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*METHODS OF CRYOSPHERIC RESEARCH*

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# THE STUDY OF TALIK UNDER A SMALL WATERCOURSE BY THE CAPACITIVE RESISTIVITY METHOD

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The results of application the method of capacitive resistivity prospecting in the complex of engineering-geocryological studies on the territory of the oil and gas industry area are presented. The presence of a closed talik under a small watercourse, formed as a result of groundwater filtration, has been established. A diagram of the talik structure has been compiled up to the depth of 12 m under the stream bed. It has been revealed that, as a result of anthropogenic changes in the terrain, the talik depth now significantly exceeds the stream channel width. The effectiveness of the application of the method of contactless electrical prospecting in the conditions of the Polar region has been demonstrated.

*Capacitive resistivity survey method, oil and gas infrastructure, talik, electrical prospecting, index of investigation depth*

## INTRODUCTION

Electrical prospecting by the method of resistivity in the geophysics of the permafrost zone takes a leading position among other methods of geophysical exploration. It is the most developed and widely used method for solving various engineering and geocryological problems. A great deal of practical and scientific experience has been accumulated in the application of electrical prospecting for the study of permafrost deposits [*Frolov, 1998; Zykov, 2007; Yakupov, 2008; Sjoberg et al., 2014*]. From the first electromagnetic studies of frozen rocks in the Transbaikalia in 1934 to the present, a large number of methods of field work, as well as methods of processing and interpreting the obtained data, have been formed [*Khmelevskoy, 1984; Ogilvy, 1990*]. The active development of oil and gas fields in the Arctic determines the increasing volume of engineering and geocryological studies at oil and gas infrastructure facilities. According to I.G. Yashchenko [*2017*], 38 % of the total number of occurrences in Russia are located in areas with insular, discontinuous or continuous distribution of permafrost, however, in terms of oil reserves, the territory of the permafrost zone is much richer. That fact necessitates the design and construction of a large number of pipelines, well pads and other structures of the oil and gas infrastructure, ensuring their high reliability during operation. In that regard, a number of engineering-geocryological problems of the oil and gas complex have been formed, for the solution of which it is promising to use electrical exploration as an independent method and in combination with other methods of geophysics and engineering-geocryological research.

On the territory of the Russkoye oil and gas condensate field, for the purpose of a detailed study of the geocryological structure of the section, the detection and mapping of thawed soils in the zone of interaction with the oil and gas infrastructure, the electrical exploration has been carried out, some of the results of which are presented in the article.

## EXPERIENCE OF THE ELECTRIC-EXPLORATION RESEARCH AT OIL AND GAS INFRASTRUCTURE FACILITIES

In general, in the modern scientific literature there are few publications on the application of the electrical prospecting and geophysical research in engineering-geocryological studies at oil and gas infrastructure facilities. In addition, modern Russian regulatory documents do not oblige, but recommend the performing of geophysical studies during engineering and geological surveys [*SP 11-105-97, 2004*], with the exception of determining the corrosiveness of soils to carbon and low-alloy steel and determining stray currents for metal structures [*GOST 9.602.2016, 2016*].

Out of the domestic works, it is necessary to note the dissertation [*Smilevets, 2003*], which summarizes the long-term experience of its author in performing geophysical research at oil and gas facilities in Western Siberia. In it, the author focusing on the inhomogeneous block structure of the upper part of the permafrost section with the presence of transition zones, recommends the all-year-round study of permafrost by geophysical methods to reveal changes in the physical and mechanical properties of soils of the foundations of buildings and structures, and also describes new methods of studying permafrost, including the using of equipment for contactless measurements of the electromagnetic field. Among the shortcomings of that work today, there is the interpretation of geophysical studies within the framework of a one-dimensional horizontally layered model.

Currently, in engineering and geocryological studies, electrotomography is actively used [*Bobachev, Gorbunov, 2005; Yanhui et al., 2013; Sjoberg et al., 2014; Christophe et al., 2018; Olenchenko et al., 2019*]. Electrotomography is understood as a modern modification of the resistivity method with a certain procedure of field observations, processing and interpretation techniques within the framework of two-dimensional and three-dimensional models [*Bobachev et al., 2006; Loke, 2009*]. With the help of electrotomography, a wide range of engineering and geocryological problems at oil and gas infrastructure facilities can be solved with high detail:

– identification of the area of permafrost heating near the production and injection wells at cluster pads [*Sergeev et al., 2015*];

– contouring of underground ice and highly icy soils, studying cryogenic processes and their dynamics along the routes of linear structures and site facilities [*Olenchenko, 2015; Kopylov, Sadurtdinov, 2019*];

– assessment of ice content and porosity of soils on the territory of the occurrence [*Kotelevets, Skobelev, 2016*];

– differentiation of frozen and cooled deposits of varying degrees of salinity, identification of structural features of the structure of the studied section in the territory of the field [*Kvon et al., 2019*];

– carrying out the electrotomography for environments with highly conductive irregularities of complex shape: here a cluster pad of the field is considered, where metal pipes (piles of structures, well casing) act as obstacles [*Sergeev et al., 2015; Marinenko et al., 2019*].

Today the significant limitations of electrotomography include the need to use the galvanic grounding of electrodes, which is difficult to perform in the winter season in the undeveloped territory of cryolithozone and is impossible to perform on a built-up area (frozen sand filling of well pads, roads, etc.). Field work is possible either in the short summer season or in the winter season, but with the additional equipment for organizing the galvanic grounding of electrodes (perforator, generator, etc.) [*Prigara, Tatarkin, 2012*], as a result the cost of work and labor increase significantly. For the conditions when it is impossible to perform galvanic grounding of electrodes, a method of contactless measurement of the electric field (CMEF) has been developed [*Sapozhnikov, 1982, 1985*]. In his dissertation work A.I. Gruzdev [*2017*] identified the areas of application of contactless technology by the resistivity method, the effect of snow cover on contactless measurements, and presented the results of comparing the resistance method with galvanic grounding and contactless one, when measuring with various modern equipment, both the domestic and imported ones.

In the contemporary scientific literature there are few publications that consider the contactless measurement of the electric field in the territory of the permafrost distribution for solving the engineering-geocryological problems [*Hauck, Kneisel, 2006; Gruzdev et al., 2013*], although at present, with the constantly growing pace of construction of oil and gas infrastructure in the permafrost zone, it is necessary to study the geocryological situation all year round.

## OBJECT AND TERRITORY OF RESEARCH

The study area belongs to the Yamal-Nenets Autonomous Okrug and is located in the northeastern part of the West Siberian Plain on the Pur-Taz Upland (Fig. 1).

Geocryologically, the site is located in the northern geocryological zone, in a subzone of continuous permafrost distribution. The thickness of permafrost in the area of work is more than 300 m; the thickness of the active layer is about 1 m. The tundra plain is lowland with hills and ridges towering 50–100 m above it. That terrain is characterized by swampy areas with wavy surface and marginal glacial formations – traces of the Zyrianka glaciation [*Andreeva, 1978*]. The geological structure is presented by the Upper Neopleistocene lacustrine-glacial deposits of the Ermakovo horizon, represented by sands, sandy loams, loams, clays, overlain by recent bog deposits, represented by peat. The hydrographic network of the region is characterized by the presence of rivers, lakes and bog complexes that belong to the Kara Sea basin (the left-bank part of the Taz river basin). The largest watercourse that crosses the field in the meridian direction is Pyandymyakha, a left tributary of the 3$^{rd}$ order of Taz River with many small nameless rivers and streams flowing into it. The study area of the Pyandymyakha river basin is a vast, swampy (up to 70 %) plain. Due to the flat relief and the close lying of permafrost table to the earth's surface, the rivers have shallow valleys, shallow and very winding channels and low banks. Basically, small and medium-sized lakes prevail, with an area of up to 1 km$^2$, located among the undrained flat-hummocky peat-

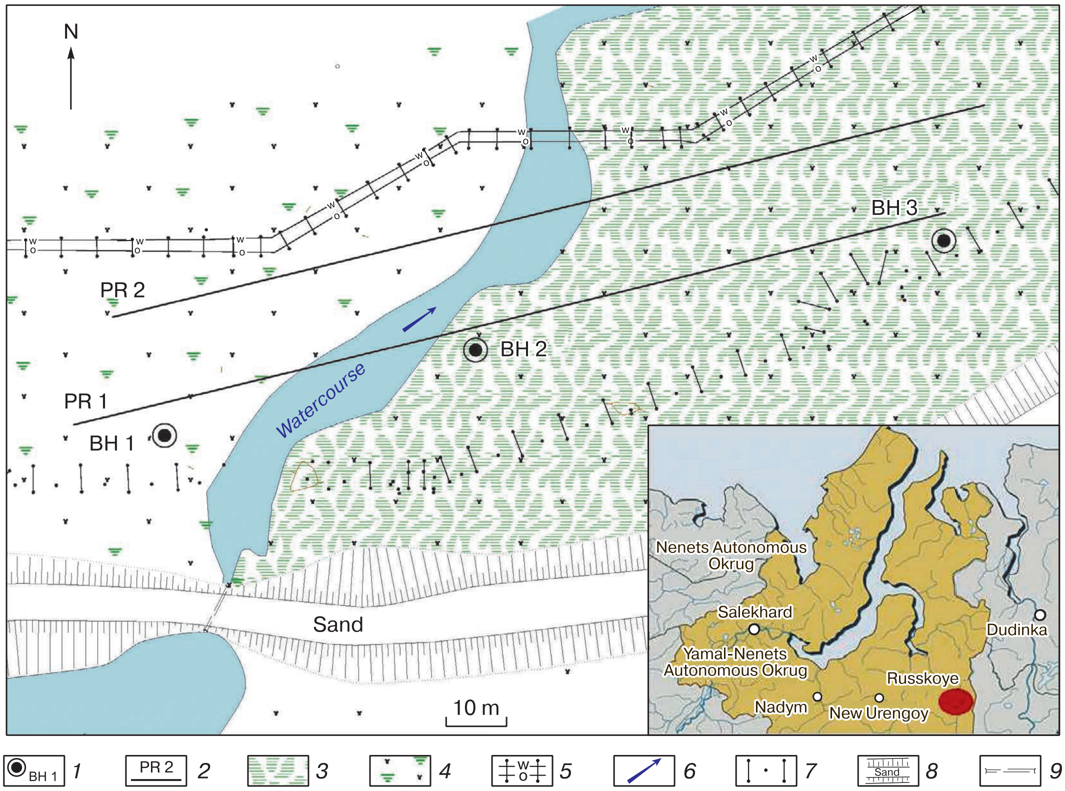


**Fig. 1. Location of the gas and oil field, and a scheme of the work site.**

*1* – engineering-geological bore-hole, its number; *2* – electrical prospecting profile, its number; *3* – wetlands; *4* – vegetation; *5* – overpass of pipelines (w – water pipeline, o – oil pipeline); *6* – direction of the watercourse flow; *7* – overpass supports; *8* – motor road; *9* – culvert.

lands. Due to the shallowness, most of the lakes freeze up to the bottom in winter.

The research of the upper part of the section within the limits of a small watercourse (brook) on the territory of the Russkoye field (Fig. 1) has been performed. The brook, flowing out of a lake, has the length of 7.8 km and a depth of 1 m. Its catchment area is 26.7 km$^2$, the swampedness of its basin is 65 %, its lake percentage is 25 %. The watercourse's valley is not clearly expressed, the floodplain is narrow, in places it is not traced at all. The brook's channel is slightly incised, in winter it freezes completely. Due to the location of the local watercourses in the area of an oil field, they undergo a significant anthropogenic load [*Beshentsev, Pavlova, 2012*]. The researches have been carried out in the area where the watercourse is crossed by two parallel highways with installed culverts. Also on the site, there are two overpasses of infield pipelines on the metal piles, buried in the ground to a depth of about 12 m. The structures exert a large technogenic load on permafrost soils in the immediate vicinity of the watercourse. In addition, in the summer season there is a significant flooding of the territory adjacent to the roads in the culverts' area.

## RESEARCH TECHNIQUE

On the territory of the field within the stream's area, a complex of engineering-geocryological studies, which included a reconnaissance survey, drilling and geophysical prospecting, has been carried out. As part of the drilling work, 3 bore-holes have been drilled up to the depth of 17 meters, in which thermometric observations have been performed. The drilling operations were carried out in October, when the seasonally thawed (active) layer had reached its maximum thickness or was just beginning to freeze. To map and delineate the distribution area of thawed soils, the method of contactless measurement of the electric field was used. The choice of the method of contactless measurements is associated with the implementation of research in the winter period of year (when the active layer began to freeze), when the use of galvanic grounding is difficult. As a recording device, the electrical exploration equipment 'BIKS' was used, developed at JSC SKB SP [*Electrical exploration equipment 'BIKS', 2012*]. The measurements were carried out using a MNAB dipole-axial array, carried along a rectilinear profile. The distance between M and N, A and B (parameter *a*) was taken equal to 2.5, 5 and 10 m, the separation coefficient of the dipoles (parameter $n$) varied from 3 to 13, the maximum separation (OO*) was equal to 130 m (Fig. 2). The studies were carried out with an operating frequency of 16.6 kHz.

The work was carried out along two parallel profiles 160 m long, located along the pipe racks (Fig. 1). The distance between the profiles was 16 m, the measurement step along each profile was 5 m. The choice of the method of electrical prospecting was due to the large difference in the resistivity of thawed and frozen soils. A decrease in temperature and an increase in ice content in soils lead to a corresponding increase in the resistivity of frozen soil [*Frolov, 1998; Yakupov, 2008*]. As a result of field measurements, an array of data has been obtained which included the values of apparent electrical resistance, spacing, station and profile numbers. The apparent resistance ($\rho_k$) was calculated by the formula:

$$\rho_k = \frac{KU_{\text{in}}}{I},$$

where $K$ is the coefficient of the measuring unit, m; $U_{\text{in}}$ is the peak value of the voltage supplied to the input of the receiver, V; $I$ is the peak value of the output current of the emitter, A.

The coefficient of the measuring unit ($K$) was calculated by the formula:

$$K = 2\pi L\left\{\ln\left[\left(\frac{b^2}{b^2-1}\right)^{2b}\left(\frac{b^2+2b}{(b+1)^2}\right)^{b+2}\left(\frac{b^2-2b}{(b-1)^2}\right)^{b-2}\right]\right\}^{-1},$$

$$b = R/L,$$

where $L$ is the length of the dipole, m; $R$ is the distance between the emitter and the receiver, m.

The processing, qualitative and quantitative interpretation of the obtained data were carried out in the ZondRes2d program [*Kaminskiy, 2012*], as a result of which the geoelectric sections and the diagram of the resistivity distribution have been obtained at the depth of the lower end of the overpass pile (12 m).

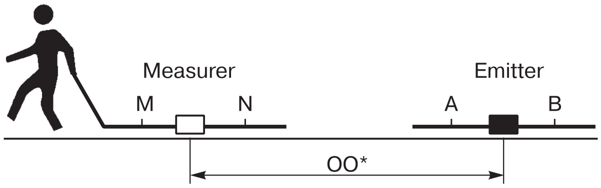


**Fig. 2. Diagram of the used array.**

AB – length of supplying line, MN – length of receiving line, OO* – distance between the centers of dipoles.

## RESULTS OF WORK

During the reconnaissance survey of the territory, the technogenic flooding of the site with surface waters in the area of the culvert of the road embankment has been revealed. The natural relief changes during the construction of industrial facilities (pipe racks, road embankments and well pads). Positive forms of anthropogenic relief appear, which change the surface and groundwater runoff in the summer season and increase snow accumulation in the winter. In that regard, large areas are being flooded, which can lead to the activation of dangerous engineering and geocryological processes. In winter, due to the large thickness of the snow, the freezing depth of permafrost decreases and in summer, as a result of flooding, the thawing depth increases due to the warming effect of surface waters.

According to the data of the engineering-geological bore-holes 1 and 3 (Fig. 3), it has been determined that the section is represented by the interlayering of hard-frozen sands of low ice content, and hard-frozen ice loams with the temperatures from –0.2 to –0.9 °C. For bore-hole 2, the section is represented by alternating water-saturated sands and soft-plastic loams with the temperatures from +0.1 to +1.1 °C.

As a result of qualitative interpretation, a pseudo-section of the observed apparent resistivities along the profile 1 has been obtained (Fig. 4). It has been used to analyze the spatial change in the apparent electrical resistance, which made it possible to determine the regularities of the distribution of the apparent resistance, to distinguish the areas of abnormally high and low values.

The obtained values of the apparent resistivity in the research area are within the range of from 48 to 2480 Ohm·m. The lower limit of values is typical of thawed water-saturated soils, the upper limit is characteristic of frozen loamy-sandy soils. By the nature of the distribution of apparent resistivity, a region of relatively low values is distinguished, typical of thawed dispersed soils. According to the classification of taliks in the permafrost zone [*Romanovskii, 1972*], the area of thawed soils is a closed talik of the hydrogenic (underwater thermal) type, under-channel subtype, soil-filtration class, thermal subclass. Hydrogenic (underwater-thermal) under-channel taliks are formed under the influence of the warming effect of the watercourse on the under-channel soils. In addition, there is a technogenic warming effect on the territory adjacent to the watercourse due to its flooding as a result of the construction of the road embankments, which impede natural runoff.

Figure 5 demonstrates a geoelectric section along the profile 1, compiled as a result of 2D inversion. The upper part of the section is heterogeneous in terms of the resistivity distribution. On the left bank of the watercourse, in the profile interval of 0–70 m, there is an anomalous area with a high spe-

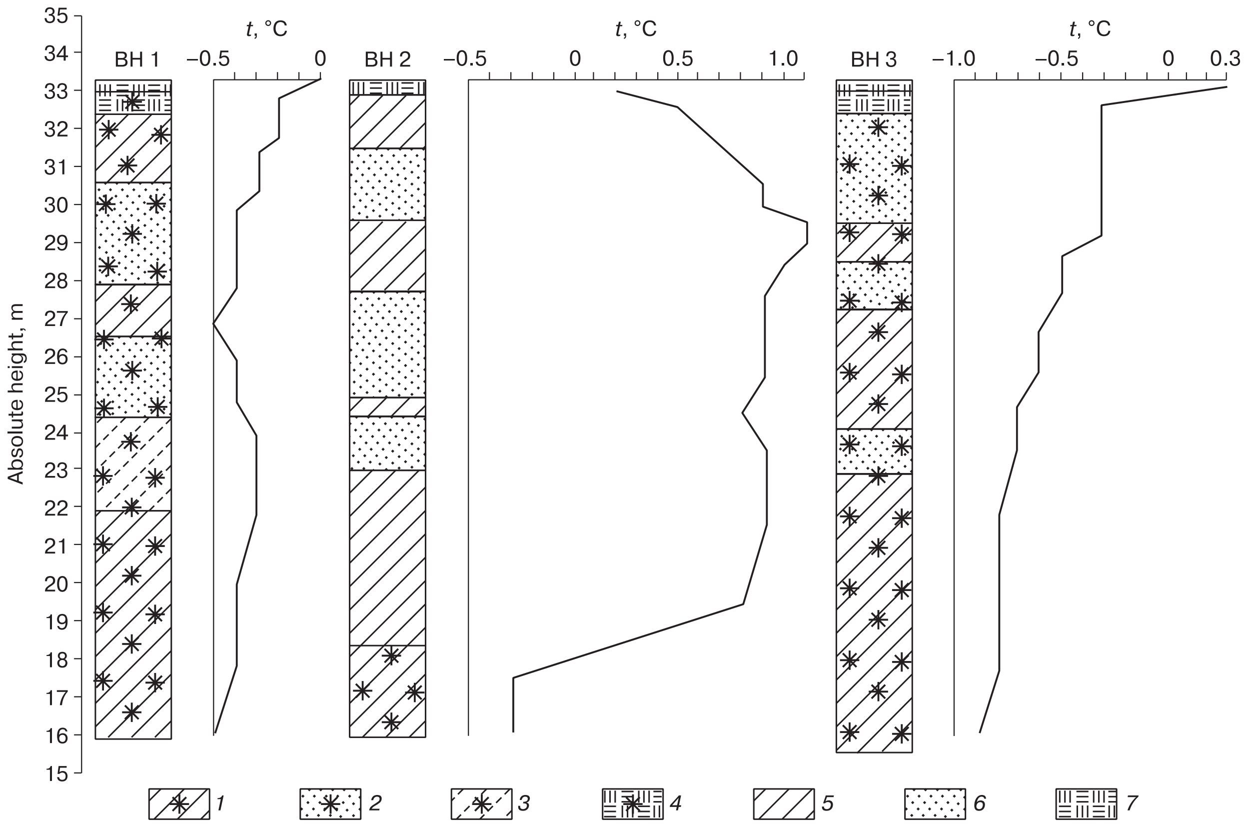


**Fig. 3. Geological columns of bore-holes 1, 2, 3 and depth distribution of soil temperature.**

*1* – frozen icy loam; *2* – hard-frozen slightly icy sand; *3* – hard-frozen sandy slight-icy loam; *4* – frozen very icy peat; *5* – thawed loam; *6* – thawed water-saturated sand; *7* – thawed peat; *8* – soil temperature, °C (11.10.2019).

cific electrical resistivity up to 3000 Ohm·m and a thickness of 2 m, confined to the frozen peat of high ice content. The soils of the right bank of the watercourse in the profile interval of 90–160 m are relatively low-resistive (the resistivity is up to 700 Ohm·m) and are also characterized by the presence of frozen peat in the upper part of the section. The resistivity's heterogeneity of the soils of the right and left banks is explained by the different freezing temperature of the upper part of the section. The increased values of the

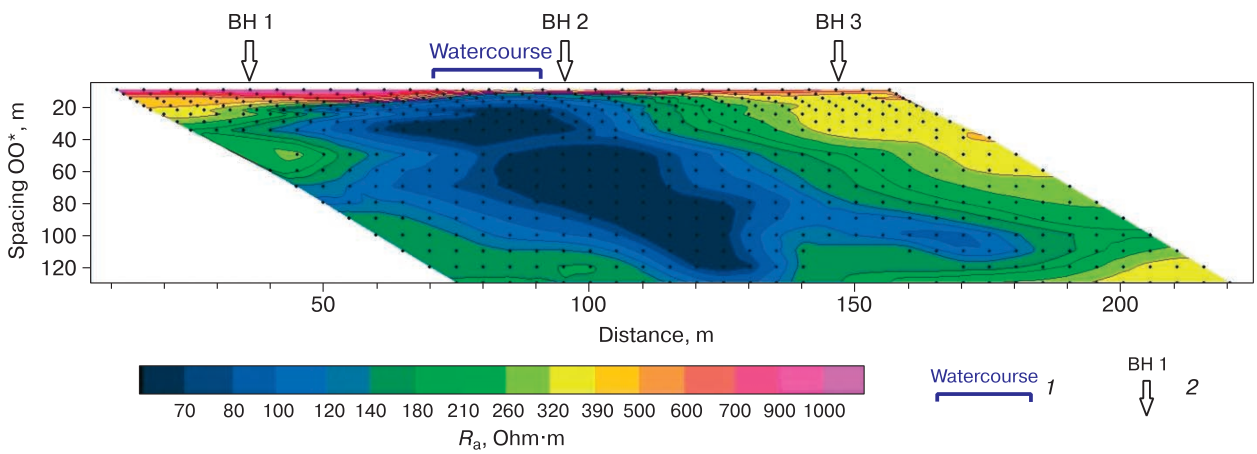


**Fig. 4. Pseudo-section of the observed apparent resistivity ($R_a$) through the profile 1.**

*1* – watercourse boundaries; *2* – bore-hole projections.

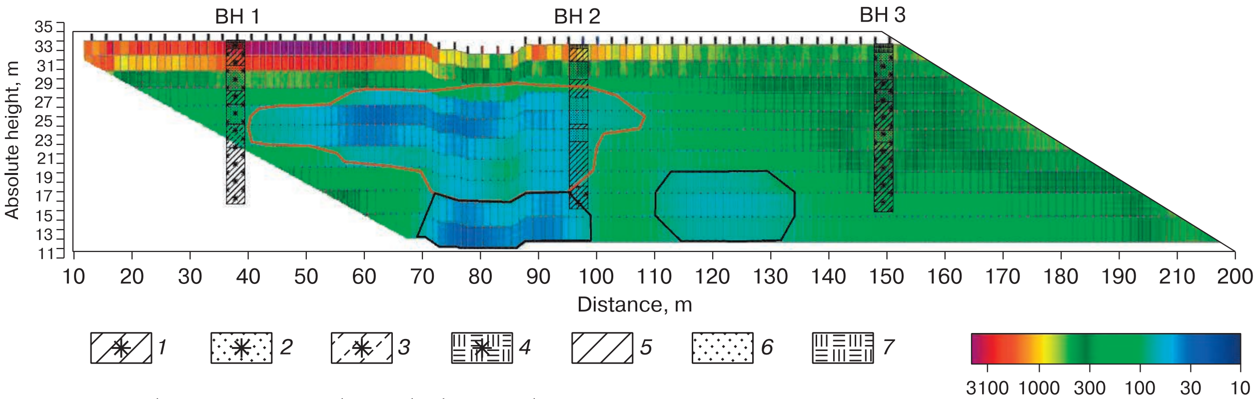


**Fig. 5. Geoelectric section through the profile 1.**

*1* – frozen loam; *2* – frozen sand; *3* – frozen sandy loam; *4* – frozen peat; *5* – thawed loam; *6* – thawed sand; *7* – thawed peat; red line – contour of an area with a resistivity of 100 Ohm·m and less; black line – the area of the proposed influence of the metal piles of communications.

resistivity of the upper part of the geoelectric section (typical for frozen soils) have been observed in the area of the bore-holes 1 and 2 due to the fact that the drilling and core sampling were carried out in October, when the active layer was in a thawed state, and the geophysical surveys were performed in December when the active layer was frozen.

Within the profile interval of 40–140 m up to an absolute elevation of 16 m, an abnormally low-resistive region with a specific electrical resistance of 30–100 Ohm·m is distinguished, which is characterized by the presence of thawed loamy-sandy soils. According to the data of the bore-holes 1 and 2, the talik is confined to sands, through which groundwater is being filtered, what leads to warming of that part of the section.

The threshold value of the resistivity of 100 Ohm·m, separating the thawed and frozen soils in the geoelectric section, has been adopted taking into account the literature data [*Frolov, 1998; Zykov, 2007*] and the results of the analysis of archival materials of geophysical studies carried out in the nearby areas with a similar soil composition.

Within the profile intervals of 70–100 m and 110–135 m, in the lower part of the section, from a depth of 15 m, a low-resistive region is distinguished, which is presumably associated with the influence of metal piles of communications on the measured values of the potential difference at the large electrode spacing.

To assess the quality and reliability of the inversion results, the DOI (Depth of Investigation) index proposed in [*Oldenburg, Li, 1999*] has been used. It is based on the comparison of two inverted resistivity models of the same data set using different values of the electrical resistance of the reference model. The first reference value ($q_A$) is usually calculated out of the average logarithm of the observed apparent resistivity value. The second reference resistivity value ($q_B$) is usually taken 10 times more than $q_A$. The DOI index value ($R_{AB}$) for the model cell is determined by the formula:

$$R_{AB}(x,z)=\frac{q_A(x,z)-q_B(x,z)}{q_A-q_B}.$$

The $R$ value will approach zero in parts of the model where the two inversion processes reproduce the same resistivity values. In such areas, the cells contain objective information about resistivity. In areas where the data does not contain information about the resistivity of the cell, the $R$ will approach a value of 1, since the resistivity of the cell will be similar to the reference resistivity.

Figure 6 represents a section demonstrating the distribution of the DOI index through the profile 1.

In the right part of the section from the point of 160 m onwards, an area of the relatively higher index values is clearly distinguished. Due to the peculiarities of the methodology of field work in that area, the measurements have been not performed, but in the process of performing the inversion, the resistivity values have been automatically calculated by the processing program. Therefore, that area is distinguished by the increased DOI values and is interpreted as a false anomaly. In the profile interval of 50–140 m, an area of DOI values from 0.08 to 0.13 is distinguished, which is a sign of an objectively selected resistivity model. It is interpreted as an under-channel talik.

Based on two almost identical geoelectric sections of the profiles 1 and 2, a diagram of the distribution of the soil electrical resistivity (Fig. 7) has been compiled at a depth of the lower end of the pile foundation – 12 m.

The distribution of thawed soils at a depth of 12 m is observed not only in the under-channel part, but also goes beyond its limits. The low-resistive re-

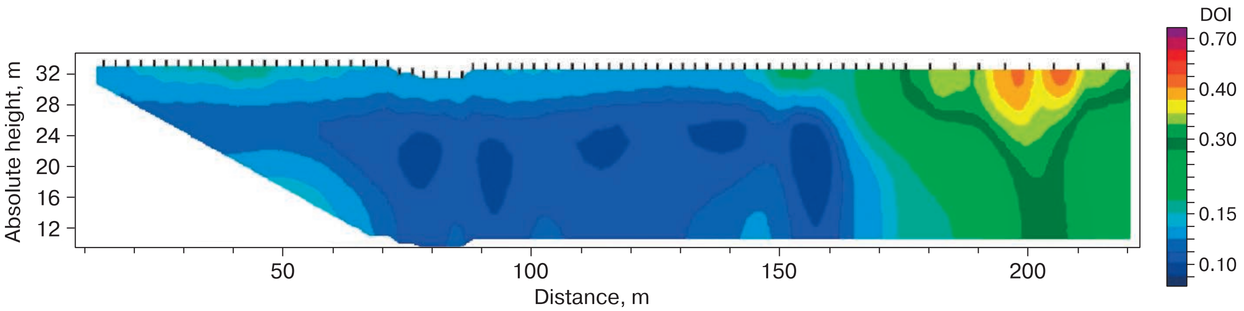


**Fig. 6. Section demonstrating the distribution of the DOI index.**

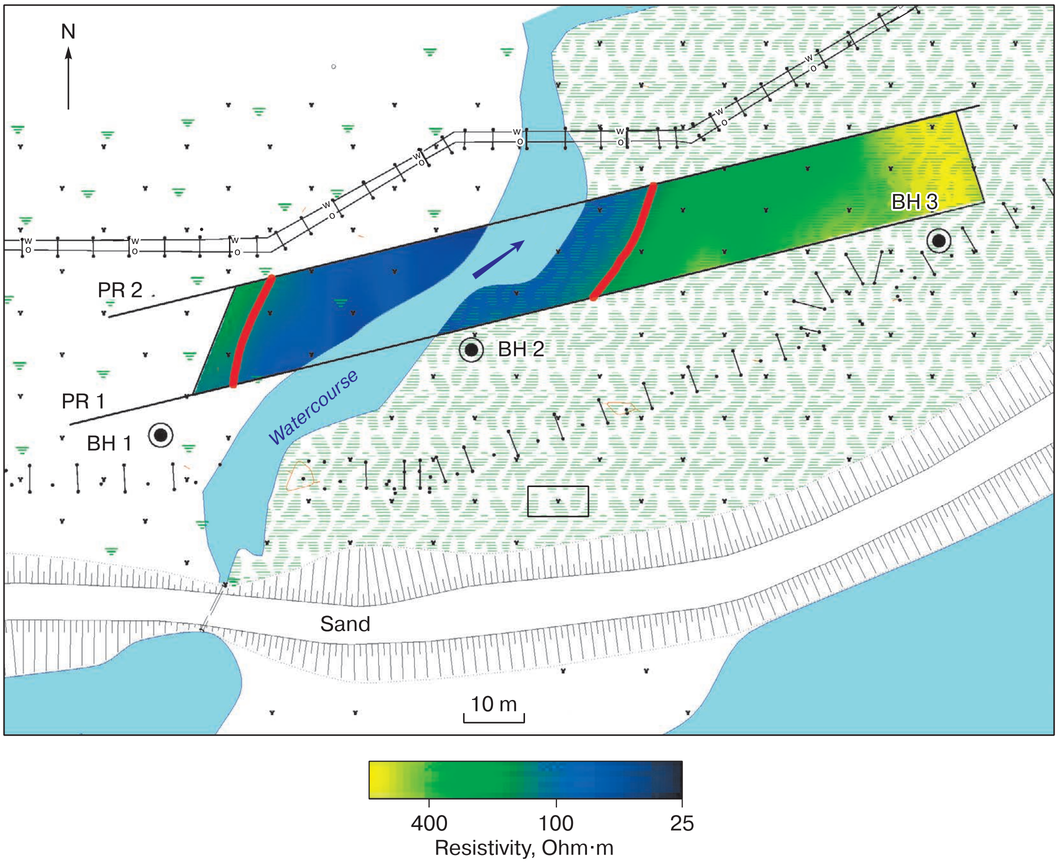


**Fig. 7. Distribution of the specific electrical resistance of the soil in the plan at the depth of the lower end of the pile (12 m).**

The red line marks the talik area according to the electrical survey data. For the rest of the legend see Fig. 1.

gion highlighted in the diagram (less than 100 Ohm·m) is interpreted as thawed soils with a low bearing capacity compared to high-resistance frozen ones. The width of the thawed soil zone at a depth of 12 m is about 70 m in plan. Due to the fact that the principle I is used in the design and construction of the oil and gas infrastructure facilities on the territory of the field – the preservation of the frozen state of the soils at the base of the structure throughout its operation, the presence of thawed soils must be taken into account when organizing the engineering protection of existing structures.

## CONCLUSIONS

As a result of comprehensive engineering-geocryological studies, the presence of a closed under-channel talik has been identified, which was formed due to the filtration of groundwater through the sands. The watercourse completely freezes over in the winter season. The technogenic flooding of the territory with surface waters has been revealed, which can activate dangerous engineering and geocryological processes. A diagram of the distribution of electrical resistivity at a depth of 12 m has been drawn up, by which an area of the thawed weak-bearing soils can be traced, which significantly extends beyond the channel part of the watercourse.

Assessment of the DOI index has demonstrated that the applied contactless array and the resistivity of the section make it possible to obtain objective information up to a depth of 20 m.

It should be noted that when using the large spacing of the array, a significant effect on the measured parameter is exerted by the metal structures located in the immediate vicinity of the investigated profile. That, in turn, leads to a distortion of the resistivity and the appearance of false anomalies in the geoelectric section.

The performed geophysical research has demonstrated good agreement of the obtained results with the data of engineering-geological bore-holes. The efficiency of the application of the contactless method of electrical prospecting in the Polar region and the need to use electrical prospecting not only at the stage of engineering surveys, but also during the operation of facilities with the aim of the express monitoring of the activating dangerous engineering and geocryological processes.

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