Monitoring of soil moisture and temperature distributions in seasonally frozen ground with fiber optic sensors

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Abstract. The evolution of moisture and temperature fields plays an important role in governing soil behavior, which heavily influences the performance of infrastructures built on the ground soil. However, conventional geotechnical instrumentation presents many limitations in the monitoring of seasonally frozen soils in cold regions. This study investigates the feasibility of actively heated fiber Bragg grating (AH-FBG) in measuring the temperature, water content, and ice content of seasonally frozen soil through laboratory tests and field monitoring. The working principle of the AH-FBG monitoring system is introduced in detail. A series of laboratory calibration tests were performed on soil specimens to explore its performance. Long-term in-situ monitoring was carried out on the Loess Plateau in northwestern China. Results show that the AH-FBG technique can be applied to measure the total water content of soils using the Côté and Konrad model. In the field monitoring, the freezing-thawing process of frozen soil was captured by measuring soil temperatures and ice contents during field monitoring, and the maximum freezing depth was deduced. The AH-FBG technique is verified to be a powerful tool in estimating the actual behavior of in-situ ground soil and provides rich information on multi-field interactions in cold regions.

1. Introduction
For seasonally frozen soils, the water-ice phase change and water migration due to temperature variations could result in severe frost heave and deterioration of their engineering properties. The importance of freezing-thawing processes in engineering construction activities in cold regions has long been recognized [1]. The soil temperature, unfrozen water content ($\theta_w$), and ice content ($\theta_i$) are three critical physical parameters used to establish soil freezing-thawing models [2, 3]. However, the accurate determination of these parameters is challenging because of the complexity associated with phase transition and the limitations of conventional monitoring techniques.

Developments over the last few decades have resulted in a series of technologies that can measure water contents and ice contents of frozen soils in laboratory. By comparison, in-situ methods that can provide reliable measurements are rare [4]. Dielectric spectroscopy is the most common technique used to measure $\theta_w$ in the field. $\theta_i$ can be deduced by subtracting $\theta_w$ from the total water content ($\theta_t$). However, underestimation of $\theta_w$ could occur under the significant influence of salinity and other phases on the measurements. Nuclear magnetic resonance can measure $\theta_i$ and $\theta_w$ with high resolution, but its application is restricted to the laboratory. The applications of the heat pulse probe (HPP) method have gradually expanded from the laboratory to the field in recent years. However, this technology is rarely applied to frozen soils because of the unavoidable phase change induced by heating. Recent studies have shown that optimization and improved theoretical solutions could render the HPP method a reliable technique for determining $\theta_w$ and $\theta_i$ of frozen soils [5, 6].

Fiber optic sensing has emerged as a powerful geotechnical monitoring technology with high accuracy and low noise [7-11]. The feasibility of fiber optic sensors in monitoring the behaviors of unsaturated and frozen soils has been verified [4, 12-16]. This paper aims to investigate the effectiveness of a newly developed actively heated fiber Bragg grating (AH-FBG) method for measuring temperatures,
θ_w and θ_i in frozen soil. The temperature profile, freezing depth, and moisture distribution of the soil are then evaluated on the basis of the field monitoring results.

2. Laboratory calibration tests

2.1. Principle of the AH-FBG sensor

FBG is a quasi-distributed strain and temperature sensing technology that has been successfully applied to geotechnical monitoring [9, 17-19]. As shown in Figure 1(a), when a broadband light source passes through an optical fiber containing a Bragg grating, FBG reflects a narrow spectral portion of light of a specific wavelength. The reflected wavelength (λ_B) changes with the axial strain and temperature of the fiber. Because the FBG sensor is encapsulated in a tube, the mechanical strain may be assumed to be eliminated, and the temperature change ΔT can be calculated as [3]

\[
\Delta T = \frac{\Delta \lambda_B}{\lambda_B c_T}
\]

where \(c_T\) is the sensitivity coefficient for temperature.

Figure 1. (a) Working principle of FBG and (b) schematic diagram of the AH-FBG sensor.

Figure 1(b) shows the structure of the newly developed AH-FBG sensor, which is capable of temperature sensing and active heating [3, 4, 14]. The optical fiber containing several FBGs is packed in a loose state for temperature sensing. The relationship between ΔT and λ_B is obtained by laboratory calibration tests, as shown in Figure 2. The serially connected FBGs should have different wavelengths so as to form a quasi-distributed sensing array of temperature, water content, and ice content of ground soils.
2.2. Calibration of total water contents

The AH-FBG sensor is developed according to the principle behind the infinite line heat source model and radial heat transfer theory to capture the soil thermal conductivity ($\lambda_u$). $\theta_0$ can be further obtained using theoretical models that consider $\theta_0$ and $\lambda_u$. Previous research revealed that the Johansen, Côté and Konrad, and Lu models could best describe the relationship between $\theta_0$ and $\lambda_u$ in unfrozen soils. However, only the Côté and Konrad model is suitable for frozen soils [4].

A series of laboratory calibration experiments were performed on soil samples collected from the Loess Plateau in northwestern China to confirm the $\theta_0$–$\lambda_u$ relationship measured by the AH-FBG sensor. The soil samples were prepared in cutting rings and divided into several groups with water contents of 0.14, 0.17, 0.20, 0.23, 0.26, 0.28, 0.31, 0.34, 0.37, and 0.40 m$^3$/m$^3$. All of the calibration tests were conducted in a temperature control container at 20°C (unfrozen soil) and −20°C (frozen soil), respectively.

Figures 3 and 4 illustrate the relationships between $\lambda_u$ and $\theta_0$ determined from the calibration tests. As shown in Figure 3, three models were used to fit the measured data of the unfrozen soil samples. The results show that the Côté and Konrad model demonstrates better applicability than the two other models. Therefore, this model is adopted in the field monitoring later. With respect to frozen soil, the Côté and Konrad model also shows consistency with the experimental data of frozen soil, as illustrated in Figure 4.
Figure 4. Relationship between the thermal conductivity and total water content of frozen soil.

The comparison of Figures 3 and 4 indicate that the Côté and Konrad model has relatively lower accuracy in frozen soil samples compared with unfrozen samples during soil moisture content measurement. Because $\lambda_u$ is considerably related to soil properties, differences in the accuracy of the model may be mainly attributed to differences in the soil structures between unfrozen and frozen soils. Freezing and thawing cycles may result in changes to the microscopic pore structure of the soil and result in crack generation and compression at the macro level.

3. Field monitoring

Long-term field monitoring was conducted to verify the relationships obtained in the laboratory calibration tests and to measure soil temperature and moisture distributions in winter. Figure 5(a) shows a satellite image of the study area at Huining, Gansu Province, China, from which the soil samples for the laboratory experiments were collected. The in-situ tests utilized quasi-distributed AH-FBG sensors for temperature sensing and active heating. As shown in Figure 5(b), two AH-FBG sensors were fixed in parallel with a probe spacing of 20 mm and buried in the ground soil. The sensors were embedded in excavation holes with a diameter of 200 mm and depth of 1200 mm.

Figure 5. Field test configuration [4]: (a) Location of the study area and (b) photograph of sensor installation.

Field monitoring was conducted from December 28, 2018 to February 26, 2019. In addition to the AH-FBG sensors used for $\theta_b$ measurement, a frequency domain reflectometry (FDR) sensor was installed to obtain $\theta_w$ at a depth of 0–100 mm. A weather station continuously collected the air temperature and humidity measurements throughout the monitoring period.
Figure 6 shows the soil temperature distribution between December 28, 2018 and February 20, 2019. The change trends of soil, especially shallow soil (0–500 mm), and air temperatures show a strong correlation. The average air temperature decreased gradually until January 17, 2019 and then began to increase above 0°C. The variation curves of soil temperatures at depths of 250, 450, and 650 mm display the same variation. The freezing depth gradually increased as air temperature decreases and tended to decrease when the air temperature exceeds 0°C. Additionally, an apparent hysteresis effect between the two parameters was observed. As depicted in Figure 6, the lowest soil temperatures were found on January 22, 25, and 27 in sequence, thereby demonstrating a few days’ lag in comparison to the lowest air temperatures.

![Air temperature](image1)

![Soil temperature profile](image2)

**Figure 6.** Variations in (a) air temperature over time and (b) soil temperature profile of the study area.
The $\theta_i$ values were calculated from the results of laboratory tests obtained by using the proposed AH-FBG method. The $\theta_i$ values were deduced by subtracting $\theta_n$ from $\theta_i$. Figure 7 shows the moisture parameters of the ground soil at a depth of 0–100 mm. As shown in Figure 7(a), the study area experienced light rainfall, and, therefore, the moisture distribution was mainly affected by the air temperature. It can be seen from Figure 7 that the changes in $\theta_i$ were synchronous with air temperature. This synchronization intuitively reflects the freezing-thawing process of soil. Moreover, the changes in $\theta_i$ noticeably lagged behind those of air temperature.

4. Conclusions

An AH-FBG method was developed to measure temperature and moisture distributions in seasonally frozen ground, and the performance of this technique was investigated through laboratory testing and field monitoring. The following conclusions can be drawn:

1) The Côté and Konrad model is recommended to describe the relationship between soil thermal conductivity measured by the AH-FBG method and total water content.

2) The freezing depth, water content, and ice content of frozen ground can be measured by the AH-FBG method with a high resolution during long-term field monitoring.

3) Owing to its superior performance in monitoring soil temperature and moisture distributions, the AH-FBG technique is verified to be a powerful tool that can capture the freezing and thawing process of in-situ ground soil.

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