PRINCIPAL PROBLEMS, PROGRESS, AND DIRECTIONS OF GEOPHYSICAL INVESTIGATIONS IN PERMAFROST REGIONS

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Abstract

The paper deals with the principal aspects of successful application of geophysical methods to permafrost conditions. Firstly, it is discussed why neither the techniques nor tools developed, and the immense experience gained by prospecting geophysics can be directly applied to permafrost regions. Further, a number of the recent examples of the uses of geophysical methods to solve practical tasks in cold regions, such as cryopog recognition, surveying for construction, buried ice layer delineation, evaluation of engineering geological parameters from geophysical data, ecological-geophysical monitoring etc., are presented and discussed. The main problems are examined and the most promising directions suggested for development and application of permafrost geophysics in the near future.

Introduction

The industrial development of northern regions, which is primarily related to mineral and oil deposit prospecting and exploitation and to a large-scale construction, requires an expansion of geophysical methods to permafrost investigations. Under conditions of severe climate, limited accessibility, and highly sensitive ecosystems, these methods are often indispensable as they permit many problems of engineering, geology, construction, etc. to be solved at lower cost and practically without any damage to ecosystems. An efficient application of geophysical methods to permafrost investigations becomes possible due to comprehensive knowledge of geocryology, as well as the physics and physical chemistry of frozen soils. Widely known advances in physical fundamentals, in the theory and practice of geophysical techniques to solve many problems of geocryology, engineering, ecology, etc. in permafrost areas, clearly indicate that a new branch of science and engineering practice has developed, that is “permafrost geophysics”.

Besides discussing new cases of successful application of geophysical methods, this paper outlines the principal problems, directions of investigations, and routes for permafrost geophysics development in the near future.

Application of geophysical methods to permafrost studies

It is impossible to cover all aspects of geophysical methods used in permafrost studies for reasons of space. Here, we take a brief look at some items of importance and consider a few new examples.

Firstly, it should be noted that the success of geophysical methods in permafrost studies results from a number of characteristics which have no analogues in extensive geophysical investigation experience accumulated in non-permafrost areas. The most important features may be summarised as follows:

1. Unusual characteristics of the formation and evolution of the physical properties of frozen soils as multi-phase, heterogeneous media in a state of unstable thermodynamic equilibrium within the temperature range corresponding to the phase transition of ice, which is a principal constituent of these soils;

2. Characteristic features of the frozen ground cryogenic structure, texture, composition (including salinity) and state, as well as their variability in time and space, which account for corresponding changes in physical properties;

3. Special conditions of field geophysical investigations, such as: high and time-varying ground resistance,
and instability of electrode potentials; high values of dielectric permittivity with significant dispersion at frequencies less than 1 MHz; shielding effect of layers with a high ice content; necessity of geophysical logging conducted in dry boreholes in permafrost; intense and prolonged relaxation after disturbance of the frozen soil state in the vicinity of boreholes after drilling, etc.;

4. Specific requirements for measuring apparatus concerning sensitivity, testing, calibration, mating with the upper part of the section, reliability of operation over wide temperature range, etc.;

5. Difficulties involved in the development of physical-geological models for the upper part of the permafrost section, developments which are necessary for correct interpretation of geophysical data because of instability in the medium properties and state of the medium.

These, and some other special features, explain why neither the physical-geological base, nor the techniques and tools developed and the immense experience gained by prospecting geophysics, can be directly expanded into permafrost areas. That calls for comprehensive special studies. Considerable progress toward this goal has been made by Russian geophysicists-geocryologists (see the list of major publications in Frolov, 1995).

Secondly, these as well as many other works (for instance Burns et al., 1995; Krylov and Bobrov, 1995; Tice et al., 1988; Scott et al., 1990; see also the bibliographies in these works) show that various geophysical methods (both on land and in boreholes) may be successfully employed in mapping talik boundaries, zones of increased ice content, island permafrost, etc., as well as in the subdivision of frozen sediments in section into layers according to their lithology and cryogenic state, in monitoring and forecasting of stress-strain in the foundations of large structures, in seismic hazard forecasting taking into consideration the variability of conditions in the upper part of permafrost. The techniques most commonly applied for these purposes are varieties of electrometry using static and alternating fields and seismoacoustics.

Besides the tasks outlined above, there are a number of other problems which have been solved only recently using various geophysical methods and some new approaches to interpreting the results. Some examples are given below.

SUBDIVISION OF THE UPPER PART OF PERMAFROST

Some important results have been obtained recently when dealing with this group of problems.

1. The recognition of cryopegs within frozen sediments is essential, in particular when surveying for construction. The most hazardous cryopegs are shallow intra-permafrost which may seriously affect the stability of basements. This is the case on the Yamal Peninsula where large-scale engineering and construction work is underway in connection with exploration for oil and gas. Within the range of the upper 50 m, cryopeg occurrence can be detected most easily using direct current soundings (DCS). In many cases this procedure is very effective (Figure 1). However, because of the principle of equivalence, a cryopeg can be recognised by DCS only if its thickness $h > H (\rho_{cr}/\rho_{un})$, where $\rho_{cr}$ and $\rho_{un}$ are specific resistivity values for the cryopeg and the underlying layer respectively, and $H$ is an equivalent thickness of the overlying sediments.

2. In surveying for construction (e.g., of pipelines), rapid subdivision of the permafrost section is important in order to choose the best locations for boreholes. This permits interpolation of the frozen soil characteristics obtained by logging and standard sampling of the boreholes within the surrounding area. Figure 2 shows an example for the site of a gas pipeline compressor station in Western Siberia. The methods applied included: electroprofiling and DCS by the two component technique.
Bogolyubov et al. (1987) and seismic survey. These studies distinguished 6 blocks and determined the position of their boundaries in three dimensions. The two component DC technique, with measurements taken along two mutually perpendicular lines, permitted determination of the direction and dip angles of the boundaries.

The uppermost part of the section (Figure 2) is the active layer - block 1. It is underlain by a horizon subdivided into blocks 2, 3, and 4 on the basis of their specific resistivities and also V_p and V_s velocities. The blocks consist of frozen silts that differ in ice content and temperature. Maximum ice content values correspond to block 3 and even more so to block 4 (high values of ρ, V_p and V_s). Silts below the horizon feature lower ice content, with the exception of block 5 where ρ exceeds 15 kΩm. The ρ values obtained by DCS and later by borehole logging are in a good agreement with each other which permits expansion of the results to the whole massif within the delimited blocks.

Figure 2. Block delineation of the geological section using the land electric and seismic data (West Siberia).
1 - points of DCS, 2 - permafrost surface, 3 - geoelectric boundaries, 4 - resistivity Ωm, 5 - velocities m/s (V/V_p), 6 - boreholes.

(3) Reliable identification of buried ice layers is of fundamental importance. This problem may be approached using electromagnetic sounding, and seismic surveying with shear waves (Burns et al., 1995). More reliable, however, are borehole measurements. Among them, various types of electric and seismic logging are believed to be the most efficient. Our experiments proved, however, that gamma-ray spectrometry and magnetic susceptibility measurements in boreholes are also effective. As shown in Figure 3, the methods permit clear determination of ice layers even in the case of ice saturated overlying and underlying sediments.

EVALUATION OF ENGINEERING PARAMETERS AND THEIR VARIABILITY

This set of application of geophysical techniques includes a wide range of problems related to survey, engineering geology, mining, etc. in permafrost regions. The principal goal is to translate measured geophysical parameters into engineering characteristics. To do this, it is necessary to find basic relationships between the two groups of parameters.
Figure 3. Ice layer delineation by gamma spectroscopy (GL) and magnetic susceptibility (MS) logging.
1 - ice, 2 - sand, 3 - loam, 4 - gravely sand, 5 - clayey limestone; cryotextures: 6 - massive, 7 - horizontal layered, 8 - inclination layered, 9 - by cracks, 10 - ice.

Figure 4. Examples of main interrelationships.
(a) - resistivity of soils vs. initial pore solution concentration $C_{ps}$, $t = -3^\circ C$; (b) - elastic wave velocity vs. soil plasticity index at various $C_{ps}$: 1-0; 2-5; 3-10 g/L; (c) - equivalent cohesion vs elastic wave velocity for saline sandy-clayey soils, $t = -3^\circ C$; (d) - DCA vs $D_{sal}$ for saturated saline soils at various temperature ($^\circ C$). $D_{sal}$ is soluble salts weight - dry soil weight ratio.
Let us consider practical applications of this procedure with special reference to the Yamal Peninsula. A distinctive feature of this region is that saline sands and silts occur practically everywhere in the upper permafrost. In order to find the basic relationships, models of soils were tested in laboratory. The measured characteristics included electrical resistivity $\rho$, elastic wave velocities $V_p$ and $V_s$, equivalent cohesion $C_{eq}$ (by a ball stamp test), degree of corrosive aggressiveness (DCA) within the required range of initial concentrations of saturating pore solutions (chloride salinity - marine type), plasticity indices, and soil temperature.

The large number of analyses resulted in a number of statistically reliable relationships being obtained. As shown in Figures 4a and 4b, it is possible to evaluate certain soil characteristics, such as salinity and plasticity index, from measured values of $\rho$ and $V_p$ and the frozen soil temperature.

The laboratory experiment data show a reasonable agreement with the results of electric and acoustic logging from some key bore-holes, which confirm that they may be applied to the interpretation of logging results within this region.

From $V_p$ and $V_s$ measurements, the dynamic elastic moduli can be easily calculated and the strength characteristics of frozen soil evaluated on the basis of the relationship (see Figure 4c). It should be noted that this $C_{eq}(V_p)$ relationship is correct for frozen soils of different salinity, temperature and plasticity index (Chervinskaya et al., 1998). It has been obtained from measurements of both artificially modelled samples and those taken from undisturbed bulk samples.

DCA has been estimated for samples of frozen soils of various salinity at fixed negative temperatures. The experiments were carried out using a standard procedure which requires measurements of resistivity and cathode current in the process of corrosion. In addition, metal losses on the anode electrodes were determined. As a result, representative relationships were obtained similar to that shown in Figure 4d. They make it possible to find DCA from the salinity and temperature of sandy-clayey soils without field measurements.

Practical uses of the relationships in Figure 4 are illustrated by Table 1 and Figure 5. Table 1 shows interpretation of results of geophysical measurements in boreholes (including resistivity, acoustic, gamma-gamma, neutron logging and thermometry) at the site of an engineering survey for construction of a railway bridge. The data given in the table were obtained using correlations of the type shown in Figure 4.

Figure 5 presents a schematic map of DCA compiled using the relationships in Figure 4d on the basis of geocryologic map which contains data on soil salinities and temperatures in the region of the Bovanenkov oil field.

### Table 1. Borehole Geophysical Data and their Interpretation

<table>
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<tr>
<th>h,m</th>
<th>FIELD RESULTS</th>
<th>ANALYTICAL CALCULATIONS</th>
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<tr>
<td></td>
<td>$\rho$, Ohmm</td>
<td>$V_p$, m/s</td>
<td>$V_s$, m/s</td>
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<td>8.35 - 9.05</td>
<td>6</td>
<td>2310</td>
<td>840</td>
</tr>
<tr>
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<tr>
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ECOLOGICAL-GEOPHYSICAL MONITORING

Ecological-Geophysical Monitoring, or regime long-term geophysical studies in the permafrost, is a relatively undeveloped area. Within this domain, one comparatively simple task, which is important from a practical standpoint, is the study of freezing-thawing dynamics of the active layer. Traditionally, borehole temperature measurements produce precise and reliable data in nonsaline soils. In saline soils, however, the well-known phenomenon of “zero curtain” restricts this method. Investigations to clarify the possibilities of other geophysical methods conducted at an experimental station in western Yakutia have shown that neither DCS, nor resistivity logging, nor any other kind of standard geophysical logging produces satisfactory results. The most versatile and precise determination of the active layer state and position of the phase boundary appeared to be borehole measurements of electrode potentials and of electrode transient resistance with a buried measuring electrode array.

Figure 6 illustrates an example of this technique applied in the version of potential difference measurement between adjacent electrodes in the array. The left side of the graph clearly shows that when the phase boundary in the thawing process passes through the upper electrode, the potential difference rises steeply. After that, it remains approximately at the same level while the phase boundary maintains its position between the electrodes, and then drops back to the background value. In the course of seasonal freezing (from above) an inverse pattern is recorded (right part of Figure 6).

The accuracy with which the phase boundary can be located depends on the distance between the electrodes and does not exceed 0.5 of this distance. The time of active layer thawing and freezing at a depth of the electrodes position is determined unambiguously. When conditions are favourable, the results fit perfectly with the temperature data, while in the period of “zero curtain” the electrometric data are much more informative.

This example confirms, on the one hand, the efficiency of ecological-geophysical monitoring, and on the other, it indicates the necessity of searching for non-standard techniques.

Principal problems and future directions of investigation

In our opinion, the most important future tasks are:

1. To investigate more comprehensively the nature of physical and physical-chemical processes and phenomena in permafrost areas (both at global and regional scales).

2. To make a thorough study of physical fields (stationary and time variable) controlled by natural physical-chemical processes in permafrost areas and by anthropogenic impacts.

3. To study non-linear processes and mechanisms of mutual energy conversion of different physical fields in frozen media and to establish firm relationships between the different physical properties of frozen soils.

4. To promote theoretical and experimental studies aimed at the development of new techniques and to assist the choice of optimal combinations of geophysical...
methods to be applied to engineering and ecological tasks, as well as to oil and mineral deposits prospecting in permafrost regions.

The principal directions in the development and application of geophysical methods in permafrost areas are seen to be as follows:

1. Engineering-geological mapping of frozen sediments;
2. Surveys for construction;
3. Handling civil engineering, mining and other tasks related to surficial and underground large-scale construction;
4. Long-term ecological-geophysical monitoring aimed at global climatic changes and human impact on permafrost regions.

Concluding remarks

It seems reasonable to organise an international scientific community (working group) of geophysists-geocryologists with the aim of elaborating and implementing co-ordinated programs, which should include (at least) the following:

(1) laboratory and field investigations using unified procedures and aimed at finding basic representative patterns in frozen soil properties (physical and engineering ones), and their interrelationships;

(2) development of an world-wide network of combined (temperature, electrometry, seismoacoustics) ecological-geophysical monitoring in permafrost regions.

References


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