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Investigation of the earth roof through the combined method: mechanical way and ground penetrating radar in the Yamalo-Nenets Autonomous Okrug

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Abstract The paper presents the results of the multidisciplinary experimental investigation of the soils in the sporadic permafrost Northern-taiga subzone (Yamalo-Nenets Autonomous Okrug, Western Siberia) based on the combination of the methods of radiophysical GPR investigation and classical methods of soil science. The aim is to develop the methods of objective identification of soils during the decoding of radarograms when monitoring the state of permafrost soils.

1. Introduction

Monitoring the climate features of the Arctic and subarctic regions is important when forecasting the short- and long-term climate changes in the Earth. In particular, important information about such changes can be inferred from the state of permafrost soils that cause the appearance of new water bodies and the deformation of the ground relief.

Classical methods of determination of the upper permafrost level suggest obtaining information using steel probes that penetrate through the active soil layers in test sites before until they contact a solid cryogenic layer [1]. In this case, errors are possible if the soil contains other solid inclusions. More objective information can be obtained by studying the cores obtained during drilling. The information increases to a great extent when excavating the soil and visualizing the boundary between frozen and unfrozen soil layers [2]. However, all traditional methods result in soil disturbances in the vertical direction, which leads to warm air penetrating into the lower layers of the soil and enhances further permafrost thawing. In addition, the mechanical methods are "point-like" and do not allow examining large areas.

These problems can be overcome using the method of remote sensing of the Earth (RSE) in aerospace research. Optical range is most widely used, which is convenient from the point of view of processing results [3-5]. To penetrate into the earth's cover the radiophysical methods are used, which are based on the fundamental interaction between microwave radiation and substance media [6]. The amplitude and phase characteristics of the electromagnetic response that carry the required information depend on the state of the surface, on the thickness and magnitudes, of the complex dielectric permittivities (CDP) of the layers [5]. The frequency dependences of the CDP of the samples from different layers of the earth's cover are investigated in laboratory conditions [6,7], i.e. in a “point-like” way. The main factor that determines the CDP values of cover layers is humidity. Current research shows that not only the water content determines the values of the CDP, but also the state of water that can be: free (gravitational), bound, layered [8] and capillary [9]. The quality and quantity of dissolved conductive impurities is of great importance. The electrical conductivity makes it possible to distinguish between the water from thawing permafrost and the one from atmospheric precipitation [10-13].

Thus, RSE and laboratory methods are at the extreme positions of an experimental study of the structure of the earth's cover. Mesocosm experiments aimed at determining soil relief can be fulfilled with the help of georadars, which have been relatively used for the purpose of subsurface sounding [14, 15]. Most successfully georadars were used to control the quality of pavements during their manufacture and the condition of roads during operation [16], to study small-scale objects [17,18]. Using the subsurface sounding method to determine the level of permafrost layers in the Yamal-Nenets Autonomous Okrug was not carried out previously because of the complexity of the description of the radargrams. Interdisciplinary studies combining radiophysical methods (georadar) with classical soil methods are of interest.

2. Theory

The principle of the operation of georadar locating devices is based on sounding the surface layer of the Earth by electromagnetic waves of various frequencies, capable of penetrating into its thickness. If there is a boundary in the investigated object that distinguishes layers with different complex resistances $Z = \sqrt{\mu^*/\varepsilon^*}$ ($\mu^* = \mu' - i\mu''$, $\varepsilon^* = \varepsilon' - i\varepsilon''$ – complex magnetic and dielectric permittivity, respectively, i – imaginary unit), part of the electromagnetic wave is reflected and enters the receiving device of the GPR, where the time of appearance of the reflected signal is recorded, which is determined by the electromagnetic thickness of the layer (geometric length multiplied by the square root of the product of the layer). In the presence of a multilayer structure, the number of boundaries with different electrophysical characteristics is fixed.

$$R = \frac{Z_{\text{вх}}^{n} - 1}{Z_{\text{вх}}^{n} + 1} \tag{1}$$

where $Z_{\text{вх}}$ – sending-end impedance of n layer, equals

$$Z_{\text{вх}}^{n} = \frac{Z_{\text{вх}}^{(n-1)} - iZ_n \operatorname{tg}(\gamma_n d_n)}{Z_n - iZ_{\text{вх}}^{(n-1)} \operatorname{tg}(\gamma_n d_n)} Z_n \tag{2}$$

In formula (2) Z_n – acoustic impedance of n layer, γ_n – its wave number

$$\gamma = \frac{2\pi f \sqrt{\varepsilon^* \mu^*}}{c} \tag{3}$$

If the object under study consists of electromagnetically contrasting plane layers, located normally to the direction of the incident electromagnetic wave, then the determination of the soil relief is made confidently. In case such layers change the angle of inclination within the surveyed area, or their electromagnetic characteristics change smoothly, the delineation of boundaries encounters certain difficulties. The task of delineating boundaries becomes more complicated because of the presence in the thickness of a layer of scattering (pebble, crushed stone, tree roots, etc.) or absorbing (coal, graphite, etc.) inclusions that distort the reflected signal. The task of delineating boundaries is complicated by the presence in the thickness of a layer of scattering (pebble, crushed stone, tree roots, etc.) or absorbing (coal, graphite, etc.) inclusions that distort the reflected signal. Nowadays, statistical methods are being developed to calculate polynomial functions for the amplitude values of a signal by its duration, multi-frequency studies are used, a pulse signal is used and the Fourier analysis of the received response is applied.

The wave resistance of soil layers can differ in water content, since the dielectric conductivity of water, especially at low frequencies, is considerably higher than in dry substrates (sand, clay, mosses, etc.). Using the theory of composite mixtures one can predict the value of DC in a damp substrate ε, if DC of the substrate ε_0 and water ε_1 is known, depending on the volume content of water p:

$\varepsilon = \varepsilon_0(1-p) + \varepsilon_1 p$ Silberstein-Newton-Brown for layered structures [19] or the Birchak formula, which is used most frequently to calculate DC of wet soil or wood [20]:

$$\varepsilon^{0.5} = (1-p)\varepsilon_0^{0.5} + p\varepsilon_1^{0.5}$$

In georadar studies, different frequencies are used [17], which determines the resolving power of the method and the depth of penetration of the electromagnetic field into the soil. In this case, it is necessary to take into account the dispersion of the CDP, which for different states of water is described by different relationships: Debye, Cole-Cole, Cole-Davidson, or Gavriliac-Negami:

$$\varepsilon^* = \varepsilon + \frac{\varepsilon_s - \varepsilon_\omega}{1 + i\omega\tau}; \quad \frac{\varepsilon^* - \varepsilon_\infty}{\varepsilon_s - \varepsilon_\infty} = \frac{1}{1 + (i\omega\tau)^{1-\alpha}}; \quad \frac{\varepsilon^* - \varepsilon_\infty}{\varepsilon_s - \varepsilon_\infty} = \frac{1}{(1 + (i\omega\tau))^{\beta}}; \quad \frac{\varepsilon^* - \varepsilon_\infty}{\varepsilon_s - \varepsilon_\infty} = \frac{1}{(1 + (i\omega\tau)^{1-\alpha})^{\beta}}$$

where ε_∞ – statistical and ε_s – high-frequency permittivity, ω – frequency of electromagnetic radiation, τ – relaxation time, $0 \le \alpha \le 1$, $0 \le \beta \le 1$ – empirical coefficient, i – imaginary unit.

If we take into account the temperature dependences of CDP, relaxation time, as well as the variety of concentration dependencies, it becomes clear why the application of georadars has not found wide application in soil science research at the present time. Decoding the measurement information yields ambiguous results without clarifying the real soil relief, at least at individual points. However, it is the application of this technique that allows us to significantly increase the research area in a relatively short time and to obtain objective information by a non-destructive method. Refinement of the actual profile, determination of moisture and electrical conductivity, which are necessary for the processing of radargrams, can be carried out by a traditional mechanical method - excavation in the area of using georadar experiments. Interdisciplinary research provides a set of large amounts of data, which facilitates the development of theoretical models and adequate techniques for the determination of frozen horizons by a radiophysical method.

3. Materials and methods

The experiment was carried out in the area of the Yamalo-Nenets Autonomous Okrug, in the test site of “Khanymei” located at the southern boundary of sporadic permafrost area in the northern taiga of West Siberian Plain (Figure 1). The area abounds in numerous lakes of thermokarst origin (Figure 2). To conduct the research we chose the georadar SIR-2000 – the fastest and universal one compared to other georadars, which makes it possible to work with both screened (from 100 MHz and above), and unshielded (up to 100 MHz) antenna blocks, “X-raying” the soil to a depth of 20-30 m.

Figure 1. The location of the key site «Khanymei»

Figure 2. Research scheme

The choice of operating frequency is important from the point of view of meeting two requirements: resolution, when it is necessary to find small objects, and the penetrating power of electromagnetic radiation, which is necessary for conducting investigations in the warm season, when the permafrost lies relatively deep. In our case, it is required to fulfil the second condition, so the frequency is chosen to be 100 MHz.

In September 2017 we investigated the areas of flat-hummocked peatlands with Cryic Fibric Histosol (Turbic) soils (Figure 3) and lichen pine forest with white sandy podzolic soils (Figure 4).

Figure 3. Conducting experiments in the area of flat-hummocked peatlands (points 1 and 2 Figure 2)

Figure 4. Conducting experiments in the area of lichen pine forest (point 3 Figure 2)

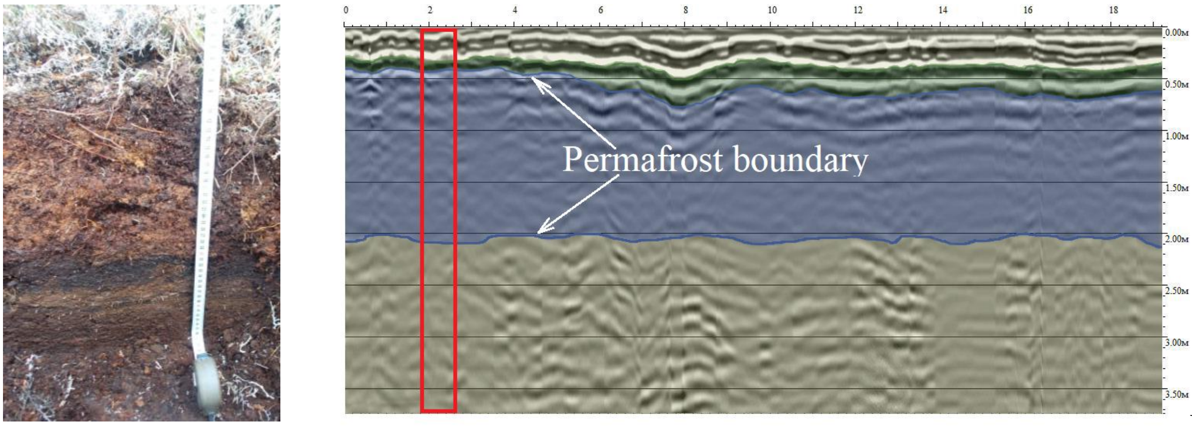
The sounding was carried out in natural conditions, without levelling the surface. In the characteristic places of the site where landscapes were probed, soil sections were laid to use them as a reference and to verify the validity of radargrams. The coordinates of finding the georadar were determined by the GPS navigator.

4. Results and discussion

Two sites under study were located in the area of flat-hummocked peatlands, in the lichen cover of which *Cladonia stellaris (Opiz) Pouzar & Vezda* and *Cladonia stygia* (Fr.) Ruoss dominated, whose projective cover was more than 95%. In the shrub layer *Bétula nana* L., *Lédum palústre* L., *Vaccinium vitis-idaea*, *Rubus chamaemorus* L. prevailed. In the first site Cryic Fibric Histosol (Turbic) soil was opened, in which the layers of sphagnum and shrub peat with varying degrees of decomposition alternated (Figure 5a). The permafrost layer was located at a depth from 47 to 200 cm, with a layer of structureless sands located lower it. Figure 5b) shows the radargram of the passage through a section whose location is indicated by vertical lines.

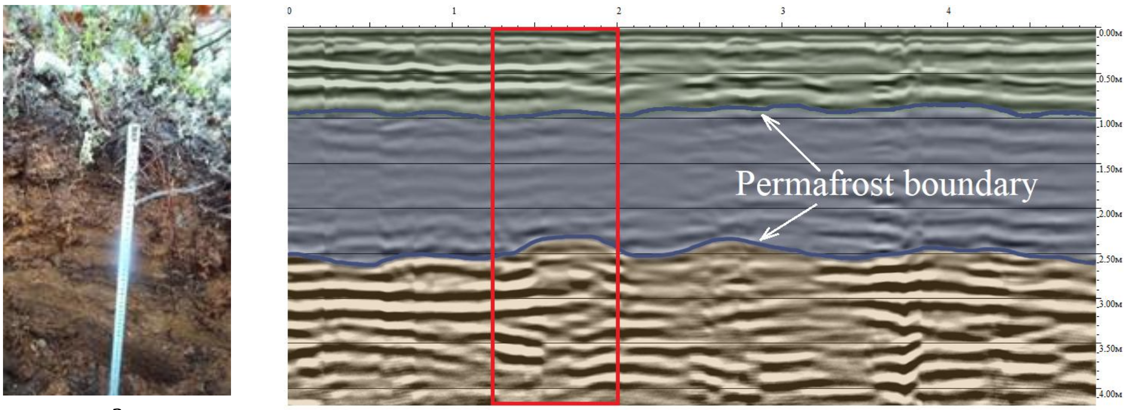
Since the depth of the permafrost here turned out to be small, the studies were carried out at a higher elevation to assess the depth of penetration of electromagnetic radiation. In the second site with Cryic Fibric Histosol (Turbic) soil the thickness of the active layer was up to 1 m (Figure 6 a, b), permafrost layer was 2.5 m, and the peat layers in terms of the degree of decomposition and composition differed not so clearly.

Radar patterns clearly define the boundaries of peat and permafrost. However, the radargram shows the relief of the soil to a depth much larger than the soil cut, and additional research is required to decode the information.



a b

Figure 5. Soil profile 2-17 (a) and radargram 29 (b) of site 1.



a b

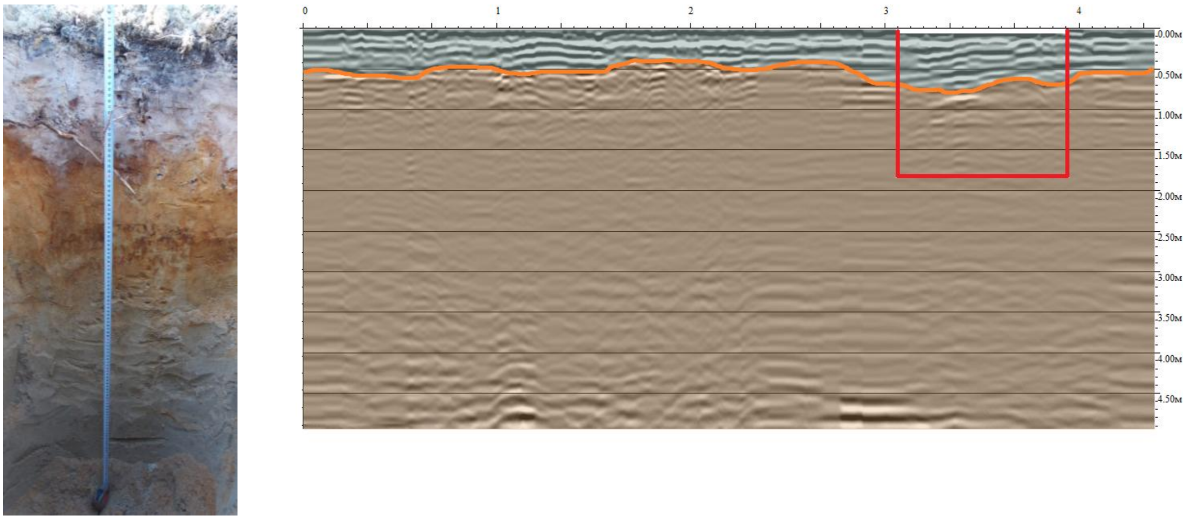
Figure 6. Soil profile (a) and radargram 29 (b) of site 2

In the lichen pine forest the profile of sandy podzolic soils with a different degree of development of the podzolic horizon, ferruginization and groundwater level was sounded. The research was carried out on the smooth hill slope in the sparse lichen pine forest, the projective cover of lichens (*Cladonia stellaris (Opiz) Pouzar & Vezda*) in which was 100%, the regrowth consisted of *Pínus sylvéstris* and *Pínus sibírica*; *Lédum palústre L.*, *Vaccinium vitis-idaea*, *Vaccínium myrtíllus* and *Empetrum nigrum* dominated in the shrub layer.

A podzolic illuvial-ferruginous soil horizon was opened (Figure 7) with profile Ad(0-3)-El(3-16)-ElB(16-23)-BFe(23-56)-B2(56-110)-BC(110-170).

The podzolic horizon here has a tongued boundary, the fragmentary transition horizon ElB, which carries the features of both eluvial and illuvial parts of the profile, is located below. Lower lies the ferruginous BFe horizon with a significant amount of inclusions of iron-manganese concretions, passing into B2 horizon, the iron content of which is not so significant. However, in this horizon the water content significantly increases, which is reflected in the radargram (Figure 7 b).

The results of the research show that the main factor determining the reflection of the electromagnetic signal at the working frequency of the GPR is the humidity. To adequately process the radargrams, it is required to perform an express analysis of the permittivity of the soil, preferably at the working frequency of the GPR.



a) b)

Figure 7. Soil profile (a) and radargram 43 (b) of profile A-B

5. Conclusions

The research showed that the method of interdisciplinary mesocosm experiments makes it possible to foster obtaining reliable data on the depths of the permafrost layer. In the case of monitoring the selected areas, this method will provide information on the dynamics of the thickness of the active layer of soils. This information can be used to process remote sensing data of the Earth's surface, which will increase the reliability of global climate change assessment. The research showed that the selected frequency of the sounding signal makes it possible to confidently determine the depths of the permafrost occurrence. A full description of the features of the soil structure might require multifrequency measurements. To adequately process radargrams, it is necessary to measure the permittivity of the layers or, at least, the humidity. The information can be obtained in real time mode, if the dielectric permittivity measurements are carried out on-site by the express method at the working frequency of the GPR.

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