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Innovative and traditional monitoring system for characterizing the seepage inside river embankments along the Adige River in Salorno (Italy)

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Abstract

Despite notable improvements in geotechnical and hydraulic engineering in recent years, seepage still periodically causes levees to collapse. It is therefore fundamental to promote greater knowledge on existing embankment structures through investigation and monitoring activities, in order to evaluate their safety. Nevertheless, monitoring is complex due to their considerable length and the high spatial variability of the soil, which affect both the body and the foundation of the levee, especially when paleo river networks are present. Innovative techniques, such as the use of distributed optical fiber sensors to measure temperature variations, have greatly improved field surveying and monitoring. Researchers and land managers consider this method to be very attractive because it allows high spatial resolution distributed measures over large areas.

This paper addresses the monitoring of an Adige River embankment carried out in Salorno (BZ) in 2021. Here, a field test was installed to characterize the seepage within the foundation soils in as detailed a way as possible. Five boreholes were drilled at the corners and the center of a square-shaped area measuring 20 m a side, straddling the embankment structure. Each borehole hosts four different types of monitoring equipment: optic fiber cables for detecting the temperature variations along the well, electrical cables for 3D ERT measurements, two piezometric cells, and two thermal probes. In addition, numerous undisturbed samples were collected in order to obtain a comprehensive characterization of the soils through laboratory tests. The monitoring data collected in the field will be used to better understand the hydraulic behaviour and safety conditions of the levees in this area, but also to fully assess the reliability and potential of these innovative monitoring techniques.

Keywords: Levee monitoring, distributed fiber optic sensors, ERT survey, temperature, seepage.

1. Introduction

The investigation and monitoring of embankment structures are complex, due to the considerable length of the studied structure and the high spatial variability of the soils constituting the embankment body and its foundation, especially when ancient paleo-beds are present. Recently, several experimental studies have found temperature to be an indicator of seepage within the levee body and its foundation (Bersan et al., 2018; Cola et al., 2021). To this aim, integrating traditional field monitoring with the use of distributed optical fiber sensors to detect and track variations in temperature can be interesting, as the sensors allow high spatial resolution distributed measurements over large distances and with high sampling frequency. This paper presents an innovative field test that combines traditional sensors of temperature and pressure with fiber optic temperature distributed monitoring to study seepage through the embankment during floods.

The field test is located along the Adige River near Salorno (Bolzano, Italy), in an alpine valley in Northern Italy. In the area under study, the embankments were built at the end of the 19th century to straighten the course of the river. Traces of ancient meanders are therefore easily recognizable in aerial photographs or satellite images (Angelucci, 2013). In order to characterize the embankment structure and its geotechnical behaviour thoroughly, five boreholes were drilled at the corners and center of a square 20m-side area, straddling the right embankment (Figure 1a).

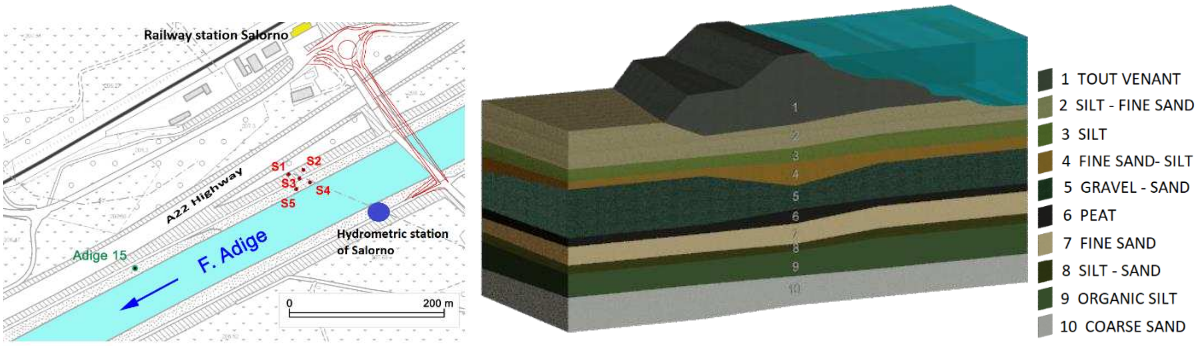
Standard legacy (piezometric cells, thermal probes) and innovative sensors (optical fiber, electrical tomography cables) were placed side-by-side in each borehole. In addition, several in-situ permeability tests were conducted to fully characterize the soil stratigraphy. Finally, many undisturbed samples were collected, both with Shelby sampler and by Gel Push Sampling technique (Chen et al, 2014). The latter is an alternative to the expensive freeze sampling method, which was developed by Kiso-Jiban Consultants and the Yokhoama National University to obtain high-quality undisturbed granular soil samples.

The monitoring campaign is ongoing, so that the potential of fiber optic and ERT measurements as monitoring techniques can be thoroughly assessed. At the same time, the temperature and pressure data will be analyzed to understand and characterize the hydraulic behaviour of the embankment and define the safety conditions of the embankment in this area.

2. Embankment monitoring system

2.1 Fiber optic cables as diffuse temperature sensors

Over the last 30 years, fiber optic (FO) sensors have found significant development and use in the engineering field, primarily due to the advantages that this technology offers when compared to traditional sensor technology. In addition to being a tool for transmitting information, FOs accurately measure the temperature of the soil and are also able to detect temperature changes induced by seepage during a flood. The best known mechanism through which an FO can be used as a thermal sensor is based on the comparison of optical signals generated by a laser and introduced by an interrogator in the optical cable and backscattered in them: given the speed of light in the cable, it is possible to determine the position at which the backscattered signals are generated and evaluate their intensity, related to the temperature of the cable itself (Schenato, 2017). There are different types of FO interrogation methods suitable for different applications and needs as well as different measurement systems with spatial resolution varying from mm to meters, within measurement ranges varying from about one meter to over 100 km (Palmieri et al, 2013).



a) b)

Figure 1: a) Monitoring system location; b) Local stratigraphy.

2.2 Geotechnical investigations

In May and June 2021, the following geotechnical investigations were conducted for the site characterization:

1. Five boreholes were drilled at the corners and the center (corresponding to the axis of the embankment) of the square (Figure 1a). The central borehole (S3) has a depth of approximately 30m, while the ones located at the corners are about 25m deep, in order to reach roughly the same elevation. S1 and S2 are situated on the side of the bank towards the land and S4 and S5 are situated on the side of the bank near the river. A schematic stratigraphy of the soil in the study area is shown in Figure 1b.
2. Eleven undisturbed samples were collected by Gel-Push Sampling in S3, while ten undisturbed thin-wall samples and 16 reworked samples were collected in the other holes.
3. SPT and Lefranc tests were performed in the most permeable soils.
4. Other in-situ permeability tests were performed using an experimental device properly constructed to determine the permeability of coarse-grained soils (sand and sandy gravels).

2.3 Novel permeameter prototype

In addition to an in-situ permeability test carried out using traditional techniques, a new experimental device derived from the BAT permeameter was tested for the first time. This device must be attached to the bottom of the borehole during a pause in the drilling;it consists of a vial which connects to the soil through a porous stone, the latter protected by a retractable seal sleeve during application. The vial contains two internal pressure sensors and is initially depressurized and then lowered into the borehole. The device, threaded in its lower part, is driven approximately 40 cm into the ground, enough to completely immerse the porous stone in the soil. The stone is then uncovered to allow water to fill the vial while the change in pressure over time is measured. The test stops when a stable pressure value is reached. The device has been tested in different types of soil, and the obtained results suggest that it is suitable primarily for sandy soils. When used in gravel the vial fills up too quickly and the collected data cannot be used to calculate permeability; on the other hand, in silty soils the porous stone becomes clogged, and the flow too slow.

2.4 The monitoring system

The following instrumentation was installed in each well:

1. an FO cable to measure temperature variation along the vertical profile;
2. electrical tomography (ERT) cables to perform 3D surveys; the ERT interrogator in use is capable of testing three holes at a time to obtain a 3D map of the resistivity of the foundation soil;
3. ten piezometric cells and ten thermometric probes previously calibrated in the laboratory. The sensors are connected to an A/D controller and interrogated hourly.

The FO, interrogated with a Raman interrogator (Sensornet's Oryx SR DTS), provides a temperature datum along its entire length with a spatial resolution of 2 m and an accuracy of 0.1°C. In particular, the cable houses 2 multimode fibers (in addition to a conductive strand for active heating mode not used in this case, Schenato 2017): it has an external diameter of 4 mm and withstands a minimum bending diameter without tension of 12cm. It was installed vertically in u-loop configuration, anchored externally to a 60 mm diameter micro-slotted pipe. A specific support has been designed to protect the cable at the bottom of the hole and prevent the cable from being bent too tightly (Figure 2a). Once the drilling was completed, the slotted pipe and fiber cable were lowered into the hole; the casing was then removed. To allow for casing removal, the fiber optic cable was previously cut to the exact length of each borehole and was then spliced to the cable from the adjacent holes to create a single optical path that can be interrogated from one location (Figure 2b) in a dual-ended configuration. The fiber running from one borehole to the other was protected within a PVC corrugated pipe placed in a trench approximately 0.5m deep. About 20 m of cable was hosted in a thermic bath, at one end of the optical path, to calibrate the measurements.The cable section is shown in Figure 3c.

Two pressure and temperature probes, with an accuracy of 2 cm of water-column and 0.1°C, respectively, were installed in each hole at different depths (visible in the caption of Figure 3).

a) b) c)

Figure 2: a) Protective support of the FO cable at the borehole bottom. b) Setup for the FO measurements. c) Cross section of the fiber optic cable for temperature measurements (4 mm outer diameter): 1) multimode optical fiber, bend insensitive with dual layer acrylate coating; 2) Stainless steel 316L, gel filled, loose tube; 3) Metal wires armoring stainless steel 316L; 4) Copper conductors (total cross-section area 0.83 mm²); 5) Double layer, outer sheath polyamide/nylon. (from Solifos AG - BRUsens DTS AHFO)

3. Monitoring results

A large amount of data has been collected during the surveys and subsequent monitoring, but only a portion are described here for brevity. Specifically, we report and comment the data recorded during a flood event on August 5, 2021.

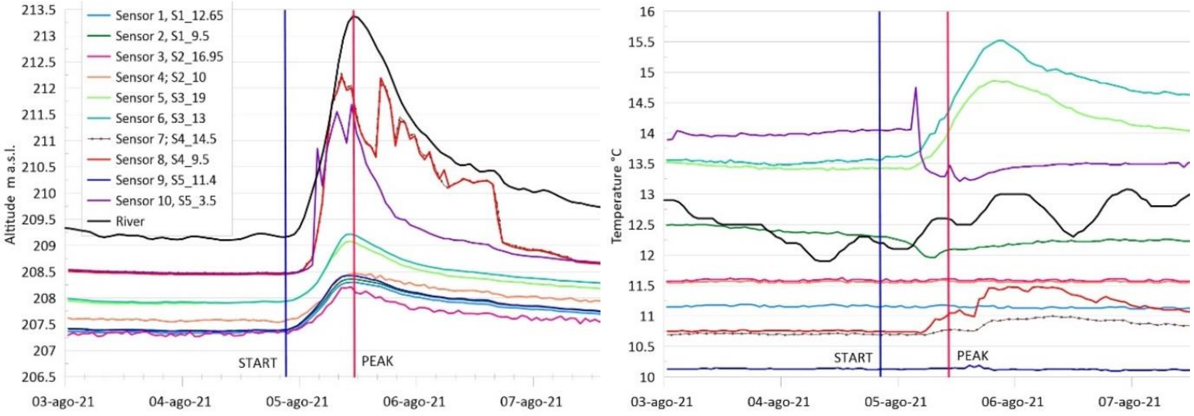
In Figure 3a, the piezometric levels recorded by the pressure transducers are compared with the river water level recorded at the hydrometric station of Salorno (located on the other side of the river in the same section, Figure 1 a). It can be observed that the flood produced an increase in the water river level of about 4.2 m in only

11 hours, reaching the maximum elevation of 213.4 m a.s.l. (about 70 cm below the bank crest) at about 11.00 a.m. on August 5, 2021. Meanwhile, numerous springs formed on the land-side foot of the levee: near the experimental site, four springs of a modest entity characterized by the emersion of clean water were identified, which indicated that the water did not erode the embankment internally.

Probes n.7, 8, and 10 (brown, red, and dark purple curves in Figure 3a), respectively located at S4_14.5m, S4_9.5m, and S5_3.5m, are the most sensible to the river level oscillation, since they registered a variation of about 3-3.8m, reaching the highest piezometric levels. This behaviour was foreseeable for sensor n.10, located at a shallow depth and close to the river bed. Conversely, it was less predictable for sensors n.7 and 8, which are located in sandy layers 4 and 7 (see soil stratigraphy in Figure 1b), especially if compared with the response of probe n.9, which is located at S5_11.4m, i.e., at a small distance horizontally in gravel layer 5 (between layers 4 and 7). The piezometric level measured by probes n.7 and 8 began to rise after 1-2 hours, which is exceptionally quick if compared to the 4- or 5-hour delay in the response of the other sensors. By moving from the river-side towards the land-side (sensors n.5 and 6 and then sensors n. 1, 2, 3, and 4), the pressure oscillation registered during the flood strongly reduced to only 1-1.2 m.

During the flood, the water temperature of the river dropped by about 1°C. Only sensor n.10, probably due to its proximity to the river bed, recorded a similar drop. Sensors n.5, 6, 7, and 8, on the contrary, recorded a temperature increase of about 1.5 °C, with some delay with respect to the passage of the flood wave, probably ascribable to the migration of warm water previously residing in deeper layers, in turn caused by the increase of the piezometric gradient between the two levee sides.

In well S3, where sensors n. 5 and 6 are located, the slotted pipe was still open, so vertical movements of water and air inside it are possible. Consequently, data recorded by sensors n. 5 and 6 were influenced by the external air temperature (about 25 °C at the moment of the peak of the flood event).



a) b)

Figure 3: Pressures (a) and temperatures (b) registered by traditional sensors during the studied flood event (3- 8 August 2021).

For a better comparison, Figure 4 visualizes the cross-sections S1 – S3 – S5 in which the piezometric line is represented at different instants of the flood event. The pressure in the foundation layers of the embankment was not significantly affected by the flood wave, so it is reasonable to hypothesize that the springs that formed during the flood developed entirely within the bank body or at the interface between layers 1 and 2.

Figure 5 compares temperature profiles measured by the FOS in August during the flood event with those measured two to three weeks beforehand, when the water level in the river was low. Plots on the left show the temperature; on the right, the temperature differences recorded in August with respect to July. As S1 (Figure 5c), a significant temperature decrease is observed in landside wells in the shallowest layers. It should be noted that generally, in S1 (and in S2), the water table (WT) is at -4.3 m from the wellheads. Therefore, in July the soil temperature above the WT is warmed by solar irradiation and air temperature (daily peak higher than 30°C).

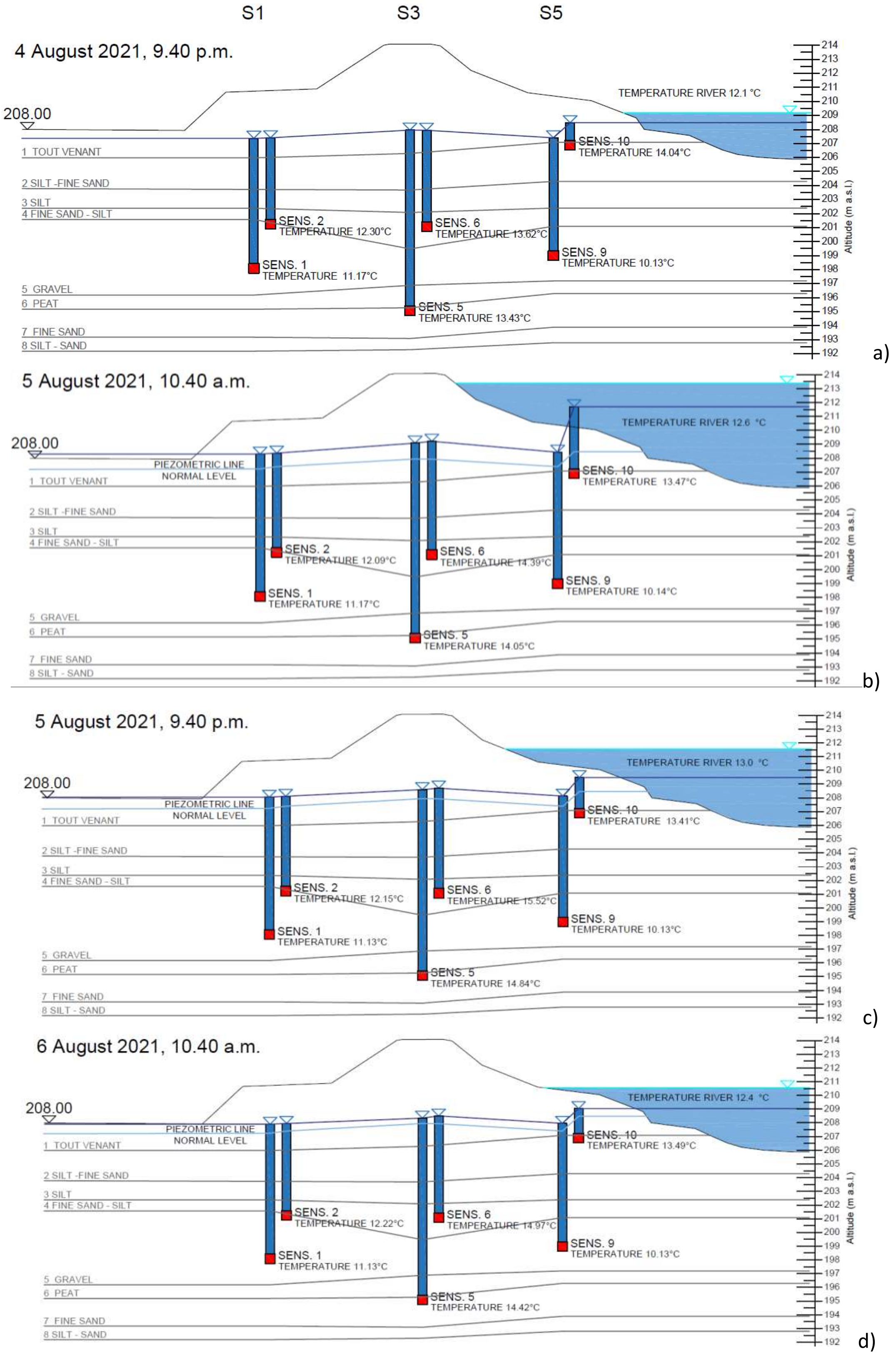


Figure 4: Piezometric lines derived from pressure measurements at a) 4 August 2021 at 21.40, normal level of the river; b) 5 August 2021 at 10.40, flood peak; c) 5 August 2021 at 21.40, 11 hours after the flood peak; d) after 24 hours from the flood peak.

During the flood, the soil in the first 4-5 m saturated rapidly due to the infiltration of cold rainwater, and temperature of the soil dropped by about 8°C. In the river-side wells and S5 (Figure 5a), the temperature drop is observed only in the first 2-3 m, probably because the wellheads are only 2 m above WT. Data from borehole

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S3 (Figure 5b) are more difficult to interpret because the slotted pipe was open and air circulation influenced the temperature inside. In addition, the vertical profile measured in central well S3 records the variation of about 1°C in the deep layers as the flood wave passed, confirming what was recorded by traditional sensors.

The temperature trend measured by FOS is comparable that previously reported by Cola et al. (2021) in another test site near Salorno, where a horizontal FO cable for detecting temperature variation was installed along 300 m of embankment. At that site, during an important flood that occurred in October 2018, the seepage induced by the flood into the soil substituted the pre-existing water, characterized by a higher temperature level. Correspondingly, the FOS recorded a temperature decrease toward the river temperature.

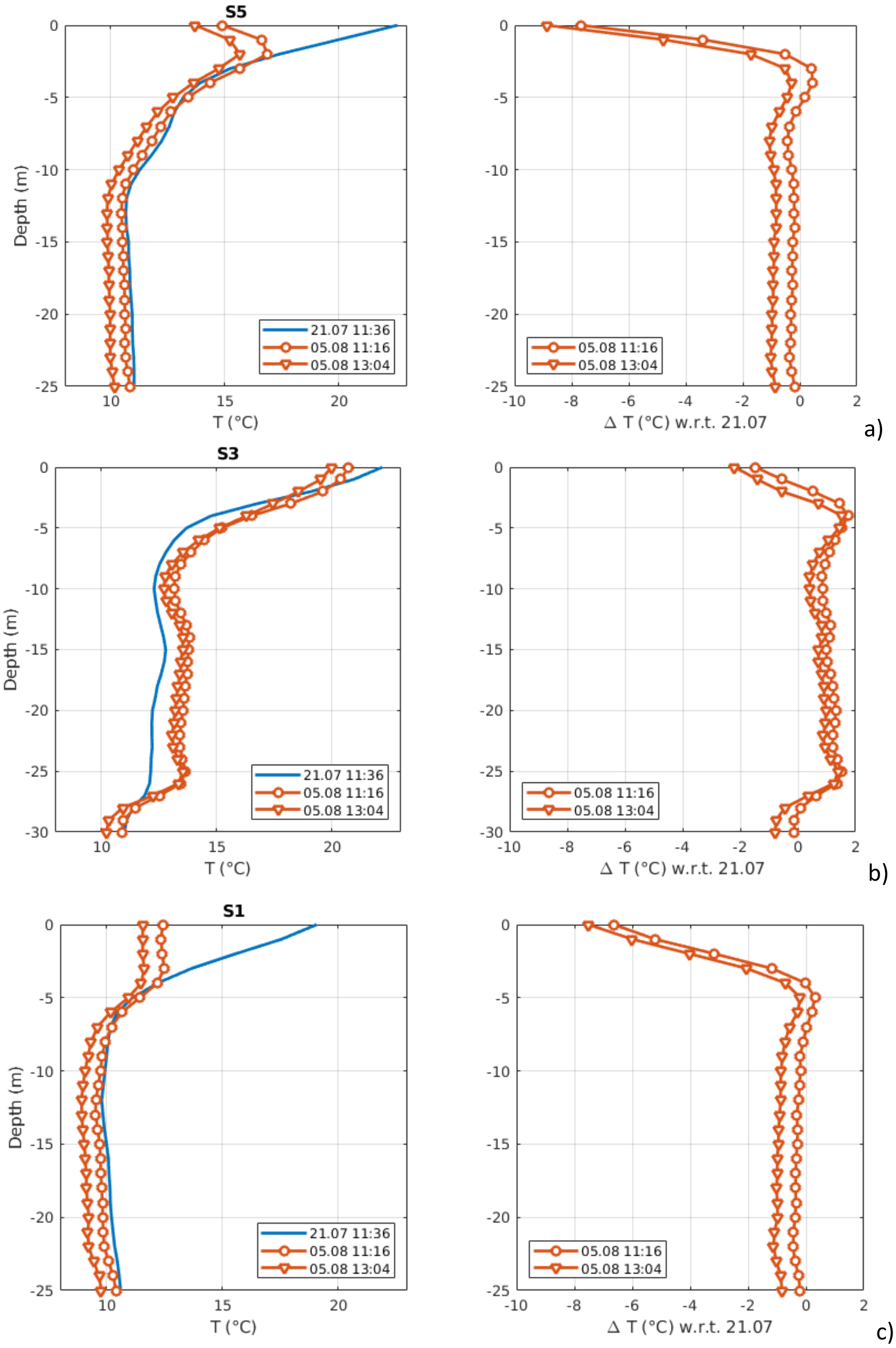

Figure 5: Temperature and temperature variation profiles measured by FO in the boreholes S5 (riverside), S3 (levee axis) and S1 (landside) on August 5, 2021 at 11:16 and 13:04 and comparison with the profiles registered in absence of flood in July 21, 2021.

4. Conclusions

The measurements obtained from this case study provided noteworthy information. In particular:

1. the monitoring system applied here combined traditional sensors with fiber optic cables; the first provided the temporal evolution of temperature and pressure in a single predetermined point, while the second provided a distributed measure of temperature all along the vertical well profile during the field campaign, in this case the 2-3 hours of flooding. This combination provides more detailed knowledge of the levee's behavior.
2. apart from sensor n.10 (S5_3.5) that is located closest to the river, the other punctual sensors are positioned within the levee foundation soils, in the more permeable layers, at a depth from 12 to 17 m from the top of the embankment, hence 4 m lower than the depth of the riverbed. Despite considerable flooding, the measured data shows a constrained pressure increase, suggesting that the seepage affects only the levee body and the shallower layers and does not concern the deeper layers. The same observation can be obtained from the measured temperatures; again, sensor n.10 (S5_3.5) is the only sensor that displays a trend converging to the temperature of the river.
3. conversely, the fiber optics measured a significant temperature decrease constrained in the shallower layers (down to 4m). The temperature of this portion, above the water table, was previously affected only by the warm air temperature. During the flood, the temperature decreased by 8°C due to water from the river, whose temperature measured about 12.5° C, which penetrated and saturated the body levee.

Therefore, the combined measurements show the advancement of the saturation front inside the embankment, as evidenced by the optical fibers. The FOs, by monitoring the entire vertical profile, can detect the depth at which seepage occurs. This detection is more difficult to obtain using punctual sensors because their positions must be decided in advance. Although the results obtained so far, and summarily reported here, already provide some initial observations on the behavior of the embankment structure, further measurements and analyses will be performed in different flooding conditions. This will allow the potential of fiber optics in the monitoring of embankment structures to be further assessed.

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