Influence of Seasonal Temperature Variations on Electromagnetic Characteristics of Frozen Soils by the Degree of Thawing and Freezing

V N Efremov

1Melnikov Permafrost Institute SB RAS, Merzlotnaya, 36, Yakutsk, Russia

E-mail: vne@mpi.ysn.ru

Abstract. Seasonal temperature fluctuations in frozen soils cause changes in their ice content which are accompanied by resistivity changes and electromagnetic emission. This study examines the periodic seasonal variation in apparent resistivity of permafrost soils based on field measurements of the surface impedance in the 100–1000 kHz frequency range. The characteristic changes in soil temperature and apparent resistivity associated with particular time periods are presented. The data show that the apparent resistivity values are consistent with the degree of soil freezing. Rapid freezing or thawing of the active layer causes electromagnetic emission in frozen soils. These features can be used to monitor and predict changes in permafrost conditions under climatic or anthropogenic impacts.

1. Introduction
Temperature fluctuations in permafrost caused by annual heat gains and losses affect the thermal condition of soils differently on a seasonal basis. The frozen and thawed conditions are associated with particular electromagnetic characteristics of soils [1] and their values are dependent on the degree of soil freezing or thawing. For soil condition assessment, we have monitored the soil electromagnetic characteristics using radio-impedance sounding since 2005 [2] and radiomagnetotelluric (RMT) sounding since 2017 [3].

Monitoring studies at a site located in the outskirts of Yakutsk have shown that electrical or electromagnetic [4] resistivity can be used to qualitatively assess the degree of soil thawing and freezing which is difficult to make by temperature measurements.

The term ‘degree of thawing’ is used here to refer to a decrease in ice content of the soil, while the ‘degree of freezing’ means an increase in its ice content. Complete thawing, as well as complete freezing can occur in the active layer.

Based on the idea that solid bodies generate an electromagnetic field [5] and the results of our monitoring studies using the RMT instrument, we have discovered the phenomenon of electromagnetic emission in frozen soils which is also dependent on the degree of freezing and thawing.

2. Methods
In 2008–2010, combined monitoring of seasonal variations in temperature and apparent resistivity of sand soils was carried out at the Tuymaada Station, a research and monitoring site of the Melnikov Permafrost Institute on the outskirts of Yakutsk.
Soil temperatures measured at different depths show the advancement and position of freezing and thawing fronts in the ground, and indicate the thermal state of the soil at a given depth at the time of measurement. During the monitoring period, soil temperatures were measured in a borehole down to a depth of 3.5 m using 15 thermistors spaced at 0.25 m.

More information about soil conditions can be obtained, as physical properties change with freezing, by measuring the electrical resistivity of soils in the radio-frequency electromagnetic field in the 100-1000 kHz range. The apparent resistivity of the ground shows the thermal condition of soils and the degree of soil freezing or thawing at a given time. The change in physical properties associated with the phase transitions of water, as well as the impact of such climatic factors as rainfall amount and snow depth are taken into account. The apparent resistivity was determined at the same site by measuring the surface impedance at frequencies of 171, 334, 549, and 864 kHz. The IPI-1000 impedance meter [5] (developed and produced by the Institute of Earth’s Crust, Leningrad State University, 1992) with an ungrounded symmetrical receiving line was used for measurements. The electromagnetic emission of frozen soils was recorded by sounding with the RMT instrument [6].

3. Results and discussion

Soil temperature monitoring at different depth has shown (figure 1a) that the seasonal temperature fluctuations over the year form a period with half-periods with reversed values defined as the period of soil cooling and the period of soil warming. The active-layer temperatures are characterized by a longer period of cooling which lasts seven months from August to February of the following year, while the period of warming is five months long (March to July). For temperature soft he under lying permafrost, the period of cooling is reduced to three months (January to March of the following year), while the period of warming consists of four months (April–July) of pronounced warming and five months (August–December) of subtle warming.

The apparent resistivity (figure 1b) is characterized by a rapid increase associated with freezing during the first three months of the cooling period (October–February), stable values in January–February and some additional increase during the following two months (March–April). The decrease in apparent resistivity associated with thawing of the active layer and warming of the underlying permafrost is rapid during the first two months of the thawing period (May–June), but is reduced during the next three months (July–August). The small increase in apparent resistivity observed in March–April is explained by a decrease in permafrost temperature occurring simultaneously with an increase in active-layer surface temperature. The small decrease in apparent resistivity in July–August is due to the lower thermal conductivity of the active-layer soils in the thawed state.
Figure 1. Seasonal variations in soil temperature at different depths and apparent resistivity at two frequencies at the Tuymaada Station (Yakutsk area).

Hence, changes in the degree of soil freezing can be determined from changes in apparent resistivity in the range of 100 to 1000 kHz.

Soil temperature variations are mostly dependent on surface air temperature. Therefore, we used the latter for comparative assessment of the degree of freezing of permafrost soils and the apparent resistivity values obtained by monitoring.

Monitoring of seasonal variations in apparent resistivity of sand soils in a forest-covered area at the Tuymaada Station has demonstrated that the apparent resistivity remains at about the same level during the winter months (December–February) corresponding to the winter degree of soil freezing. During the spring months (March–April) when air temperature rises almost linearly towards 0°C, the apparent resistivity slightly decreases, reflecting the lower, springtime degree of soil freezing. When air temperatures approach 0°C in late April, the apparent resistivity increases significantly due to further increase in the degree of freezing of the permafrost as the active-layer surface is still frozen. From May to June, the apparent resistivity rapidly decreases, reflecting rapid thawing of the active layer. In July and August, the asymptotic levels of the apparent resistivity reflect two degrees of soil freezing: those of summer and autumn. Thus, the seasonal changes in effective resistivity reflect four degrees of soil freezing: winter, spring, summer and autumn.

The degree of soil freezing reflected by the position of the level of the value of apparent resistivity depends on its level in the previous cooling period and the duration of this period. The high levels of apparent resistivity in April 2006 and 2008 correspond to relatively high June levels in these years. The comparatively low level of apparent resistivity in April 2007 due to the shorter duration of the cooling period that year corresponds to the anomalously low level of apparent resistivity in June-July of that year which led to merging of the summer and autumn levels (figure 2). In general, from 2005 to 2008, the degree of soil freezing corresponds to the average apparent of 3900 Ohm·m for spring, 1900 Ohm·m for summer and 900 Ohm·m for autumn. Thus, apparent resistivity levels corresponding to the identified degrees of freezing differ by about two times.
Figure 2. Seasonal variations in apparent resistivity of sand soils at the Tuymaada Station in 2005-2008.

The data from apparent resistivity monitoring suggest that, in addition to the impact of surface air temperature, snow depth and rainfall amounts also have an effect on the degree of freezing of permafrost soils. The snow cover has an insulating effect, while rainfall decreases the thermal conductivity of thawed soils. Both the values of these factors and the duration of their impact play a role.

At a frequency of 864 kHz, one can see complete thawing of the soil which corresponds to the minimum values of apparent resistivity in July, while complete freezing of the soil is related with maximum values in February (figure 3a).

Figure 3. Seasonal variations in soil temperature at depths of 0.5 m (a) and 3.5 m (b) compared with seasonal variations in apparent resistivity at frequencies of 864 (a) and 171 kHz (b) based on RIS.

The permafrost occurring immediately beneath the active layer does not freeze or thaw completely. Partial thawing of the soils corresponds to lower values in August–October. Partial soil freezing corresponds to increased apparent resistivity at a frequency of 171 kHz in November–January, which increase further in February–March (figure 3b).

Another finding from the monitoring study was the increase in magnetic field strength observed in the frequency range of 1-300 kHz in April–May and September–October. The data obtained led us to the discovery of the phenomenon of electromagnetic emission in frozen soils [1, 3]. Electromagnetic emission occurs in frozen soils which experience volumetric strains resulting from rapid thawing or freezing of the active-layer soils. For example, the maximum amplitude of the noise component of the
frequency spectrum in the range of 6-200 kHz caused by electromagnetic emission increased in the spring days of 2020 by more than an order of magnitude, from 24 μV on April 18 to 340 μV on April 23 (figure 4). The increase in the signal amplitude of electromagnetic emission in frozen soils was due to the increase in mechanical stresses caused by volume changes in the active-layer soils resulting from melting of the water that had frozen during the winter. This melting was caused by an abrupt rise of air temperature from +0.2°C on April 21 to +7.3°C on April 23.

Figure 4. Amplitude spectra of Hz signals in the frequency range of 1-200 kHz received by the RMT instrument on April 18 (left) and 23 (right) 2020.

4. Conclusions
Monitoring of seasonal variations in electrical or electromagnetic resistivity of soils makes it possible to assess the degree of freezing or thawing at any given time. These assessments can be used, with consideration of the determined effects of climatic factors, to predict further changes in soil conditions on an on-going basis.

Observation of electromagnetic emission in frozen soils can be helpful in early detection of significant soil thawing and prediction of building foundation problems.

5. References
[1] Efremov V N 2013 Radioimpedance Sounding of Permafrost (Russia, Yakutsk: Melnikov Permafrost Institute SB RAS) p 204
[2] Efremov V N 2008 Seasonal variations of surface radiowave impedance of frozen ground Proceedings of the Ninth International Conference on Permafrost I (Alaska: Fairbanks 2) pp 409-414
[3] Efremov V N 2019 Geophysical assessment and indication of the cumulative effect of climatic factors on the state of frozen soils BST Byulleten Stroitelnoy Tekhniki vol 12 (Moskow) pp 46-50
[4] Efremov V N 2017 A possibility for recording geophysical anomalies from aquifers and groundwater in permafrost Earth s Cryosfere vol 6 (Moskow) pp 129–133
[5] Malyshev Yu P, Gordeev V F, Dmitriev V P, Smirnov V A, Fursa T V, Ulchenko V I 1984. The generation of an electromagnetic signal by solids under mechanical action Zhurnal Tekhnicheskoy Fiziki vol 2 (Moskow) pp 336-341
[6] Parfentev P A, Pertel M I 1991 Instrument for surface impedance measurement in the SLW-MW ranges Low-frequency Waveway "Earth – Ionosphere (Alma-Ata: Galim) pp 133-135
[7] Saraev A K, Simakov A E, Shlykov A A 2014 Radiomagnetotelluric soundings method with a controlled source Geofizika vol 1 (Moskow) pp 18-25