Intelligent sensing and evaluation of thermo-hydraulic behaviors of frozen soil

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Abstract: The thermo-hydraulic behaviors of frozen soil under freeze-thaw conditions significantly influence its stability and engineering properties, yet field-based insights remain limited. In this paper, field monitoring and assessment were performed on the Loess Plateau, China with an intelligent sensing system. This system successfully captured the spatiotemporal variations in multivariable of seasonally frozen soil in near real-time, including in-situ soil temperature, unfrozen water content, and ice content. The monitoring results collected during the 2020/2021 winter offer unique insight into the water and heat redistribution processes under freeze-thaw cycles. Additionally, transient soil-freezing characteristic curves (SFCCs) observed in the field deviated from laboratory findings, underscoring the importance of accurate in-situ SFCC measurements. This study introduces a comprehensive framework for real-time thermo-hydraulic monitoring in frozen soils, improving the understanding of freeze-thaw processes for engineering and geohazard research.

Introduction

Cold regions, covering nearly half of the Earth's land surface [1], pose significant challenges to engineering and infrastructure stability due to frost action, a complex phenomenon driven by the coupled interactions of thermal and hydraulic processes during freeze-thaw (FT) cycles [2]. These cycles induce water migration towards freezing fronts under thermal gradients, resulting in frost heave during freezing and thaw subsidence during melting—processes collectively referred to as thermo-hydraulic (TH) behaviors. These behaviors critically influence key soil properties, including temperature, moisture content, and mechanical strength, and are central to understanding soil stability under dynamic environmental conditions [3]. Therefore, understanding and evaluating the TH behaviors of frozen soil under natural environmental conditions is essential.

Despite significant advancements in understanding TH behaviors during FT cycles through theoretical, experimental, and numerical approaches [1,4-7], these studies primarily rely on controlled laboratory conditions. However, such conditions often fail to replicate the complex and heterogeneous nature of in-situ environments, limiting their applicability to real-world scenarios. This highlights the necessity of field-based monitoring to accurately characterize TH behaviors, especially in seasonally frozen soils. Reliable field measurement of key parameters, such as soil temperature gradients, unfrozen water content (θ_w), and ice content (θ_i), remains challenging due to dynamic environmental factors. Among these, θ_i plays a critical role in governing soil-ice interactions, yet its field quantification is particularly difficult. While nuclear magnetic resonance (NMR) and dielectric spectroscopy techniques have been employed to measure θ_i in laboratory settings, their invasive nature and sensitivity to soil structure variations hinder their suitability for in-situ applications [8-11].

To address these challenges, the actively heated fiber Bragg grating (AH-FBG) method has emerged as a promising non-invasive optical sensing technique for in-situ ice content measurement [12]. This method operates by analyzing heat transfer characteristics around a fiber optic sensor embedded in soil, enabling indirect estimation of θ_i based on changes in thermal conductivity. Compared to conventional methods, AH-FBG sensors offer high spatial resolution, real-time monitoring capability, and long-term deployment potential. However, several limitations persist, including the influence of unfrozen water migration, ice-induced alterations in soil thermal properties, and calibration uncertainties in open-system conditions. Further adaptation and validation of the AH-FBG method under natural environmental settings are necessary to enhance its reliability and applicability.

In this study, an intelligent opto-electronic approach was developed to simultaneously measure in-situ soil temperature (T_s), unfrozen water content (θ_w), and ice content (θ_i), which are critical for characterizing TH behavior. Deployed on the Loess Plateau in China, the system captured the dynamic responses of seasonally frozen soils undergoing pronounced freeze-thaw cycles under natural boundary conditions. The research integrates the AH-FBG method for real-time, multi-variable monitoring to analyze the spatiotemporal variations of T_s, θ_w, and θ_i, thereby offering a comprehensive characterization of in-field TH processes. This work advances our understanding of water-heat interactions in frozen soils and contributes to more accurate engineering designs and geohazard risk assessments in cold regions.

Intelligent sensing of in-situ frozen soil

Site description

Field monitoring was conducted in a bare soil-covered area in Huining County, Gansu Province, China (35°36′49′′N, 104°58′54′′E), located on the northwest Loess Plateau (Figure 1(a) and (b)). The region is characterized by a middle temperate semiarid climate, with average annual air temperatures of 6–9°C and a recorded minimum of −23.3°C. It features widespread seasonally frozen soil, making it an ideal site for FT studies. The surface layer comprises 10–20 m of Quaternary loess, predominantly silty clay with high porosity, low density, and sensitivity to FT cycles, which significantly impact its thermo-hydro-mechanical properties. Detailed descriptions of the soil and its geotechnical characteristics are provided in Wu et al. [13].

Field instrumentation

A comprehensive intelligent sensing system was established to monitor TH behaviors in frozen soil. This system integrates multiple sensor types, including fiber optic sensors (FBG and AH-FBG), time-domain reflectometry (TDR) sensors, and a weather station, to capture key thermal and hydraulic parameters under natural FT conditions (Figure 1(c)). The AH-FBG sensor consists of a fiber optic cable combined with an electrical resistance heating element, an aluminum oxide tube, and a stainless-steel protective casing [14]. It includes six fiber Bragg gratings (FBGs) connected in series at 20 cm intervals. Sensors were installed in boreholes using a dig-install-backfill method to ensure proper soil contact and minimize disturbance.

The instrumentation setup comprised three key components. First, a deep borehole (30 m) was equipped with fifteen serially connected FBG temperature sensors, spaced 1 m apart, to monitor subsurface thermal gradients. Second, a shallow borehole (2 m) was instrumented with AH-FBG sensors to measure both soil temperature and ice content. These sensors were positioned at depths of 20 cm, 40 cm, 60 cm, 80 cm, 100 cm, and 120 cm. Additionally, five TDR sensors (NH148-40) were installed at corresponding depths above 100 cm to provide real-time measurements of unfrozen water content (θ_w). Third, a weather station continuously recorded meteorological parameters, including air temperature, humidity, wind conditions, radiation, and precipitation.

All sensors were connected to a multi-channel interrogator and data collection units, which were equipped with wireless transmission modules for real-time data acquisition and cloud-based storage. The system was fully deployed in March 2020, and continuous monitoring commenced in April 2020, providing long-term field data on the TH behaviors of seasonally frozen soils.

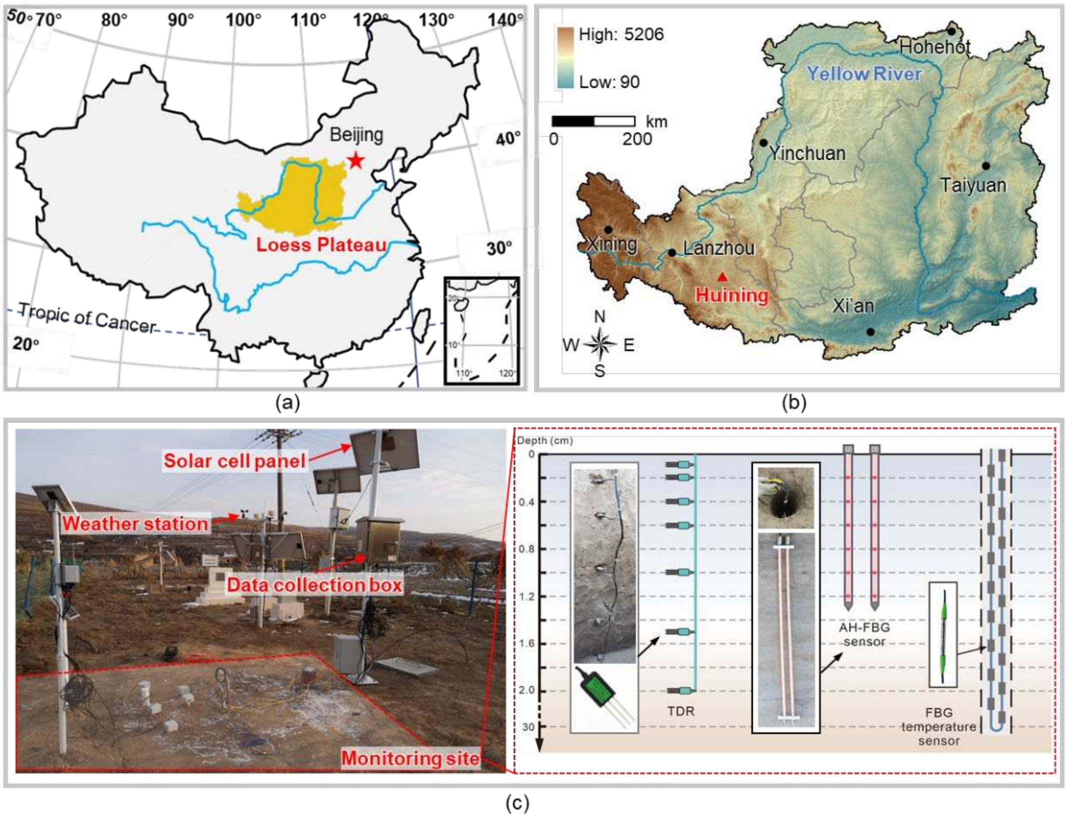

Figure 1. (a) Location map of the Loess Plateau; (b) Location map of the monitoring site; (c) Overview of the field monitoring site and schematic diagram of system deployment.

Field monitoring results

Identification of freezing process

Figure 2(a) and (b) illustrate the variations in daily air temperature (T_a) and T_s within the active layer (0–2 m depth) during the 2020/2021 winter. The data demonstrate a strong correlation between T_s and T_a, with fluctuations in solar radiation significantly influencing T_a and, consequently, T_s. As shown in Figure 2(b), T_s exhibits a hysteresis effect with depth, showing greater fluctuations in shallower layers and stabilizing below 80 cm. Additionally, laboratory tests determined the freezing temperature (T_0) of the soil at the monitoring site to be −0.3°C. The depth of the T_0 isotherm within the T_s profiles represents the freezing depth, as shown in Figure 2(c). The monitoring captured a unidirectional freezing process from December 20 to February 14, followed by a bidirectional thawing process from February 15 to February 23.

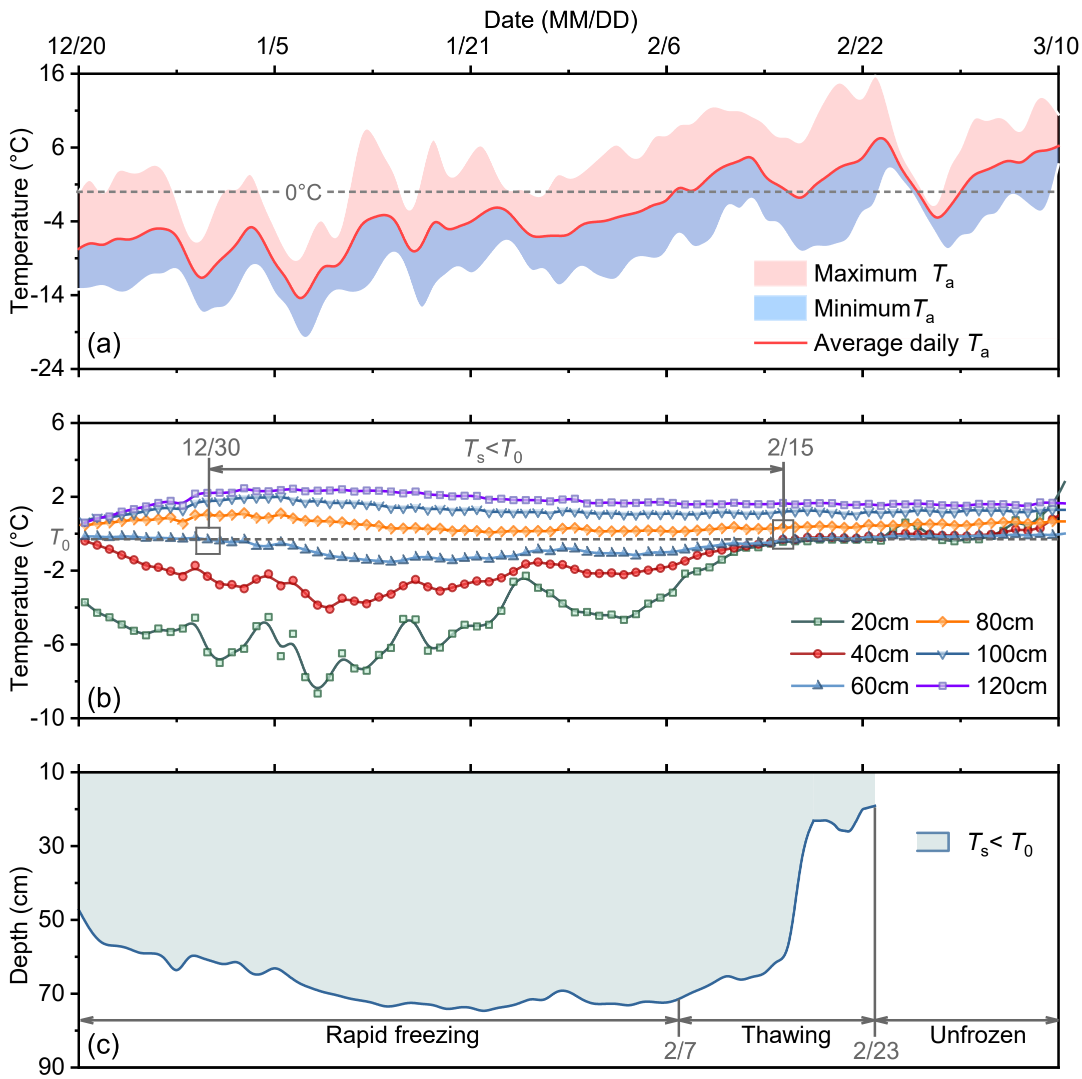

Figure 2. (a) Variations in air temperature (T_a), (b) soil temperature (T_s) at deferent depths, and (c) variations in freezing depths. [14]

Characterization of moisture migration

The migration of moisture in frozen soil is governed by phase changes and thermal gradients during freeze-thaw (FT) cycles. In this study, real-time measurements of θ_w and θ_i obtained through the intelligent sensing system enabled an in-depth analysis of total water content (θ_t) evolution at different depths. These field observations provide direct insights into the redistribution of heat and moisture under natural FT conditions, offering a comprehensive characterization of moisture migration patterns.

Figure 3 illustrates the spatiotemporal gradients of T_s (∇T_s) and θ_t ($\nabla\theta_t$). The observed consistency between ∇T_s and $\nabla\theta_t$ confirms that ∇T_s drives phase changes between water and ice and influence moisture migration. During freezing, heat transfer occurs primarily in the upward direction, leading to water migration and accumulation at the frozen fringe, where it subsequently freezes. In contrast, during thawing, meltwater moves from both the shallow and deep soil layers toward the middle zone, following the heat flux direction. This process underscores the role of heat convection induced by water migration, which further modifies the soil temperature distribution.

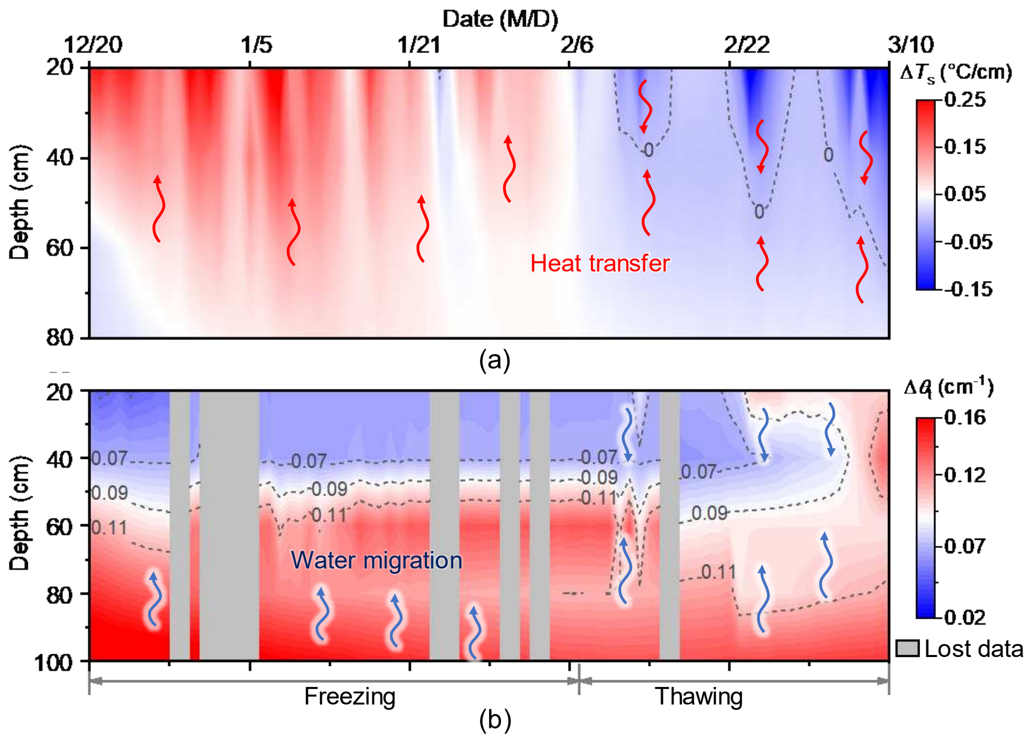

Figure 3. Spatiotemporal distribution of (a) soil temperature gradient (∇T_s) and (b) total water content gradient($\nabla \theta_t$).

Characterization of transit SFCC

The soil-freezing characteristic curve (SFCC) describes the relationship between θ_w and T_s in frozen soil, playing a crucial role in understanding phase change dynamics and simulating water-heat transfer processes [15]. In this study, in-situ transient SFCCs were derived from field monitoring at different depths (Figure 4(a)), demonstrating significant depth-dependent variations. These field-derived SFCCs were compared to laboratory-equilibrated SFCCs (Figure 4(b)), which exhibit more stable and predictable behavior under controlled conditions.

The primary differences between the two datasets arise from the transient nature of field conditions. In contrast to laboratory tests, where soil samples remain in a controlled thermal environment, in-situ SFCCs are influenced by fluctuating air temperatures, precipitation events, and variable snow cover, all of which contribute to non-equilibrium water redistribution. At greater depths, such as 60 cm, the field temperature variations were more moderate, limiting complete phase transitions and resulting in higher residual unfrozen water content. This stands in contrast to the laboratory results, where θ_w follows a well-defined empirical relationship with T_s across different initial water contents.

To quantify these differences, empirical functions [16] were used to describe SFCCs. The field-derived SFCCs exhibited depth-dependent fitting parameters (Figure 4(a)), while the laboratory SFCCs followed a single empirical function across different initial water contents (Figure 4(b)). These findings highlight the influence of transient environmental conditions on in-situ SFCCs and emphasize the limitations of directly applying laboratory-based SFCCs to field-scale modeling.

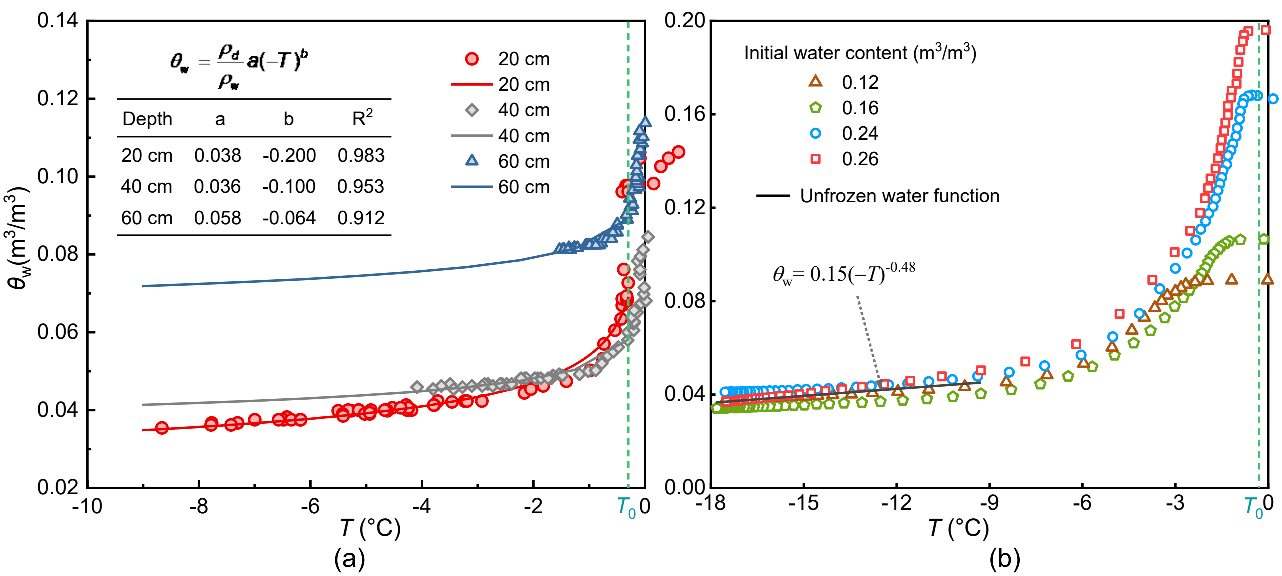

Figure 4. (a) In-situ transient SFCCs at depths of 20 cm, 40 cm, and 60 cm. (b) Equilibrated states SFCCs measured in the laboratory with different initial water contents of 0.12, 0.16, 0.24, and 0.26 m^3/m^3. [12, 14]

Conclusions

This study implemented an intelligent sensing system to investigate the thermo-hydraulic behaviors of frozen soil under freeze-thaw conditions on China's Loess Plateau. By integrating fiber optic sensors with real-time monitoring techniques, the system captured key soil parameters and provided new insights into natural freeze-thaw processes. The main conclusions are as follows:

1. The intelligent sensing system enabled continuous, real-time measurements of soil temperature, unfrozen water content, and ice content under field conditions, demonstrating the feasibility of applying advanced sensing technology for multi-variable TH behavior analysis.

2. Freeze-thaw cycles significantly influenced soil temperature and moisture redistribution. In-situ monitoring revealed distinct patterns of heat and moisture migration during directional

freezing and bidirectional thawing processes, highlighting the dynamic nature of TH interactions.

3. The transient soil-freezing characteristic curves (SFCCs) observed in the field varied with depth and deviated from laboratory findings, emphasizing the necessity of in-situ SFCC measurements for improving the accuracy of field-scale modeling and engineering applications.

These findings enhance the understanding of water-heat interactions in frozen soils and demonstrate the importance of field-based monitoring for capturing freeze-thaw dynamics under natural conditions. The results provide a basis for refining predictive models and improving engineering designs in cold regions.

References

[1] Q Luo, P Wu, and T Wang. Evaluating frost heave susceptibility of well-graded gravel for HSR subgrade based on orthogonal array testing. *Transportation Geotechnics*, 21:100283, 2019.

[2] S Zhang, D Sheng, G Zhao, F Niu, and Z He. Analysis of frost heave mechanisms in a high-speed railway embankment. *Canadian Geotechnical Journal*, 53:520–529, 2015.

[3] Z Tian, Y Kojima, JL Heitman, R Horton, T Ren. Advances in Thermo-Time Domain Refl ectometry Technique: Measuring Ice Content in Partially Frozen Soils. *Methods of Soil Analysis*, 4: 190003, 2019.

[4] J Teng, F Shan, Z He, S Zhang, G Zhao, and D Sheng. Experimental study of ice accumulation in unsaturated clean sand. *Géotechnique*, 69(3):251–259, 2019.

[5] M Hayashi. The cold vadose zone: Hydrological and ecological significance of frozen-soil processes. *Vadose Zone Journal*, 13(1):1–8, 2013.

[6] D Sheng, S Zhang, Z Yu, and J Zhang. Assessing frost susceptibility of soils using PCHeave. *Cold Regions Science and Technology*, 95:27–38, 2013.

[7] B Li, E Norouzi, HH Zhu, and B Wu. A thermo-poromechanical model for simulating freeze–thaw actions in unsaturated soils. *Advances in Water Resources*, 104624, 2024.

[8] G Liu and B Si. Soil ice content measurement using a heat pulse probe method. *Canadian Journal of Soil Science*, 91(2):235–246, 2011.

[9] H He and M Dyck. Application of multiphase dielectric mixing models for understanding the effective dielectric permittivity of frozen soils. *Vadose Zone Journal*, 12(1):1–22, 2013.

[10] Z Tian, T Ren, Y Kojima, Y Lu, R Horton, and JL Heitman. An improved thermo-time domain reflectometry method for determination of ice contents in partially frozen soils. *Journal of Hydrology*, 555:786–796, 2017.

[11] M Wang, X Li, L Chen, S Hou, G Wu, and Z Deng. A modified soil water content measurement technique using actively heated fiber optic sensor. *Journal of Rock Mechanics and Geotechnical Engineering*, 12(3):608–619, 2020.

[12] B Wu, HH Zhu, DF Cao, L Xu, and B Shi. Feasibility study on ice content measurement of frozen soil using actively heated FBG sensors. *Cold Regions Science and Technology*, 39:103332, 2021.

[13] B Wu, HH Zhu, DF Cao, TX Liu, and TX Liu. Fiber optic sensing-based field investigation of thermo-hydro behaviors of loess for characterizing land–atmosphere interactions. *Engineering Geology*, 315: 107019, 2023.

[14] HH Zhu, B Wu, DF Cao, B Li, Z Wen, XF Liu, and B Shi. Characterizing thermo-hydraulic behaviors of seasonally frozen loess via a combined opto-electronic sensing system: Field monitoring and assessment. *Journal of Hydrology*, 622(1): 129647, 2023

[15] RW Koopmans and RD Miller. Soil freezing and soil water characteristic curves. *Soil Science Society of America Proceedings*, 30(6):680–685, 1966.

[16] DM Anderson, AR Tice. Predicting unfrozen water contents in frozen soils from surface area measurements. *Highway Research Record*, 393: 12-18, 1972.