Active Heating-Based Distributed Fiber-Optic Sensing for Groundwater Characterization

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Abstract: Distributed fiber-optic sensing (DFOS) has rapidly advanced across many engineering fields, offering significant advantages for slope and groundwater monitoring. This study demonstrates the application of a phase noise–compensated optical frequency-domain reflectometry (PNC-OFDR) method for characterizing subsurface hydrologic features in turbiditic fractured aquifers. Heating and temperature-sensing cables installed in a cement-grouted borehole enabled high-resolution thermal monitoring under controlled heating. Analysis of thermal responses revealed several groundwater flow and high-saturation zones. Depth-dependent variations reflected lithological heterogeneity, while recovery (cooling) data proved crucial for identifying water-bearing zones and estimating thermal properties. Field results agreed well with laboratory thermal conductivity, confirming AH-DFOS as an effective tool for high-resolution and reliable detection of active groundwater pathways.

Keywords: ***Optical frequency-domain reflectometry, Active heating, Temperature sensing, High-saturation zone, Water flow zone***

Introduction

Characterizing groundwater flow by heat tracing method is a promising technique to investigate subsurface flow processes and assess the environmental risks. distributed fiber-optic sensing (DFOS) techniques opened the possibility to study underground temperature where a fiber-optic sensor can provide a vast number of measurement points along its entire length, therefore called as “distributed” sensing.

Active heating (AH) is the widely adopted novel technique in engineering geology for the groundwater characterization within a vertical borehole. In AH method, the heated fiber-optic cable installed inside the borehole can be considered the heat source for monitoring the distributed temperature profile and the sensing fiber installed next to the heated cable senses the temperature change (ΔT), thus providing the information of water-bearing zones. Despite the great amount of previous work based on AH-DFOS in high permeable settings, the information on groundwater dynamics in low permeable and highly fractured rock remains sparse and highly uncertain.

This study aims to delineate high-saturation and groundwater flow zones, and to characterize ground thermal conductivity within a highly fractured, low-permeability turbiditic formation under ambient flow conditions. The study integrates the phase noise-compensated optical frequency-domain reflectometry (PNC-OFDR), a high-resolution DFOS method, with AH approach. This work is an extension of the previous feasibility experiment presented in Acharya et al. (2024), which aimed for assessing water position using distributed temperature measurement.

Methodology

The study site is a 50 m-deep, 66 mm-diameter boreholes in the Miocene Josoji Formation near Mt. Misaka, Shimane Peninsula, Japan. The formation consists of submarine-slumped sandstone and mudstone interbedded with rhyolitic and andesitic tuffs, indicating Miocene volcanic and hydrothermal activity.

Two fiber-optic cables were embedded in the cement-grouted borehole: (1) a Fujikura hybrid cable for heating and strain sensing (H- and S-cables) and (2) a pico-tube cable for temperature measurement (T-cable). The cables extended from the surface to the bottom and were grouted to prevent vertical leakage and maintain natural groundwater conditions. A constant electrical heating of 9.4 W/m was supplied using a Takasago ZX-S-1600M unit, while temperature variations were continuously monitored with a PNC-OFDR system. Each test included 3 h of heating followed by 3 h of natural cooling. The OFDR interrogator operated with a 15 nm sweep width, 150 GHz/s sweep rate, and achieved 5 cm spatial and 0.01 °C temperature resolution, enabling precise detection of flow-related temperature changes.

Figure 1 illustrates the concept of detecting water-bearing zones (high-saturation and flowing zones) in a cement-grouted borehole using the AH-DFOS method. Effective thermal conductivity (λ_r) was determined in the laboratory using the transient heat pulse method on rock core specimens, whereas apparent thermal conductivity (λ_a) was derived from in-situ AH-DFOS temperature response curves. The combination of high-resolution sensing and controlled heating enabled detailed identification of hydraulically active fractures and depth-dependent thermal heterogeneity within the turbiditic aquifer.

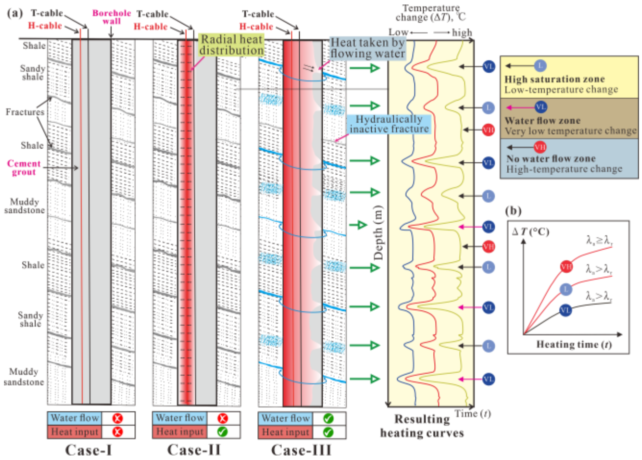

Figure 1, (a) Conceptual illustration of the AH-DFOS method for characterizing high saturation and water flow zones in a grouted borehole; and (b) rate of temperature change with time.

Results and Discussions

Figure 2 illustrates the spatio-temporal thermal response over depth and time collected over 6 h of monitoring period under natural gradient conditions. Low-temperature intervals corresponded to hydraulically active or highly saturated zones, whereas high-temperature bands represented conduction-dominated regions. Excluding the upper 1.2 m to avoid anomalies caused by the fluctuations in surface temperatures, seven distinct active water flow zones and several warm bands were identified between 2 and 48 m depth. After 3 h of heating, the maximum ΔT of 26.7°C was recorded at a depth of 47.67 m, and minimum ΔT of 3.7 °C was recorded at a depth of 3.57 m. The warm bands concentrated in the deeper horizons (34~48 m) occurred in massive sandstone and less-fractured shale, partly due to cable proximity effects. Overall, the AH-DFOS data clearly distinguish conductive from advective regimes, demonstrating its ability to map groundwater pathways in fractured turbiditic formations.

Laboratory tests showed that the average λ_r of the core specimens was 2.66 W m/mK, ranging from 2.58 to 2.86 W/mK. In contrast, AH-DFOS results during the recovery phase yielded λ_a values between 1.51 and 7.70 W/mK, with an average of 3.38 W/mK. Within the 32–40 m depth range, the mean λ_a (2.70 W/mK) closely matched the lab-measured λ_r (2.66 W/mK), confirming excellent agreement. The close alignment of AH-DFOS and laboratory results validates the method's reliability for in-situ thermal conductivity estimation.

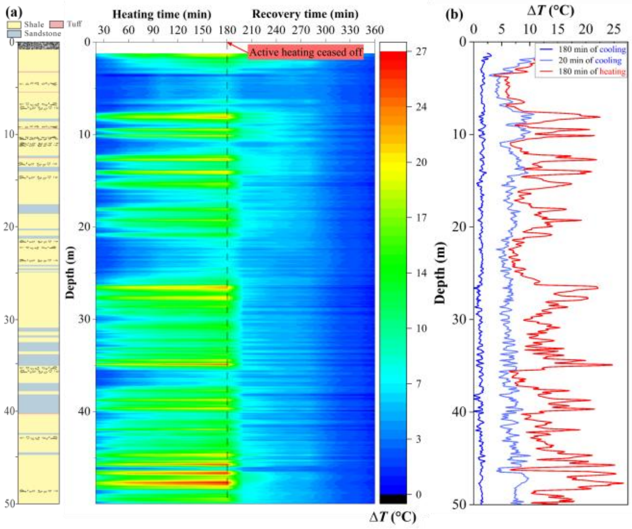

Figure 2, (a) Spatio-temporal thermal response over depth and time during; and (b) line profiles of temperature rise over depth at different times.

One challenge of the AH method is the uncertainty in the relative positioning of the H- and T-cables within the borehole, which can cause inconsistent temperature readings. The heating-phase curves also exhibit increasing noise over time, while the cooling-phase data show smoother, more stable trends. In this study, the λ_a values derived from recovery data closely matched the laboratory-measured λ_r values. Hence, this study highlights the importance of recovery data to minimize cable misalignment effects and accurately determine ground thermal properties.

Conclusions

The AH-DFOS method using Rayleigh scattering proved highly effective for high-resolution groundwater flow characterization in fractured aquifers. With 5 cm spatial resolution and 2.5 ms data acquisition, active water flow zones rapidly detected, high-saturated zones, and fine-scale fractures, reducing monitoring time compared to conventional monitoring methods. Using 9.4 W/m heating power enhanced thermal responses and allowed accurate identification of active flow zones, especially when combined with recovery data. Thermal conductivity values aligned well with lab tests, showing depth-related variations. Despite minor environmental temperature effects in shallow layers, the technique demonstrated strong potential for real-time subsurface monitoring.

References

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