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Electrical and seismic response of saline permafrost soil during freeze - Thaw transition

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ABSTRACT

We conducted laboratory studies on the geophysical signals from Arctic saline permafrost soils to help understand the physical and mechanical processes during freeze-thaw cycles. Our results revealed low electrical resistivity ($<20\ \Omega\mathrm{m}$) and elastic moduli (7.7 GPa for Young's modulus and 2.9 GPa for shear modulus) at temperatures down to ~−10 °C, indicating the presence of a significant amount of unfrozen saline water under the current field conditions. The spectral induced polarization signal showed a systematic shift during the freezing process, affected by concurrent changes of temperature, salinity, and ice formation. An anomalous induced polarization response was first observed during the transient period of supercooling and the onset of ice nucleation. Seismic measurements showed a characteristic maximal attenuation at the temperatures immediately below the freezing point, followed by a decrease with decreasing temperature. The calculated elastic moduli showed a non-hysteric response during the freeze – thaw cycle, which was different from the concurrently measured electrical resistivity response where a differential resistivity signal is observed depending on whether the soil is experiencing freezing or thawing. The differential electrical resistivity signal presents challenges for unfrozen water content estimation based on Archie's law. Using an improved formulation of Archie's law with a variable cementation exponent, the unfrozen water content estimation showed a large variation depending on the choice of the resistivity data during either a freezing or thawing cycle. Combining the electrical and seismic results, we suggest that, rather than a large hysteresis in the actual unfrozen water content, the shift of the resistivity response may reflect the changes of the distribution pattern of the unfrozen water (or ice) in the soil matrix during repeated freeze and thaw processes. Collectively, our results provide an improved petrophysical understanding of the physical and mechanical properties of saline permafrost during freeze – thaw transitions, and suggest that large uncertainty may exist when estimating the unfrozen water content using electrical resistivity data.

1. Introduction

Saline permafrost is widespread both onshore and offshore in the Arctic region (Hivon and Sego, 1993; Humlum et al., 2003; Krylov and Bobrov, 1998; Osterkamp, 2001). It is defined as perennially subzero temperature soil with pores filled by high-salinity water that remains partially unfrozen at temperatures below 0 °C due to freezing point depression (Banin and Anderson, 1974; Marion, 1995). While most of the unfrozen water in freshwater permafrost soils exists as surface-bound water and thin water films in the vicinity of soil grains, unfrozen water in saline permafrost could also occupy the bulk pore space (Hivon and Sego, 1995). The unfrozen water content in saline permafrost can fluctuate significantly during freeze – thaw transitions with temperature change, and is the dominant factor controlling its mechanical and hydrological properties. Nixon (1987) demonstrated dramatic reduction in the mechanical strength of saline permafrost at subzero temperature with pile load tests. Hivon and Sego (1995) observed significant loss of strength of saline permafrost at subzero temperatures when compared with less saline soils. The compromised mechanical strength of saline permafrost could have a significant impact on infrastructure stability built on permafrost soils (Hivon and Sego, 1995; Brouchkov, 2003).

Geophysical methods, such as electrical and seismic methods, have been widely used in permafrost research at both lab and field scales to estimate the unfrozen water content of permafrost and its implications on permafrost physical and mechanical properties (Dou et al., 2016, 2017; Dafflon et al., 2016; Wu et al., 2013; French et al., 2006; Krautblatter and Hauck, 2007; Oldenborger and LeBlanc, 2015). Significant contrasts in electrical resistivity and elastic properties between frozen and unfrozen soil are the basis for these methods. For example, while unfrozen soils have a typical resistivity value from a few to hundreds of ohm-meters depending on pore water salinity, saturation, soil type and texture, typical resistivity for frozen soils ranges from tens to

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hundreds of kilo-ohm-meters (French et al., 2006; Krautblatter and Hauck, 2007; Fortier et al., 2008; Dafflon et al., 2013; Wu et al., 2013), with the except of soils with high clay contents. While studies on freshwater permafrost are extensive, similar studies on saline permafrost are limited. Due to freezing point depression, unfrozen water content in saline permafrost is expected to be considerably higher than its freshwater counterparts under the same temperature and texture conditions, resulting in vastly different geophysical and mechanical properties and behaviors. In addition, hysteresis in unfrozen water content during the freeze – thaw cycles of frozen soils has been known for permafrost soil due to metastable ice nucleation as well as capillary and adsorption effects (Bittelli and Flury, 2003; Ishizaki et al., 1996; Tian et al., 2014). Most of these studies focus on freshwater soils, generally showing a higher unfrozen water content during the freezing than the thawing cycle, and studies for saline permafrost are sparse. If hysteresis exists in saline permafrost, how it affects its geophysical and mechanical properties are important for the development of geophysical permafrost monitoring methods.

In this research, we present a laboratory study to understand geophysical properties of saline permafrost soils during freeze-thaw cycles, and their implications for the estimation of unfrozen water content and the soil's physical and mechanical properties. We acquired the saline permafrost soils from a site in Barrow, AK, ~300 miles north of the Arctic Circle. Multiple geophysical (electrical, seismic and electromagnetic) surveys at this site have identified an extensive saline permafrost layer overlain by a shallow active layer and freshwater permafrost (Hubbard et al., 2013; Dou and Ajo-Franklin, 2014). This saline permafrost layer, characterized by low resistivity in the range of a few to tens of Ωm, may be less than two meters below ground surface in some locations, confirmed by coring.

During the experiment, we conducted electrical resistivity, spectral induced polarization (SIP), and low- (sonic-) frequency seismic measurements (Young's, **E**, and shear, **G**, modulus). To the best of our knowledge, low frequency (<1000 Hz) SIP signals of natural saline permafrost soils during freeze – thaw transition has not been explored and how changes of temperature, unfrozen water content, salinity and ice formation collectively impacts its SIP response is not well understood. In addition, we discussed how electrical resistivity measurements were used to estimate the unfrozen water content and proposed a modified formula based on Archie's law. Specifically, we took into account the changes of the soil cementation factor due to soil structural change induced by ice formation and the effect of temperature and increase in salinity on fluid conductivity of the unfrozen water explicitly. We evaluated the uncertainty of unfrozen water content estimation based on Archie's law during freeze – thaw cycles. For seismic monitoring, while most of previous seismic studies on permafrost were conducted at ultrasonic frequency range, our sonic frequency seismic measurements offered several advantages. First, the wavelengths at sonic frequencies were much large, therefore its velocity and attenuation were less affected by wave scattering from soil grains, fluid/ice inclusion and layer heterogeneity. Second, seismic velocity dispersion and attenuation are inherently frequency dependent, therefore it is desirable to conduct laboratory measurements with frequencies close to those used in the field to help with field data interpretation. Co-collection of both electrical and seismic data allowed joint data interpretation, which lead to better understanding of the physical and mechanical processes in the saline permafrost soil during the freeze - thaw process.

2. Electrical and seismic methods for saline permafrost studies

Multiple geophysical methods have been used for permafrost studies. Numerous studies have used both ground-based and airborne electrical resistivity and electromagnetic surveys to explore resistivity contrasts to delineate permafrost structures and dynamics over time and space. For example, Minsley et al. (2012) conducted airborne electromagnetic surveys to map permafrost distribution in the Yukon flats region. Hubbard et al. (2013) combined ground based Electrical Resistivity Tomography (ERT) with remote sensing and point based measurements to explore permafrost zonation and correlations with biogeochemical properties. Dafflon et al. (2016) used ERT to estimate shallow permafrost distribution in an ice-wedge polygon dominated arctic tundra. Hilbich et al. (2008) conducted ERT survey of a mountain permafrost and identified the dynamics of active layer thickness over time. Krautblatter and Hauck (2007) and Krautblatter et al. (2010) conducted ERT surveys of permafrost rock walls to study temperature effects on permafrost dynamics in order to evaluate its mechanical stability based on laboratory calibrated temperature – resistivity correlation. Fortier et al. (2008) combined ERT survey with field temperature logging, cone penetration tests and core logging to study the internal structure of permafrost mounds.

All studies confirm that temperature has a significant effect on electrical resistivity in permafrost. However, while a linear correlation between temperature and resistivity is widely observed for unfrozen soils at temperature above 0 °C (Hayley et al., 2007; Krautblatter and Zisser, 2012), both linear and exponential correlations have been observed for partially frozen soils (Hayley et al., 2007; Krautblatter and Zisser, 2012; Wu et al., 2013). This is possibly related to soil texture, especially tightness and interconnectedness of water saturated pores (Krautblatter and Zisser, 2012).

In addition to resistivity, induced polarization (IP, in forms of single frequency, spectral IP or complex resistivity) signals have also been explored to study permafrost (Frolov, 1973; Olhoeft, 1977; Krylov and Bobrov, 1998; Wu et al., 2013; Banville et al., 2016). Frolov (1973) studied the elastic and electrical signals of frozen ice and soils and showed the effects of soil texture, moisture content and temperature on these properties. Specifically, dielectric measurement at frequencies >3 K Hz shows that the electrical properties of the frozen soil are determined by the specific surface area of the soil, the ice and unfrozen water content. Similar studies by Maeno et al. (1992) also found the unfrozen water weakly bounded on mineral surface generates large dielectric polarization and conduction. Olhoeft (1977) studied the complex resistivity behavior of clay-rich permafrost and observed strong frequency-dependent behavior of the complex resistivity at frequencies above 10 Hz. Olhoeft (1977) suggested a few different mechanisms responsible for the observed electrical behavior that include ionic conduction, a Maxwell–Wagner type of effects, Bjerrum defects (Bjerrum, 1952) as well as the relaxation of unfrozen water molecules in the soil. Grimm et al. (2008) and Stillman et al. (2010) studied the induced polarization signals of silicate – ice mixtures. They also observed strong frequency dependent behavior of the electrical signals that are related to these effects. Fortier and Allard (1998) identified IP anomaly at the boundary between frozen and unfrozen layer that is likely relevant to interfacial Maxwell–Wagner effects. Wu et al. (2013) explored low frequency electrochemical IP effects of permafrost soils. They observed an increase of the polarization signal during isothermal thawing at 0 °C which are related to the increase of the unfrozen soil grains and pore fluid. Krylov and Bobrov (1998) performed field studies of the saline permafrost on the Yamal Peninsula in Russia and identified different soil layers having different soil texture and ice content with resistivity. They also observed polarization anomalies that were attributed to the existence of frozen saline clay. In addition to vertical profiling, induced polarization tomography has been used for periglacial studies in recent years (Banville et al., 2016). Studies by Grimm et al. (2008) and Stillman et al. (2010) on artificial mixtures of silicate with saline proposed multiple polarization mechanisms that are linked with the different structural components of the mineral-ice-brine system. This includes contributions from both low frequency diffusive and Maxwell–Wagner type of polarization to higher frequency ice polarization and polarization associated with surface absorbed water.

Seismic velocity and attenuation of permafrost, frozen soils or gas hydrates have also been studied in both laboratory and field. Kurfurst