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Measuring thermal conductivity of frozen soil using fiber optic sensors

Abstract. The thermal conductivity is crucial for determining heat transfer in frozen soil. However, it is a challenge to obtain accurate measurement values due to the instability of soil properties. Recently, the fiber optic sensing technologies has enabled accurate and distributed in-situ monitoring of a variety of geotechnical parameters. This paper aims to explore the feasibility of actively heated fiber Bragg grating (AH-FBG) method in measuring thermal conductivity of frozen soil. A series of laboratory experiments were performed on frozen soil samples at different initial temperatures from −16 to 5 °C. The theoretical upper and lower limits of thermal conductivity were used to evaluate the AH-FBG measurements. The thermal conductivity recorded by a heat transfer analyzer was used to identify the measurement accuracy. The experimental results that the AH-FBG method can accurately measure the thermal conductivity of frozen soil when the initial temperature is below −6 °C, and the measurement error is within acceptable range of 0.8%. When the soil temperature is between −6 and 0 °C, significant measurement errors were observed due to the disturbance of heating to the frozen soil.
Keywords: frozen soil; fiber optic sensor; fiber Bragg grating (FBG); actively heated fiber optics (AHFO); monitoring; phase change.

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Introduction

Frozen soils have complicated thermal properties governing the heat transfer and freeze-thaw process [1,2]. In heat transfer modeling of frozen soils, thermal conductivity is one of the most important input parameters [3]. It has long been recognized that the thermal conductivity of soil is strongly influenced by its density and compositions (soil particles, water, ice, and air) [4,5]. In particular, the thermal conductivity of frozen soil is hard to determine due to the complex phase change process.

In the last few decades, many studies have been conducted in this research area, and some theoretical and empirical models have been proposed [3,6-8]. Transient and steady-state methods have been used to determine thermal conductivity, but most of them are only applicable to laboratory tests. It is therefore of great importance to develop an effective and reliable in-situ measuring technology of thermal conductivity for frozen soils [4,5,9]. This is a bottleneck problem that seriously hinders the development of fundamental theories and engineering design schemes of frozen soils.

In engineering practices, the heat pulse (HP) method is widely used to measure the soil thermal properties based on the analogies of radial heat flow from a line source [8,10,11]. For frozen soils, this method has been applied to estimate unfrozen water contents or ice contents [12-14], water and heat flux [15], and snow density [16], as well as thermal properties [15,17]. It has the advantages of fast measurement, low cost, and superior portability for field applications [18]. However, some drawbacks are encountered during field monitoring, such as limited measurement ranges and low accuracy. More importantly, only point-type measurement can be achieved, so large-scale and long-distance monitoring can hardly be performed.

Fiber optic sensing technologies, which have the advantages of distributed measurement, anti-interference, and corrosion resistance [19-22], have been dramatically developed and employed in strain and temperature sensing in recent years [22,23]. Based on distributed temperature sensing (DTS), the actively heated fiber optic (AHFO) method has been developed to overcome the shortcomings of traditional HP methods. For unfrozen soils, it has been widely applied for measuring water and heat flux [24-28]. However, it was rarely used in frozen soils due to the complex phase change process and temperature dependence of thermal properties [18].

In this paper, the actively heated fiber Bragg grating (AH-FBG) has been proposed to perform quasi-distributed monitoring of thermal conductivity of frozen soils. A series of laboratory experiments were carried out at different initial temperatures to explore the feasibility of the proposed method in thermal conductivity measurement and determine its measurement accuracy and range.

Methodology

Figure 1 shows the working principle of an FBG sensor. According to Bragg's law, when a broadband source of light has been injected into the fiber, FBG reflects a narrow spectral part of light at a specific wave length λ_B. For the FBG sensor, this wavelength is sensitive to changes in temperature (T) or strain (ε). To accurately measure the actual temperature, strain relief of the FBG sensor is very important. In this study, the loose FBG sensor is encapsulated in a small corundum tube to avoid strain effects. Thus this sensor is only for temperature measurement, and the temperature can be expressed as [29]

$$\Delta T = \frac{\Delta \lambda_B}{\lambda_B c_{\mathrm{T}}} \tag{1}$$

where c_{T} is the wavelength sensitivity coefficients for temperature, $\Delta\lambda_B$ is the wavelength change, ΔT is the temperature change.

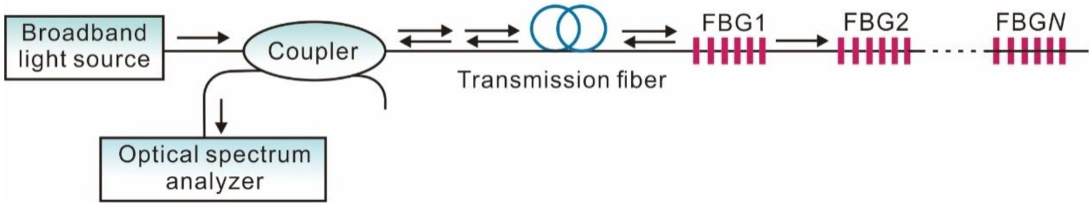

Figure 1. Working principle of the FBG sensing technology

When an AH-FBG sensor is inserted in frozen soil, due to the infinite line heat source model and cylindrical geometry of the single probe dissipation sensors, the temperature (T) of the AH-FBG sensor during heating is related to time (t) according to the theoretical solution for a line heat source [30]:

$$T - T_0 = -\frac{q}{4\pi\lambda}\ln t + B \tag{2}$$

where T_0 is the initial temperature before heating (°C). t and q are the heating time (s) and the heat source strength per unit of length (W/m), respectively. λ is the thermal conductivity (W/(m·°C)) of the frozen soil. B is a constant.

Accounting for the finite dimensions of the heat source and the contact resistance between the heat source and the medium outside it, Eq. (2) is valid for the constant heating strength and sufficient heating time. Linear regression can be used to calculate λ from the slope K of the heating data with Eq. (2)

$$\lambda = \frac{q}{4\pi K} \tag{3}$$

For frozen soils, the thermal parameters are related to several factors such as soil moisture, ice content, soil composition, and density. The thermal conductivity has an upper limit (λ_U) and a lower limit (λ_L), which can be expressed as [6]

$$\lambda_L = \sum \theta_\alpha \lambda_\alpha \tag{4}$$

$$\frac{1}{\lambda_U} = \frac{1}{\sum \frac{\theta_\alpha}{\lambda_\alpha}} \tag{5}$$

where θ_α and λ_α are the volumetric content (m^3/m^3) and thermal conductivity of the phases (unfrozen water, ice, soil particles, and air). The sum of the volumetric contents of all components is 1. Thus, the thermal conductivity can be calculated according to the volume fraction of each substance in the frozen soil, which can be used as the reference value for the thermal conductivity measured by the AH-FBG method.

Material and laboratory test setup

To measure the thermal conductivities of the frozen soil using the AH-FBG method, a series of laboratory experiments have been conducted. Figure 2 shows the structure of the AH-FBG sensor. The AH-FBG sensor includes an aluminum oxide tube with high thermal conductivity, a bare FBG sensor, an electrical resistance wire, and a stainless-steel tip and flange for packaging and protecting. The electrical resistance wire is used for heating, and the FBG sensor is used for temperature sensing. They are installed in parallel in different holes of the corundum tube.

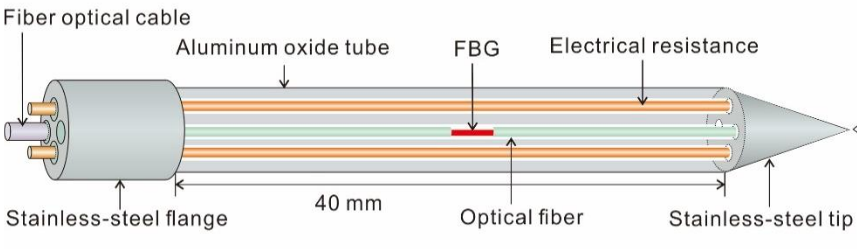

Figure 2. Schematic diagram of AH-FBG sensor

The experiments were carried out in a low-temperature test chamber. Different experimental temperatures were set to control the temperature of the soil samples from -16 to 5°C. The soil samples were collected from Huining, Gansu Province, China. The basic properties of the test soil are given in table 1.

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Table 1

Basic physical parameters of the test soil

Soil type	Liquid limit (%)	Plastic limit (%)	Optimum water content (%)	Natural dry density ($g \cdot cm^{-3}$)	Maximum dry density ($g \cdot m^{-3}$)	Specific gravity
Low plasticity clay	34.0	17.3	13.8	1.42	1.53	2.76

As shown in figure 3, the soil samples were compacted and filled in the stainless-steel cutting rings and PVC molds. The dry density was 1.4 $g/cm^3$and the initial moisture contents were set as 16%. The AH-FBG sensors were inserted into the center of the soil samples and connected to an FBG interrogator and a direct current (DC) power supply, respectively. The FBG interrogator was connected to a computer for real-time FBG data collecting. The total heating time was determined to be 300 s, and the heat source strength was set between 6~8 W/m. The FDR sensors and thermistors were installed in the PVC samples to measure the unfrozen water contents and soil temperatures, and both were connected to the data logger. In addition, a heat transfer analyzer was used to obtain the thermal conductivity reference value (λ_c) of the frozen soil sample at the temperature of -16 °C.

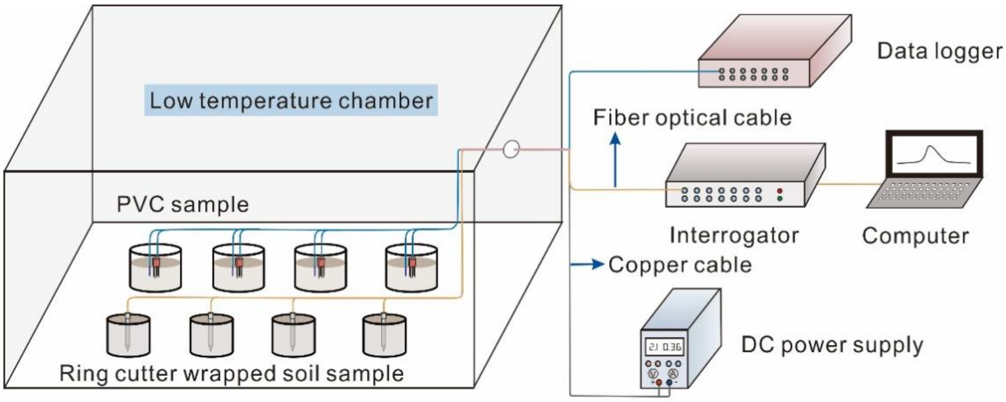

Figure 3. Schematic image of the experimental setup

Results and analysis

The soil temperature data measured by the thermistors and the unfrozen water content data measured by the FDR sensors are shown in figure 4. The results show that the freezing evolution of soil samples can be divided into four stages. In Stage I and Stage IV, the soil samples were completely unfrozen and frozen states, respectively. The compositions of the soil did not change. In Stage II, the soil temperature was between −3.16 and −1.2 °C (severe phase transition zone), and the soil temperature curve reached a relatively stable state, as shown in Fig. 4(a). Simultaneously, the unfrozen water content decreased sharply as the temperature decreased in Fig. 4(b). This phenomenon can be explained by the fact that the moisture in the sample underwent a severe phase change and the process of water freezing into ice is exothermic [9]. The heat generated by the phase change offsets part of the heat dissipation of the sample at a lower ambient temperature. It has to be noted that the thermal properties of the frozen soil are very unstable due to the severe phase change in Stage II. While most of the free water freezes, the temperature of the soil sample continued to drop, and the unfrozen water content slowly decreased to a final value, as shown in Stage III. According to the measured unfrozen water content, the initial moisture content, and dry density of the soil samples, the theoretical limits of the thermal conductivity (λ_L and λ_U) can be calculated using Eqs. (4) and (5).

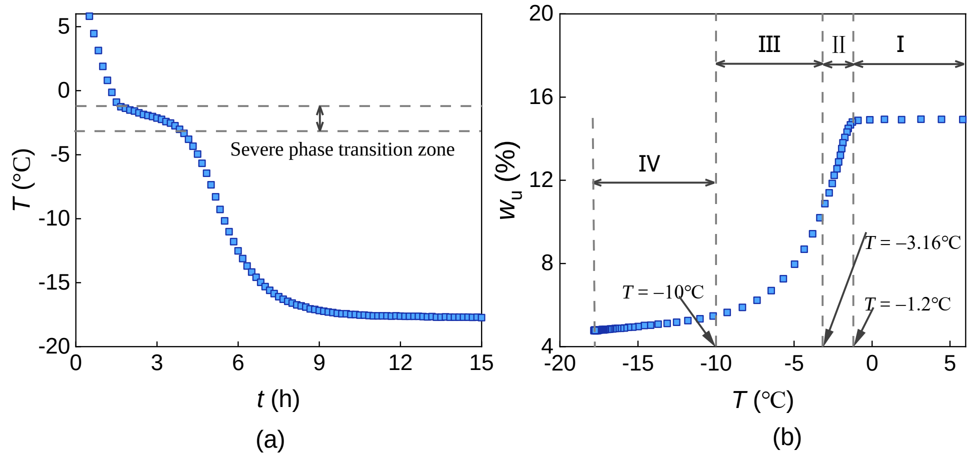

Figure 4. Evolution of (a) soil temperatures (T) obtained by thermistors and (b) unfrozen water contents (w_u) obtained by FDR sensors

Figure 5 shows the temperatures of the AH-FBG sensors during heating with different initial temperatures. It can be seen from figure 5(a) that under the same moisture content and heating power, the temperature rise rates of AH-FBG sensors varied significantly at different temperatures, which means the variant thermal conductivities of the frozen soil.

As described above, when using the linear heat source method to infer the thermal conductivity of the surrounding soil, the heat transfer time in the probe is invalid due to the sensor size and contact thermal resistance [18]. As such, the measurement temperature during this period is also useless and would not be considered. In this study, the sensor temperatures increase rapidly and have a linear relationship with time in the first 40 s of heating due to the heat conduction inner the sensor tube, as shown in figure5(a). After 40 s, the heat starts to transfer in the soil, and the temperature growth slows down. Thus, the valid period for the soil samples is considered 40~300 s, as shown in figure 5(b). The thermal conductivity measured by the AH-FBG method (λ_a) can be calculated after substituting the temperature within the valid period into Eqs. (2) and (3).

Figure 6 shows the comparison between the limit values of thermal conductivity (λ_L and λ_U) calculated by Eqs. (4) and (5), the reference value (λ_c) obtained by the heat transfer analyzer and the measured values (λ_a) obtained by the AH-FBG method. As shown in figure 6, when the initial temperature was less than -6 °C and greater than 0°C, λ_a is between the upper limit (λ_U) and the lower limit (λ_L). They all have the same trends with the temperature, which indicates the rationality measurement of λ_a. In addition, at the temperature of -16 °C, λ_c and λ_a have great consistency, and the error between them is only 0.8%, which shows the high accuracy of λ_a. While the initial temperature is between -6 and 0°C, especially between -3.16 and 0°C, λ_a fluctuates wildly. This can be explained by the fact that the frozen soil with a higher initial temperature undergoes a severe phase change after heating, and its properties are greatly disturbed. So, the accuracy of thermal conductivity measurement is reduced. This result denotes that when the soil is unfrozen, or its temperature is lower than -6 °C, there would have a higher measurement accuracy of the thermal conductivity using the AH-FBG method. The proposed method is currently not applicable to measure the thermal conductivity of frozen soils with an initial temperature of $-6\sim0$ °C.

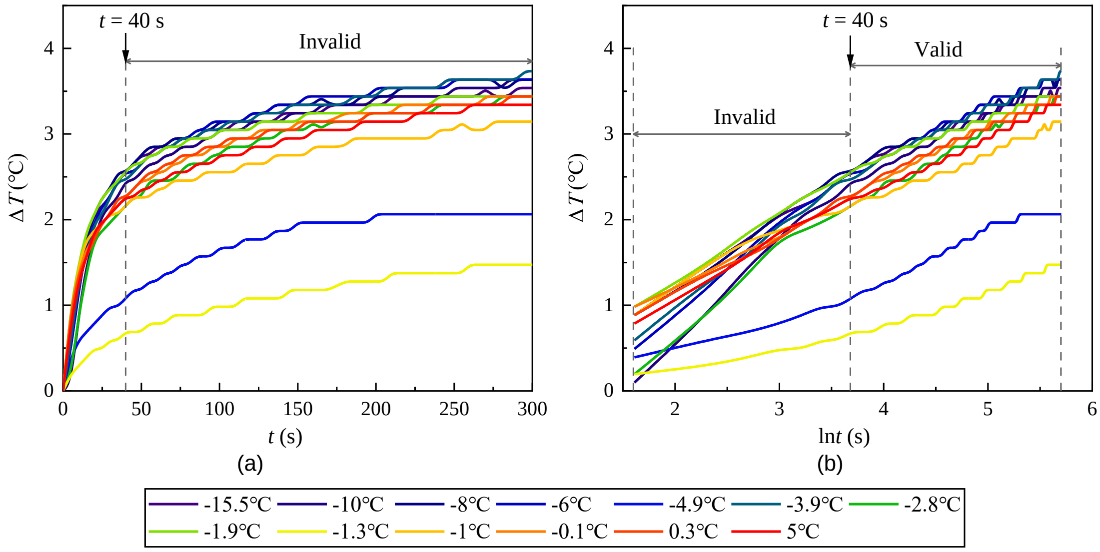

Figure 5. Measured temperature changes (a) as a function of *t* and (b) as a function of $\ln t$ during heating at different initial temperatures

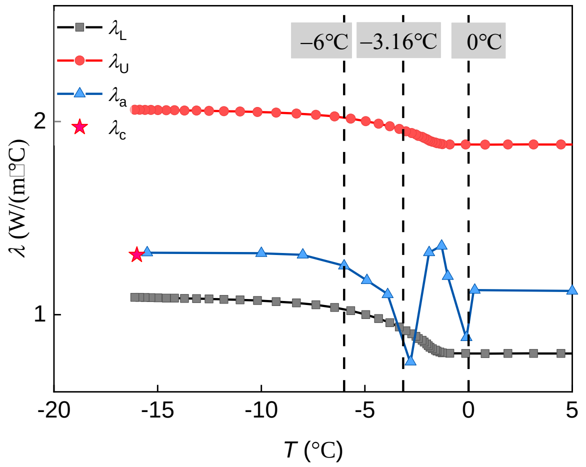

Figure 6. Comparison between the reference values of thermal conductivity (λ_L, λ_U and λ_c) and the measured values of thermal conductivity (λ_a) obtained by the AH-FBG method

Conclusion

The AH-FBG method for measuring the thermal conductivity of frozen soil is proposed and developed. The feasibility of the proposed method was verified by laboratory experiments. Some conclusions are drawn in this study: Due to the unavoidable process of ice-water phase change, the AH-FBG method is only applicable to the soil with the initial temperature below −6 °C and above 0°C. And the measurement error can be within the acceptable range of 0.8%. The disturbance of heating to frozen soil will cause more significant measurement errors when the soil temperature is between −6~0 °C.

More theoretical and experimental studies are needed to solve severe phase change caused by heating and further improve the measuring parameters of the AH-FBG method. Several field observations stations have been established in Hebei, Gansu, and Sichuan Provinces of China. Long-term fiber optic monitoring of in-situ frozen soils is in progress.

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Мұздатылған топырақтың жылу өткізгіштігін талшықты-оптикалық датчиктерді қолдану арқылы өлшеу

Аңдатпа. Жылу өткізгіштігі мұздатылған топырақтағы жылу беруді анықтау үшін өте маңызды, бірақ топырақ қасиеттерінің тұрақсыздығына байланысты дәл өлшеу мәндерін алу қиынға соғады. Жақында талшықты-оптикалық зондтау технологиялары әртүрлі геотехникалық параметрлерді дәл және таралатын орнында бақылауға мүмкіндік берді. Бұл жұмыста мұздатылған топырақтың жылу өткізгіштігін өлшеу кезінде белсенді қыздырылған талшықты Bragg торы (AH-FBG) әдісінің орындылығы зерттеліп, мұздатылған топырақ үлгілері бойынша бастапқы 16-дан 5 С-ге дейінгі әр түрлі бастапқы температураларда бірқатар зертханалық тәжірибелер жасалды. AH-FBG өлшемдерін бағалау үшін жылу өткізгіштіктің теориялық жоғарғы және төменгі шектері қолданылды. Өлшеу дәлдігін анықтау үшін жылу өткізгіштік анализаторы жазған жылу өткізгіштік қолданылды, AH-FBG әдісі мұздатылған топырақтың жылу өткізгіштік коэффициентін бастапқы температура - 6 °C градустан төмен болғанда және өлшеу қателігі дәл болғанда өлшей алады деген тәжірибелік нәтижелер алынды, ал өлшеу қателігі 0,8% деңгейінде қалыптасты. Топырақтың температурасы −6 мен 0 С аралығында болған кезде, мұздатылған топыраққа қызудың бұзылуына байланысты өлшеудің айтарлықтай қателіктері байқалды.

Түйін сөздер: мұздатылған топырақ, талшықты-оптикалық датчиктер, Bragg талшықты торы (FBG), белсенді қыздырылған оптикалық талшықтар (AHFO), жылу өткізгіштік, фазалық өзгеріс.

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Измерение теплопроводности мерзлого грунта с помощью оптоволоконных датчиков

Аннотация. Теплопроводность имеет решающее значение для определения теплопередачи в мерзлом грунте. Однако получить точные значения измерений сложно из-за нестабильности свойств почвы. В последнее время технологии оптоволоконного зондирования сделали возможным точный и распределенный мониторинг на месте различных геотехнических параметров. В данной статье исследуется возможность использования метода активно нагретой волоконной Брэгговской решетки (AH-FBG) для измерения теплопроводности мерзлого грунта. Серия лабораторных экспериментов была проведена на образцах мерзлого грунта при различных начальных температурах от -16 до 5 °С. Теоретические верхний и нижний пределы теплопроводности использовались для оценки измерений AH-FBG. Для определения точности измерения использовалась теплопроводность, зарегистрированная анализатором теплопередачи. Экспериментальные результаты показывают, что метод AH-FBG может точно измерять теплопроводность мерзлого грунта, когда начальная температура ниже -6 °С, а ошибка измерения находится в пределах допустимого диапазона 0,8%. Когда температура почвы составляет от –6 до 0 °С, наблюдаются значительные ошибки измерения из-за нарушения нагрева мерзлого грунта.

Ключевые слова: мерзлый грунт, оптоволоконные датчики, волоконная Брэгговская решетка (FBG), активно нагреваемая волоконная оптика (AHFO), теплопроводность, изменение фазы.

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