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Physico-chemical and electrical properties of Cryosols in the Lena River Delta

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Summary. Vertical electrical sounding method is an express and most accurate method for measuring and analysing the resistivity through the soil profile. As a result of climate change, permafrost is melting, which leads to a significant transformation of landscapes, both natural and anthropogenically transformed. In the vulnerable environments of the Arctic region (long recovery after anthropogenic impact), this method allows to determine the active layer thickness and the heterogeneity in the soil structure without disturbing of the soil cover. This method is based on the measurement of electrical resistivity in the soil, the data obtained were processed in the form of one dimensional model. In the course of field research, the heterogeneous islands of the Lena River Delta were investigated. Complex soil investigations using the method of vertical electrical sensing allows to fully assess the most important properties of cryogenic soils formed in the delta complex of the Lena River. As a result of the work, the modeled boundaries of the active layer were determined, which were confirmed during the laying of soil transects, as well as the main physical and chemical parameters of soils. During the vertical electrical sounding observation an inhomogeneity in the distribution of resistivity under a drained lake was found, which may correspond to the presence of a talik or a layer of salt unfrozen water in a permafrost. Due to the change in the soil horizons, there is a sharp change in the electrical resistivity indicator occur, which corresponds to the change from soil to frozen rock.

The paper contains 6 Figures, 3 Tables and 37 References.

Keywords: vertical electrical sounding, permafrost-affected soils, electrical resistivity, Arctic

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Научная статья
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Физико-химические и электрические свойства криоземов в дельте реки Лены

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Аннотация. Метод вертикального электрического зондирования является экспрессным и наиболее точным методом измерения и анализа удельного сопротивления в профиле почвы. В результате изменения климата происходит таяние многолетнемерзлой породы, что приводит к значительной трансформации ландшафтов, как естественных, так и антропогенно-преобразованных. В уязвимых условиях Арктического региона (длительное восстановление после антропогенного воздействия) данный метод позволяет определить границу активного слоя и неоднородность структуры почвы без нарушения почвенного покрова. Данный метод основан на измерении удельного электрического сопротивления в почве; полученные данные обрабатывались в виде одномерных моделей. В ходе полевых исследований были исследованы острова дельты р. Лены. Проведение комплексных почвенных исследований с использованием метода вертикального электрического зондирования позволяет в полной мере оценить важнейшие свойства криогенных почв, формирующихся в дельтовом комплексе р. Лены. В результате работ определены смоделированные границы активного слоя, которые были подтверждены при закладке почвенных разрезов, а также основные физико-химические параметры почв. В ходе наблюдений вертикального электрического зондирования была обнаружена неоднородность в распределении удельного сопротивления под дренированным озером, что может соответствовать наличию талика или слоя соленой незамерзшей воды. В связи со сменой почвенных горизонтов происходит резкое изменение показателей электрического сопротивления, что соответствует переходу от почвы к мерзлой породе.

Ключевые слова вертикальное электрическое зондирование, многолетнемерзлые почвы, удельное электрическое сопротивление, Арктика, криоземы

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Introduction

Permafrost-affected soils occupy an area of more than 8.6 million km^2 in the Norther hemisphere [1-2]. A characteristic feature of permafrost-affected soils are the presence of ice, which is often found in the form of a permafrost table and cryogenic process (turbation, cracking) [3]. Permafrost layer acts as a geochemical barrier that leads to stagnation of water, especially in the summer months, causing a decrease in the amount of oxygen in the soil (redoximorphic conditions) [4]. Arctic soils are quite vulnerable to the disturbance of the soil cover [5]. It leads to the development of permafrost processes in the soil and degradation of landscapes affected by permafrost [6]. The most common method of soil cover analysis is the research of a soil section, which provides complete information on the structure of the soil cover. To determine the active layer thickness, a soil probe is also used, its length is usually up to 1.5 m, it practically does not disturb the soils, but at the same time does not provide information about the structure of the soil profile [5-6]. Soils in polar deserts can show signs of waterlogging and gley conditions due to waterlogging as a result of melting of ice. In permafrost-affected soils, the absence of horizontal layers may be observed [7]. This process is known as cryoturbation and leads to mixing of soil material, involutions, migration of dissolved organic matter, frost heaving, separation of coarse inclusions from fine-grained soil, cracks and patterned soil [8].

One of the effective and informative method for analyzing soil cover, determining the active layer thickness and water table is the method of vertical electrical sounding (VES) [9-10]. For the first time, the method of VES was used in the work of Parasnis [11], which noted the simplicity of use of such a technique in electrical exploration. The use of VES has recently been discussed by A.I. Pozdnyakov, his work led to a comprehensive understanding of the nature of stationary electric fields in soils, grounds and landscapes [9, 12]. Due to VES investigation as a non-intrusive method, it is possible to carry out an express survey of soil-permafrost strata in order to establish the thickness of the active layer, the depth of the upper layer of permafrost and clarify the structure of the stratum of permafrost [5, 13-14]. This method is also actively used in the urban environment, it allows to quickly and accurately determine the risks of flooding, without disturbance of the soil cultural layer [9, 12, 15-16]. The method is applicable to compilation of landscape maps in the field of agricultural complex based on soil organic matter (SOM) content, cation exchange capacity and texture class [9]. In the Arctic zone, due to the presence of a layer of permafrost, SOM indicators, cation exchange capacity, texture class do not provide much information about the profile structure, due to the relatively high electrical resistivity (ER) of frozen rocks [6]. In the polar zone, the indicator of ER in the soil has been insufficiently studied. The main areas of research were carried out in the European part of Russia, Western Siberia, Svalbard archipelago and the Antarctic Peninsula [6, 12, 17-18]. Further study of induced electric fields will make it possible to study the detailed structure of soils, the redistribution of substances in the soil cover, their course and intensity [9, 16]. As a result of climate change, cities located in the area of permafrost are at risk due to soil subsidence and possible flooding, therefore expanding the study of natural electric fields in soils is a powerful tool for preventing damage and ensuring public safety [5, 19]. This method makes it possible to study saline, flooded, agrotechnical and drained soils [16, 20]. Based on these works, relationships were established between the content of organic matter, texture class, and the cation exchange capacity [15]. Recently, the VES method is used in the conditions of occurrence of permafrost, since it is suitable for determining the active layer thickness [21]. Geophysical methods in comparison with traditional soil excavations have a number of advantages, such as coverage of a large area and low impact on the soil cover [5-6,14]. In the Arctic zone, in context of investigations of Cryosols and permafrost-affected soils, geophysical methods are mainly used to study the thickness of the occurrence of permafrost and the shapes and sizes of taliks under thermokarst lakes and rivers [5-6]. Soils in the area of occurrence of permafrost are quite different in the context of ER, the ER here ranges from 1000-5000 to 10^5-10^6 Ohm m, while soils not affected by cryogenic processes have a resistivity approximately 1000 Ohm m, depending on the structure and degree of moisture [6, 17]. Thus, the aim of this work is to use VES to study the vertical stratification of strata on various islands of the Lena River Delta. To achieve the aim of work, the following tasks were set:

- to measure the active layer thickness of the Lena River Delta by traditional methods;
- to investigate the electrical resistivity and constructing profile curves of apparent electrical resistivity of different soil horizons;
- to analyze the active layer thickness according to VES method in various landscape of the Lena River Delta.

Materials and methods

Study area. The Lena River Delta is the largest northern delta in the world, which is located in the Arctic zone and has an area of about 30,000 km^2 [22-23]. Due to such a huge area and location, it has a significant impact on the water regime of the Arctic Ocean. The delta was formed as a result of river activity: sediment transport, erosion, abrasion under the influence of sea level fluctuations [23]. The Lena River Delta is covered with tundra vegetation of various types [24]. The main components are lichens, mosses, grasses and some types of shrubs [25]. The Lena River delta is separated from the mainland by the Primorsky Ridge and the Chekanovsky Ridge [23]. Thus, the Delta of the Lena River has been formed in a lowland and heavily watered.

The Lena River Delta is located in a zone with an arctic continental climate. The average annual air temperature is -13 °C, the average January temperature drops to -32 °C, the average July temperature is 6.5 °C. The duration of the period with snow cover is 250–270 days. Most of the land is characterized by the presence of permafrost at a depth of about 50-60 cm [24-25].

Sampling strategy. The sampling and classification procedure of soils and soil horizons was carried out according to the standard procedure [26]. To analyze the physicochemical properties of the soil sections were prepared.

During the field work, two islands were explored - Kurungnakh and Samoylov. The exploration was performed in August 2020. Samoylov Island covers an area of about 5 km^2. The western part is formed by recent channel and aeolian processes. The eastern part is represented by ice veins and small thermokarst lakes. Kurungnakh Island is located near the top of the Lena River Delta and is washed away by the Olenek Channel [23]. The Kurungnakh island consist from the ice complex (IC) deposits and underlying sands from the surface [27]. One of the investigated areas of the Kurungnakh Island is represented by a drained lake that began to form over the past hundred years (Figure 1).

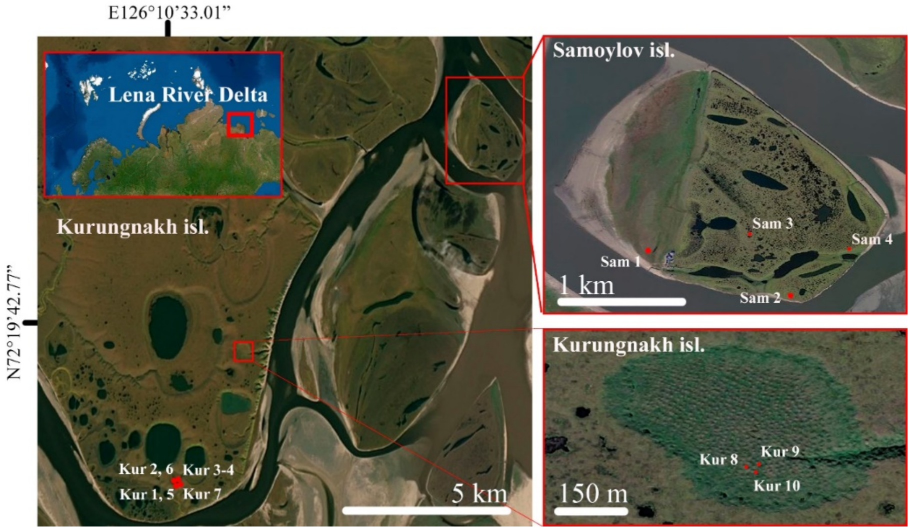

Fig. 1. The study area. Lena River Delta. Source: ESRI: Geographic information system company (West Redlands, California, United States of America)

*Vertical electronic sounding method***.** Measurements of the ER of soil and ground layers were carried out using a portable LandMapper ERM-02 (Penza, Russia) device. This device is widely used in near-surface (up to 2 m) soil surveys, as it allows to determine heterogeneities of various soil properties (salinity, stoniness, texture, contamination with oil products, depth of groundwater occurrence, as well as the boundary of the active layer). Measurements were carried out with grounding into the day soil surface. In our study, the resistivity measurements were performed using four-electrode (AB + MN) arrays of the AMNB configuration with use of the Schlumberger geometry, with amperage 7 mA [6]. The results of field measurements were recalculated according to the method of A.I. Pozdnyakov [9, 16] in accordance with the geometric coefficients (K) for different depths and spacing of electrodes AB and MN:

$$K = 3.14 * (AB/2 + MN/2) * (AB/2-MN/2) / (2*MN/2) \quad (1)$$

where, ABMN – space between electrodes.

Specific ER (Ωm) was calculated using the formula:

$$Ra = K*(\Delta U/I) \quad (2)$$

where, K - geometric coefficients, ΔU - voltage in mV, I – amperage mA.

The device scheme is shown in Figure 2.

The results of field measurements were recalculated according to the methodology proposed by A.I. Pozdnyakov [12]. Zondip software (ZondIP ver.7) was used to analyze VES data. It was used to obtain inverted 1D images. This is due to the fact that the main task was to determine active layer thickness in various natural conditions (flooded, non-flooded, periodically flooded territories), and to consider the heterogeneity of the structure of soil profiles developing under cryogenic conditions. The distance of the MN electrodes was the same in all studies (10 cm). According to the A.I. Pozdnyakov on small research areas (up to 5 m), we can use the distance MN equal to 10 cm, and not increase it. The distance AB varied depending on the terrain conditions in the studied areas (the presence of ponds, small lakes, as well as hills).

Laboratory method. Soil samples were air-dried (24 hours, 20 °C), ground, and passed through 2 mm sieve. Chemical analyses were performed using classical methods: C and N content were determined using an element analyzer (EA3028-HT EuroVector, Pravia PV, Italy), pH in water suspensions using a pH meter (pH-150M Teplopribor, Moscow, Russia). The particle-size distribution analysis was carried out according to the Kachinsky method, which is the Russian analogue of analysis by Bowman and Hutka [28].

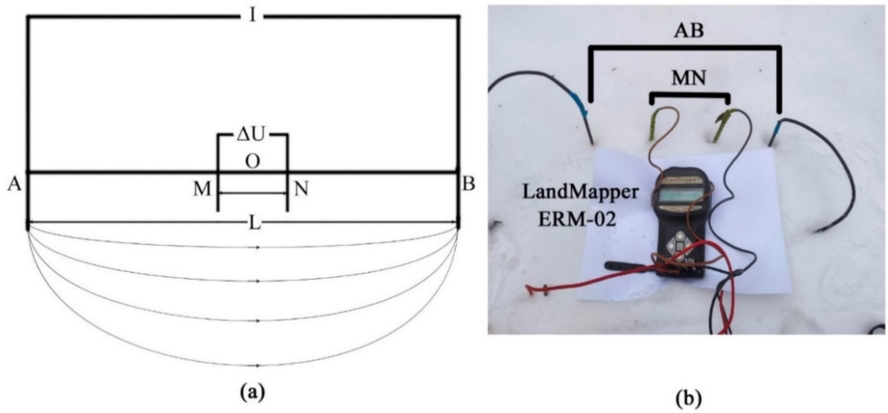

Fig. 2. (a) Schematic of the four-electrode measuring configuration. (b) field observation. ABMN - the place where the electrodes are installed; ΔU - voltage in mV; I - amperage in mA; L is the distance between the electrodes AB; O is the distance between the MN electrodes

Results

Physico-chemical characteristics of soil. The studied soils have been classified as Cryosol [26]. In the studied soils, the thickness of active layer is up to 1 meter, and in most of the soils there are signs of cryoturbation, which is present in the mixing of soil horizons under the influence of cryogenic processes [29]. Due to the close presence of permafrost, stagnic conditions are formed in soils, this is presented in the formation of ferruginous nodules, and the migration of iron and aluminum oxides along the soil profile [1]. The description of studied soils is presented in Table 1.

Table 1

Description of soil cover from the Lena River Delta

Soil ID	Horizon	Depth, cm	Description	Coordinates	Soil name
Samoylov island					
Sam 1	Ah	0-22	Organomineral horizon with the accumulation of organic matter	N 72°22'15.7" E 126°28'11.5"	Umbric Cryosol
	A/C	22-29	Stratified soil horizon, with layers with different particle-mass distribution		
	A/Cg	29-60	Stratified soil horizon with iron spots and Fe-Al migration		
Sam 2	Oe	0-9	Moderatly decomposed organic matter	N 72°22'11.4" E 126°31'06.5"	Folic Cryosol
	Bg	9-38	Mineral horizon with iron spots and Fe-Al migration		
Sam 3	Oe	0-5	Moderatly decomposed organic matter	N 72°22'21.8" E 126°29'38.5"	Folic Cryosol
	Bg@	5-29	Mineral horizon with a sign of cryoturbation		
Sam 4	Oe	0-8	Moderatly decomposed organic matter	N 72°17'20.2" E 126°11'00.2"	Folic Cryosol
	Bg@	8-32	Mineral horizon with a sign of cryoturbation		
Kurungnakh island					
Kur 1	Oe	0-4	Moderatly decomposed organic matter	N 72°17'21.1" E 126°10'48.9"	Folic Cryosol
	Bg@	4-27	Mineral horizon with with iron spots, Fe-Al migration and sign of cryoturbation		
Kur 2	Oe	0-3	Moderatly decomposed organic matter	N 72°17'25.5" E 126°10'54.9"	Folic Cryosol
	Bg	3-29	Mineral horizon with iron spots and Fe-Al migration		
Kur 3	Oe	0-10	Moderatly decomposed organic matter	N 72°17'26.3" E 126°11'03.2"	Folic Cryosol
	Bg@	10-20	Mineral horizon with iron spots, Fe-Al migration and sign of cryoturbation		
Kur 4	Oe	0-11	Moderatly decomposed organic matter	N 72°17'29.2" E 126°11'10.6"	Folic Cryosol
	Bg@	11-29	Mineral horizon with iron spots, Fe-Al migration and sign of cryoturbation		
Kur 5	Oe	0-8	Moderatly decomposed organic matter	N 72°17'23.1" E 126°10'51.5"	Folic Cryosol
	Bg@	8-39	Mineral horizon with a sign of cryoturbation		
Kur 6	Oe	0-5	Moderatly decomposed organic matter		
	Bg@	5-40	Mineral horizon with a sign of cryoturbation	N 72°17'20.8" E 126°10'46.9"	Foilc Cryosol
Kur 7	Oe	0-3	Moderatly decomposed organic matter	N 72°17'20.2" E 126°11'00.2"	Folic Cryosol
	Bg@	3-51	Mineral horizon with iron spots, Fe-Al migration and sign of cryoturbation		
Kur 8	Ah	0-30	Organomineral horizon with the accumulation of organic matter	N 72°19'17.8" E 126°15'10.9"	Umbric Cryosol
	Bgb	30-50	Mineral horizon with a sign of cryoturbation and buried organic matter		

Soil ID	Horizon	Depth, cm	Description	Coordinates	Soil name
Kur 9	Ahg	0-25	Organomineral horizon with the accumulation of organic matter, iron spots and Fe-Al migration	N 72°19'17.9" E 126°15'13.8"	Umbric Cryosol
	Bgb	25-40	Mineral horizon with a sign of cryoturbation and buried organic matter		
Kur 10	Ah@	0-50	Organo-mineral horizon with iron spots and Fe-Al migration and buried organic matter	N 72°19'18.0" E 126°15'15.1"	Umbric Cryosol

From the data obtained, relatively young areas (first terrace) of the Lena River Delta (flooded and drained) are associated with an active soil-forming process, which is presented in the formation of the Umbric horizon. The zonal areas on the islands of Samoylov and Kurungnakh are represented by typical Folic Cryosols, their development is associated with the formation of a moss cover and the development of active cryogenic processes. The thickness of such soils is much less than in flooded areas (approximately is 30-40 cm), this is due to the development of a moss cover, it acts as a temperature regulator and prevents the degradation of permafrost in the soil. Areas subject to periodic flooding process have a significantly greater thickness of the active layer, this is due to the active influence of the river on this territory. Such area is quite different from the zonal landscape, it's presented by different vegetation, the particle-size distribution is represented by the sand fraction and accumulation of humified organic matter (Table 2). Soil sections are shown in Figure 3.

The physicochemical characteristics of the studied soils are presented in Table 2.

The pH value varies within a wide range from 4.5 to 7.2. The most acidic condition is associated with zonal variants of soil formation, humification of organic substances, the precursors of which were mosses and lichens, leads to acidification and activates the process of migration of aluminum and iron along the soil profile. In areas that are subject to periodic flooding process, the pH level shifts to neutral. The Lena River in the downstream erodes carbonate rocks, which in dissolved form can accumulate in the river delta, which serves as a place of accumulation for various elements [26]. The carbon content is highest in the upper humus horizons, as well as in the Oe horizons, which consist of moderate decomposed organic remains. The nitrogen content is relatively low, which is typical for the Arctic soil, since the precursors of humification contain a small amount of nitrogen, which passes into the soil [30, 31]. In areas subject to flooding process, the nitrogen content is higher, this is the result of the formation of legumes and the fixation of nitrogen from the atmosphere. Flooded areas are characterized by the predominance of the sand fraction, which accumulates during periodic flooding. Zonal soils are characterized by a relatively high content of the dust fraction in relation to the flooded areas, this is due to the processes of physical, chemical and biological weathering [32].

Electrical parameters of cryogenic soils in the Lena River Delta. During the field work, measurements of the ER of soils were carried out (Table 3).

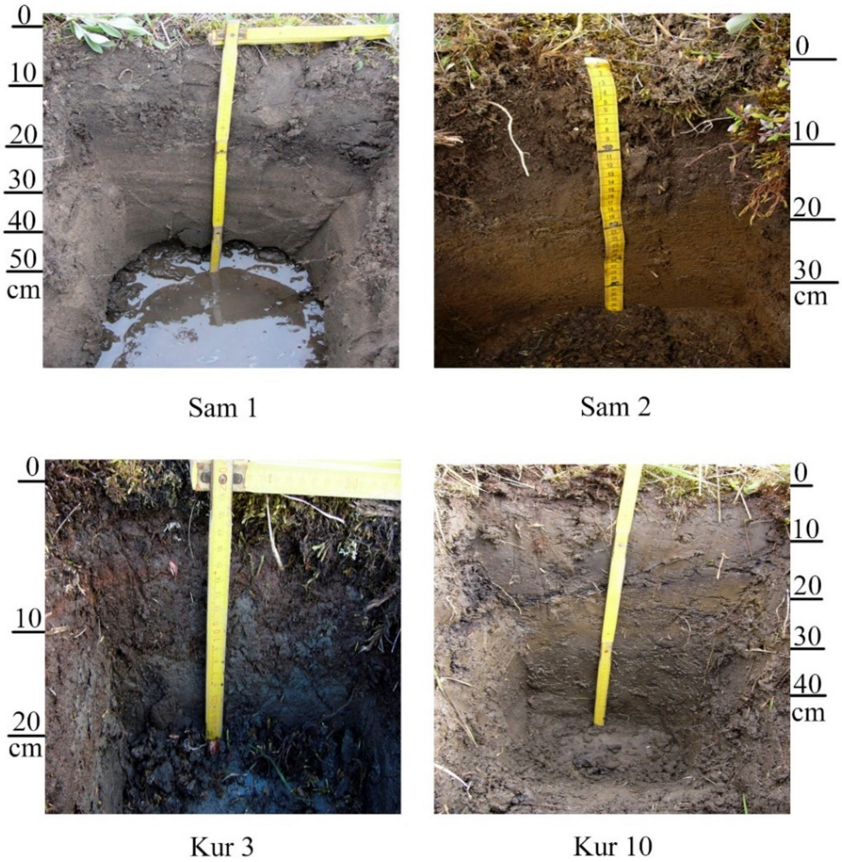

Fig. 3. Studied soil profiles. Soil ID correspond to Table 1

Table 2

Physicochemical parameters of the studied soils in the Lena River Delta

Soil ID	Depth, cm	pH (H_2O)	C, $g*kg^{-1}$*	N, $g*kg^{-1}$*	Particle-size distribution		
					Clay	Silt	Sand
Samoylov island							
Sam 1	0-22	7.2	3.4	0.01	3	22	75
	22-29	7.1	2.8	0.41	5	12	83
	29-60	5.4	2.7	0.55	18	12	70
Sam 2	0-9	6.2	3.3	0.01	n.d.	n.d.	n.d.
	9-38	7.1	1.2	0.01	3	23	74
Sam 3	0-5	5.7	2.4	0.01	n.d.	n.d.	n.d.
	5-29	6.4	0.8	0.01	6	10	84
Sam 4	0-8	6.1	2.1	0.01	n.d.	n.d.	n.d.
	8-32	6.9	0.9	0.01	1	25	74
Kurungnakh island							
Kur 1	0-4	5.8	2.3	0.43	n.d.	n.d.	n.d.
	4-27	4.5	0.4	0.01	15	42	43

Soil ID	Depth, cm	pH (H_2O)	C, g*kg^{-1}*	N, g*kg^{-1}*	Particle-size distribution		
					Clay	Silt	Sand
Kur 2	0-3	5.9	2.5	0.01	n.d.	n.d.	n.d.
	3-29	5.4	0.5	0.01	14	31	55
Kur 3	0-10	5.8	3.1	0.01	n.d.	n.d.	n.d.
	10-20	5.3	0.9	0.01	10	70	20
Kur 4	0-11	5.7	2.7	0.11	n.d.	n.d.	n.d.
	11-29	5.5	0.6	0.22	2	47	51
Kur 5	0-8	5.5	2.8	0.13	n.d.	n.d.	n.d.
	8-39	5.4	0.3	0.01	3	35	62
Kur 6	5-40	5.3	1.1	0.01	3	32	65
Kur 7	0-3	5.7	2.4	0.04	n.d.	n.d.	n.d.
	3-51	5.4	1.2	0.2	14	29	57
Kur 8	0-30	6.4	2.6	0.8	8	28	64
	30-50	5.9	1.3	0.3	10	19	71
Kur 9	0-25	6.6	2.7	0.6	18	40	42
	25-40	5.8	1.8	0.06	20	41	39
Kur 10	0-50	5.7	2.2	0.05	6	70	24

Table 3

Electric resistivity of studied soil profiles

VERS section name	P-modelled resistivity (Ohm*m)	Z-bottom layer depth (m)	Field permafrost table (m)
Sam 1	3.23	0.00	
	263.7	0.087	
	9.15	0.17	
	11237.88	0.24	
	3732.79	0.32	
	567214.03	0.72	0.60
Sam 2	11.36	0.00	
	504.99	0.22	0.38
Sam 3	7.80	0.00	
	259.14	0.15	0.29
	101.52	0.47	
	745181.07	1.12	
Sam 4	8.36	0.00	
	103.35	0.15	
	51.81	0.47	0.32
	1000252.88	1.12	
Kur 1	8.27	0.00	
	1367.79	0.12	
	99.09	0.32	0.27
	264.12	0.59	
Kur 2	60.9	0.00	
	3095.02	0.22	0.29
Kur 3	10.28	0.00	
	291.07	0.22	0.20
Kur 4	2.09	0.00	
	277.34	0.15	
	101.85	0.23	0.29
	284.44	0.71	

VERS section name	P-modelled resistivity (Ohm*m)	Z-bottom layer depth (m)	Field permafrost table (m)
Kur 5	11.28	0.00	
	85.86	0.14	
	35.19	0.45	0.39
	343846.02	1.07	
Kur 6	9.56	0.00	
	24.70	0.19	
	87.21	0.34	
	43.67	0.47	0.40
	1078191.49	1.12	
Kur 7	11.37	0.00	
	68.70	0.11	
	33.61	0.27	
	67.16	0.32	
	30.84	0.37	
	955297.70	1	0.51
Kur 8	13.34	0.00	
	57.99	0.19	
	16.35	0.27	
	43.71	0.32	
	22736.28	0.37	
	28.40	0.45	0.50
	2021.77	1.12	
Kur 9	8.51	0.00	
	13.47	0.21	
	19661.74	0.32	
	505.94	0.37	
	25411.83	0.45	0.40
	179.51	0.71	
	1114.82	1.41	
Kur 10	9.36	0.00	
	8.43	0.19	
	12329.10	0.27	
	3760.75	0.32	
	15569.81	0.42	0.50
	6726.78	0.71	
	134701.62	1.41	

The measurements extended to a depth of 1–5 m. The results of VES investigation obtained in the field were further processed in the form of a one-dimensional model (resistivity – depth axis) (Figures 4-6).

The data obtained for the resistivity values within the permafrost strata revealed several trends. The main trend is that ER increases with depth. At the same time, on the border with permafrost, there is a significant increase in ER from hundreds to thousands of Ohm*m. The increase in ER in the profiles of permafrost soils is associated with the presence of ice in the profile [6, 12].

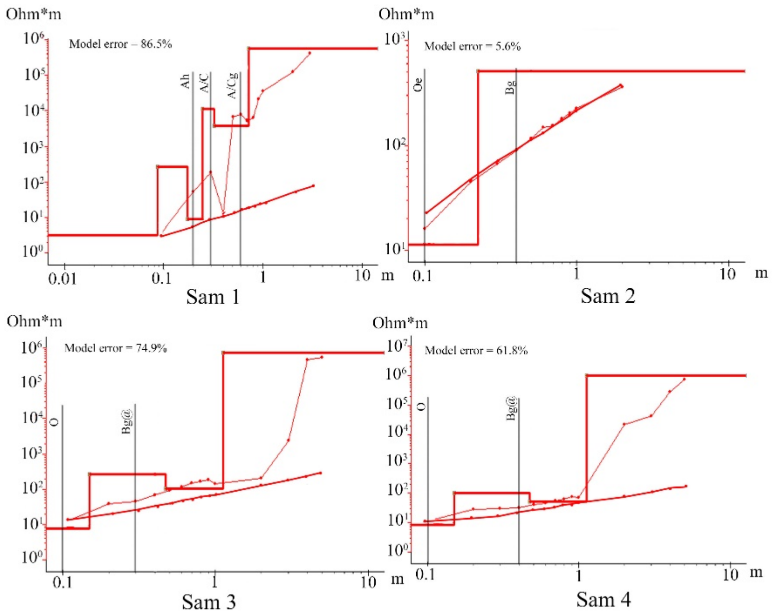

Fig. 4. Profile distribution of ER in soils on Samoylov Island. Vertical scale: ER values (Ohm*m); horizontal scale: AB/2 distance (m)

Figure 4 shows the graphs of ER on Samoylov Island. The Sam 1 profile is characterized by the presence of several peaks in the soil profile, which are associated with the processes of flooding and deposition of fresh organomineral material (Fig. 4). The highest ER value is noted at a depth of 72 cm, which is slightly deeper than the depth of permafrost found during field work. This can be interpreted as an increase in permafrost homogeneity. The upper boundary of the permafrost found in the field work is under the water layer, which leads to the formation of pores and cracks, but with depth the number of pores decreases and the ER increases. For zonal variants of soil formation (Sam 2 - Sam 4), which are not influenced by the flooded process, a sharp increase in the value of ER is characteristic when passing from soil to permafrost, which is presented in the obtained graphs. A characteristic feature of permafrost-affected soils is the presence of a dynamic active layer thickness, which corresponds to freezing/thawing processes in a soil at different times of the year (maximum in late August-early September). On Samoylov Island, from the graphs obtained, we can determine the change in conditions at a depth of about 110 cm (Sam 3 - Sam 4), these profiles are not subjected to the flooded process. Samoylov Island is a relatively young formation in the Lena River Delta and is confined to the Holocene period. The data obtained well corresponds with the data from Western Siberia (Yamal Peninsula, Gydan), the increase in the ER was confirmed by the obtained soil sections and corresponded to the active layer thickness [6, 19]. On the Yamal Peninsula, the distribution of ER varies from several to tens of thousands, this is caused by the peculiarities of permafrost formation, which can have pores and stratify [5].

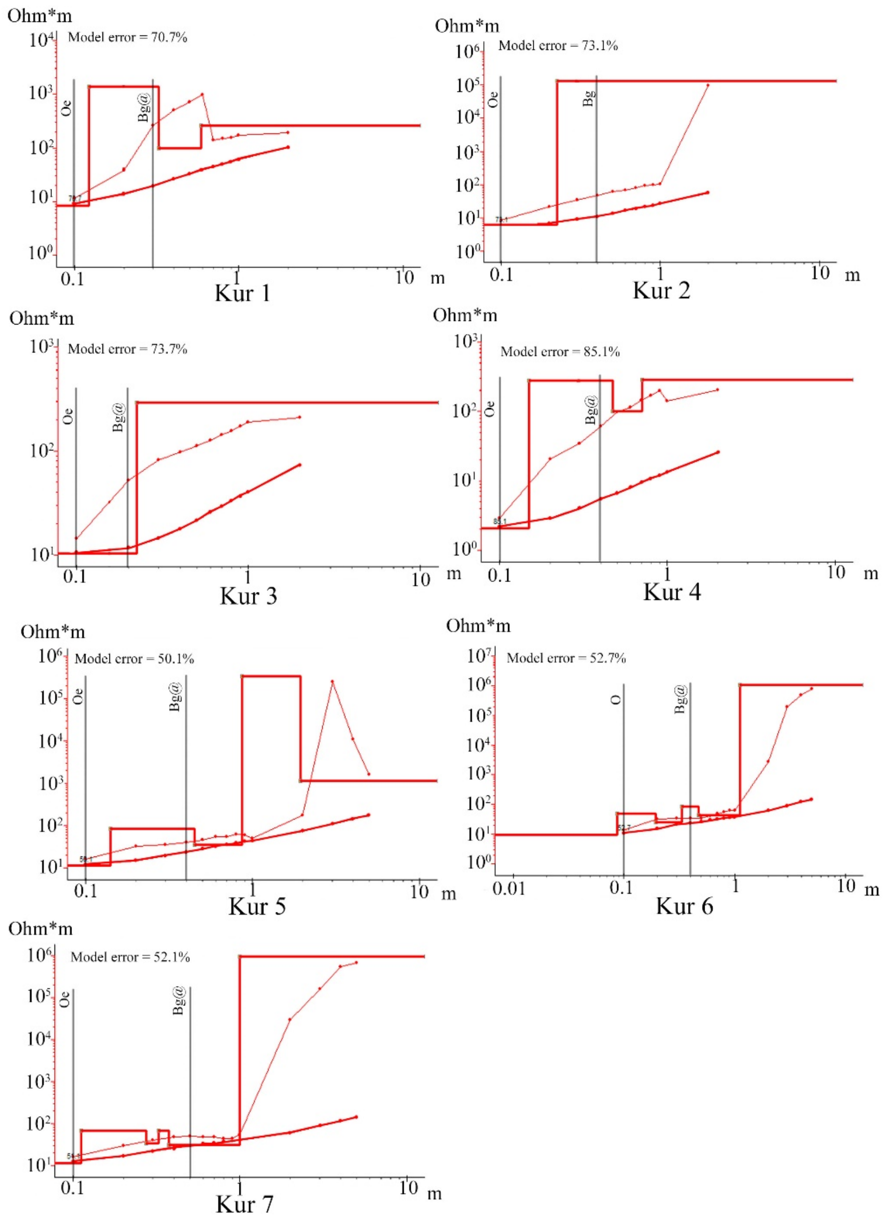

Fig. 5. Profile distribution of ER in soils on Kurungnakh Island. Vertical scale: ER values (Ohm*m); horizontal scale: AB/2 distance

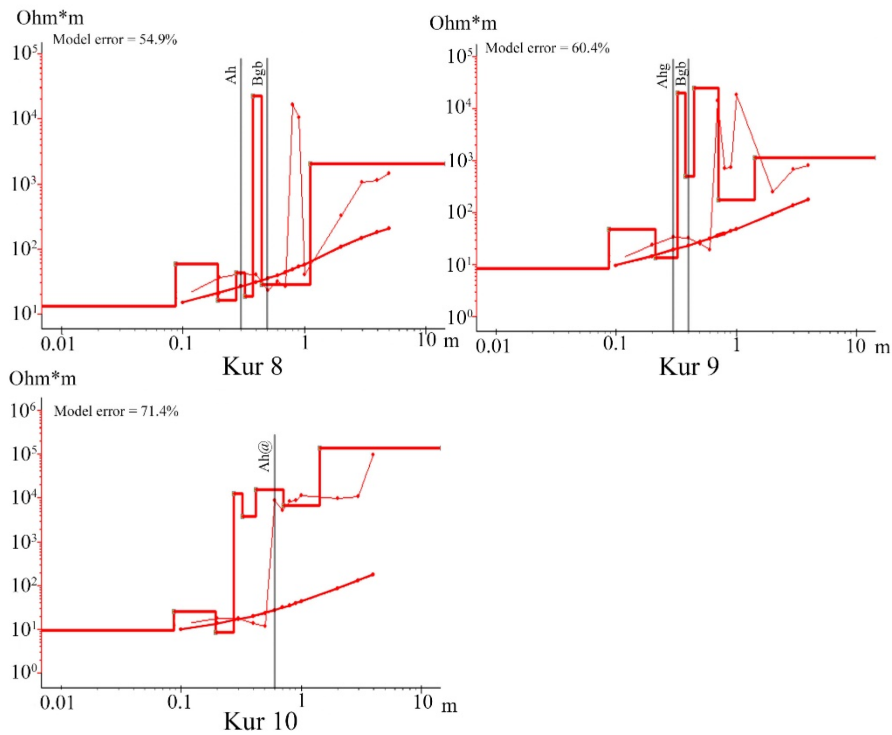

Fig. 6. Profile distribution of ER in the soils of a drained lake on Kurungnakh Island. Vertical scale: ER values (Ohm*m); horizontal scale: AB/2 distance

Kurungnakh Island was formed during the Late Pleistocene and is characterized by inhomogeneous structure. From the surface, the island is composed of modern soils and is underlain by deposits of IC, which reaches several tens of meters and is underlain by ancient siltstones.

Figure 5 shows the obtained VES graphs, all the graphs obtained clearly show the permafrost layer, which corresponds to the boundary found when the soil section was placed. In the profiles Kur 4 - Kur 7, there is a sharp increase in resistivity at a depth of 90-110 cm. These profiles are located at the bottom of the alas and the obtained data may correspond to the upper boundary of the IC. Alases appear in the landscapes of the permafrost zone due to an increase in the volume of suprapermafrost waters. Soil sections Kur 1 - Kur 3 correspond to the tops of the alas, in that soils water does not stagnate and less protected from the wind, therefore they have a relatively close occurrence of permafrost border.

According to ER distribution and field determination of the active layer thickness, the model depths of permafrost distribution were established by ZondIP. They coincide with most of the studied soils, except for the Sam 3 and Kur 7 profiles. This may be due to the permafrost parameters (presence of cracks and pores in the frozen rocks). Another reason may be the presence of layers saturated with poorly decomposed organic residues, which is quite a characteristic feature in the Lena River delta. The other studied profiles are characterized by the presence of the upper permafrost edge, which is less dense than the underlying permafrost, which has higher ER values.

Kurungnakh Island has a rather complex structure, degradation of the IC and coastal erosion, leading to the formation of a rather dissected relief. As a result of coastal erosion, about hundreds years ago, the lake was degraded, and at the moment hilly landscapes (the height of the mounds up to 3-4 m) with grass vegetation are formed in the place. The resulting VES profiles are shown in Figure 6.

On the graphs obtained, we can distinguish the permafrost border, which corresponds to the boundary found during the formation of soil sections, about 50 cm. Then, there is a sharp decrease in the electrical resistivity in the profiles Kur 8 and Kur 9, which are associated with the top of the heaving mound. This anomaly may be the result of the presence of a talik under a drained lake, which was observed before by Olenchenko [21]. At the same time, an increase in resistivity inside the active layer is noted, which corresponds to the occurrence of buried organic matter. Thus, the study of the vertical heterogeneity of the soil layer made it possible to establish the depth of presence of the permafrost layer, to reveal the nature of the change in the resistivity value in the soil layer.

Discussion

The 1D VES method has been effectively used to study cryogenic soils in the (Yamal Nenets Autonomous Okrug (YNAO), according to a study by Abakumov and Tomashunas [5], it was found that the 1D VES method effectively allows determining the active layer thickness by increasing the ER based on changing thawing/freezing conditions. In addition to 1D, 2D and 3D models are used for spatial analysis of natural and anthropogenic objects. Great interest in the use of geophysical research is focused on the Polar Regions [33]. Similar studies were carried out to study the permafrost-affected soils of Spitsbergen [13]. In their study, Gibas et al. notes that the DC (direct current) resistivity sounding method is an effective and convenient method for studying moraine ridges in the preglacial zone. The obtained data on the location of ice cores can be used to predict the transformation of the landscape under conditions of climate change. Geophysical study of mountainous areas has been going on for a long time, because these areas are the most dangerous in terms of landscape changes as a result of permafrost degradation. Thus, in the Alps, Hauck and Mühll [34] used DC resistivity tomography to determine the structure of permafrost. The use of 2d models makes it possible to determine with high accuracy the occurrence of ice wedges in soils affected by permafrost. Scandroglio et al. [35] used long-term data obtained according to 2d and 3d electrical resistivity tomography and thus built a 4d model of the degradation of the Alpian permafrost zone. The data obtained over the past 13 years have shown how the transformation of the landscape took place in the zone of occurrence of permafrost rocks. The obtained data with a high degree of reliability will help in forecasting creeping, rockfalls and slides in the alpine zone.

In the Lena River delta, taliks under the river channel, as well as thermokarst lakes, are of the greatest interest for geophysical research [21]. Thus, using the 2d and 3d VES methods, a talik under a drained lake on Kurungnakh Island was investigated. This modeling is well suited for the study of large objects, the thickness of bottom sediments, the zone of thermal influence of water bodies, as well as the structure under the lake and under the river channel. To determine the active layer thickness, mechanical methods are used as well, the use of a steel probe, and preparation of soil sections [36]. These methods undoubtedly make it possible to determine the upper layer of permafrost, but at the same time, the soil section violates the soil cover of the territory; polar ecosystems are especially vulnerable, since it takes longer to restore the soil cover than in other climatic zones. The use of a probe avoids significant disturbances to the soil cover. But with the annual survey of the monitoring site, the temperature regime of the soil is disturbed, which leads to the degradation of permafrost. Cryogenic soils and grounds are complex heterogeneous environments, so the application of classical concepts of current conductivity in such systems is inapplicable for them. Cryogenic soils of the Lena River delta are formed in conditions of great influence of both cryogenic (heaving, cryogenic mass exchange, ice formation) and river processes, which lead to frequent change of soil-forming rocks (interlacing of sandy, sandy loam, loamy and clayey sediments within one profile). Such shifts lead to rather sharp changes in resistivity. This can be observed in soils from Samoylov Island, as well as on Kurungnakh Island (drained lake). The data obtained by us agree with the data of Frolov (1998), high resistivity of frozen rocks is caused by the formation of a large number of pores in alluvial soils of the Lena River delta, the resistivity of coarse-grained sands can reach 10^6 Ohm m, which is associated with the formation of schlier cryogenic textures, ice complex, and massive ice with the inclusion of organomineral matter [37]. In Olenchenko et al. [21] also noted that the electrical resistivity under the drained lake on Kurungnagh Island can reach up to 105 Ohm*m, which is confirmed in this work. The abrupt increase in resistivity can be caused by changes in the variations of particle-size distribution, freezing conditions, the appearance of melt water at the boundary with the permafrost, as well as talik zones, may indicate a sharp decrease in resistivity in the studied profiles.

Conclusions

For the first time, the VERS method was used to study direct current electric fields in the ground of the permafrost zone of the Lena River Delta. It was found that in the cryogenic soils of the Lena River Delta, the ER parameter increases with depth, the maximum values correspond to the boundary of the permafrost. It was noted that on various islands of the Lena River Delta, a permafrost table, which is not affected by thawing processes has been observed. This boundary is characterized by maximum values of ER (> 10000 Ωm). An atypical distribution of electric fields was noted under a drained lake on Kurungnakh Island, this may be due to the presence of a talik under the lake. In the soils on the islands of the first terrace (Samoylov), the thickness of the active layer is greater (up to 60 cm), this is due to the warming effect of the river. The permafrost table, is observed on the studied islands within the range (100-120 cm).

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