GPR Technologies for Predicting the Development of Dangerous Cryogenic Processes in Subsurface Soils

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Abstract. The paper presents the results of comprehensive engineering and geophysical studies on road sections of the city of Yakutsk. Actual studies aimed at improving modern geophysical technologies and methods for studying frozen rocks are considered. The results of studying the characteristic features of wave fields to develop signs of interpretation and prediction of the development of dangerous cryogenic processes in subsurface soils according to GPR data are presented. The data of two-stage autumn-spring measurements are presented, the results of which made it possible to study the complex cryogenic structure of the road section of Dzerzhinsky Street. Good convergence of the GPR results with the data of electrical exploration (non-contact measurement of apparent resistance) on the section of Lenin Avenue is shown. Potentially dangerous areas of the development of dangerous cryogenic processes associated with permafrost degradation were identified on the basis of low resistivities on the obtained $\rho_k$ graphs and on the basis of the presence of discontinuities in the events, chaotic signals and low-frequency reflections in the radar section.

1. Introduction
One of the main reasons for the low quality of engineering and geological surveys is the so-called “deficit” of the data volume – the lack of geological workings (borehole) that are remote from each other [1]. At present, geophysical methods are the most effective way to study the interwell space. In difficult conditions of permafrost propagation, the leading methods of geophysics are rightfully considered electromagnetic methods, including GPR technologies [2-4]. These technologies are successfully applied in archeology, hydrology, geology, occupying a certain niche in engineering-geological and geocryological research, both in Russia and abroad.

Experimental studies and testing of GPR technology are given by the example of a survey of the central streets of Yakutsk. The purpose of the presented research is to improve modern geophysical technologies and methods for studying frozen rocks, in particular, to study the characteristic features of wave fields to develop signs of interpretation and prediction of the development of dangerous cryogenic processes in subsurface soils according to GPR data.
2. Research site

The photographs (Figure 1) show the pavement damage that occurred in 2015, near Ordzhonikidze Square (Figure 1a) and the site opposite the Kulakovsky Culture House (Figure 1b). Pits formed at about the same time in May - June on the roadway of Lenin Avenue and Dzerzhinsky Street.

![Figure 1. The pavement damage in Yakutsk: a) Lenin Avenue; b) Dzerzhinsky Street.](image)

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The diameter of the pits formed was several meters. As city services explained, the cause of the accident was the void formation as a result of poor cementing of the old collector. Under the investigated object of Lenin and Dzerzhinsky Streets, a sewer collector passes. Sewer collector No. 1 was put into operation in 1968 and currently does not function. According to the research of Geotechnology LLC (Yakutsk) in 1994, mainly small brownish-gray, slightly moist and “dry” melt sands lie under a layer of pavement (0.8–1.2 m thick) to a depth of 2.5–3.4 m., sometimes in the upper part with thin (0.1 - 0.3 m) layers of sandy loam and clay loam. Further to a depth of 6.4 - 7.1 m, the soil is represented by light gray and gray medium sands, which are in a frozen state. Then, to the roof of the collector tunnel to a depth of 8.3 - 9.8 m, melt light gray middle quartz-feldspar micaceous sands lie (Figure 2a).

In addition, in 2007 (Georesurs LLC, Yakutsk), in the area of Ordzhonikidze Square (Lenin-Dzerzhinsky intersection), electrical exploration studies were carried out by TDEM sounding using an ungrounded circuit [5].

According to the TDEM sounding data, the geoelectric section is characterized by a three-layer structure (Figure 2b). The first surface layer of high electrical conductivity up to 3 m belongs to the active layer and is characterized by the melt state of soils at the time of research. Below to a depth of 7-8 m, a layer of frozen rocks (a layer of poorly conducting soils) is marked, even lower a thawing zone (a layer of high electrical conductivity) is identified in the area of the collector. Thus, according to the results of previous engineering-geological and geophysical works, a general idea of the base soils of the object under study is obtained. A three-layer section with melt sand, interbeds of sandy loam, clay loam from above to a depth of 3.5-4 m was determined. Further to a depth of 7-8 m, the soil is represented by medium sands that are in a frozen state. Then, up to the roof of the collector tunnel up to 10 m, melt soils occur.
3. Research methodology

The accumulated experience [6-8] showed that in the conditions of permafrost propagation, the ground penetrating radars of OKO-2M series produced by the LogiS-Geotech group of companies (Russia) have proven themselves well. Antenna units with a central frequency from 1200 to 150 MHz were used to achieve the required research depth and measurement detail in the considered areas. In addition to GPR surveys, a complex with electrical exploration was carried out at the research site using non-contact measurement of apparent resistance. Their combination provides the opportunity to build the most unique interpretation model of the road section.

3.1. GPR method

To study the permafrost section of Dzerzhinsky Street used the antenna unit AB-250 and AB-1200 GPR “OKO-2M”. Measurements were taken in November 2015, and in March 2016. GPR profiles were laid in 4 lanes and in the center of the road. A vehicle is used to transport antenna units. Speed not more than 20 km / h. Due to the high traffic density and street congestion in the daytime, the site was investigated at night and in the morning.

The studies were carried out in two stages. The first stage was during the period of soil freezing (spring). The second stage was carried out during the period of maximum soil defrost (autumn). The advantage of this research technique is the ability to determine contrasting dielectric media, for example, identifying frost-free zones in winter of highly moist soils, and monitoring the state of soils based on comparison of multi-season data [9]. Permafrost rocks with a low attenuation coefficient of electromagnetic energy (probable values of 0.6–2 dB / m [10]) are the most favorable environment for GPR. The energy potential of modern GPR used theoretically allows the study of permafrost to a depth of 25 m. The presence of layers with large contrasts in dielectric properties makes it possible to distinguish the boundaries of frozen and thawed rocks. The determination of the depth of these boundaries reflecting electromagnetic waves is directly related to the accuracy of determining the signal propagation velocity, which depends on the real part of the dielectric constant.

Processing and analysis of field measurements begins with determining the reference boundary. The bottom of the geological basement is taken as the reference boundary, and the GeoScan32 procedure “layers on the profile” is used. It is proposed to use the method of correlation analysis [11, 12] for automated layer boundaries resolution when obtaining large amounts of data. When searching for “local inhomogeneities”, the developed module is used, which allows one to automatically
evaluate the features of the wave pattern of radargrams due to the increased value of the signal amplitude dispersion [13]. At the last stage, the results of processing and interpretation of GPR data with reference to the terrain are imported into the geographic information system. To work with the database, software based on the Quantum GIS geographic information system is used, which allows you to store, display and edit received GPR data [14].

3.2. Non-Contact Measurement of Apparent Resistance (BIKS)

Electrical exploration work was performed using BIKS equipment (JSC “Special design bureau for seismic instrumentation”, Saratov) in the multi-profile profiling mode with a non-contact dipole axial installation at a frequency of 16.5 kHz. In the mode of electric profiling (EP), measurements are made along the road with a constant spacing between the supply and reception lines (Figure 3). In the process of shooting, the dipole axial setup, consisting of generator and measuring units, moves along the profile line with a change in separation, i.e. the distance between the generator and the meter. The spacing is changed to obtain the required depth of research. Considering the great complexity of electrical exploration and the intensity of road traffic, the work was performed on two spacing of the generator and the OO’/2 meter – 5 m and 10 m. These parameters (the OO’/2 spacing) were determined by the results of processing GPR data, which allows us to quickly determine the apparent electrical resistivity in predetermined depth intervals.

Further, the prepared graphs of apparent resistivities and GPR sections are subjected to a comprehensive interpretation. Based on the results of a comprehensive interpretation, the resulting sections containing information on the presence or absence of soil characteristics recommended for the study are constructed.

![Figure 3. The working time of shooting with BIKS equipment.](image)

4. The results of experimental studies

4.1. Section of Dzerzhinsky Street

On the section of the road, to detail the pavement layer to a depth of 1.5 m, the antenna unit AB-1200 (OKO-2M) was used [15]. A fragment of the GPR section obtained in November is shown in Figure 4. According to the road project, the selected layer No. 1 and No. 2 corresponds to the structural layers of pavement up to 0.8 m. Below the basement soils are represented by sand (layer No. 3). At the time of the study, the soil in the section was in a thawed state. According to the data processing results, anomalies are distinguished, characterized by discontinuities in the events, a change in the delay time, and the presence of random reflection signals (indicated by a dashed line). Taking into account surface disturbances of the asphalt pavement (cracks, subsidence, etc.), the considered wave characteristics of GPR can be interpreted with a violation of the structure of the road boundaries as a result of
mechanical suffusion and their overwatering, both in the structure itself and on the border of the basement soils.

Figure 4. The result of the data interpretation obtained to detail the pavement layer.

To detect the presence of signs of deep cryogenic processes, the AB-250 antenna unit (OKO-2M) was used. As we noted above, the studies were carried out in two stages. A comparison of the data obtained with the maximum freezing and thawing of the pavement soils and their foundation allowed us to study the complex cryogenic structure of the site. Based on the analysis of seasonal measurements, the characteristic features of GPR wave fields in the areas of activation of potentially dangerous natural and technological processes are identified. The roof of frozen rocks is most clearly identified and refined according to November data with the maximum thawing of soils (border - a) (Figure 5). According to spring measurements, with maximum freezing of soils, the most confidently determined inclined boundaries in the section, differing in their contrast and the presence of a border of thawed soils below 8 m (border - b). Presumably, the thawing of frozen soils and their sediment occurs as a result of the infiltration of surface and seasonal melt water into the permafrost along the selected inclined boundaries. The presence of thawed soils below 8 m is most likely due to the long-term technogenic impact of the sewer collector during its operation [16]. The obtained GPR section and its interpretation do not contradict the general geological and geophysical model according to previous engineering-geological and geophysical studies, and indicates the presence of negative cryogenic processes in the form of permafrost degradation on the road section.

Figure 5. Results of GPR studies by the antenna unit AB-250 according to the method of multi-season measurements.
4.2. *The section of Lenin Avenue*

In the absence of the possibility of galvanic grounding in the conditions of asphalt pavement on the section of the road in combination with GPR, electric profiling was used in a non-contact version with BIKS equipment. A feature of the research was that the determination of the apparent electrical resistivity was carried out in predetermined depth intervals according to GPR data. And vice versa, when the data of apparent electrical resistivity are used as a priori data for the interpretation of GPR.

Graphs of changes in the apparent resistivity values along the profile, from Dzerzhinsky Street to Khabarov Street, are averaged for the base soils of the road to a depth of 2 m and 8 m (Figure 6a). As you can see, the graph of the change in resistivity is complicated by local minima (below 200 Ohm*m) in the base soil layer of the road. The sections of the minima correlate well with discontinuities of events, low-frequency and chaotic reflection signals (Figure 6b).

As a result of a comprehensive interpretation of the data of the two methods, the most promising profile point for drilling was established – 280 meters from the beginning of the profile. In this interval, subsidence of asphalt pavement with very intense geophysical anomalies at the base was noted. A well laid at this point will open a zone of low-resistance anomalies in the depth range of 2 m and 8 m, which will make it possible to find out the true nature of the observed horizons of presumably thawed rocks.

![Graphs of apparent resistivity](image)

**Figure 6.** *a*) Graphs of the apparent resistivity in the section of Dzerzhinsky Str. – Khabarova Str. (depths of 2 m and 8 m, respectively) and *b*) GPR section of the road.

An analysis of the results of complex data processing showed that the nature of these anomalies is most likely associated with the processes of degradation of frozen rocks in the base soils, due to which annual asphalt pavement subsidence and the void formation in road pavement occur.
5. Conclusion
As a result of the studies, it was found that potentially hazardous sections of the roads under investigation are distinguished by the low resistivities on the obtained graphs and by the presence of discontinuities in the events, chaotic signals and low-frequency reflections in the radar section. A comprehensive analysis of geophysical data, drilling results and the location of communications showed that one of the reasons for the occurrence of negative cryogenic processes in the surveyed sections of roads is the lack of a perfect rain and melt water drainage system, as well as leakage of culvert and sewer pipes.

Based on the data of complex geophysical studies, locations for drilling engineering-geological wells were determined, the results of which will carry the most complete information about the cryogenic structure of the road section. Our further research will focus on the development of technology for the joint analysis of drilling data and geophysical sections to build the most unambiguous interpretation model of the road section that most closely matches the geocryological situation of the site.

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