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A note on electrical freezing and shorting potentials

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Abstract

Electrical potentials developed by charge separation during freezing of water and dilute $CaCl_2$ solutions were studied in the laboratory, using gold-plated copper electrodes placed across the freezing boundary. A sudden increase in the potential occurs when the freezing front reaches an electrode. A shorting potential was observed at the electrodes when the freezing front advanced past the reference electrode. The magnitude of the freezing and shorting potentials is of the order of a few hundred millivolts. This technique can be used to detect and monitor the movement of freeze–thaw boundaries in water and moist soils. © 2004 Elsevier B.V. All rights reserved.

1. Introduction

An electrical potential develops across a freezing interface in aqueous solutions and moist soils due to charge separation and preferential entrapment of ions in the two different phases (Workman and Reynolds, 1950; Parameswaran and Mackay, 1996). The magnitude of the potential depends on various factors including the rate of cooling and species and concentration of solute present in the solution or soil. Under normal rates of cooling experienced in nature, the freezing potentials measured are in the range of a few

millivolts. Under fast cooling using very cold circulating baths, potentials of several volts have been measured (Workman and Reynolds, 1950; Gill and Alfrey, 1952). The wide range of values of freezing potentials observed in solutions by different authors under similar conditions indicates that the measured potential depends on various factors such as the purity of the solution, the experimental setup, including the type of electrodes and wires used, the connection to the measuring/recording equipment, internal resistance of the recorder, and so forth. Pressure also has an effect on the development of potentials, especially in soils, where frost heaving is commonly observed (Kelsh and Taylor, 1988). The magnitude of the potentials measured by various authors has varied over three orders of magnitude, 100 mV to 230 V (Workman and Reynolds, 1950; Pruppacher et al., 1968; Cobb and Gross, 1969; Murphy, 1970). In pure

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water, the values of the freezing potentials measured were between 200 mV and 120 V (Arabadzhi, 1948; Workman and Reynolds, 1950; Gill and Alfrey, 1952; Bayadina, 1960; Murphy, 1970; Korkina, 1975; Parameswaran, 1982).

Fortier et al. (1993) measured the electrical potential developed across a thawing boundary in the active layer of permafrost in Umiujaq in Nunavic, located on the east coast of Hudson Bay, in the Arctic regions of Quebec. They used a reference electrode located deep in the unfrozen ground and the potentials developed on each electrode above that were measured. The potentials measured were interpreted as a combination of freezing potentials, streaming potentials due to water migration and changes in the electrolyte concentration. They concluded that by monitoring these potential differences, changes in temperature, water content and migration and ionic distribution can be studied.

Outcalt and Hinkel (1989, 1990) carried out combined measurements of soil temperature and electric potential in the seasonally freezing top layer of a sandy loam soil at a site in the Botanical Garden inUniversity of Michigan, Ann Arbor. They measured electric potentials of 300–700 mV and interpreted the data as the result of thermally induced ionic concentration in the soil. They suggested that secondary effects due to advective flow of water to the freezing front (streaming potential) could also give rise to electric potentials. They concluded that valuable information on the geotechnical conditions of freezing soils (the state and mobility of the soil water) can be gathered by combining thermal and electrical potential measurements.

Past measurements in the laboratory and in the field indicate that the potentials developed during freezing of water and soils containing ionic impurities in solution, are on the order of a few hundred millivolts (Parameswaran, 1982; Parameswaran and Mackay, 1983, 1996; Burn et al., 1998). Field measurements near the western Arctic coast of Canada include those carried out in the lakes near Inuvik, pingos and at the bottom of a drained lake of the Tuktoyaktuk Peninsula area where permafrost was aggrading. The ionic impurities in these systems consisted mainly of cations: Ca^{2+}, Mg^{2+}, K^+ and Na^+ and the anion, Cl^-. For example, the drill hole water from Pingo 9 contained 230–260 ppm of Ca^{2+},

85–95 ppm Mg^{2+} and about 250 ppm Cl^-, besides small amounts of K^+ and Na^+. The water from the Inuvik lakes contained 16–30 ppm Ca^{2+}, 5–8 ppm Mg^{2+}, and less than 10 ppm each of Na^+ and K^+.

These measurements showed a finite potential difference between an electrode located at the freezing interface and a reference electrode in the unfrozen region. These observations indicate the possibility of using this technique to monitor the movement of freezing/thawing interfaces in the ground. An experimental program was set up to systematically study freezing potentials developed in different solutions and at different freezing rates.

2. Experimental setup

Fig. 1 shows a schematic diagram of the experimental cell. This consisted of a cylindrical PVC vessel (A) of internal diameter, 146 mm (5.75 in. nominal), height 368 mm (14.5 in.), wall thickness 6.3 mm and closed at one end with an aluminum base (B). The cylinder was insulated with Styrofoam rings (C) of thickness 51 mm. The cylinder was placed on a cooling chamber (D) through which a cold fluid (Prestone antifreeze) could be circulated. The cooling plate had inlet and outlet PVC tubes connected to a Haake G cooling bath with a Haake D8 temperature controller. The temperature of the bath could be controlled to ±0.1 °C accuracy. A Plexiglas rod (E) of diameter 9.5 mm (0.375 in.) and length 406 mm and containing six electrodes in the form of gold-plated copper strips (F) (25 mm×9.5 mm×0.8 mm thickness) was placed at the center of the cylinder. The copper strip electrodes were parallel to the base of the cell. The bottom electrode was 10 mm above the bottom of the vessel and the others were positioned at 25 mm intervals. Thermistors (Beta Therm 2.2K3A1A) were also attached at each electrode location. Coaxial cables (G) were soldered to the electrodes and thermistors and connected to an external data logging system (Campbell Scientific Model CR 10). The time, temperature and electrical potentials were measured by the recorder every 5 min and averaged every 15 min and the data was stored in a storage module SM192 attached to the CR-10.

The CR-10 data logger has an internal impedence of 200 GΩ (2×10^9 Ω), sufficiently large to measure even very small potential differences. Resolution of