

Sensing technology for measurement of thermal properties of frozen soil

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ABSTRACT: Soil is one of the most widely used materials in the civil engineering sphere. Different types of soil can be broadly used in its natural or compacted form in the construction of roads, dams, canals, and railways. Due to the differences in moisture content and temperature, soil can be in various states; saturated and unsaturated, frozen or thawed. Advances in the development of laboratory testing equipment for unsaturated soil properties along with the ability to measure soil suction have prepared the way for the implementation of unsaturated soil mechanics. It is now possible to measure most unsaturated soil properties, and these achievements help for unsaturated soil property characterization that best describe the actual unsaturated soil properties. However, the static and dynamic responses of frozen soils have been found to be distinctly different from those of unfrozen soils. The behavior of frozen soils is expected to depend on the inter-particle friction and particle interlocking, the unfrozen water content, pressure melting, and the ice/water phase change. Therefore, unsaturated frozen soil properties should be measured and investigated separately from unsaturated unfrozen soil. The objective of this study is to investigate the appropriate sensors for the measurement of thermal properties of unsaturated frozen soil.

1 INTRODUCTION

Extreme weather conditions, such as lengthy periods of drought, rain or frost significantly impact building foundations. The level of soil moisture is a critical factor in potential detrimental influence. During rainy seasons, the soil absorbs large amounts of water, combined with freezing and further thawing, threatening urban infrastructure (Azmatch et al., 2012). Such activities can severely damage the foundation and load-bearing structures of houses, buildings, and facilities. During frosts, unfrozen water remains in the soil's pores, and the processes of freezing and thawing strongly influence it. These processes significantly affect the physical and mechanical properties of the soil. Therefore, studying the relationship between the amount of unfrozen water and sub-zero temperatures is an important aspect, and it is defined as the soil freezing characteristic curve (SFCC) (Malaya and Sreedeeep, 2012). During the freezing period, the pore model changes, and a water film forms around the ice, which is located between the soil particles (Wang et al., 2017). According to the studied information, soil freezing begins with ice formation in the pore with the largest radius (Watanabe and Mizoguchi, 2002).

The freezing and thawing and drying and moistening cycles have similar characteristics. Water with a low matrix potential remains in the soil during the drying process, and the pores filled with water are gradually filled with air. A similar process occurs during the process of freezing, water takes on a solid form. Adsorption and capillary forces affect changes in the matrix potential of water in the soil. The decrease in the matrix index is considered to be the same for both processes, due to the fact that during freezing, water is absorbed by the soil pores in the form of a thin film and the presence of water or air and considered insignificant

(Spaans and Baker, 1996). For capillary strength, there is a difference in the values of the matrix index, since the surface energy of particles is different for soils in the cycles of freezing and drying (Spaans, 1994).

Figure 1 describes the process of soil freezing. The following conclusions emerge from it. The upper part of the soil undergoes freezing, while the lower layers remain unfrozen. There is a partially unfrozen layer which leads to negative pore pressure, which causes water to move into the frozen ground and ice lenses formation (Ren, 2018). The formation of ice lenses and their uneven distribution leads to the appearance of cracks, which can be a problem for infrastructure system in cold regions.

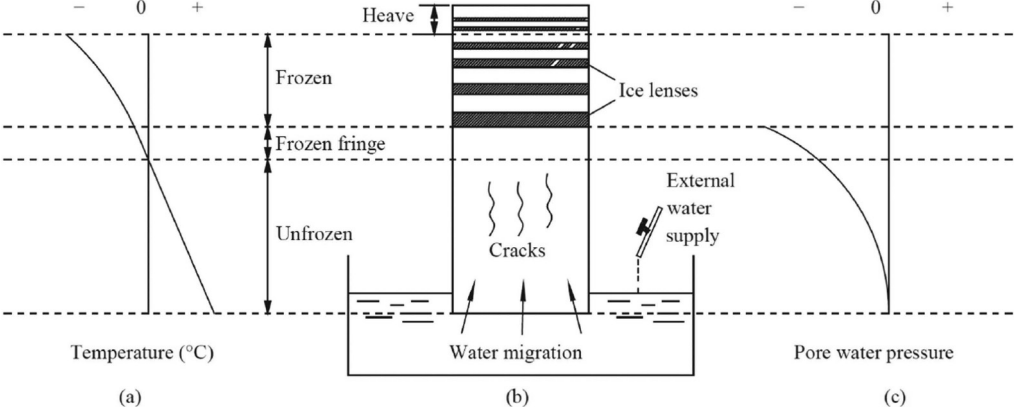


Figure 1. Soil freezing process (Ren et al., 2018).

The inter-particle friction and particle interlocking, the amount of non-frozen water, pressure melting, and the ice/water phase change are all expected to affect the behavior of frozen soils (Xiantiang et al., 2018). These distinctive features are primarily caused by the ice lens and the ice solidifying between soil particles. For instance, the presence of ice in the soil pores for frozen soils result in a decrease in hydraulic conductivity (Fredlund et al., 2012). Due to the distinct behavior of frozen soils, using existing well-established knowledge of mechanical behavior and modeling frameworks for non-frozen soil is not recommended for frozen soils without firstly performing a thorough analysis and examination. Therefore, unsaturated frozen soil properties should be measured and investigated separately from unsaturated non-frozen soil, so that a concept of unsaturated soil properties in frozen soil can be implemented in engineering practice. The objective of this research is to review the sensing technology for the measurement of thermal properties in unsaturated frozen soils.

2 THE HP METHOD FOR MEASUREMENT OF FROZEN SOIL PROPERTIES

Precision measurements of soil thermal and hydraulic parameters are required for environmental sciences and engineering applications and steady-state methods are impractical in determination of these parameters. In lab and field settings, the heat pulse (HP) method is a rapid way to detect soil thermal parameters and a range of other physical features (He et al., 2018).

Single-probe HP (SPHP) and dual-probe HP (DPHP), shown in Figure 2, are the two categories into which HP probes fall. Since SPHP can be either short or long, there are several available sampling volumes. In addition, SPHP is sturdy which provides the reduction in

inaccuracy caused by needle deflection (He et al., 2018). Unfortunately, single-probe HP can only be used to test soil thermal conductivity. In order to improve SPHP to assess other parameters such as heat capacity and soil water content, a deeper understanding of the thermal contact conductance between the soil and the probe is required (He et al., 2018).

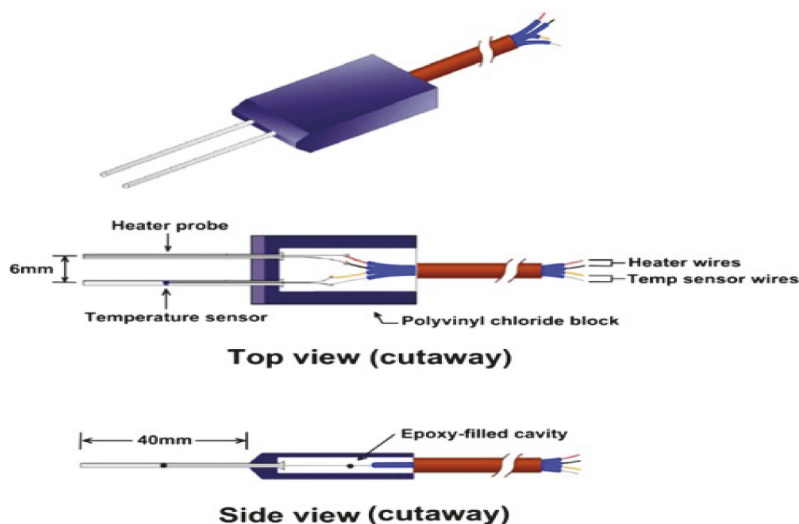


Figure 2. Example picture of dual-probe HP probe (He et al., 2018).

Heat and water flow in non-frozen soils have been measured extensively using the HP technique. However, heat causes soil ice to melt and then refreeze, complicating the use of the HP approach in partially frozen soils (He et al, 2018). When ice melts and subsequently refreezes, a considerable part of the energy in the heat pulse is concentrated on phase shifts rather than conduction heat transfer (He et al, 2018). Thermal properties of the system, such as thermal conductivity and thermal diffusivity, vary in conjunction with phase transitions, such as when water crystallizes or ice melts (Zhang et al., 2015). The measurement of soil thermal properties during such a process can be extremely useful in understanding and forecasting heat transport in such material systems.

Melting ice increases the volumetric heat capacity anticipated by HP and reduces the thermal diffusivity of the soil because partially frozen soils do not fulfill the general assumptions of the HP approach, namely no phase change and temperature invariant thermal characteristics. In accordance to the findings of Ochsner and Baker (2008), dual-probe HP sensors overestimated λ and C values in partially frozen soils (Kojima et al., 2018). Overestimation of λ was most common between 2 °C and 0 °C, whereas Putkonen (2003) discovered that C was overestimated between 10 °C and 0 °C (Kojima et al., 2018). C readings from dual-probe HP sensors were utilized in certain studies to determine the quantity of soil ice. Zhang et al. (2011) observed that the ice content of sand based on C measured with DPHP sensors was incorrect at temperatures ranging from 2 °C to 0 °C (Kojima et al., 2018). Furthermore, in partially frozen soils, as compared to non-frozen soils, C and κ (thermal diffusivity) have a distinct dependence on ambient soil temperature (Ochsner & Baker, 2008). For example, when the soil ambient temperature is very low (below 20 to 2 °C depending on the soil type), the HP melts less ice and the thermal values obtained by the HP are more accurate (He et al, 2018).

The heat conduction Equation (1) shows how heat flows from the heater to the sensors by using the radial coordinate system and refers to the phase shift in partially frozen soils.

$$C_v \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda \frac{\partial T}{\partial r} \right) + L_f \rho_I \frac{\partial \theta_I}{\partial t} \quad (1)$$

There is no analytical alternative to equation (1) for practical soil conditions and using HP technology in frozen soils is difficult by the melting and refreezing of ice induced by the heat pulse. There are three ways in the literature for applying the heat pulse to experiments on partially frozen soil (He et al, 2018):

- By utilizing the analytical procedure applied in non-frozen soil and assuming the absence of phase change.
- By limiting ice melting through optimal heat application. Nevertheless, the only temperature range where ice melting induced by HP could be stopped was between -2 and 20 degrees Celsius, and ice melting was substantial at low temperatures, particularly around 0 °C.
- By considering how the melting of the ice changes the thermal parameters that were measured. Ochsner and Baker (2008) included the effects of melting ice into apparent thermal properties to quantify lumped conduction and latent heat components. Once the HP-induced temperature change and the change in λ with temperature are both low, λ can be removed from the partial derivatives in equation (1) and the equation simplified as in Equation (2).

$$C_a \frac{\partial T}{\partial t} = \lambda_a \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) \quad (2)$$

The apparent heat capacity is defined as the amount of energy required to raise the temperature of a unit volume of partially frozen soil by one degree whereas the phase shift between water and ice occurs as a result of the temperature change caused by the HP. The technique employed by Ochsner and Baker (2008) did not try to monitor ice melting or calculate real thermal soil values. He et al. (2015) evaluated the Time Domain Reflectometry (TDR) method's capacity to quantify ice melting and improve the chance of getting exact thermal properties of frozen soil. For non-frozen liquid water and ice content, they combined Ochsner and Baker's (2008) technique with composite dielectric mixing models (He et al., 2018). C might be determined before to adding HP using the liquid water and ice content observed by TDR using Equation (3). The amount of ice melt may be calculated by comparing the computed C to the C_a estimated using the HP technique, which is influenced by ice melting (He et al., 2018).

$$C_v = \theta_v \rho_I c_I + \rho_g c_{gf} + (1 - \phi) \rho_s c_s \quad (3)$$

He et al. (2015) applied this approach to a sandy soil and observed that ice melting of 0.5% and 2% had a major influence on the soil thermal characteristics as determined by the heat pulse method. This investigation proved that the HP technique without extra modifications was useless for measuring thermal properties of frozen soil at temperatures ranging from 5 to 0 °C (Putkonen, 2003). The soil freezing characteristics, freezing and thawing curves, and heat capacity estimations from TDR and HP all exhibit hysteretic behavior (He et al., 2018). At temperatures ranging from 5 to 0 °C., determining both λ and C simultaneously remains problematic.

3 CONCLUSION

This paper described the applications of heat pulse (HP) method and HP sensors to determine the thermal properties of frozen and partially frozen soils. In frozen soils when the ambient temperature is between 20 and 2 °C, HP sensors gave more accurate thermal values. However,

at 5 to 0 ° C, HP method without developments can not be applied to measure the frozen soils parameters. Therefore, it is needed to conduct further research on modification of HP technique and HP sensors to identify frozen and partially frozen soil properties under variable low temperature conditions.

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