TRANSIENT EM SOUNDING IN THE STUDY OF PERMAFROST

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Abstract

In the paper, we consider the special characteristics of electromagnetic field behavior in permafrost conditions. In permafrost areas, induced polarization effects complicate electromagnetic field processes. A solution of the problem for horizontally layered dispersing media is presented. The high accuracy of the modeling is demonstrated for transient EM sounding in permafrost. A way of detecting of unfrozen rocks in permafrost is proposed. Testing of these methods on the Zapolyarnoe deposit allows us to detect unfrozen water in permafrost. Borehole data confirm the interpretation of lithological and hydrogeological structure of the section as well as the groundwater salinity.

Introduction

Permafrost covers more than 60% of the surface area of Russia (Figure 1). Therefore, geophysical methods, which allow studies of permafrost rock structure, composition and distribution, are extremely important. Recently in Russia, the transient EM sounding method has taken the leading position with respect to other electric methods for permafrost studies, and in hydro-geological and engineering applications.

Theory

The high level of geological information and technological effectiveness of the transient EM sounding method are well known. However, the processes of induced polarization distort practically all the E(t) curves obtained in the course of transient EM sounding in permafrost regions. In the case of non-polarization layers, the transient processes in coincident loops for multilayers with arbitrary heterogeneity are characterized by a monotonic decrease of electromotive force in time t after current I switch (turning on or turning off) in generating contour. According to several authors (e.g., Gubatenko and Tikshaev, 1979; Weindelt, 1982), the electromotive force decreases to zero for the case \( t \to \infty \), is monotonic, and its sign and the signs of its derivatives with respect to the time are not changed. Simultaneously, theoretical papers have been published which showed that in the case of homogeneous half-space with induced polarization, this should be accompanied by the process of electromotive force sign E(t) reversed from the positive to the negative, and after its minimum value is reached, the negative values approached 0 monotonically (Astrakhantsev et al., 1975; Zhuravleva, 1983).

Primary observation of the process of the sign change, was made by V. A. Sidorov and his collaborators in the course of soundings in permafrost in Yakutia. These processes differed not only from the classic ones, that assumed purely active medium conductivity, but the majority were not adequately described (e.g., Astrakhantsev et al., 1975; Zhuravleva, 1983). To explain these unusual processes, which were never described before, V. A. Sidorov and A.M. Yahin developed the approximate theory of induced influence, caused by polarization in arbitrary ground, having axial symmetry (Sidorov and Yahin, 1978, 1979). This theory explains the main types of these processes by special correspondence of the time characteristics of induced polarization and the response of non-polarization layers. These authors also made several quantitative estimations of ground polarization ability. However, the quantitative estimations developed by these authors do not allow the interpretation of the lithological, hydro-geological and cryological parameters of sub-surface layers.

For these problems, the most effective solution is the method of selection, which requires software for solution of direct problems, having high speed of execution and high accuracy in calculation. The author made calculations and created a set of programs for the transient sounding processes calculation in polarized multilayered media. We used a set of horizontal polarizing conductive plates to model layered-earth. The problem was solved using the method of serial approximation (Vladimorov, 1981). This makes it possible to separate and analyze both the induction and polarization components of EM field. The problem solution includes the following stages:
1. Calculation of the pulse transient EM characteristic function for a single plate. In practice, the conductivity current density in the ground can be represented as a convolution of the field strength with a pulse function for a specific ground conductivity \( g(t) \). In general, it can be expressed in the following way:

\[
g(t) = \gamma_0 [\delta(t) + p(t)]
\]  

where \( \gamma_0 \) is the ground specific conductivity, \( \delta(t) \) is Dirac’s \( \delta \)-function; \( p(t) \) is a function reflecting the process of inner charge accumulation (polarization effect).

In the case of exponential changes in charge in the polarizing medium (surroundings) with time duration (the thin planes, double layers) the \( p(t) \) function can be presented as (Zadorozhnaya and Tikshaev, 1990):

\[
p(t) = -\eta e^{-\frac{t}{\tau}}
\]

where \( \eta \) is an extent of medium polarization, \( \tau \) is decay constant for induced polarization. For a layer with thickness equal to \( \Delta h \) with transit limit \( (\Delta h \rightarrow 0; \Delta h, \gamma \rightarrow 0 \Rightarrow S_0) \) we obtain the pulse transient EM characteristic of the plate:

\[
S(t) = S_0 \cdot \delta(t) + S_0 \cdot p(t)
\]  

where \( S(t) \) is plate conductance.

The existence of two terms in equation (3) allows the induction and polarization processes to be considered independently to a certain extent.

2. EM field setting in non-polarizing plates by means of mirror image method (the method of fictitious sources) (Smayt, 1952; Zadorozhnaya).

3. Calculation of polarization effect for each plate by means of convolution of the plate response as a function of conductivity \( (S_0) \) with the graded current alteration in the generator frame with function \( p(t) \).

4. Estimation of the second order approximation terms specified by polarization currents, which allow the determination that their contribution to the joint result at any time is negligible.

A program to calculate E(t) curves was developed according to the algorithm described above.
Field example

An example of transient EM sounding from the northern Tyumen region is presented. A field survey was designed to investigate fresh water aquifers in polar oil and gas fields. The soundings were carried out mainly along profiles parallel to the Tolyangyakha River and along other lineament features (Figure 2).

For the purpose of inducing vortex currents in the rocks and measurements of transient processes, square combined receiving-transmitting loops with dimensions of 60X60 were used. Figure 3 shows the transient EM E(t) decay curves for soundings along the profile carried out near the Zapolyarnoye oil and gas condensate field.

The fieldwork in this area was carried out in 1995. For TEM soundings, we used the KOD system, which contains both receiver and transmitter. For the KOD system, the current pulse duration, and receive window, are set by the repetition frequency of the transmitted square wave. The time range of the KOD equipment is as follows:

This equipment allows exploration of the ground down to depths of 300-500 m. Compactness, small weight, low level of power consumption and small loops permit such devices to be used in regions with difficult access and without environmentally destructive vehicles.

<table>
<thead>
<tr>
<th>TX repetition [Hz]</th>
<th>1st channel [ms]</th>
<th>11th channel [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2600</td>
<td>0.002</td>
<td>0.062</td>
</tr>
<tr>
<td>650</td>
<td>0.008</td>
<td>0.248</td>
</tr>
<tr>
<td>162.5</td>
<td>0.032</td>
<td>0.992</td>
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<tr>
<td>40.7</td>
<td>0.128</td>
<td>3.968</td>
</tr>
<tr>
<td>10.16</td>
<td>0.512</td>
<td>15.872</td>
</tr>
<tr>
<td>2.54</td>
<td>2.048</td>
<td>63.488</td>
</tr>
</tbody>
</table>

In 1995, field data were interpreted using the method of selection in which a single polarizing plane was used as a model. As the result of the interpretation on the south-western edge of Lake 12, an anomalous water zone was predicted at a depth of 60-70 m (see Figure 2). According to the interpretation it was assumed that the water saturated sand apparent resistivity would be equal to 22-25 Ωm. Well drilling was recommended and was undertaken (well #8). The new set of programs permitted comparison of the interpretation with a previous one that was obtained using other programs and with drilling data.

The geological logging from well #8 can be summarized as follows:

The points of transient EM sounding on the map of Zapolyarnoe oil-and-gas condensate field. 1 - sounding location station, 2 - permafrost boundary, 3 - well, 4 - swamp, 5 - stream.
0 - 45 m - dark gray loam, frozen, with rare layers of pure ice; 45-75 m - layering of loam and sandy loam. The sediments are unfrozen from 62-68 meters with layers of fine water-saturated sand; 75-80 m - dark gray clay, dense, frozen. The daily rate of water output from the well during March was 12-17 m$^3$. 

Figure 4 shows an electrical diagram of the section conducted using the method of selection according to the new set of programs for multi-layered media. Seasonally thawed loamy clays, having 6-7 $\Omega$m resistivities compose the upper 2-3 m of the section. Frozen loam resistivity is 130 - 450 $\Omega$m, while the resistivity of thick masses of layered loam and sandy loam is more uniform at about 160 $\Omega$m. Fine water-saturated sands overlie the frozen clays with extremely high resistivity.
values of 450 – 600 Ωm. Higher resistivity sediments lie immediately below in the cross section. At depths of 140–160 m, low resistivity sediments suggest the presence of free water. Figure 5 shows examples of curve interpretation with the method of selection.

On the edges of the anomalous zone (the EM sounding at site # 106 is also located on the edge of anomalous zone, see Figure 2) the cross-section is represented by rocks with water in the frozen state. Electrokinetic processes in such rocks are not present: their resistivity is only hundreds or thousands of W m.

From transient EM sounding data interpretations using the method of selection, it was discovered that the time-decay (τ) of permafrost does not exceed 25–35 microseconds which agrees with the data from Molchanov and Sidorov (1985). Polarization η of loam is low and equal to 16%. The layered loam and sandy loam, as well as frozen clay polarization is 5–15%. This suggests that even small values of τ and η in highly resistive ground promote the abnormal EM field response such as negative transients.

EM sounding data interpretation, using the method of selection, suggests that water-saturated sand resistivity is 6.5 – 8.0 Ωm. The higher value of resistivity for this thick layer, obtained earlier (22-25 Ωm), can be explained by the use of a simple ground mathematical model (the single polarizing plane).

We are able to estimate the water salinity in the formation. Fortunately, we can use the well data to compare theoretical estimates to real measurements.

Let us consider the model calculation studies. We assume the main component of the homogeneous sediments to be the psammitic-aleurite fraction with an extremely high electrical resistivity. Its pore space is filled with clay material with low variable resistivity. The central parts of the pores are filled by an electrolyte solution with lower resistivity. The resistivity of such a model (saturated clay sediments) can be calculated with the following equation (see Kobranova, 1986):

$$\rho = \frac{P_{pore,PS+AV} \rho_w}{1 + \left(\frac{\rho_w}{\rho_{clay}} - 1\right) \left(\frac{k_{clay,V}}{k_{PS+AV}}\right)}$$

where ρw is free electrolyte solution resistivity that fills the pores of the sediment; ρclay is the resistivity of the clay fraction of the sediment; kclay, V is the clay content in the sediments; Ppore,PS+AV is the psammitic-aleurite sediment porosity.

First, let us calculate the free solution electrical resistivity. ρw depends on salinity (C), chemical composition and solution temperature. Itenberg (1978) contains a nomogram sketching water resistivity dependence on NaCl salinity and temperature.

Calculation of the clay cement resistivity and determination of clay fraction resistivity is then undertaken. The dependence of clay electrical conductivity (χd) on the extent of clay water saturation (d = 1 - k=pore,clay) for different NaCl salinities (see Figure 6), was estimated using experimental data obtained by Fridrikhsberg et al. (1960).

For the sake of comparing the values, χd values are divided by the value of free solution electrical conductivity χv.

An example of extrapolating of the discussed dependencies for the case d > 0.6 is the following:

if C = 0.01 (0.56 g/l), χd / χv = ρw / ρclay = 0.8;
if C = 0.018 (1.0 g/l), ρw / ρclay = 0.68;
if C = 0.05 (3.0 g/l), ρw / ρclay = 0.42 and so on.

The theoretical dependence of Ppore on the porosity ratio k=pore and rock grading extent (specified by the
The value of $n_0$ - the ratio of rock filling with fractures of fixed dimensions) can be determined for homogeneous or close to homogeneous rocks, in particular (see Dahnov, 1962):

$$P = \left(\frac{2 + n_0}{2(1 - n_0)}\right)^{\frac{\lg K_p}{\lg(1 - n_0)}}$$ \[5\]

(Note, that $n_0$, the ratio of consecutive rock filling, is understood as a residual part of the pore space volume, filled by the next rock's fracture. For example, the first fraction fills the volume equal to $n_0$, the second fills the volume $= (1 - n_0)n_0$, the third fills the volume $= (1 - n_0)^2n_0$ and so on till the residual volume $(1 - n_0)^n$ is equal to the fixed rock porosity ratio).

Let us assume $k_{\text{pore, clay}}$ to be 0.25, that is, it corresponds to fine sands according to granulometric gradient classification (Ruhin, 1953).

Figure 7 represents the results obtained using equation (4). The dependence of fine sand resistance on the porosity ratio is shown for different pore-water salinities. Note that the fine sand porosity can be up to 28–33% and its resistance up to 6.5-8.0 $\Omega$m. Thus, the water salinity according to transient EM sounding data is 3–4 g/l (see Figure 7). This compares with chemical analyses, which indicated a concentration of 3 g/l. The taste of this water is slightly salty. However, groundwater in taliks located beneath the lakes do not meet drinking water standards. Frequently these taliks are the only source of water supply. The water of the discovered deposit can be primarily used for the industrial needs. Well # 8 is drilled on the south-western edge of the deposit contour. Probably the main fresh water resources are located immediately below the lake and the use of transient EM sounding exploration on ice could show the boundaries of underground water deposit.

Conclusions

1. The use of transient EM sounding allows permafrost zones to be differentiated with a high degree of accuracy, and the delineation of different lithological and cryological boundaries.

2. In addition to the delineation of thawed zones in the cross section, electrical resistivity data can be used to estimate porewater salinity, which is extremely important for water resource evaluation and other technical purposes.

References

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