

A Novel Approach on Monitoring Fully Grouted Rock Bolt Instrumented with Distributed Fiber-Optic Sensor for Groundwater Characterization: Laboratory Feasibility Experiments

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Received: July 5, 2025, Accepted: September 2, 2025

Abstract: This study introduces a new method to detect high-saturation zones using active heating-based distributed fiber-optic sensing (AH-DFOS) with a fully grouted rock bolt (FGRB). Using Rayleigh-based phase-noise compensated optical frequency-domain reflectometry (PNC-OFDR), temperature changes were measured in a fibre-instrumented cement grout specimen with simulated high-saturation zones. Results show AH-DFOS can effectively identify water zones and closely spaced fractures, especially with a separate sensing cable. A thermal halo effect was observed, and wider saturation zones showed slower temperature change. This method has significant practical implications for groundwater characterisation in geotechnical applications, including slope stability assessment, tunnelling, foundation monitoring, and dam reinforcement, where rock bolts are commonly employed as stabilizing structures.

Keywords: Rock bolt, Optical fibre, Optical frequency-domain reflectometry, Active heating, Temperature sensing, High-saturation zone.

Introduction

Distributed fibre-optic sensing (DFOS) technology has emerged as an advanced monitoring technique due to its distributed nature, real-time, and high accuracy of the measurement results, making it a research hotspot in the field of geotechnical monitoring (Acharya and Kogure, 2025). The active heating-based DFOS (AH-DFOS) approach is a novel method to characterize groundwater, soil moisture, seepage identification, leak detection, and thermal response monitoring whose research and development is still in infancy. In the AH-DFOS method, heat is injected along an electrically conductive metallic line source by applying electrical power at a constant rate (Acharya et al., 2024). The rate of temperature change and temperature anomalies

caused by water influence is detected by the adjacent fibre-optic sensing cable. This technique

This study investigates the effectiveness of a FGRB to detect high-saturation zones, effect of sensor placement relative to the heating element on temperature measurements, and the applicability of a composite cable on AH experiments. The approach presents a novel framework for groundwater characterisation in the vicinity of grouted bolts.

Methodology

In this study, a 20 mm × 20 mm, single-row groove aluminum frame was used to simulate the behavior of a bolt. The frame had a length of 1000 mm and a cross-sectional area of 208 mm². A DFOS cable (Fujikura Ltd., Tokyo, Japan) was used for both heating and temperature sensing, which is comprised of four single-mode fibers and two metallic wires. The heating cable (H-cable) was embedded in the groove, while the temperature-sensing cables (T-cables), were affixed to the outer surface of the frame. The distances of the two temperature sensing cables (T1- and T2-cables) from the H-cable were 7 mm and 13 mm, respectively. During installation, the cables were attached using epoxy resin while being tensioned to ensure proper placement. The cable-instrumented frame (i.e., mock bolt) was centrally positioned within a high-strength PVC pipe, 1000 mm in length with an inner diameter of 77 mm, and cement slurry was poured in to encapsulate it.

A Rayleigh-based phase-noise compensated optical frequency-domain reflectometry (PNC-OFDR) technique was employed for temperature measurements. The grout specimen was heated using the metallic armor of the H-cable, with a voltage slider maintaining a constant heating power of 7.6 W/m for 150 minutes. To simulate the effect of water along rock

fractures within a grouted borehole, water was introduced at four specific sections of the specimen mimicking high-saturation zones (Figure 1). Such water-supplied sections, in this study, referred to as enhanced-conduction dominant (ECD) zones, represent areas where heat transfer is influenced by the presence of water. Sections without stagnant water serve as pure conduction zones (i.e., conduction-dominant; CD).

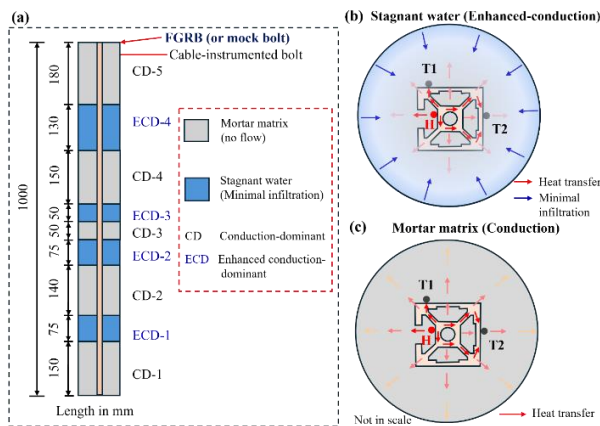


Figure 1, (a) Cross-section of FGRB; (b) heat transfer within ECD zones; and (c) heat transfer within CD zones.

Results and discussions

Figure 2 presents the spatial and temporal thermal response semblance plots along the axial length of the grouted bolt subjected to continuous heating for 150 minutes at a constant heating power of 7.6 W/m. The water effects were recorded within a remarkably short heating duration, i.e., less than 30 minutes. This rapid response is a significant improvement over previous studies required heating periods of up to several tens of hours in deep grouted boreholes (Zhang et al., 2023). The data recorded by two different fibre-optic cables, T1 (d : 7 mm) and T2 (d : 13 mm), illustrate the impact of distance from the heating cable on heat propagation and dissipation. The results demonstrated that increasing the distance between the sensing cable and the heat source leads to a more diffused and less stable thermal response.

The formation of a thermal halo as a result of thermal anomalies induced by supplied water was detected. When multiple transmissive fractures are closely spaced, a coarse spatial resolution may detect the entire cooler region as a single thermal halo, masking the distinction between individual fractures. The proposed PNC-OFDR sensing method demonstrated clear capability in detecting ECD zones with widths ranging from 5 to 13 cm. Wider ECD sections allowed a greater volume of water to interact with the heat generated by the H-cable, facilitating more efficient heat transfer from the cable to the surrounding grout. The experimental results suggest that while a composite cable can serve as a dual-purpose sensor, it showed that, for a grouted bolt, limitations in clearly identifying

the enhanced saturated zones, likely due to its self-heating nature affecting temperature sensing accuracy. Although the results of this study demonstrated the effectiveness of using a separate sensing cable, it underscores the need for further testing under varied structural configurations to better generalize the findings.

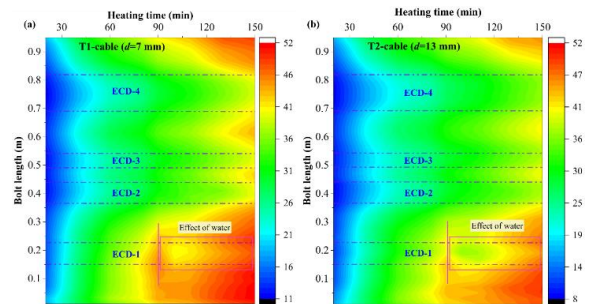


Figure 2, (a) Thermal response plot recorded by T1-cable; and (b) thermal response plot recorded by T2-cable.

Conclusions

The AH-DFOS method demonstrates significant potential for rapidly detecting water saturation-related thermal anomalies, making it particularly advantageous for engineering geological applications where time-efficient assessments are critical. When sufficient heating power is applied, two widely spaced sensing cables show minimal discrepancies, ensuring reliable detection. While a composite cable can function as both a heating and sensing element, its self-heating nature introduces measurement uncertainties. Detecting closely spaced high-saturation zones, and their corresponding thermal halos requires fine spatial resolution. The rate of temperature change decreases as the width of the high saturation zones increases.

References

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