

AUTOMATIC MONITORING WITH DISTRIBUTED TEMPERATURE SENSORS FOR IMPROVED LEVEE KNOWLEDGE: ADIGE RIVER CASE STUDY

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The behaviour of river levee is significantly influenced by various factors, including the soil heterogeneity on foundation or within the embankment. These heterogeneities can serve as preferential pathways for water, leading to anomalous seepage flows that may potentially compromise the levee structural integrity during the flood events. As this aspect is becoming more frequent for effect of the global climate change, the safety evaluation of existing levees is a strong challenge requiring to improve their monitoring. The presented study investigates the application of Distributed Temperature Sensors (DTS) to measure temperature variations in an advanced levee monitoring system. Thermal anomalies detected in such structures can indicate water leakage, thereby initiating erosive processes, heterogeneity, cracks or voids. Key advantages of DTS over conventional methods include high spatial resolution for data collection over distances up to kilometres, survival in harsh environments, automated data acquisition and the generation of dense datasets suitable for developing AI prediction models. The case study here presented is about the continuous monitoring of a levee stretch along the Adige River in Salorno (BZ), where a DTS interrogation unit was recently installed. Prior to this update, measurements were conducted manually on a bi-monthly basis, a factor that introduced uncertainties related to temperature variation due to seasonality. The collected data serves two primary objectives: enhancing the understanding of hydraulic behaviours and stability conditions within this specific levee section and assessing the reliability and potential of this promising monitoring technique.

Keywords: Soil heterogeneity; seepage flows; Distributed Temperature Sensors (DTS); Optical Fiber; Monitoring.

1. Introduction

The challenges associated with studying and overseeing levee structures stem from their considerable length and the significant spatial heterogeneity of the soils constituting both the embankment and its foundation. These challenges are particularly pronounced in mountainous valleys and where ancient paleo-beds are present. Traditional levee monitoring methods rely on visual inspections and the deployment of devices for localized measurements, such as piezometers, tensiometers, and extensometers. However, this approach is limited by its low spatial resolution, as well as the significant human effort and time required for data analysis. In contrast, Distributed Fibre Optic Sensors (DFOS) offer notable advantages, including high spatial resolution over distances of up to several kilometers, durability in harsh environments, and the ability to directly measure deformation (e.g. Brezzi et al., 2024), temperature, and pore water pressure (e.g. Höttinges et al., 2023). Additionally, these sensors facilitate automated measurements and enable the rapid generation of dense datasets suitable, in a close future, for the application of AI-based predictive models. In the last ten years, DFOS have been directly embedded in the ground and utilized across a range of applications. These include monitoring dams (Brezzi et al., 2023), detecting leaks and studying groundwater–river interactions (Fabbian et al., 2024a), measuring soil moisture levels (Dong et al., 2016) and evaluating subsurface thermal characteristics in geothermal contexts (Violante et al., 2024). The identification of preferential seepage paths using the passive method relies on several fundamental assumptions: the existence of a temperature gradient between water in the reservoir and the surrounding soil, the dominance of heat transfer by conduction (a slow process) when water is stagnant or has minimal filtration velocities, and the prevalence of heat transfer by advection (a rapid process) when water filters at significant velocities. However, identifying leakage is challenging due to the multiple factors that influence temperature and the minimal variations induced by localized seepage phenomena, with spatial resolutions of 1 m revealing temperature variations below 1°C. To address these challenges, analytical and statistical methods have been developed to facilitate data interpretation, along with efforts to establish alarm thresholds for calculated statistical parameters (e.g., Khan et al., 2008; Radzicki et al., 2021). In scenarios where the temperatures of seepage water and soil are nearly identical, the active method, also known as the heat-pulse method, offers a viable solution. Furthermore, the spatial resolution of distributed temperature sensing (DTS) using the Raman effect is primarily determined by the duration of the injected pulse. Spatial resolution, acquisition frequency, measurement precision, and fiber length are interdependent, and improving one parameter often compromises another. Commercially available distributed

sensing instruments achieve spatial resolutions of 1 m with a precision of $\pm 0.1^\circ\text{C}$, acquisition times of approximately some minutes, and fiber lengths up to several tens of kilometers. These advancements underscore the versatility and precision of fiber optic sensing methods.

2. Case study and results

The Adige Valley in northern Italy has experienced several significant flood events, partially attributable to human interventions such as the construction in the 19th century of straight levees that modified the Adige natural course. A testing field site was established in spring 2021 on the right levee of the Adige river near the village of Salerno. This site includes five boreholes arranged at the corners and center of a square area with 20-meter sides, as illustrated in Fig. 1b. The central borehole, designated as S3, aligns with the embankment central axis and extends to a depth of 30 m. The other boreholes, S1 and S2 on the landside berm and S4 and S5 on the waterside, reach depths of 25 m (Fig. 1a). Further details on the site geotechnical characterization can be found in Fig. 1a and are fully described in Fabbian et al. (2023) and Fabbian et al. (2024c). To investigate seepage within and beneath the levee, a comprehensive suite of monitoring devices was installed. Each borehole was equipped with two transducers, pressure (TP) and temperature (TT), featuring accuracies of 2 kPa and 0.1°C , respectively, and placed at varying depths as shown in Fig. 1a. Furthermore, a distributed temperature sensing (DTS) cable was utilized to accurately measure temperature variations along the full vertical extent of each borehole. An electrical cable was also incorporated to enable 3D Electrical Resistivity Tomographies (ERT) in cross-hole and time-lapse modes, though this aspect is beyond the scope of this paper. All sensors were attached to a micro-slotted pipe, with the corner boreholes filled with grout to prevent water flow, while the central borehole remained unfilled to facilitate additional testing as propose in Fabbian et al. (2024b). The DTS cable was installed in a U-loop configuration, forming a continuous optical cable that propose in traverses all boreholes and is automatically interrogated (since September 2024) from a hydrometric station located 200 m away. The DFOS, utilizing a Raman interrogator (Sensomet's Oryx SR DTS), delivers temperature data along its length with a spatial resolution of 2 m and a precision of 0.1°C after proper calibration, as detailed in Schenato et al. (2022).

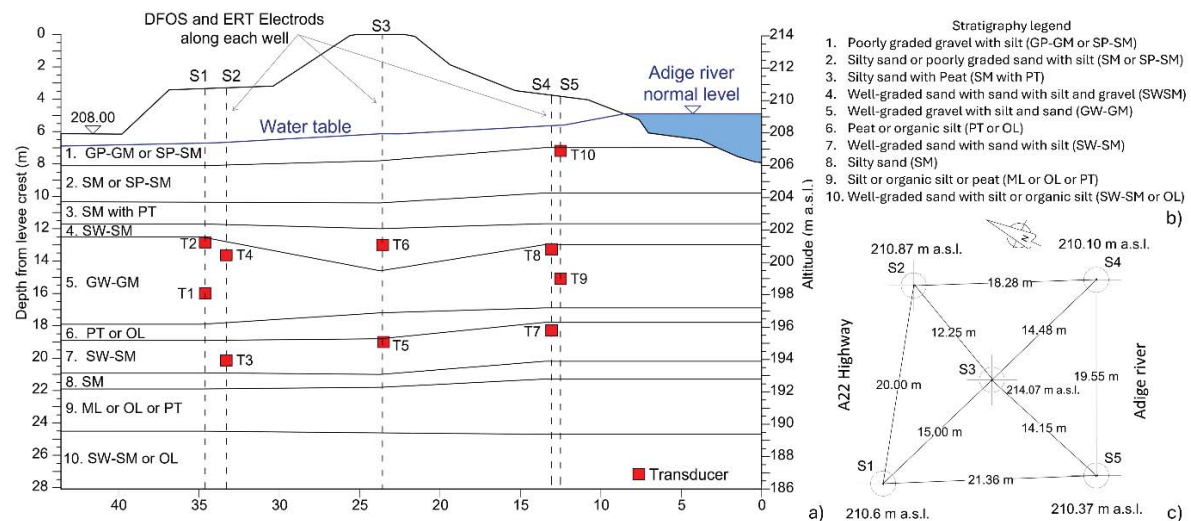


Fig. 1 a) Soil stratigraphy and distribution of monitoring sensors; b) Stratigraphy Legend; c) quoted plan of the surveys. (Fabbian et al. 2024c)

Fig. 2 presents the rain (a), total head (b) and temperature measurements (c) obtained from traditional sensors during the period from September 18, 2024, to November 13, 2024. River data are measured by the hydrometric station, located on the opposite riverbank; rain and air temperature are measured by a weather station located 400 m away from the site. It is noteworthy that four out of ten conventional sensors (T2, T3, T6 and T7) ceased functioning three years post-installation. On October 8, the Adige River underwent two consecutive flood events of medium intensity that impacted its levee system. During the flood peaks, small springs with low discharge, characterized by the emergence of clear water, were observed on the landside just below the levee foot, in close proximity to the experimental site. All pressure transducers detected variations corresponding to fluctuations in the river water level, capturing even minor peaks. However, their responses varied depending on their specific locations, with none significantly exceeding the total head at ground level, less than 1 m. The daily variation in air temperature averages $5\text{--}8^\circ\text{C}$, and its trend is reflected in the river water temperature. Daily temperature variations in the river water were approximately 1°C , while more substantial changes of $2\text{--}3^\circ\text{C}$ were recorded during the flood events. Temperature transducers (TT) installed at depth generally exhibited minimal variation, with the exception of TT10, positioned near the river. This sensor was notably affected by rapid heat transfer caused by advection processes.

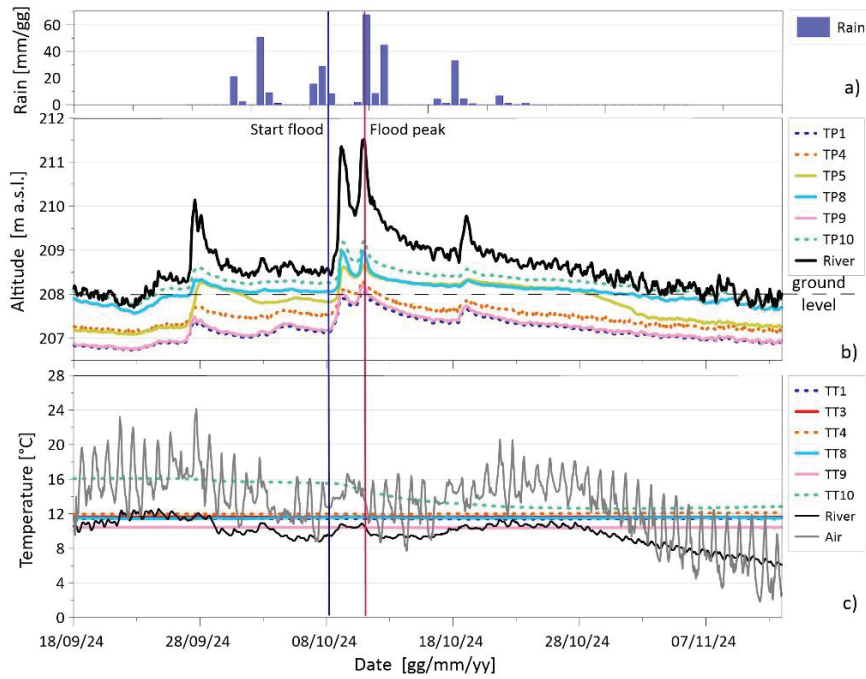


Fig. 2 Rain (a), total heads (b) and temperatures (c) registered by traditional sensors during the period 18 September 2024 – 13 November 2024.

Fig. 3 depicts the temperature distribution measurements with DTS, every 2 hours, along borehole S2, S3 and S5 over time. The DTS system identifies subtle temperature fluctuations, evident at the upper sections of the graphs, which correspond to daily variations in air temperature. In all boreholes, temperatures remain constant below a depth of 10 m, as verified by conventional sensors, indicating the likely absence of significant advection processes. In the countryside borehole (S2), the onset of the flood event is distinctly marked by a rapid cooling of the berm and the upper layers of the foundation. This cooling is attributed to the infiltration of both rainwater and river water into the countryside berm. A similar cooling phenomenon is observed in the floodplain; however, it occurs more gradually and evolves continuously over time. Interpretation of the temperature profiles in borehole S3 presents notable challenges, as the slotted pipe open allows air circulation, which influences internal temperature measurements.

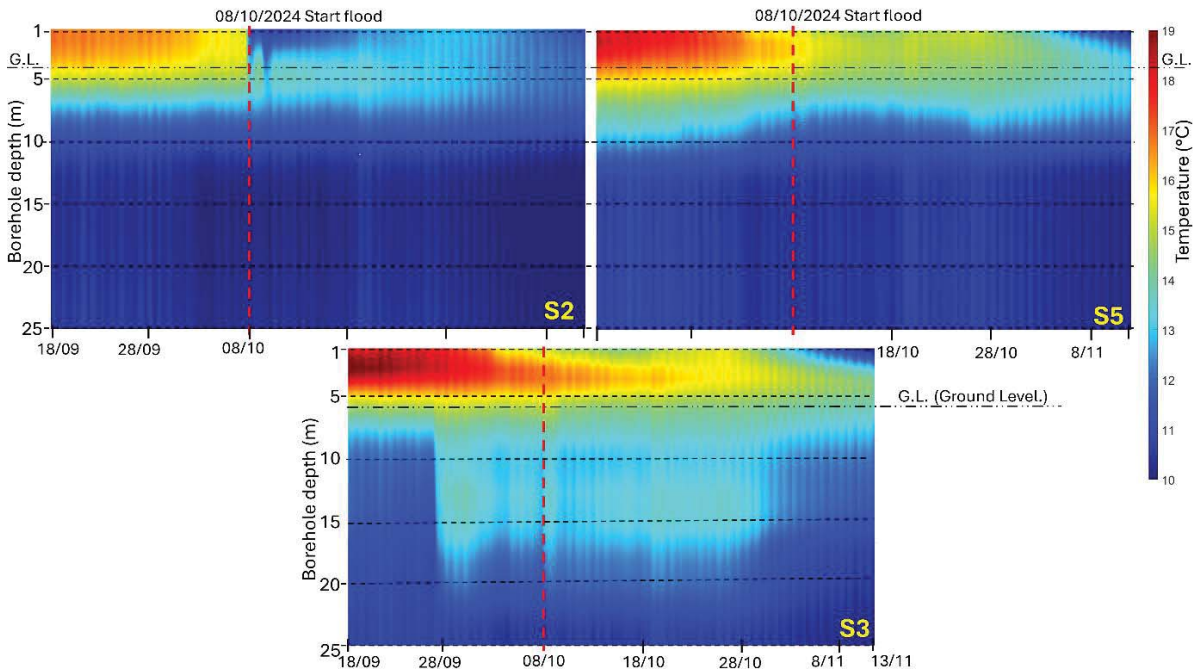


Fig. 3 Temperature distribution measurements with DTS, every 2 hours, along borehole S2, S3 and S5 over time (period 18 September 2024 – 13 November 2024)

3. Conclusion and Future activity

Performing continuous measurements with the DTS system, thereby overcoming the limitations of manual data collection as carried out in previous studies, enabled a precise assessment of the levee system's response time and facilitated the identification of layers exhibiting heat transfer by advection (rapid process) also synonymous for seepage. Data acquired along the entire vertical profile of the well offer a more comprehensive monitoring approach than the point measurements provided by traditional transducers, making DTS better suited for detecting unforeseen local phenomena. Future activities will include the continuation of the measurement campaign, with data acquisition every 2 hours, aiming to obtain at least a one-year-long data series. Simultaneously, a 3D thermo-hydraulic numerical model representing the study section will be developed and calibrated using the measured campaign data. The primary objective is to define scenarios of water leakage and analyse the associated thermal variations. The temperature calculated by the model at the fiber location will then be used to define thresholds. Additionally, models proposed in the literature, such as those by Khan et al. (2010) for processing thermometric data analytically, Guidoux et al. (2024) to set up the system in a user-friendly manner, and Xu et al. (2025) to use machine learning and artificial techniques, will be tried. The goal is to develop an advanced monitoring system designed as an early warning tool to detect concentrated seepage, which may lead to internal erosion or stability concerns that could compromise the structural integrity of the embankment. Furthermore, the system aims to provide critical insights into the appropriate type and depth of interventions required to mitigate potential risks and enhance the overall safety and resilience of the embankment.

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