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Geophysical Methods in Geocryological Monitoring

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Abstract—This paper substantiates the necessity of using geophysical methods in geocryological monitoring to study the conditions of permafrost rock occurrence, search for taliks and cryopegs, and determine the physical and mechanical properties of frozen rocks. The advantages and disadvantages of these methods and examples of their use for solving geocryological problems are described both in natural conditions and in the impact zone of buildings and engineering structures.

Keywords: permafrost rocks, geocryological monitoring, geophysical methods, seismic exploration, electrical exploration, ground penetrating radar

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INTRODUCTION

The development of the Arctic should take climate changes into account. The increase in the temperature of the upper horizons of the cryolithozone, which occupies 65% of the Russian territory and determines the key conditions for the natural environment, economic activity, and life of the local population, will cause loss of stability of the foundations of buildings and engineering structures. The estimated damage to the economy can reach 5–7 trillion rubles by 2050 for the Russian Arctic zone alone (Mel'nikov et al., 2021). The situation has become critical in the Arctic: the number of deformed buildings is close to 40% (about 40% in Amderma, 33% in Dixon, 22% in Tiksi, and 50% in Pevek). Permafrost is also widespread outside the Arctic, in particular, in Yakutia, where it occupies 95% of the territory.

It is possible to insure the stability of the infrastructure based on a geocryological monitoring system. However, its implementation requires a comprehensive analysis of the capabilities of the Earth sciences, including geophysics, a modern research tool. The potential of geophysical methods is insufficiently discussed in the literature and hardly taken into account during the design of monitoring. Judging from publications in the press [https://www.mnr.gov.ru/press/news/sozdanie_sistemy_-monitoringa_vechnoy_merzloty_plany_ nauchnykh_ekspeditsiy_ledostoykoy_platformy_itog/], the Ministry of

Natural Resources of Russia is on the path of creation of an observation network exclusively for analyzing the thermal state of permafrost in natural (background) conditions. Areas under development and built-up areas and dangerous permafrost processes are outside the scope of this monitoring. In large human settlements, the soil temperature differs from the temperature in natural conditions by 3–6°C. Instead of solving this important state task, it is only proposed to expand the existing background network. Observations should cover not only soil temperature but also other parameters that are necessary for predicting the development of hazardous natural processes. To determine these parameters (the properties of snow and vegetation cover, composition and structure of soils in the upper horizons of the lithosphere and their thermophysical, physical and mechanical, and other characteristics), we can and should use geophysical methods. This article discusses the possibilities of using geophysical research methods to solve the problems of permafrost monitoring.

The observation network for the state of permafrost is based on the construction of thermometric wells. Temperature serves as a basis for determining the characteristics of a cryolithozone, namely, its spatial position and mechanical properties, which are necessary for estimating the stability of the foundations of buildings and structures. Geophysical methods significantly complement the study of the section. These are nondestructive research methods; they are used on the Earth's surface, within water areas, in wells, and remotely (aerogeophysics). Geophysical works have almost no negative effect on the ground cover, which is especially important in tundra, where its destruction causes thermokarst and other negative processes. Unlike drilling, geophysical methods make it possible to obtain continuous information on depth and strike, as well as on the variability of the state and properties of permafrost rocks (PRs).

It is important to note that it is not always possible to determine the state of rocks (frozen/thawed) based on temperature data. Geophysical methods help answer this question. They provide data on the physical and physical and mechanical characteristics of the environment, including deformation and strength characteristics, which are necessary for designing the foundations of structures. Therefore, geophysical monitoring makes it possible to assess change in the bearing capacity of frozen rocks.

According to regulatory documents, it is recommended to carry out stationary geophysical observations at specially equipped points of the observation network with fixed sensors and receivers or on a network that was established on the ground during engineering and geological surveys (SP-11-105-97-6, 2004). The frequency of observations should allow the registration of the extreme values of change in the components of the geological environment in specific conditions. In practice, such stationary networks are organized extremely rarely and observations on the state of cryolithozone (background monitoring) are often limited to studying the seasonally thawed layer (STL) (e.g., in the CALM software, https://arcticdata.io/catalog/portals/CALM/About).

The purpose of monitoring the permafrost (or monitoring of cryolithozone) is to assess its structure and state both in natural conditions and in developed areas and develop a forecast for its change under the influence of natural and anthropogenic factors. The tasks of geocryological studies, including geophysical monitoring (in particular, under conditions of technogenic impact) are to determine the position of the roof of PRs; study the structure of the PR stratum with identification of underground ice, taliks and cryopegs, areas of gas accumulations, filtration zones, etc.; assess the physical and mechanical properties of PRs and their changes; and monitor and predict slope (sea and river shore slopes and quarry walls) and other processes leading to the disturbance of the soil mass.

Extensive experience in field and laboratory geophysical studies of frozen rocks has been obtained; the currently developed research methods have proven their effectiveness (Skvortsov, 1997; Krylov and Bobrov, 2002; Ermakov and Starovoitov, 2010; Mel'nikov et al., 2010; Sadurtdinov et al., 2011; Skvortsov et al., 2011; Sadurtdinov et al., 2016; El'tsov and Olenchenko, 2017; Olenchenko and Kondratyev, 2017; Selyaev et al., 2017; Sudakova et al., 2019; Koshurnikov et al., 2020).

SUBSTANTIATION OF THE USE OF GEOPHYSICAL METHODS

The temperature transition through 0°C leads not only to the phase transition of water in rocks but also to a qualitative transformation of their composition, structure, and properties (Ershov, 2002).

The geophysical properties also significantly change in this case (Dzhurik, 1982; Voronkov and Frolov, 1992; Frolov, 1998; Omel'yanenko, 2001; Zykov, 2007; Sudakova and Vladov, 2020).

The rate of propagation of elastic waves increases during the transition of rocks to the frozen state. This is due to the difference in the values of the velocity of elastic waves in ice and in water. The velocity of P-waves (V_p) is 3100–4200 m/s in ice and 1450 m/s in water. The velocity of S-waves (V_s) is 1600–2100 m/s in ice and 0 in water. The cementing effect of ice plays an important role. Thus, during the freezing of coarse rocks, the V_p values increase by 3–5 times and V_s values by 5–15 times; in fine rocks, where there is more unfrozen water, they increase by 1.5–3 and 5–7 times, respectively. During the freezing of fractured hard rocks, the values of the velocity of elastic waves usually increase by no more than 2–3 times. In rock masses, the velocity of elastic waves in the absence of fractur-

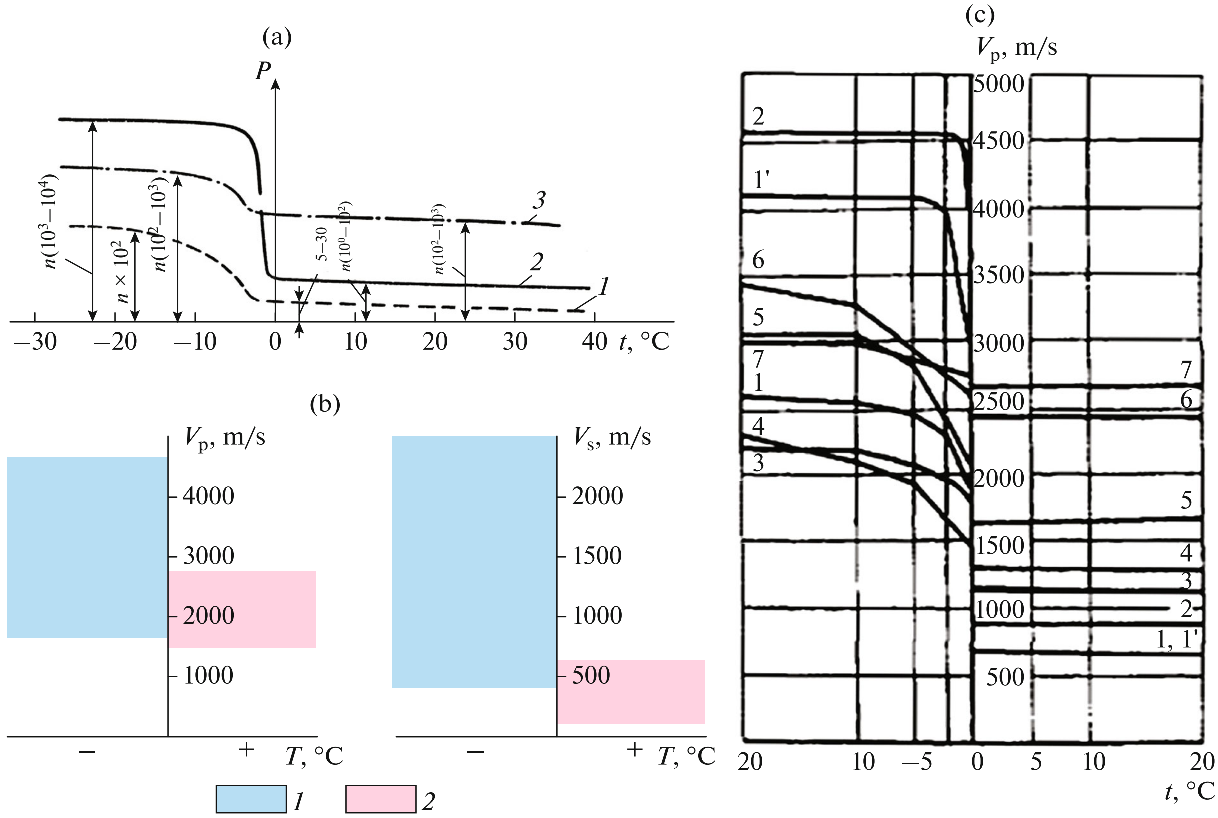

Fig. 1. The dependences of geophysical parameters of rocks on temperature for: (a) electrical resistivity: (*1*) hard rocks; (*2*) sands; (*3*) clays, according to (Ogilvy, 1990); (b) P-wave velocity in different types of rocks (natural water content $W = 10–15\%$): (1) clayey sand, (1') quartz sand ($W = 19\%$), (2) pebbles ($W_c = 15\%$), (3) interbedded clay and sand, (4) clay, (5) sandstone, (6) marl, (7) chalk, according to (Frolov, 1998); (b) ranges of P- and S-wave velocities in frozen (*1*) and thawed (*2*) water-saturated unconsolidated sandy–clayey rocks (Skvortsov et al., 2014).

ing changes very little during the temperature transition through 0°C.

The electrical resistivity (ER) of fresh ice is very high (10^5–10^8 Ohm m), while that of ice from mineralized waters is lower (10^2–10^4 Ohm m), and it depends on the content and composition of salts in the ice. Therefore, the ER of rocks increases during their freezing: by no more than 10 times in hard rocks, 10–100 times in fine loose rocks (clays and loams), and 100–1000 times in coarse rocks (sands and gravel–pebble deposits).

The electrochemical activity of frozen and thawed rocks can significantly differ because of the presence and movement of supra-permafrost and inter-permafrost waters. The induced polarization of frozen rocks is higher than that of thawed rocks and reaches 2–3% for fine rocks, 10% for ice, and 15% for coarse rocks. The relative permittivity of water is 80, i.e., an order of magnitude higher than its value for most rock-forming minerals, and its value for ice is 4. Therefore, the value of the relative permittivity during rock freezing decreases with decrease in the concentration of unfrozen water. Some dependences of the physical properties of frozen rocks are given in Fig. 1.

GEOPHYSICAL METHODS IN GEOCRYOLOGICAL MONITORING

The main methods in cryolithozone geophysics are seismic and electrical prospecting methods, including ground penetrating radar (GPR). Each of these groups of methods has its advantages and disadvantages.

The advantages of **seismic methods** are that they make it possible to unambiguously identify the frozen state of rocks based on certain criteria (Skvortsov et al., 2014). Another advantage is the possibility to directly calculate the dynamic moduli of elasticity, followed by estimates of the strength and deformation characteristics of in-situ rocks. The disadvantages of seismic methods are their laboriousness and high cost. The choice of seismic methods for monitoring purposes is determined by the pattern of the problem to be solved, as well as by the structural features of the section (Skvortsov, 1997) and the season in which the research is carried out. It is preferable to use transverse SH-waves. During monitoring studies, it is necessary

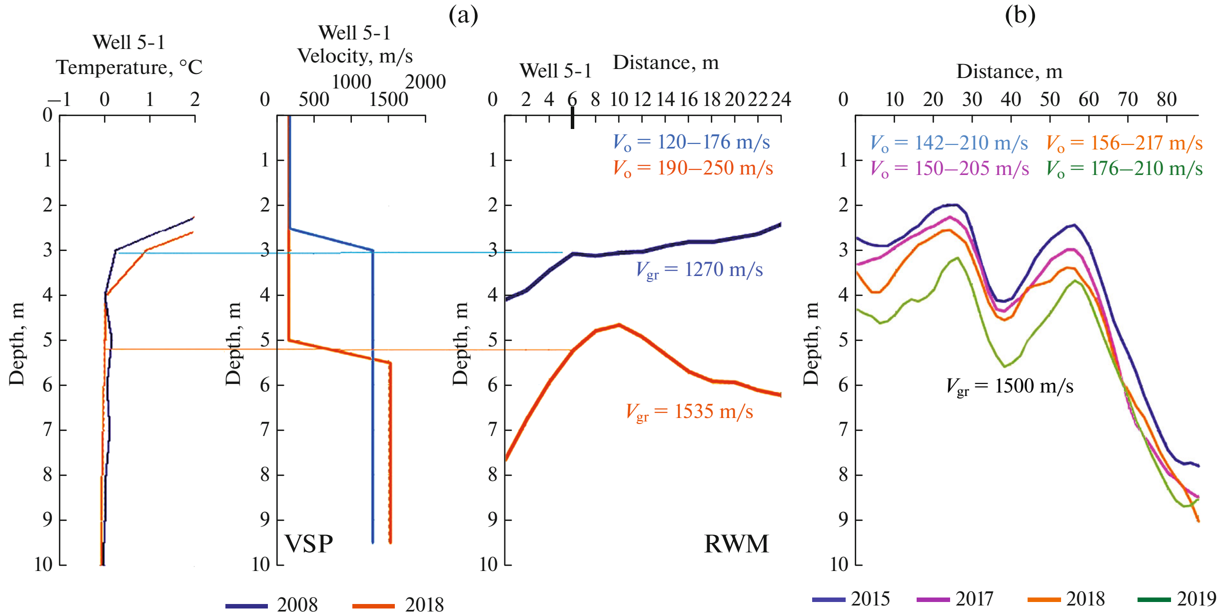

Fig. 2. The results of seismic monitoring observations of the position of the PR roof at stations near the Urengoy field (a) and Kumzha (Nenets Autonomous Okrug, Pechora River floodplain) (b).

to observe the identity of the network of observations and conditions for their performance.

Among the **electrical exploration methods**, the group of resistance methods is most often used for studying frozen strata. Their effectiveness is determined by the contrasting difference between frozen and thawed rocks in ER, which can differ by orders of magnitude (Ogilvy, 1998; Zykov, 2007). The contrast of properties decreases for clayey or saline rocks, which limits the potential of these methods. The advantage is a good resolution in high-resistivity media (selection of weakly conductive objects in a medium with increased resistivity). The disadvantages of the group of resistance methods are the need for galvanic grounding, which imposes seasonal restrictions on the work performance. In addition, experience shows that these rocks become a nonconductive shield for direct current when the ER of frozen rocks and ice reaches 100 kOhm m or more, which reduces the transmission distance and makes it impossible to determine the thickness of the frozen stratum.

Electrical resistivity tomography (ERT) is effective for solving monitoring problems at many facilities; however, this method has some restrictions (El'tsov et al., 2017). The presence of metal objects, such as piles or casing pipes on well pads, causes low resistivity false anomalies, which make it difficult to interpret the sections. In addition, when the salinity is high (Skvortsov et al., 2014) (>5 g/L), the rocks do not differ in their ER; however, ground ice can be identified in the presence of these rocks.

Other methods of electrical prospecting (electromagnetic methods, airborne electrical prospecting, radio-frequency survey, induced polarization, etc.) are less often used for solving geocryological tasks.

The GPR method is based on studying sections using high-frequency electromagnetic waves. The roof of a PR is a contrasting boundary for them, which makes it possible to use GPR to determine its depth and identify taliks (Omel'yanenko, 2001; Schwamborn, 2002; Starovoitov, 2008; Ermakov and Starovoitov, 2010; Shean and Marchant, 2010; Sadurtdinov et al., 2016; Sudakova et al., 2017). This method is least laborious compared to the above-described ones. Among its disadvantages is its small depth, most often 10–15 m (the exception is the study of glaciers). In addition, GPR is usually inapplicable in clayey or saline soils (Vladov and Sudakova, 2017).

RESULTS AND DISCUSSION

Determination of the dynamics of the PR roof. Figure 2 shows an example of using seismic surveys by the refraction wave method (RWM) for monitoring the roof of a PR. At the station near the Urengoy field, ground observations were carried out together with borehole seismic studies and thermometry. The accuracy of determining the position of the PR roof under the conditions of this high-temperature section according to seismic logging data is higher than that based on thermometry. Ground observations provide more detailed information about the dynamics of the position of the PR roof than borehole observations. The roof of a PR tends to dip, which is confirmed by drilling data (Fig. 2). The depth of the PR roof increased by 1.8–3.8 m over the 10 years. At the

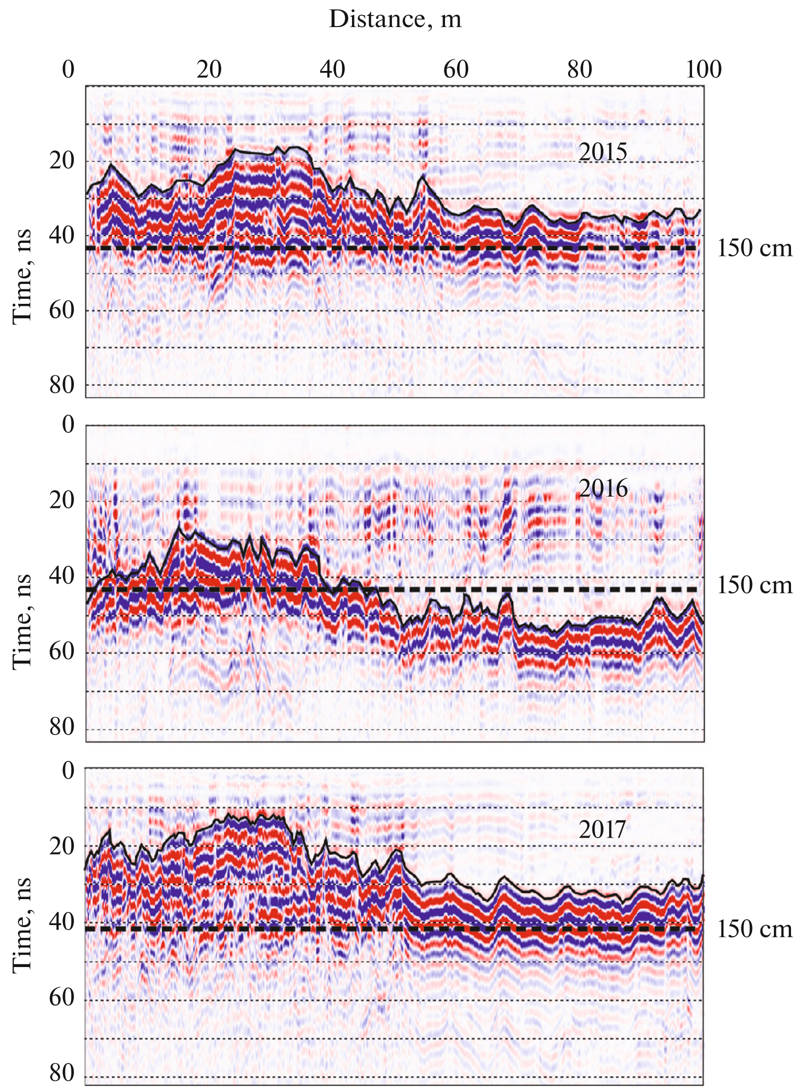

Fig. 3. Georadarograms obtained by profiling at the Kashin geocryological station in 2015–2017. The black line is the in-phase axis corresponding to the STL base. The dotted line shows the line corresponding to a depth of 150 cm with a constant velocity of 7 cm/ns.

Kumzha station on the Pechora River, the depth of the PR roof also tends to increase for the past 4 years (by an average of 30 cm/year).

Figures 3 and 4 show the results of GPR observations along one of the profiles at the geocryological Kashin station (Nenets Autonomous Okrug, the mouth of the Pechora River). The table presents the generalized results of measurements at this station (Sudakova et al., 2021). The average temperature of rocks is given according to the results of measurements in the immediate vicinity of the observation site. A correlation was noted between the data of measurement of the average annual temperature, STL thickness, and rock moisture (Table 1). The average thickness of the STL at the site was 30% higher in 2016 than in 2015 and 2017; in 2017, the average thawing depth almost returned to its value in 2015. The average volumetric water content W_{vol} is 30% lower in 2016 than in 2015 and 2017: the abnormally hot year of 2016 led to STL drying.

Obviously, GPR studies can be effectively used to monitor the state of permafrost in the foundations of motor roads and other linear structures as part of geotechnical monitoring (GTM).

Electrometric monitoring of the state of icy soils and ice beds by the ERT method. As an example of using ERT for monitoring the state of frozen rocks, Figure 5 shows the results of observations of change in the ER of the section within the reclaimed area of thermal erosion development (Fig. 5). The study area is on the territory of the Bovanenkovo gas condensate field (GCF) (Yamal Peninsula). Thermal erosion developing along the ice beds threatened the high-voltage

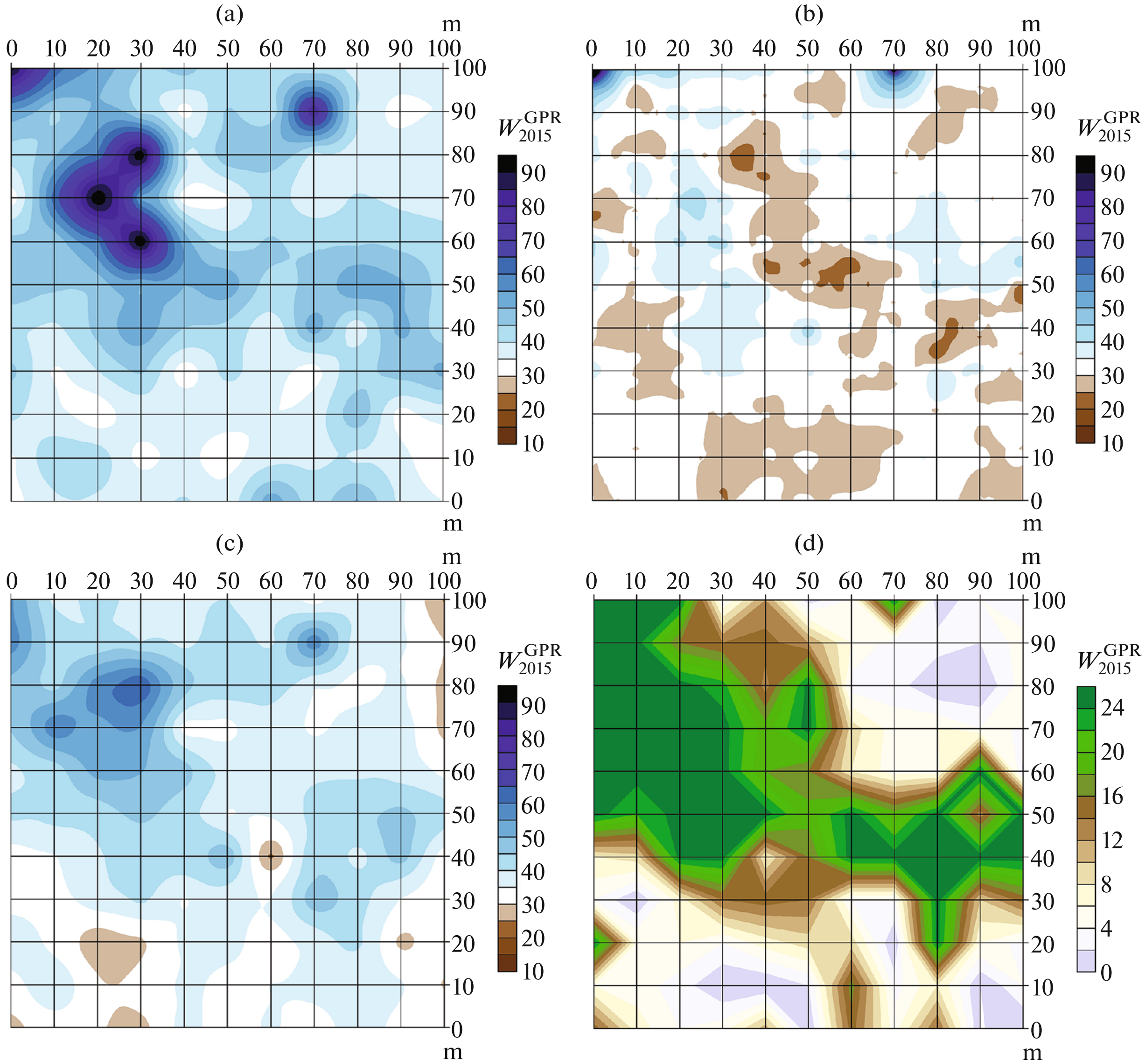

Fig. 4. The STL volumetric water content calculated from GPR data, % (W_{vol}) at the Kashin station (CALM R24A-1) in 2015 (a), 2016 (b), and 2017 (c): (d) peat thickness, cm.

power transmission line. Engineering protection measures were completed there at the time of the geophysical surveys: the formed ravine with its head approaching the power transmission line support was covered with sand and the surface was covered with a layer of hydro- and thermal insulation (polyethylene film and foam plastic). Within the area, studies were carried out along the network of profiles using the ERT method. On the geoelectric section, local anomalies of high ER, which were caused by the effect of ice beds with a

Table 1. The results of monitoring at the Kashin station according to thermal and GPR data

Period	Average temperature of rocks, °C	Field season	Kashin (CALM R24A–1)	
			STL thickness, cm	volumetric water content of the STL, W_{vol}, %
August 14, 2014–August 13, 2015	–1.6	August 2015	80	44
August 14, 2015–August 13, 2016	–0.2	August 2016	109	32
August 14, 2016–August 13, 2017	–1.6	August 2017	76	39

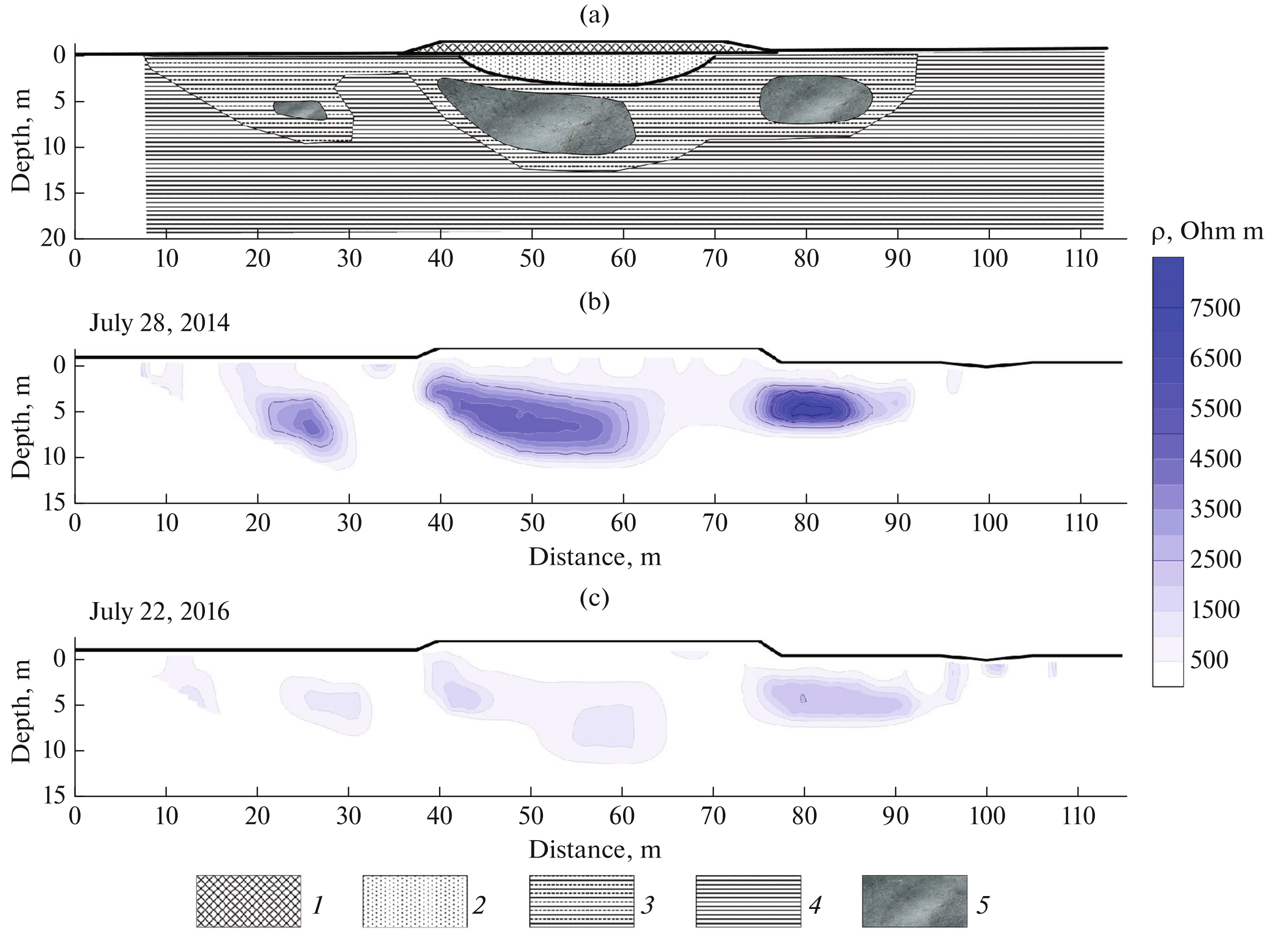

Fig. 5. Geocryological section (a) and geoelectric sections through the reclaimed area with ravine erosion at the Bovanenkovo GCF in 2014 (b) and 2016 (c) according to ERT data: (*1*) thermal insulation; (*2*) sand; (*3*) sandy loam; (*4*) clay; (*5*) ice.

ravine developed along them, are differentiated along one of the profiles made after reclamation in 2014 (Fig. 5). Host rocks are represented by frozen sandy loams and clays with low ER.

Comparison of the geoelectric sections made in 2014 and 2016 showed that the intensity of anomalies from ice beds decreased from 5000–10000 to 1000–3000 Ohm m (Figs. 5b, 5c) over 2 years, which is determined by an increase in their temperature. Electrometric monitoring showed that the frozen stratum continued to degrade, despite engineering measures. In the future, the thawing of underground ice will lead to the formation of thermokarst and activation of ravine erosion.

Monitoring of the state of frozen soils at the base of a large engineering structure (based on the example of the Vilyui HPP). A number of large hydraulic structures, e.g., the Vilyui HPP (including the Vilyui Reservoir), which supplies western Yakutia with industrial electricity, were built and operate in a cryolithozone. Due to the high available power, such facilities are heat sources initiating the degradation of permafrost. Its state is monitored using geophysical monitoring facilities.

The Vilyui HPP was built in a rock massif of dolerite traps up to 200-m thick with inclusions of highly icy carbonate xenoliths, which are expressed on the day surface and have a total length of about 100 m along the right-bank junction. A technogenic water-saturated talik with thawed carbonate xenoliths serving as a collector develops in this area since 1996. The thermal state of rocks at the dam junction is continuously monitored at a borehole thermometric test site, including additional geophysical wells drilled along the right-bank junction in the 2000s. Long-term bypass filtration of groundwater began to threaten the filtration stability of the entire HPP; parameters of its channels are still known only in the most general form. Therefore, to avoid the skipping of its channels, it became necessary to carry out profiling-based monitoring of the right-bank junction of the dam using geophysical methods under the control of temperature measurements at the borehole site.

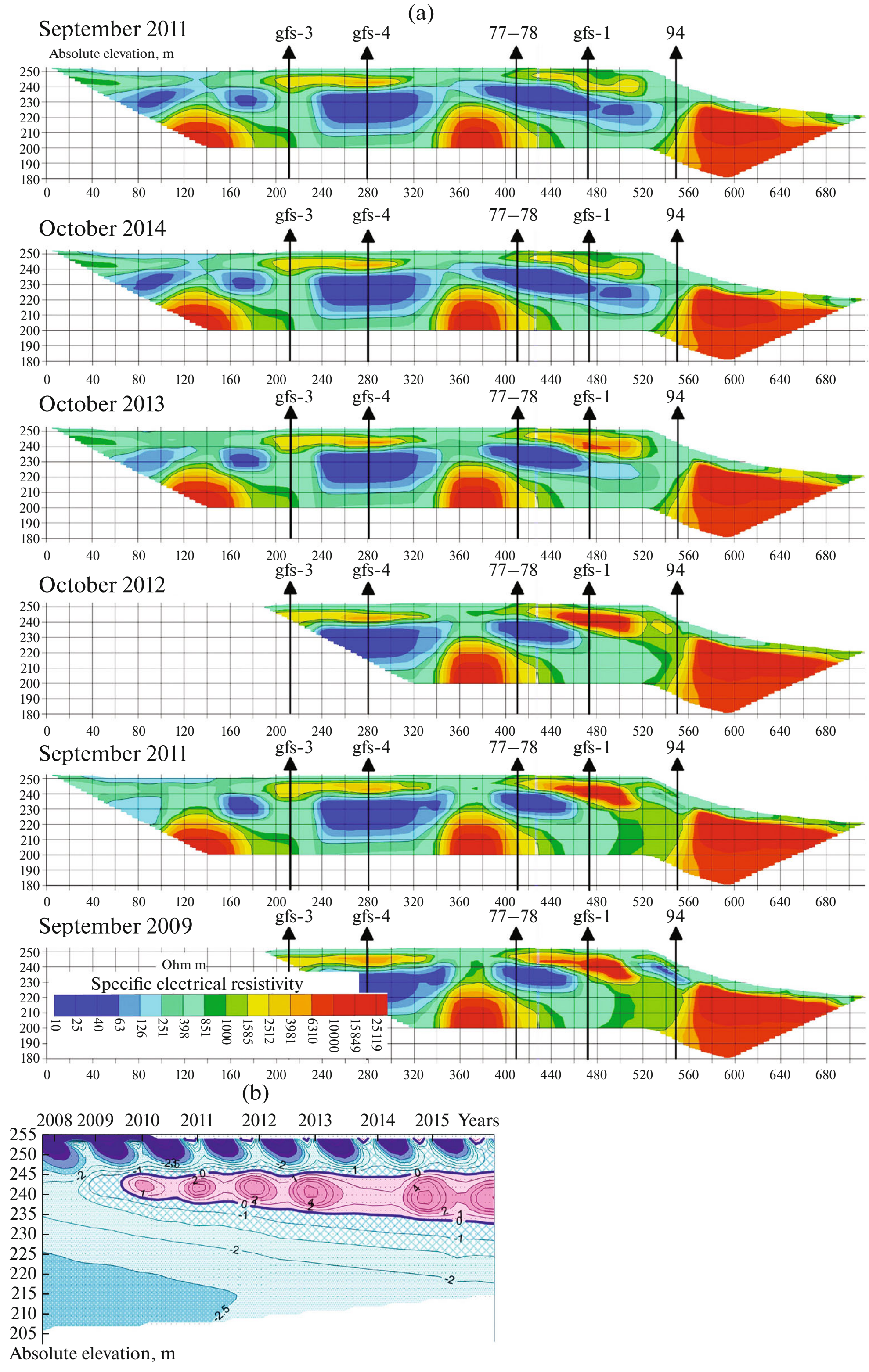

Fig. 6. Geoelectric sections (a) and a fragment of the temperature section (b) (well 78) for 2008–2014 during the monitoring of the state of the junctions of the dam of the Vilyui HPP.

The result of geothermal monitoring of the right-bank junction of the dam by the method of electrical resistivity tomography (ERT) is shown in Fig. 6. On the left, the "geoelectric" degradation of the high-resistance (frozen) near-surface lens (red) is visible near well GFS-1; a similar development is shown for

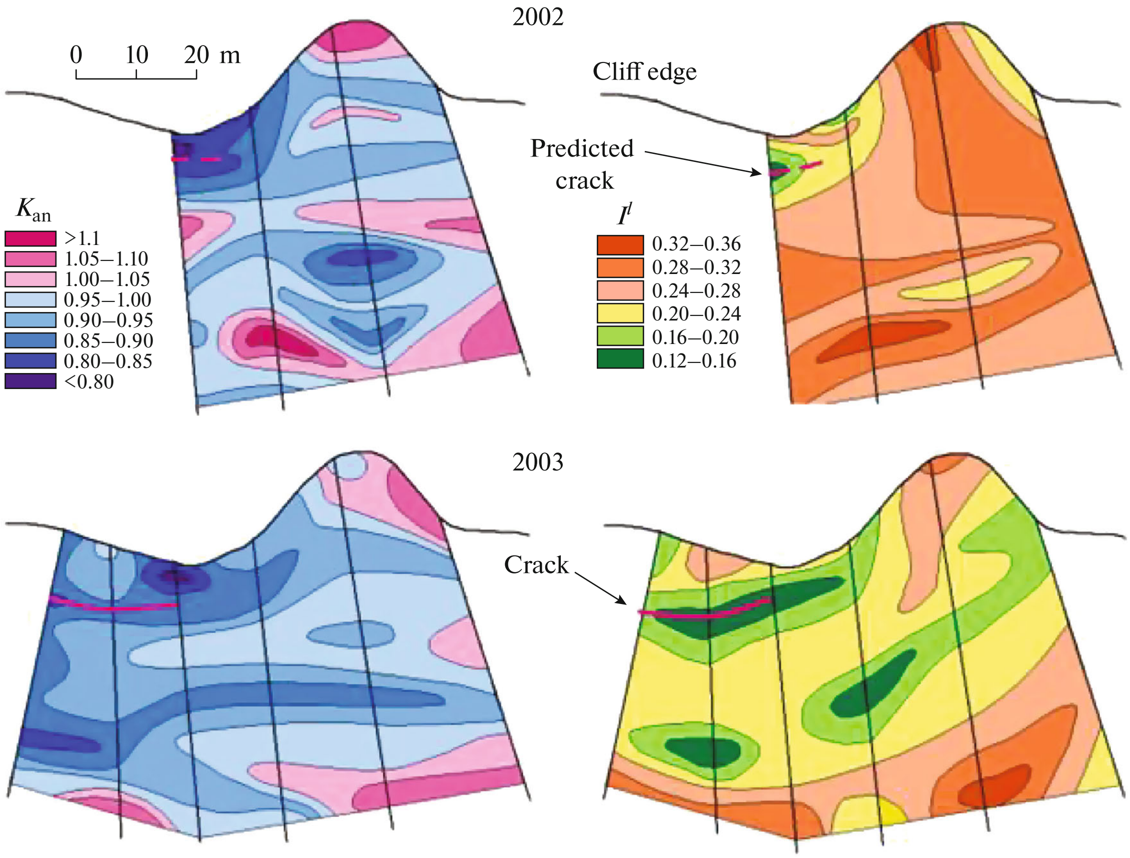

Fig. 7. The distribution of the P-wave anisotropy coefficient (K_{an}) and Poisson's ratio (μ) of soil mass in the coastal cliff (Bolvansky geocryological station, Nenets Autonomous Okrug, Pechora River mouth), according to (Skvortsov et al., 2006).

the low-resistance lens (the channel of bypass filtration of groundwater) near well 78.

The temperature section of well 78 (Fig. 6, right) shows the development of a talik from 2010 to 2015 in the depth range of 230–250 m. As can be seen in Fig. 6, the thicknesses of the talik and low-resistance lens coincide; i.e., the data of geoelectric monitoring are confirmed by the results of temperature observations.

Monitoring of slope processes. Figure 7 shows an example of using geophysical methods for monitoring slope processes on the seashore in the Pechora River mouth at the Bolvansky geocryological station. Here, the PR roof is at a depth of 1–1.5 m.

Based on the pattern of distribution of the values of the P-wave anisotropy coefficient and Poisson's ratio, the spatial position of the weakened zone was established in 2002; it is characterized by abnormally low values of these parameters. The area of possible disturbance of the continuity of soil mass at a distance of 5–7 m from the cliff edge was predicted. In 2003, a large landslide crack was formed in this place. Analysis of the areal distribution of the seismic characteristics obtained in 2003 showed a change in the stress-deformed state in the study site throughout the year. A new weakened zone was formed at a distance of 20–30 m from the cliff edge. The appearance of cracks in this zone was recorded two years later.

CONCLUSIONS

Monitoring of the state of the permafrost is important not only for natural conditions (background monitoring) but also (as part of geotechnical monitoring) for ensuring the stability of residential and industrial buildings and engineering structures (including the infrastructure of oil and gas fields in the cryolithozone) (hydraulic structures). In addition to thermometry and other studies, the organization of the state system for permafrost monitoring requires the use of a set of relevant geophysical methods to assess the state and properties of rocks beyond the limits of the information capacity of thermometric wells.

The above examples of monitoring geophysical studies under different cryolithozone conditions show that geophysical methods can be successfully used to solve the problems of cryolithozone monitoring, including areas exposed to anthropogenic impacts.

In particular, seismic exploration methods are effective for monitoring the position of the roof of permafrost rocks and assessing changes in their physical and mechanical properties during temperature increase, especially in saline rocks, as well as in the presence of metal structures, when the possibilities of electrical exploration are restricted. Electrometric monitoring of the state of soils is based on a significant difference between thawed and frozen rocks in the ER. In coarse and nonsaline rocks, it is recommended to use GPR to determine the boundaries and properties of the section to a depth of 10–15 m, including monitoring of the position of the permafrost roof, STL moisture, and vegetation and snow cover thickness.

These results demonstrate the high efficiency of geophysical monitoring in a cryolithozone. Clearly, it is necessary to make organizational decisions for including geophysical methods in the system of geocryological monitoring. It is especially important to use geophysical monitoring in built-up and disturbed areas, which are characterized by a contrasting space-time variability of permafrost conditions, which cannot be reliably assessed using temperature observations.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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