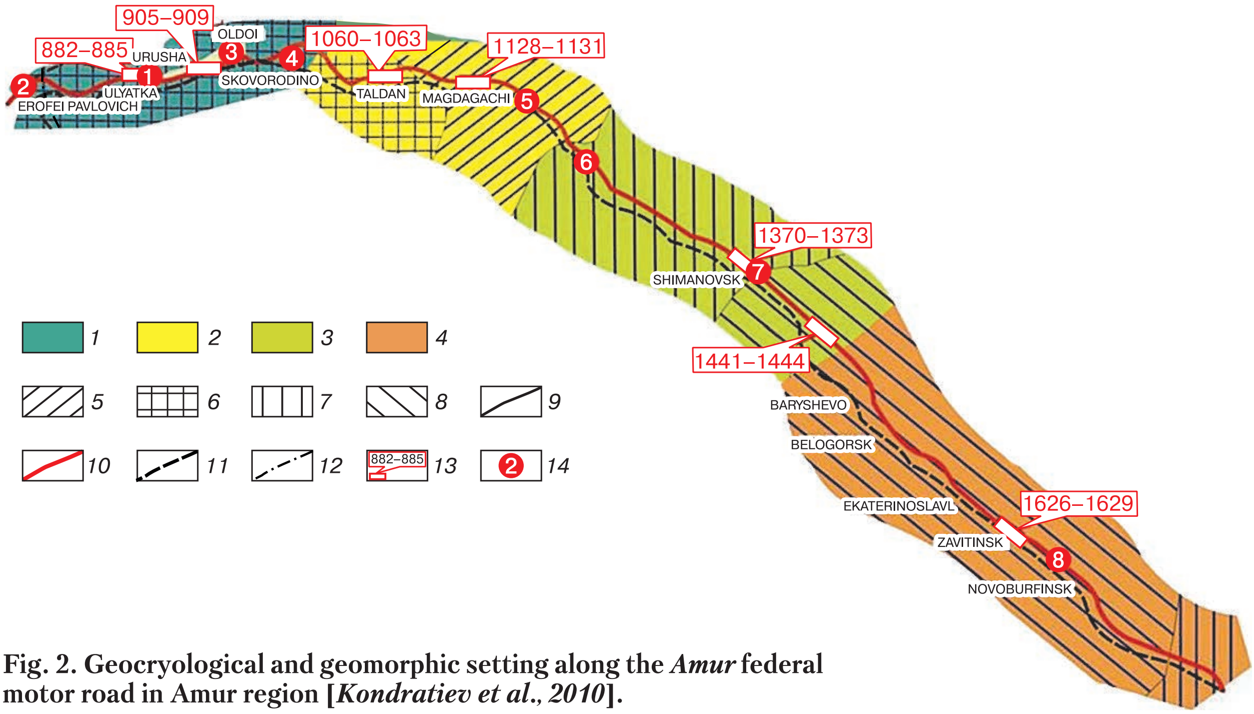

Fig. 2. Geocryological and geomorphic setting along the *Amur* federal motor road in Amur region [*Kondratiev et al., 2010*].

Geomorphological units: 1 – Shilka basin and range province, *2* – East Transbaikalian basin, *3* – Amur basin, *4* – Bureya-Amur fold area; *permafrost units*: *5* – continuous permafrost, *6* – discontinuous permafrost with sporadic taliks, *7* – sporadic permafrost, *8* – deep seasonal thaw; *9* – conventional boundaries between permafrost zones; *10* – motor road; *11* – Trans-Siberian Railway; *12* – administrative boundary; *13* – key segments at some distances along the road; *14* – key sites selected and run by Institute of Permafrost (Yakutsk).

METHODS

Temperatures were measured in boreholes following the standard procedure [*State Standard, 1982*] using advanced DS18B20 loggers calibrated to a precision of ±0.5 °C at the Melnikov Institute of Permafrost. The data automatically appeared in the laptop screen and were saved for further laboratory processing.

EMI data were collected at every 25 m along 100 m profiles that crossed the road at the sites of reference thermal boreholes. Within each profile, soundings were performed at five points in holes drilled to a depth of 10 m on road sides. The embankment was sounded at a single point near borehole No. 7. Natural ground adjacent to the road was sounded at four points (two on the right and two on the left of the carriage way). Induction responses (amplitudes of vertical and horizontal magnetic field components) were acquired by a MF-EMIS system[8] at 1.125 MHz. The transmitter antenna was mounted horizontally on a tripod with a direction finder and was fixed at the borehole site, while the receiver antenna was moved along the road away from the transmitter to a distance of 30 m, at an interval of 5 m. The antennas rose about 1 m above the ground surface.

In this configuration, a vertical magnetic dipole excited the fill and the natural ground. Effective resistivity (ρ_{ef}) was found from the amplitude ratio of vertical (H_z) to horizontal (H_r) magnetic components and plotted as a function of separation (source to receiver distance). The values of ρ_{ef} were computed using the VMD-1D software of A.E. Kaminskiy and assigned to receiver points. The decay rates of the H_z and H_r amplitudes and their modulus values were estimated by power approximation. The exponent of the power function at the maximum separation 30 m was assumed to be an empirical estimate of the decay rate (k) in the embankment and its foundation referred to the receiver points. The exact errors in unknown true k values were impossible to constrain from field experiments and were assumed to equal the measurement errors in H_z and H_r (about 4 % on average).

The EMI results show the effective penetration depth of 1.125 MHz EM soundings, at the 30 m separation, to vary from 6 to 10 m.

[8] The *Meson* R&D Center for Radio Engineering at the Krasnoyarsk Technological University fabricates a digital equivalent of this system, KAV-EMM.

RESULTS AND DISCUSSION

We studied correlation between the decay rate of EMI signals and temperature of frozen ground, which was revealed earlier within the active layer of Yakutia. The upper permafrost is subject to continuous heat redistribution, especially in the 3 m thick seasonally thawing and freezing layer, where positive and negative temperatures alternate periodically with a difference reaching tens of degrees. Below 3 m, most often to depths of 10–15 m, the temperatures remain negative but may fluctuate from a few degrees to tenths of a degree. The temperature variations with depth and laterally (to a lesser extent) produce complex thermal interactions, or rather a consistent behavior of soil properties changing in space and time. Note that the effect of temperature patterns in this respect is superior over other cryogenic and soil processes, which allows us to study the temperature dependence of geophysical parameters in the field.

Theoretical analysis of previous field results shows that the temperature and electromagnetic (induction in this case) fields, though being physically different, have similar depth-dependent patterns. Namely, the amplitudes of temperature and EM waves decay nonlinearly and monotonously with depth according to transcendent function equations, as it follows from the Fourier laws in the theory of thermal conductivity [*Dostovalov and Kudryavtsev, 1967*] and the Maxwell laws in the theory of electrodynamics [*Alpin et al., 1985*].

Thus, the correlation of the decay patterns of temperature and EM fields has a well known fundamental physical background. Our results prove valid this theoretical prediction for a specific case, within the uppermost permafrost (active layer). Continuous cyclic processes of heat re-distribution, which are controlled by heat exchange with the ground surface, shift the temperatures to negative or positive values and cause the respective phase changes to permafrost. The changes in structure, properties, and relative percentages of ice, bound unfrozen water, and gas in the soil skeleton generate, in their turn, *changes of basic electrical properties (resistivity and dielectric permittivity) concordant with the temperature variations*. Resistivity and permittivity eventually control the decay rate of EM signals in the active layer. The vertical and lateral resistivity patterns may be diverse but they are expressed via an integral parameter of decay rate at each point of the space. The general increase in average resistivity of frozen soil in the active layer causes a decrease in the voltage decay rate and vice versa. That is the reason why the spatial dynamics of resistivity (convolved to average values) is transferred to a different information level in the form of monotonous nonlinear decay with depth of induction and other EM signals.

All these signals, as well as temperature, faithfully record the thermal regime of frozen soil as a cryogenic system of the Earth, though in different aspects and to different accuracy degrees. This understanding is novel and important as it opens new avenues to more thorough and comprehensive investigation into temperature dynamics of frozen ground jointly by temperature logging (with semiconductor sensors), induction logging, and other EM surveys.

Average temperature curves below 5 m, where annual temperature variations are within 1 °C (Fig. 3), compared to average moduli of the H_z and H_r components (Fig. 4), show that the magnetic field in frozen soils at the depth 5–10 m under the Amur motor road in Transbaikalia, with an average temperature of –0.2 °C, decays more slowly than in unfrozen soils beneath the Amur segment of the motor road

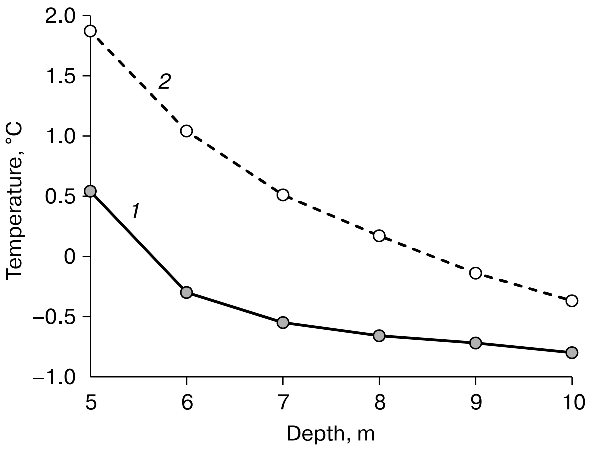

Fig. 3. Average ground temperatures from monitoring along the *Amur* federal motor road in September 2013.

1 – Transbaikalia; *2* – Amur region.

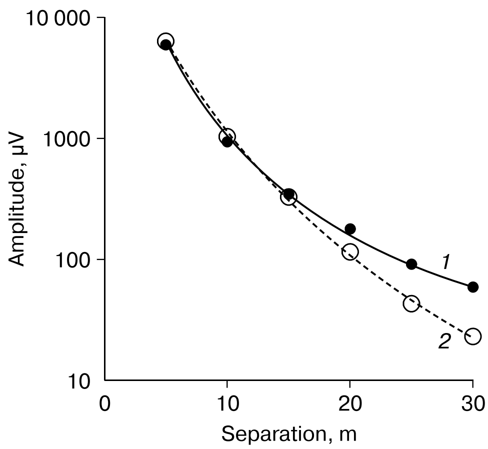

Fig. 4. Average separation-dependent induction responses (voltage decay in vertical and horizontal magnetic field components), from surveys of 2011.

1 – Transbaikalia; *2* – Amur region.

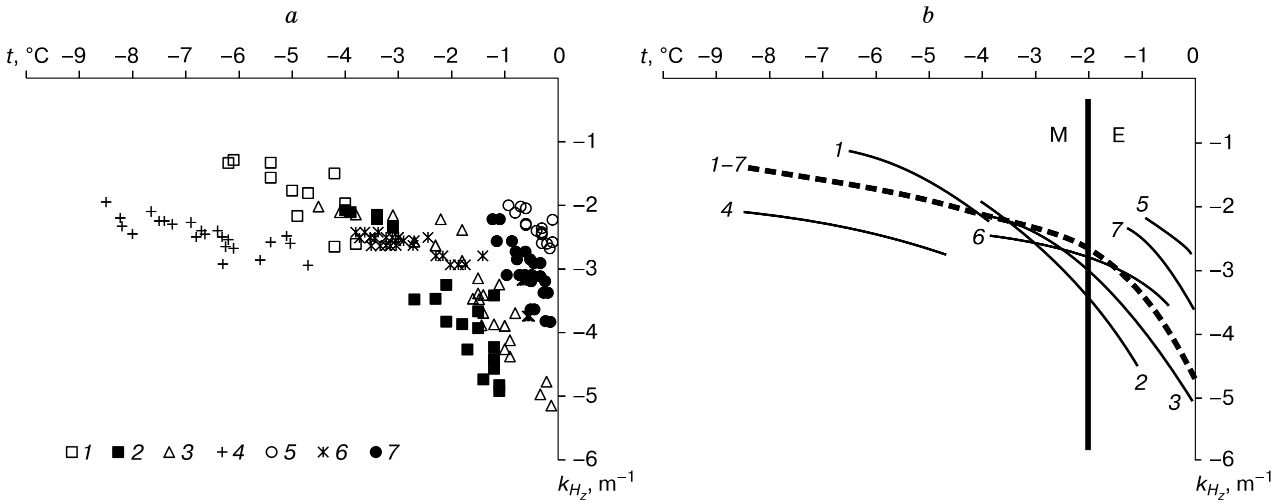

Fig. 5. Composite field of correlations (*a*) and polynomial curves (*b*) at monotonous (M) and extreme (E) segments of the temperature dependent decay of the vertical magnetic component in the active layer of East Siberia and Russian Far East.

1 – Service Center in Cherskiy Village; *2* – Amur-Yakutsk motor road; *3* – railway Tommot–Kerdem–Nizhniy Bestyakh; *4* – Kyuchus deposit; *5* – sands of the Bestyakh terrace in the Lena valley; *6* – Vilyui motor road; *7* – Amur motor road. See text for other explanations.

(at the rate k_{MOD} = –2.561 m^{-1} against k_{MOD} = = –3.143 m^{-1}) with the respective temperature +1.1 °C. The k_{MOD} difference is only 20 %, but it is sufficient for studying soil temperature variations in space and time and transitions between frozen and unfrozen states of the road foundation.

The principal result is presented as correlation of the decay rate of the vertical magnetic component (k_{H_z}) vs. frozen soil temperature at the depths 6–10 m (Fig. 5) obtained in field experiments in the permafrost in the territory of Yakutia, Transbaikalia, and Amur regions. The data collected in different times and from geographically dispersed areas indicate that regional physiographic, climate, geocryological, and other conditions, in which various engineering structures are operated, leave their particular imprints on the patterns of H_z decay in frozen soils of different ages, facies, and compositions. The cryogenic diversity modulated by the thermal regime of the active layer is expressed in different levels of background (average over an object) k_{H_z}. Therefore, reasonably accurate temperature estimates inferred from EMI data can provide local models of temperature-decay rate correlation specific to objects (single or multiple buildings, roads, or utility structures) exposed to certain conditions of prospecting, construction, and operation.

In our case, accumulation of heat in the active layer leads to concerted increase in ground temperature and k_{H_z}. There are two features in this general trend (curve *1–7* in Fig. 5, *b*): monotonous slowly increasing decay at relatively low and moderate temperatures (curve segment M) and extremely rapid decay at high temperatures in the zone of active ice-water phase change (segment E). Thus we generally have proved the hypothesis of regionally consistent correlation between permafrost temperatures and induction responses (voltage decay rates) in East Siberia and Russian Far East.

The mechanism of this correlation stems from continuous changes in properties and relative percentages of pore water, ice, and gas in frozen soils within the active layer, which are open thermodynamic systems.

The practical outcome of the study consists in testing the EMI method as a way of estimating space-time ground temperature variations under the *Amur* motor road. Calculations of the correlation matrix (Table 2) from input data (Table 1) show that the solutions for the active layer base can be extended to other depths within this layer, which was previously unknown.

Table 2 displays pairs of variables with relatively high correlation. For instance, the penetration depth *Z* (first column) shows the highest correlation (r = –0.59) with k_{H_z} which refers to the decay rate of the vertical magnetic component but is less strongly correlated with that in the horizontal dimension (k_{H_r}), in air and uppermost ground. Joint use of k_{H_z} and k_{H_r} provides a gain in information on the magnetic field decay under the road, and the respective temperatures of frozen soils are thus calculated using k_{MOD} found as a root of the sum of k_{H_z} and k_{H_r} squares (RSS).

Table 1. **Input data from Amur motor road**

Area	Distance along road, km	Borehole	Z, m	k, m^{-1}			Downhole t, °C					t in section layers, °C		
				k_{H_z}	k_{H_r}	k_{MOD}	t_6	t_7	t_8	t_9	t_{10}	t_{uf}	t_f	$t_{uf\text{-}f}$
1	531	10	8.5	2.567	1.617	2.893	–0.45	–0.64	–0.86	–1.02	–1.15	7.41	–0.75	–0.37
1	538	9	7.1	2.731	1.731	2.987	–0.28	–0.52	–0.61	–0.67	–0.79	4.02	–0.61	–0.05
1	548	8	8.3	3.377	2.425	3.406	5.37	0.20	–0.19	–0.21	–0.269	8.61	–0.21	5.65
1	559	7	7.3	2.221	1.369	2.680	–0.82	–0.99	–1.09	–1.15	–1.23	3.83	–0.99	–0.77
1	653	4	7.9	3.117	2.343	3.305	–0.20	–0.26	–0.33	–0.45	–0.45	7.90	–0.30	–0.17
1	653	4	7.9	2.910	2.033	3.144	–0.20	–0.26	–0.33	–0.45	–0.45	7.90	–0.30	–0.17
1	690	3	6.4	3.099	1.893	3.160	–0.52	–0.58	–0.62	–0.64	–0.96	6.82	–0.62	–0.20
1	690	3	6.4	3.099	1.893	3.160	–0.33	–0.42	–0.49	–0.54	–0.72	4.25	–0.49	–0.20
1	696	2	7.5	3.195	1.744	3.143	–0.06	–0.19	–0.24	–0.46	–0.50	3.91	–0.24	0.07
2	802	2	10.0	2.853	1.868	3.073	–0.43	0.45	–0.52	–0.58	–0.77	11.28	–0.44	–0.41
2	892	1	5.7	3.638	2.255	3.433	–0.14	–0.26	–0.44	–0.47	–0.51	8.65	–0.35	–0.11
2	1006	4	6.0	3.835	2.388	3.528	1.59	0.71	0.12	–0.08	–0.14	2.265	–0.11	1.86
2	1018	5	6.0	3.823	2.569	3.575	0.89	0.83	0.43	–0.14	–0.23	1.415	–0.19	1.11
2	1220	6	6.0	4.043	2.669	3.664	2.52	2.01	1.97	1.95	1.76	9.87	0.00	3.29

Note. 1 = Transbaikalia; 2 = Amur region; Z = effective penetration depth of EM field, m; k_{H_z}, k_{H_r}, k_{MOD} = decay rates of vertical and horizontal magnetic components and their modulus values, m^{-1}; t_6–t_{10} = ground temperatures at the depth 6–10 m, °C; t_{uf} = average temperature of unfrozen fill and seasonally thawing active layer, °C; t_f = average temperature of frozen soil at the depth 6–10 m, °C; $t_{uf\text{-}f}$ = average temperature of undifferentiated frozen and unfrozen soils, °C.

Table 2. **Correlation matrix of input data from Amur motor road**

Variables	Z	k_{H_z}	k_{H_r}	k_{MOD}	t_6	t_7	t_8	t_9	t_{10}	t_{uf}	t_f	$t_{uf\text{-}f}$
Z	1.00											
k_{H_z}	–0.59	1.00										
k_{H_r}	–0.39	0.91	1.00									
k_{MOD}	–0.50	0.98	0.97	1.00								
t_6	–0.48	0.83	0.77	0.81	1.00							
t_7	–0.23	0.80	0.79	0.80	0.92	1.00						
t_8	–0.41	0.81	0.78	0.80	0.93	0.94	1.00					
t_9	–0.38	0.76	0.74	0.76	0.90	0.91	0.98	1.00				
t_{10}	–0.37	0.77	0.77	0.77	0.91	0.90	0.98	0.99	1.00			
t_{uf}	0.49	–0.03	0.14	0.06	–0.05	0.18	0.13	0.25	0.24	1.00		
t_f	–0.26	0.88	0.88	0.91	0.77	0.80	0.78	0.74	0.78	0.11	1.00	
$t_{uf\text{-}f}$	–0.10	0.58	0.66	0.62	0.62	0.61	0.58	0.60	0.62	0.15	0.60	1.00

Note. Symbols are same as in Table 1.

Note that the correlation peaks also reveal temperature effects on penetration depth: a stronger effect in unfrozen fill (t_{uf}) and some effect in unfrozen natural ground at a depth of 6 m (t_6).

The principal information imprint on k_{MOD} is from t_f, the average temperature of frozen soil at the depths 6–10 m, with the maximum correlation at 0.91. Average temperature of undifferentiated unfrozen fill and natural ground under the road ($t_{uf\text{-}f}$) does not affect k_{MOD}, despite the fact that the ground absorbs the EM energy more strongly when it is unfrozen than in the frozen state. Correlation of k_{MOD} with fixed temperatures at the depths 6–8 m (t_6 and t_8) is as high as 0.8 and slightly lower below 8 m, i.e., the EM energy interaction with the ground persists but becomes weaker.

The ground temperature at different depths was estimated quite easily using third-degree polynomials. The main emphasis was placed on the accuracy of calculations, but the formal correctness of the k_{MOD} vs. t_6–t_{10} correlation was neglected. The derivation and the equations omitted, the results are as follows. According to statistics over 70 determinations (Tables 3, 4) for twelve boreholes, the errors are within ±(0.13...0.18) °C, with 95 % confidence probability, while single determinations are accurate to ±0.62 °C in 70 % of cases. Thus, average k_{MOD} over several soundings in different directions in the vicinity of points of geological-geophysical exploration or monitoring networks provide better constraints on the thermal stability of road foundations than single k_{MOD} at a single azimuth. The latter values are useful

Table 3. **Errors in ground temperatures under Amur motor road inferred from EMI data**

Area	Borehole	*t*, °C (measured by logging)					*t*, °C (inferred from EMI surveys)					Errors *t*, °C				
		6 m	7 m	8 m	9 m	10 m	6 m	7 m	8 m	9 m	10 m	6 m	7 m	8 m	9 m	10 m
1	10	–0.5	–0.6	–0.9	–1.0	–1.2	–0.3	–0.3	–0.5	–0.6	–0.8	–0.1	–0.3	–0.3	–0.4	–0.4
1	9	–0.3	–0.5	–0.6	–0.7	–0.8	–0.3	–0.2	–0.5	–0.6	–0.8	0.0	–0.3	–0.1	–0.1	0.0
1	8	0.2	0.2	–0.2	–0.2	–0.3	0.1	0.0	–0.3	–0.4	–0.5	–0.3	0.2	0.2	0.2	0.3
1	7	–0.8	–1.0	–1.1	–1.2	–1.2	–0.8	–1.1	–1.3	–1.3	–1.4	0.0	0.1	0.2	0.2	0.2
1	4	–0.2	–0.3	–0.3	–0.5	–0.5	–0.2	–0.2	–0.6	–0.6	–0.7	0.0	–0.1	0.2	0.2	0.3
1	4	–0.2	–0.3	–0.3	–0.5	–0.5	–0.3	–0.3	–0.6	–0.6	–0.8	0.1	0.0	0.3	0.2	0.3
1	3	–0.5	–0.6	–0.6	–0.6	–1.0	–0.3	–0.3	–0.6	–0.7	–0.8	–0.2	–0.3	0.0	0.0	–0.2
1	3	–0.3	–0.4	–0.5	–0.5	–0.7	–0.3	–0.3	–0.6	–0.7	–0.8	0.0	–0.1	0.1	0.1	0.1
1	2	–0.1	–0.2	–0.2	–0.5	–0.5	–0.3	–0.3	–0.6	–0.6	–0.8	0.3	0.1	0.3	0.2	0.3
2	2	–0.4	0.5	–0.5	–0.6	–0.8	–0.3	–0.3	–0.5	–0.6	–0.8	–0.1	0.7	0.0	0.0	0.0
2	1	–0.1	–0.3	–0.4	–0.5	–0.5	0.3	0.1	–0.2	–0.4	–0.4	–0.4	–0.4	–0.2	–0.1	–0.1
2	4	1.6	0.7	0.1	–0.1	–0.1	0.9	0.7	0.3	0.1	0.0	0.7	0.1	–0.2	–0.2	–0.2
2	5	0.9	0.8	0.4	–0.1	–0.2	1.4	1.0	0.7	0.5	0.4	–0.5	–0.2	–0.2	–0.6	–0.6
2	6	2.5	2.0	2.0	2.0	1.8	2.5	2.0	1.6	1.4	1.2	0.1	0.1	0.4	0.5	0.6

Note. 1 = Transbaikalia; 2 = Amur region. Misfit of estimated errors with initial temperature logs and EMI data is due to automatic approximation to larger or smaller values to 0.1 °C.

Table 4. **Probabilistic errors in calculated ground temperatures at 6–10 m under Amur motor road**

Accuracy	Range of errors, °C	Probability, %	
		Transbaikalia ($N = 45$)	Amur region ($N = 25$)
High	±(0.0–0.2)	67	52
Medium	±(0.2–0.5)	33	24
Low	±(0.5–1.0)	No	24
Very low	More than ±1.0	»	No

Note. *N* is the number of temperature values.

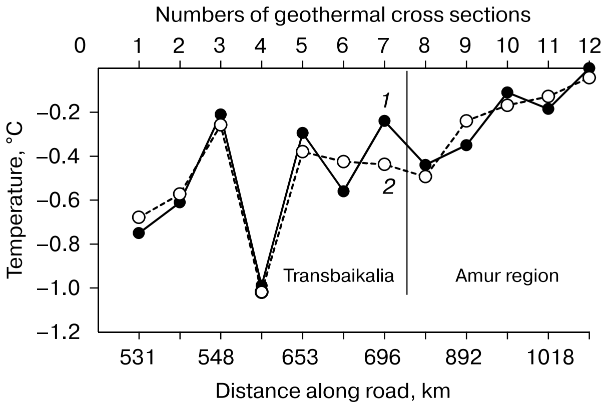

Fig. 6. Average temperature at a depth of 6–10 m. Diagnostic monitoring of lateral temperature dynamics of foundation soils under the *Amur* motor road in autumn of 2013.

1 – temperature logs; *2* – induction data.

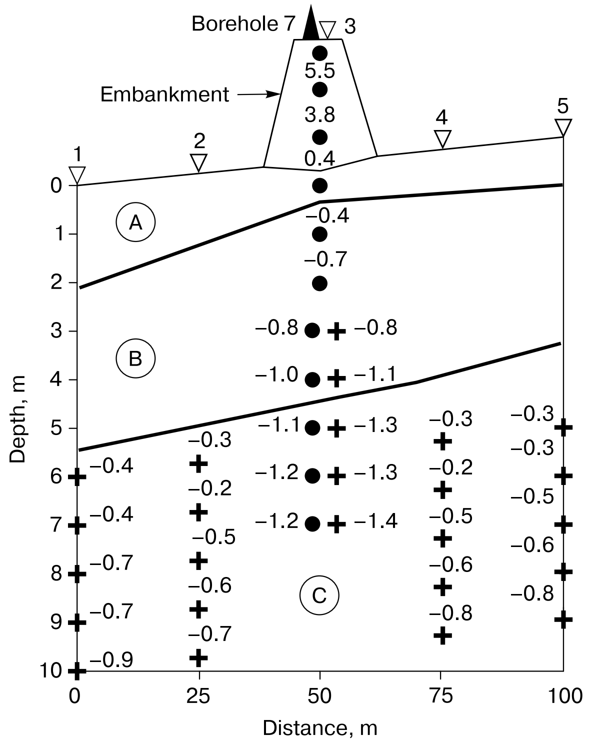

Fig. 7. Geothermal cross section of embankment and foundation soils under the *Amur* motor road in Transbaikalia, 559 + 785 km.

A: active layer (seasonally thawing); B: frozen land waste and debris (weathered bedrock); C: relatively well preserved bedrock (ganite). Crosses and circles with numerals mark temperature measurement sites (°C), from logging in borehole 7 and induction data (points 1–5).

as well, to monitor (rather than detect) seasonal or annual depthward and lateral changes in the temperature field under roads. The example of Fig. 6 demonstrates a trend of ground warming from –0.8 °C under the road in Transbaikalia to 0 °C in the Amur region, though with local ±(0.2...0.5) °C variations. The temperature logging and induction data are consistent both regionally and locally, and show the thermal field changes at 6–10 m below the road, the fit for the temperature series being 0.94.

The resulting geothermal pattern based on temperature logs and EMI data is shown for one particular section (559 + 785 km road distance) in Transbaikalia, at the point of reference thermal borehole 7 (Fig. 7). Frozen ground has a temperature of –0.4 °C at 3.5 m below the embankment surface and is colder (–1 °C) below 7.3 m, in granitic bedrock. The temperature increases at a distance of 25 m off the embankment axis to –(0.3...0.4) °C at a depth of 6 m, with a 0.8–0.9 °C average difference relative to the point of borehole 7 (a gradient of 0.034 °C/m). The reason of this difference is unclear. One explanation of relatively cold ground under the embankment axis and warmer ground off the road may be that the road crosses a swampy valley of the Guriev creek, with ice-rich wet soil, and is prone to settlement, judging by radio-impedance evidence from 2012 surveys.

The reported features of the temperature field provide important information support for safe and stable operation of linear structures, especially roads.

CONCLUSIONS

Electromagnetic induction surveys along the *Amur* motor road show that induction responses of the active layer in the sporadic permafrost of Transbaikalia and Amur region are temperature dependent: the amplitudes of vertical and horizontal magnetic components decay with depth at rates proportional to temperatures. The results, along with previous data from areas of discontinuous permafrost in Yakutia and with results from other permafrost regions in Russia, prove physical and space-time correlation of temperatures with decay rates of induction and GPR signals, as well as with electrical and seismoacoustic properties of frozen soils.

The practical outcome of the study consists in testing the EMI method and checking the frozen ground temperatures inferred from induction data against temperature logs. The resulting accuracy complies with the requirements of exploration and monitoring of temperatures in frozen foundation soils under linear structures, including roads. The most efficient in terms of geology and economy is long-term monitoring tailored to specific objects and local conditions. The results have made basis for the strategy of mitigating deformations on the *Amur* road developed by the *Irkutskgiprodornii* JSC company.

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