Seepage Detection Using Passive Temperature Measurements by Fiber Optic DTS

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Thesis summary

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This article is an extended abstract of the doctoral dissertation "Optimization of early seepage detection in embankments using a distributed temperature system based on fiber optic sensing" [1]. Distributed Temperature Sensors (DTS) measure temperature precisely with high spatial resolution, enabling seepage flow detection through the interpretation of temperature measurement. Active DTS measurement which introduces heat into the soil to monitor its dissipation, has been extensively studied for seepage detection. However, the potential of passive measurement, which measures natural soil temperature, for seepage detection demands further exploration. The doctoral research investigated the capability of passive DTS measurements for seepage detection. The findings show that passive DTS detects very small temperature variations as a result of the seepage flow. Additionally, the results offer valuable insights into the coupled hydro-thermal behavior and the influence of seepage on heat transfer. The thesis classified and compared different techniques for temperature data calibration and interpretation. Furthermore, an interpretation approach based on numerical simulation and a fully dynamic calibration technique was developed.

Povzetek: Predstavljena je doktorska disertacija z naslovom »Optimizacija postopka zgodnjega zaznavanja pojava precejanja vode v nasipih na podlagi spremljanja temperaturnega polja z optičnimi kabli«.

1 Introduction

The last decade has witnessed rapid advancements in the field of optical fiber Distributed Temperature Sensors (DTS), facilitating continuous temperature monitoring of various infrastructures. Optical fiber DTS utilizes Raman backscattering to quantify temperature along the entire length of the optical fiber. Despite the active method's capability for seepage detection by introducing heat into the soil and monitoring its dissipation, its functionality for large-scale monitoring is limited. This limitation is due to the high heating power required, which not only increases costs but also limits the measurement length. Unlike the active method, the passive method which measures the soil's natural temperature, is more suitable for long-life, large-scale coverage, and cost-effective monitoring systems.

The primary objective of the doctoral thesis was to explore the potential of passive DTS measurements for accurate and early seepage flow detection. The efficiency of DTS employment for seepage detection relies on application methods, measurement reliability, and data interpretation. Therefore, the other aim of this research was to enhance seepage detection through the optimization of data calibration and interpretation.

2 Method and results

2.1 Passive DTS performance evaluation

A series of laboratory tests were conducted on different soils subjected to transient seepage flow [1], [2], [3]. The soil temperature was measured by passive DTS optical fiber using a developed distribution configuration composed of optic loops allowing precise point-based measurements. The system's spatial resolution and response time, measured in laboratory experiments, were 64 cm and 60 seconds respectively. The accuracy of DTS temperature measurements was confirmed by the embedded thermometers. The hydraulic properties of the materials were determined and the corresponding coupled hydrothermal numerical simulations were conducted.

The findings demonstrated that passive DTS can detect the initiation of seepage and trace its flow by precise temperature measurements, even when there is a minor difference (about 3 degrees) between the temperature of the soil and the water [1].

Experimental observations and numerical modeling revealed a correlation between temperature changes and increases in degree of saturation, with the latter preceding heat flow.

As the degree of saturation increased, the temperature within the sand changed gradually due to the increased thermal conductivity caused by the presence of water in the soil pores. However, once the soil reached full saturation, temperature changes occurred dramatically due to the convection heat transfer caused by seepage flow [3]. The results indicated that within soil subjected to seepage flow, convection is the dominant heat transfer process, even at a small Darcy velocity on the order of 10^{-5} m/s. The temperature distribution within the soil was used to estimate the phreatic line, which showed reliable agreement with experimental and numerical calculations.

Experimental measurements indicated that the thermal velocity is greater within sand having a higher hydraulic conductivity, resulting in faster Darcy velocity. Minor variations in the soil's hydraulic conductivity impacted heat transfer, while the thermal conductivity of the grain (solid) had an almost negligible effect on heat transfer within the soil subjected to seepage flow [3], [4]. Long-term temperature measurements were taken after the conclusion of the seepage experiment. Once the water had drained from the soil, the temperature within the sand increased [1].

2.2 Optimization of DTS application

To extract seepage-related information from the temperature measurements, different data interpretation techniques were compared and classified. This comprehensive review can guide the selection of an appropriate method for tracing seepage at the early stages. The numerical simulation in the studies accurately predicted the seepage and thermal distribution. Having this, an interpretation technique was proposed to utilize the simulated numerical results for temperature data interpretation. A well-defined coupled hydrothermal analysis provides essential information to identify and localize potential unexpected seepage behavior and its impact on temperature distribution [1], [5]. Additionally, the monitoring system is optimized for cost and efficiency through the installation of fiber based on the seepage risk magnitude determined by numerical calculations.

The efficiency of the DTS application is strongly dependent on the precision of temperature measurements that can be enhanced through various calibration techniques. A comparative review of calibration methods was provided based on the accuracy, installation approaches, and complexity of the application [6]. Using this review, the proper calibration technique can be selected before the cable installation based on the measurement requirements and the site's availability.

The doctoral research on DTS calibration was expanded to develop a fully dynamic calibration technique, aimed to overcome the limitations of conventional methods [7]. The embedded temperature loggers within the soil were used as references for DTS measurements and a calibration method was developed by the model-independent Parameter ESTimation (PEST) tool. The developed calibrated technique improved the accuracy of DTS measurements by reducing the absolute bias of temperature measurements from 0.27 °C to 0.08 °C. A significant advantage of this method is its easy installation process, which eliminates the need for a constant temperature reference. Furthermore, the number of reference points can be easily expanded by using small-sized thermometers to improve the calibration.

3 Conclusion

The doctoral dissertation findings showed that passive optical fiber DTS provides precise temperature measurements, facilitating early seepage flow detection, even at low-temperature differences between soil and water. The study demonstrated the significant effect of seepage flow in heat transfer through the convection process and utilized temperature measurements to estimate the soil's phreatic line. The doctoral thesis offered a comprehensive review of calibration and interpretation methods, aiding in the selection of suitable techniques based on measurement requirements and site conditions. The thesis introduced a method for interpreting temperature data using a coupled hydro-thermal simulation. This approach allows the prediction and assessment of seepage and thermal behavior. The thesis results led to the development of a dynamic calibration method utilizing external thermometers to establish reference points. This method improved the measurement accuracy and simplified optical fiber installation.

References

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