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METHODS OF CRYOSPHERE'S RESEARCHES

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A POSSIBILITY FOR RECORDING GEOPHYSICAL ANOMALIES FROM AQUIFERS AND GROUNDWATER IN PERMAFROST

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A new parameter, apparent electromagnetic resistivity (EMR), is proposed for estimating the electrical properties of permafrost. It is a ratio of apparent resistivity to relative dielectric permittivity measured by radio-impedance or radiomagnetotelluric soundings in the frequency range of 10 kHz to 1000 kHz radiated by distant radio stations. The parameter records integrate variations in both electrical resistivity and dielectric permittivity and thus ensures more reliable detection of responses from unfrozen moist or water-saturated zones, aquifers, and groundwaters in permafrost than apparent resistivity. The use of the new parameter is tested in numerical and field experiments. The results show that changes in apparent electromagnetic resistivity caused by the presence of unfrozen water-bearing zones are an order of magnitude stronger than those of apparent resistivity.

Permafrost, aquifers, dielectric permittivity, apparent electromagnetic resistivity

INTRODUCTION

Highly conductive unfrozen aquifers, taliks, and groundwaters in permafrost can be successfully detected and mapped by resistivity surveys. The geoelectrical surveys commonly use resistivity as a marker to discriminate between frozen and unfrozen porous rocks. However, aquifers and groundwaters may be poorly resolvable when their hosts have low resistivity close to that of the water-bearing conductors. In this case, high dielectric permittivity may be a better indicator of water and moist rocks than resistivity and will discriminate aquifers even against low-resistive host formations. More reliable detection of moist and water-saturated unfrozen rocks and groundwater in permafrost can be achieved using electromagnetic resistivity (EMR), a new integrate parameter including the effects of both resistivity and relative permittivity (RP).

THEORETICAL BACKGROUND

The electromagnetic field penetrating into rocks excites conduction currents controlled by the field frequency and resistivity (conductivity) σ of rocks, as well as displacement currents depending on their absolute dielectric permittivity ε_a.

First Maxwell's equation including conduction and displacement currents is

$$\mathrm{rot}H = \sigma E + \varepsilon_a \frac{dE}{dt},$$

where $\sigma E = j_s$ is the conduction current density; $\varepsilon_a \dfrac{dE}{dt} = j_r$ is the displacement current density; H and E are, respectively, the magnetic and electric components of the electromagnetic field.

The conduction-to-displacement current density ratio (an electromagnetic parameter) records the electric properties of rocks depending on frequency of the applied alternating field:

$$\left|\frac{j_s}{j_r}\right| = \left|\frac{\sigma E}{\omega \varepsilon_a E}\right| = \frac{\lambda\sigma}{2\pi c \varepsilon\varepsilon_0} = \frac{60\lambda\sigma}{\varepsilon}, \tag{1}$$

where j_s is the conduction current density, A/m^2; j_r is the displacement current density, A/m^2; σ is the conductivity of rocks, S; E is the electric field component, V/m; ω is the angular frequency, Hz; ε_a is the absolute permittivity, F/m; λ is the wavelength, m; c is the light speed, m/s; ε is the relative dielectric permittivity, relative units (rel.u.); ε_0 is the permittivity in vacuum, F/m. Conduction currents predominate and the medium is conductive at $60\lambda\sigma >> \varepsilon$, while displacement currents predominate and the medium shows dielectric behavior at $60\lambda\sigma << \varepsilon$.

The ratio between conducting and displacement currents anyhow enters the known equations for the modulus and argument of the normalized impedance δ, which in a homogeneous earth are [*Tsydypov et al., 1979*]:

$$|\delta| = \frac{1}{\sqrt[4]{(60\lambda\sigma)^2 + \varepsilon^2}}; \tag{2}$$

$$\arg\delta = -0.5\,\mathrm{arctg}\,\frac{60\lambda\sigma}{\varepsilon}. \tag{3}$$

When the displacement current becomes commensurate with the conduction current, the observation results can be presented as apparent resistivity and permittivity values found via the surface impedance parameters as [*Tsydypov et al., 1979*]:

$$\rho_{ef} = -\frac{60\lambda|\delta|^2}{\sin(2\arg\delta)}; \quad (4)$$

$$\varepsilon_{ef} = \frac{\cos(2\arg\delta)}{|\delta|^2} - 1. \quad (5)$$

According to relative magnitudes of conducting and displacement currents, frozen ground in the frequency range of our interest (10–1000 kHz) is an intermediate domain subject to polarization and frequency dependence of permittivity [*Zykov, 2007*].

Unfrozen water-bearing rocks and groundwaters differ markedly from the host rocks in high permittivity and low resistivity. The latter is a common parameter in geophysical surveys but high permittivity is much more rarely used.

The suggested new parameter of apparent electromagnetic resistivity r_{em} is a ratio of apparent resistivity to relative permittivity measured at a frequency where the contribution of displacement current to the electromagnetic field is significant:

$$r_{em} = \frac{\rho_{ef}}{\varepsilon_{ef}} = \frac{60\lambda|\delta|^4}{\sin(2\arg\delta)\cdot\cos(2\arg\delta)}. \quad (6)$$

Electromagnetic resistivity (EMR) was first presented a few years ago [*Efremov, 2011*]. Measurements at a single frequency are sufficient for interpretation of profiling data because equations for ρ_{ef} and ε_{ef} always include the argument of surface impedance besides its modulus in the region of commensurate conducting and displacement currents.

The use of EMR is especially efficient within the frequency region where the conducting and displacement currents have equal values. Taking into account (1), this frequency can be found as

$$f = \frac{1.8\cdot 10^7}{\rho\varepsilon}, \quad (7)$$

where f is the frequency of the electromagnetic field, kHz; ρ is the resistivity, Ohm · m.

Simple calculations with (7) show that conducting and displacement currents are commensurate between 23 and 18 000 kHz for rocks with the resistivity from 100 to 10 000 Ohm · m and the relative permittivity within 10 to 80.

It is reasonable to use EMR as a measured and estimated parameter in resistivity profiling surveys for detection and mapping of unfrozen moist and saturated zones and aquifers in permafrost. It works especially well for target objects with high permittivity and low resistivity.

The use of EMR in profiling surveys is justified as it varies strongly as a function of the content and phase state of water in porous fine-grained rocks at radiowave frequencies. It changes especially strongly on transition from frozen to unfrozen water-bearing rocks in the range 10 to 1000 kHz, which falls within the frequencies of controlled-source radio-magnetotelluric [*Saraev et al., 2013*] or so-called radio-impedance [*Efremov, 2013*] soundings.

METHODS OF EXPERIMENTAL STUDY

Apparent resistivity (AR) and electromagnetic resistivity (EMR) anomalies produced by a conductor embedded in permafrost were compared by numerical and field experiments. The conductor in the resistivity model corresponded to unfrozen water-saturated rocks and aquifers.

Simulation was performed following the original method [*Efremov, 2013*] using the *Impedance* software [*Angarkhaeva, 2002*], with model parameters according to typical values for permafrost in Central Yakutia. Frequency-dependent surface impedance of layered permafrost with an embedded high-permittivity conductor was modeled in 1D for resistivity sections consisting of five or six layers, in the presence of an active layer (seasonal thaw).

Field experiments of radio-impedance profiling [*Efremov, 2013*] were run in the vicinity of Yakutsk city, at a site with a supra-permafrost talik lying under the active layer above permafrost. The measurement system consisted of an IPI-1000 impedance meter operated at working frequencies from 10 to 1000 kHz, with an ungrounded symmetrical electric line as a receiver, of 5 m long legs. At each point, the magnetic antenna and the electric receiver line were oriented exactly in the direction to the radio station. The profile points were spaced at 10 m. The measured impedance modulus and argument (phase) were converted to EMR using equations (2)–(6).

RESULTS AND DISCUSSION

The numerical experiment simulated the dependence of apparent electrical and electromagnetic resistivity values in a layered earth on the depth of an aquifer with a conduction of 0.02 S and a relative permittivity of 40. The apparent resistivity and the conductor thickness increased with depth (by analogy with the natural conditions): the assumed depths 2, 6, 10, 14 and 18 m (at the base of porous permafrost) corresponded to the conductor thicknesses 0.5, 1, 2, 3 and 4 m. The resistivity values close to real ones were chosen such that the conductance S remained invariable (0.02 S). The model parameters were: ρ = 25–200 Ohm·m, ε = 40, h = 0.5–4 m for the conductor; ρ = 100 Ohm·m, ε = 20, h = 1 m for the active layer; ρ = 10 000 Ohm·m, ε = 8, h = 18 m for frozen porous fine-grained rocks; ρ = 3000 Ohm·m, ε = 8, h = 300 m for frozen bedrock; and ρ = 300 Ohm·m, ε = 10 for unfrozen bedrock. The permittivity of the conductor remained constant in all cases. Apparent EMR varia-

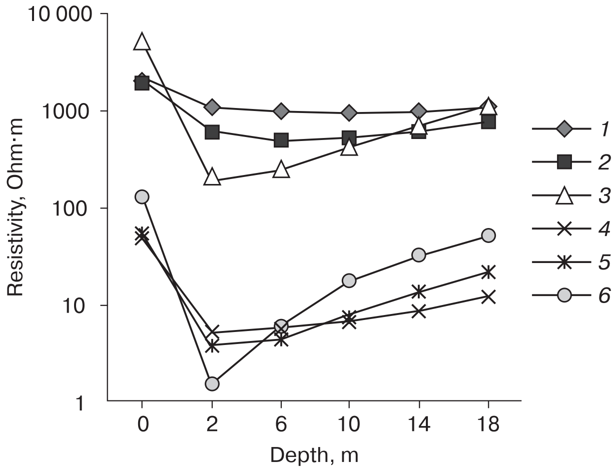

Fig. 1. Calculated dependence of apparent resistivity (lines *1–3*) and electromagnetic resistivity (lines *4–6*) on depth of conducting unfrozen water-bearing porous fine-grained zones in permafrost.

Frequency of source electromagnetic field: *1*, *4* – 100 kHz; *2*, *5* – 330 kHz; *3*, *6* – 1000 kHz.

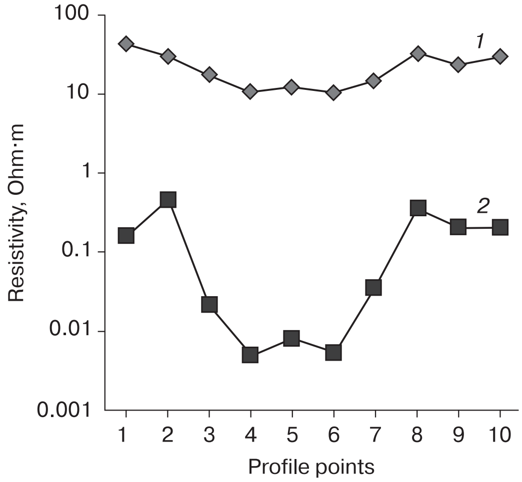

Fig. 2. Variations of apparent resistivity (*1*) and electromagnetic resistivity (*2*) at 549 kHz along a profile that traverses a supra-permafrost talik.

tions caused by changes in the conductor depth were much stronger than the variations of resistivity under the same conditions: two against one order of magnitude, respectively (Fig. 1).

The conductor in the model represents such natural objects as zones of clay silt and silt saturated with low-salinity water, as well as groundwaters, which have their resistivity and relative permittivity similar to those of the host permafrost. However, joint contribution of resistivity and permittivity to EMR resolves well these zones against the host rocks.

The electromagnetic resistivity as a measured parameter was tested in natural conditions in surveys along a profile that traversed a supra-permafrost talik in the vicinity of Yakutsk city (Fig. 2). The talik stripped in latest March 2010 was 4.2 m thick and lied under a 1.85 m thick active layer (seasonal frost). It consisted of silt with a water content up to 34 wt. % and fine sand containing 44 wt. % of water. Permafrost under the talik was fine sand with a water content reaching 52 wt. % and decreasing to 30 % at 11 m below the surface. The resistivity profile across the talik was collected by the radio-impedance method [*Efremov, 2013*] in the earliest April of the following year 2011.

The presence of a talik along the profile led to changes in measured effective parameters at a frequency of 549 kHz: three-fold decrease in resistivity, 17-fold increase in permittivity, and 41-fold decrease in electromagnetic resistivity. Thus, the talik is resolvable more clearly in permittivity and especially in electromagnetic resistivity than in resistivity. EMR changes caused by the talik are ten times greater than those in apparent resistivity along the same profile (Fig. 2).

The results of both numerical and field experiments show that EMR anomalies produced by the presence of an unfrozen water-saturated layer in permafrost are ten times stronger than ER changes.

The use of EMR measurements is especially efficient due to joint action of apparent resistivity decrease and permittivity increase (numerator and denominator in (6), respectively) that both reduce EMR. The reason is that the conducting unfrozen zone saturated with water reduces the apparent resistivity but increases the effective permittivity measured on the surface.

CONCLUSIONS

Electromagnetic resistivity (EMR) is an integrate value including both resistivity and permittivity of rocks. Being a ratio of the two parameters, EMR decreases with decreasing resistivity and increasing permittivity in unfrozen water-saturated zones of fine-grained porous permafrost.

The account for permittivity increase as an additional indicator of unfrozen aquifers and waters in permafrost besides the resistivity decrease ensures more reliable detection and mapping of unfrozen zones by EMR surveys as the anomalies become times stronger.

The EMR measurements are expected to have especially high performance in picking anomalies associated with the presence of liquid water in permafrost at the frequencies where displacement currents are either commensurate or exceeding conducting currents. This range is estimated to be from 100 to 1000 kHz proceeding from the electrical properties of frozen ground.

References

Angarkhaeva, L.Kh., 2002. The *Impedance* Program Package for Processing Radio-magnetotelluric Data. Certificate of Official Software Patent Registration, No. 2002610893, ROSPATENT, Russian Federation, 6 June 2002.

Efremov, V.N., 2011. New possibilities for investigating frozen ground by radio-impedance soundings, in: Problems of Engineering Geological Studies of Permafrost. Proc. IX Intern. Symposium (Mirnyi, 3–7 September 2011). Institute of Permafrost, Yakutsk, pp. 469–475. (in Russian)

Efremov, V.N., 2013. Radio-impedance Soundings of Permafrost. Institute of Permafrost, Yakutsk, 204 pp. (in Russian)

Saraev, A.K., Simakov, A.E., Shlykov, A.A., 2013. Controlled-source radio-magnetotelluric soundings. Voprosy Geofiziki 446 (46), 97–112 (St. Petersburg University Transactions).

Tsydypov, Ch.Ts., Tsydenov, V.D., Bashkuev, Yu.B., 1979. Studies of the Earth's Electrical Properties. Nauka, Novosibirsk, 176 pp. (in Russian)

Zykov, Yu.D., 2007. Geophysical Methods for Permafrost Studies. Moscow University Press, Moscow, 272 pp. (in Russian)

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