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ORIGINAL PAPER

Temperature monitoring in levees for detection of seepage

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Abstract

Improving knowledge of existing levees through investigation and monitoring is an important step in evaluating their safety and that of the surrounding area. Nevertheless, these activities are complex due to the considerable levee length and the high spatial variability of soil composing the body and foundation, especially when paleo-rivers are present. In order to investigate the reliability of new advanced techniques proposed for characterizing the soil stratigraphy and the seepage condition within the levee foundation, a new test site was realized along the Adige River in Bolzano Province (Italy). Here, five boreholes, drilled in a 20-m-side square area straddling the embankment, host four different types of monitoring equipment, among which some are Distributed Fiber Optical Sensors (DFOS), here used for detecting the temperature variations along the well. The present paper focuses on the critical analysis of the preliminary results obtained with DFOS and their comparison with data obtained using traditional pressure and temperature probes. The monitoring data collected in the field during the passage of a flood that occurred on 5th August 2021 are used to better understand the hydraulic behavior and the safety conditions of the levee but also to fully assess the reliability and potential of DFOS.

Keywords River embankment · Monitoring · Distributed fiber optic sensors · Soil temperature · Seepage · Piping

Introduction

Every year, levee and dike collapses cause many casualties worldwide, as well as huge financial and social losses, especially in highly developed areas. The surveying and monitoring of embankment structures are complicated by the considerable length of these structures and the high variability of soil constituting the embankment bodies and their foundation, especially when ancient paleo-rivers are present. On the other hand, understanding and monitoring the hydraulic behavior of levees are strategies that guarantee their safety conditions. Finally, to define the appropriate monitoring tools and programs, it is necessary to understand the specific site potential failure modes (Oguz et al. 2022; Zwanenburg et al. 2018; Su and Kang 2013).

In recent decades, non-invasive or minimally invasive techniques have been developed with the aim of monitoring large portions of embankments. Of course, geophysical methods play a crucial role in evaluating the stability conditions of dams, embankments, and slopes. Among them, geoelectrical measurements, which can investigate variations of soil composition and water saturation, are suitable for hydro-geological studies and detecting weak zones (Inazaki and Sakamoto 2005; Cho and Yeom 2007; Sjödahl et al. 2009; Binley et al. 2010, 2015; Perri et al. 2014; Busato et al. 2016; Amabile et al. 2020a, b; Hojat et al. 2021; Zhou et al. 2022a, b).

In the two past decades, some researchers have found temperature to be a good indicator of seepage within the levee or earth dam body and their foundation (Radzicki 2014; Utili

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et al. 2015; Bersan et al. 2018; Cola et al. 2021; Johansson and Sjödahl 2004; Zhu et al. 2009; Brothier et al. 2018; Su et al. 2018; Li et al. 2022; Cheng et al. 2021; Dalla Santa et al. 2023). The principle at the basis of detection by temperature sensing consists of assuming that when a normal flow regime exists, temperature fluctuations are driven by heat conduction from the air toward the foundation, on a seasonal basis. On the contrary, when abnormal seepage flows take place, the amplitude of temperature fluctuations increases as advection from the water upstream becomes overly significant.

In order to have an effective system for the detection of temperature distribution and variation along a long stretch of the river levees, the distributed optical fiber sensors (DFOSs) could be very convenient. These sensors are innovative sensors based on optical fiber technology which have undergone substantial advancements and witnessed widespread adoption within the domain of engineering and, among others, within the field of Civil Structural Health Monitoring. This progression is well documented in the works of many researchers, e.g., Schenato (2017), Zhang and Xue (2019), Ye et al. (2022), Zhou et al. (2022a, b), Schenato et al. (2022), Zhu et al. (2023), Brezzi et al. (2023), and Höttges et al. (2023). The heightened prevalence of DFOS in engineering can be attributed to the manifold opportunities that this technology affords in comparison to traditional sensor systems, mainly the possibility of measuring temperature distribution for long distances with high resolution and precision. With regards to hydraulic infrastructures, while DFOS systems are commonly used for dam monitoring on more than one hundred large earth dams, tailing dams, and canals (see for instance, Su et al. 2014; Goltz 2011; Johannson et al. 2015; Fabritius et al. 2017; Cejka et al. 2018; Bekele et al. 2023), their application in monitoring river or sea dikes and existing levees is relatively limited only on a few cases (Bersan et al. 2018; Cola et al. 2021; Abbasimaedeh et al. 2021). Considering these aspects, new good experiences during real flooding events could lead to more widespread use of this technology. To this aim, to detect and track variations in temperature, it can be convenient to integrate traditional field monitoring with DFOS. Two methods are employed for seepage detection with DFOS: the passive gradient method, relying on temperature changes caused by seepage water, and the active heat pulse method, which uses hybrid sensor cables combining optical fiber and copper wire to warm the ground and identify areas with high water saturation or flow regions by observing the temperature dissipation around the cable.

For evaluating the potentiality of DFOS for levee investigation, in 2016, the authors made a first attempt. In that first attempt, a single DFOS for temperature measurement was installed within a trench about 350 m long at the foot of the right embankment of Adige River (Cola et al. 2021): with the same cable, 3 spans at 3 levels with a vertical interspace of 50 cm were realized. The aim was to evaluate the DFOS capability for identifying the piping occurrence in a section specifically known for this type of problem even if in that section a cut-off wall was realized more than 20 years ago.

Although the results from this initial setup suggested the possible occurrence of a localized seepage during a flood event, its identification was not conclusive or definitive. However, these findings prompted to perform further attempts to exploit different sensor configurations. Consequently, the present paper deals with a second attempt carried out in a field test close to the previous one and with similar issues. Here, traditional sensors were combined with DFOS. All the devices were installed in vertical holes to reduce soil disturbance during installation. As far as the authors are aware, this is the first case of a DFOS application installed in a vertical hole in levee monitoring in Italy.

During the realization of the new test field, in order to characterize the embankment structure and its geotechnical behavior thoroughly, five boreholes were drilled at the corners and the center of a 20-m-side square-shaped area, straddling the right embankment (Fig. 1a). Several in situ and laboratory tests were conducted to fully characterize the soil stratigraphy, with particular regard to hydraulic parameters. In each vertical borehole, different monitoring instruments were placed side-by-side, specifically standard piezometric and thermal probes and innovative sensors, such as DFOS and cables for cross-hole electrical resistivity tomography.

The monitoring campaign is ongoing so that the potential of DFOSs as monitoring techniques can be thoroughly assessed. To this aim, the temperature and pressure data collected during future flooding events will be analyzed to understand and characterize the hydraulic behavior of the embankment under different river water levels and define the safety conditions of the embankment in this area. Here, the data collected during a first occurred medium flooding event are presented and discussed.

The field test site

The Adige Valley has been subjected to major floods in the past, since the collapse of 1882, in which the Adige River embankments failed in ten different sections. The most devastating event of the twentieth century occurred in 1966 when the city of Trento was completely submerged. A landside instability mechanism on the left levee embankments, near the village of Salorno, caused a collapse in 1981 that flooded the entire surrounding area (Cola et al. 2021). After this event, the Mountain Water Authority of the Province of Bolzano undertook an intensive monitoring program of the "health" of Adige levees, promoting monitoring activities of the levee investigation, experimental studies, and modeling (Bossi et al. 2018; Amabile et al. 2020a, b; Pozzato et al.

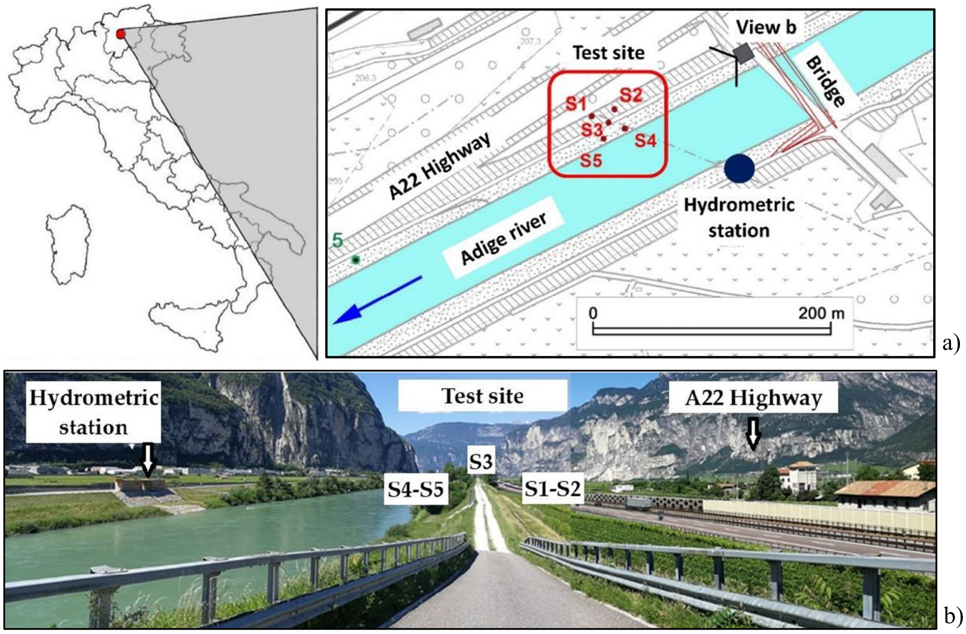


Fig. 1 Test site location: **a** maps from national to local scale; **b** view from Salorno Bridge

2020; Cola et al. 2021; Schenato et al. 2022; Fabbian et al. 2022).

Fluvio-glacial and lacustrine sediments constitute the deep stratigraphy of the Adige Valley. Above these, the more recent soil deposits, characterized by alluvial sediments transported here by the river and near landslide bodies, are present. Consequently, the valley presents high heterogeneity and interdigitation of different materials, as has emerged from the various site investigations carried out so far.

Before the nineteenth century, the river thalweg developed freely with a meandering form that migrated along the narrow field. Then, several anthropic interventions, such as the realization of straight embankments, confined and rectified the river in a fixed bed. Traces of ancient meanders are easily recognizable in aerial photographs or satellite images (Angelucci 2013). In many lineaments, the new levee system crosses the ancient paleo-river, and in the past, several of the observed levee collapses seemed to occur at those intersection points (Cola et al. 2021).

The field test here presented is along the right side of the Adige River, just after the bridge of Salorno (Bolzano, Italy) and a hydrometric station of the Bolzano Province (Fig. 1) and before the section of the first test. The main body of the levee was built in the late nineteenth century, and a countryside berm was added in 1983. This site was selected because it has no internal human interventions and because of its proximity to the A22 Highway. As the highway here runs parallel and very close to the levee, a possible collapse can have dangerous impacts on people and the economy. Occurrences of sand boiling, which typically necessitate the implementation of hazard mitigation protocols like sandbag deployment, were not detected in this area before or during the investigations. Nevertheless, several minor water inflows were observed during the most intense flood events. These piping were characterized by the discharge of clear water, indicating no evident signs of internal erosion. However, while not indicative of erosion, these occurrences serve as a warning signal, emphasizing the need for future structural interventions to improve the levee against potential risks, the latter to be better understood through monitoring of the area.

Geotechnical investigation

In May and June 2021, a careful site characterization was carried out by means of the following geotechnical investigations:

1. Five boreholes were drilled at the corners and the center of a 20-m-side square area (Fig. 1a). The central borehole (S3), located on the top of the levee, has a depth of approximately 30 m, while those located at the corners are about 25 m deep, in order to reach roughly the same elevation. S1 and S2 are situated on the side of the land bank, and S4 and S5 are situated on the side of the river bank.
2. Eleven undisturbed samples were collected with the gel pusher (GP) sampling technique in S3, while 10 undisturbed Shelby samples and 16 reworked samples were collected in the other holes. GP sampling is a technique developed in 1999 by Kiso-Jiban Consultants and the Yokohama National University as an alternative to the expensive freeze sampling method for obtaining high-quality undisturbed granular soil samples (Huang et al. 2008; Yusa et al. 2017). The technique is used here for

the large presence of granular materials that cannot be sampled with traditional methods (Fabbian et al. 2023).

3. SPT and Lefranc tests were performed on the layer below WT.
4. Twenty thermal characterization tests were carried out on-site.
5. 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).

The in situ investigation was completed by laboratory tests performed on collected undisturbed samples to determine particle size distribution, Atterberg limits, organic material content, hydraulic conductivity tests in triaxial cells, shear resistance, and compressibility of the soils.

The survey made it possible to define the soil stratigraphy, here reported in Fig. 2, in detail. Due to their proximity, the boreholes went through a similar stratigraphic succession, differentiated only by the composition of the embankment structure and by small lateral variations in the sediment granulometry. The embankment is constituted by fill material, consisting of poorly graded gravel with silt and sand or poorly graded sand with silt (GP-GM or SP-SM) according to the unified soil classification system (USCS). The foundation can be divided into 9 layers with variable thicknesses from 1 to 5 m. Specifically, the layers identified from top to bottom are

1. Silty sand or poorly graded sand with silt (SM or SP-SM)
2. Silty sand with Peat (SM with PT)
3. Well-graded sand with sand with silt and gravel (SW-SM)
4. Well-graded gravel with silt and sand (GW-GM)
5. Peat or organic silt (PT or OL)
6. Well-graded sand with sand with silt (SW-SM)
7. Silty sand (SM)
8. Silt or organic silt or peat (ML or OL or PT)
9. Well-graded sand with silt or organic silt (SW-SM or OL)

The laboratory and on-site tests permitted to define hydraulic and mechanical parameters for seepage and stability analyses. Of course, these parameters present a great variability, and in the selection of representative values, more importance is given to on-site tests, considered more reliable. The main geotechnical parameters of soil layers are also listed in Table 1.

In normal conditions, when the river is not subjected to high flooding, the water table (WT) on the landside is about 7 m from the embankment crest.

Monitoring instrumentation

As shown in Fig. 2, the following instrumentation was installed in each borehole:

1. 1 DFOS to measure temperature variation along the vertical profile
2. 24 electrodes to perform 3D electrical resistivity tomography (ERT) surveys; the ERT interrogator in use is capable of testing three holes at a time, in cross-hole mode, to obtain a 3D map of the resistivity of the foundation soil. No comment on the measure performed with this device is reported here for the sake of space
3. 2 combined sensors were installed in each hole at different depths. Each sensor is formed by a pressure transducer (TP) and thermometric transducer (TT), with an accuracy of 2 cm of water column and 0.1 °C, respectively. All the sensors were previously calibrated in the laboratory and are hourly interrogated with an A/D controller.

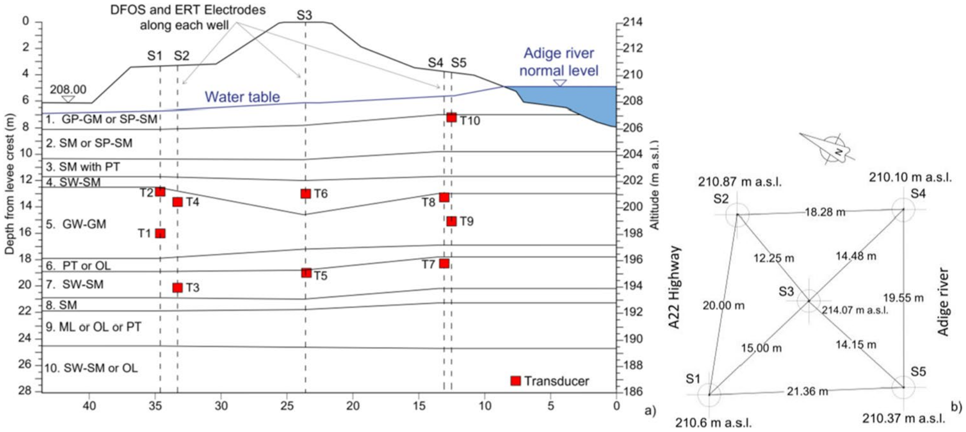


Fig. 2 **a** Soil stratigraphy and distribution of monitoring sensors; **b** quoted plan of the carried out surveys

Table 1 USCS classification and properties of soils in the Salorno test site

Formation (no.)	USCS group	γ_{sat} (kN/m^3)	D_{10} (mm)	D_{60} (mm)	$C_u = D_{60}/D_{10}$ (−)	Permeability (m/s)
1	GP-GM or SP-SM	19	0.03	0.18	6	8.3×10^{-4}
2	SM or SP-SM	18	0.007	0.04	6.8	5.0×10^{-6}
3	SM with PT	18	0.002	0.012	5.2	8.9×10^{-8}
4	SW-SM	18.5	0.014	0.088	6.3	8.8×10^{-6}
5	GW-GM	19	0.018	0.26	14.4	2.9×10^{-5}
6	PT or OL	17	0.009	0.012	1.4	1.1×10^{-7}
7	SW-SM	18.5	0.022	0.16	7.27	8.8×10^{-6}
8	SM	18	0.008	0.034	4.25	1.6×10^{-8}
9	ML or OL or PT	17.5	–	–	–	1.1×10^{-7}
10	SW-SM or OL	19	0.018	0.35	19.4	8.0×10^{-6}

DFOSs are the only available contact sensor technology capable of providing the measurement of temperature and/or strain with sufficient spatial resolution in soil over an extensive length. In this application, a DFOS for temperature measurement, also named distributed temperature sensor (DTS), is adopted. If interrogated with a Raman interrogator (Sensornet's Oryx SR DTS), it 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 (Fig. 3a) houses 2 multimode fibers (in addition to a conductive strand for active heating mode, not used in this case). It has an external diameter of 4 mm and withstands a minimum bending diameter without tension of 12 cm. It was installed vertically in a U-shaped configuration, anchored externally to a 60-mm diameter micro-slotted pipe. A specific support was designed to protect the cable at the bottom of the hole and prevent it from being bent too tightly (Fig. 3b). Once the drilling was completed, the slotted pipe and fiber cable were lowered into the hole, and the borehole casing was removed. To allow this operation, the fiber optic cable was previously cut to the length needed for each borehole and then spliced to the cable from the adjacent holes to create a single optical cable that can be interrogated in a dual-ended configuration from a unique location (Fig. 3c). The fiber running from one borehole to another was protected within a PVC corrugated pipe placed in a small trench.

In order to improve accuracy and to calibrate the FO cable, it is good practice to perform a calibration bath, which consists of placing about 20 m of fiber in a tank full of water at a known temperature, in order to translate the measurement of the difference between the measures of the fibers and at least two reference sensors (Schenato et al. 2022). Thermal bath was performed at each measurement campaign reported in the present paper (Fig. 3d).

Some examples of temperature profiles along the central borehole (S3) are presented in Fig. 4. Except for two measurements collected in October 2021 and September 2022, all the others were in spring and summer. Even though few measurements are available in winter, seasonal fluctuations, due to solar radiation and heat exchange with the

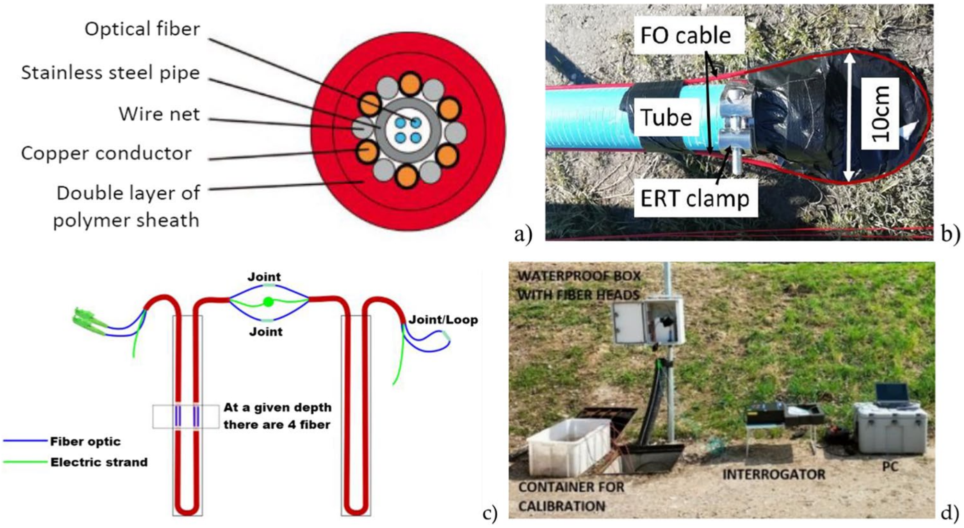


Fig. 3 **a** Cross section of the FO cable for temperature measurements (4 mm outer diameter). **b** Protective support of the FO cable at the borehole bottom. **c** Fiber Optic cable configuration after installation. **d** Setup for the FO measurements with thermal bath

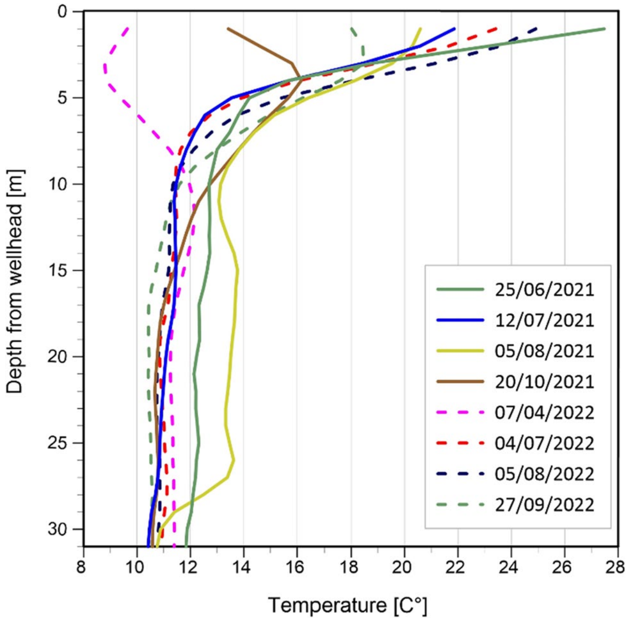


Fig. 4 Single-day distribution of temperature readings along the central borehole S3

atmosphere, are well visible in the embankment body and in the first foundation layer. During the summer, the soil receives more intense and prolonged solar radiation, which leads to an increase in soil temperature as the soil absorbs the heat from the sun; in contrast, during winter, the solar radiation decreases, and the ground gradually cools down. The thermal conductivity of soils is generally low, and the seasonal fluctuations have effects only in the upper layer (5–7 m). The deeper layers are insensitive to these fluctuations, and the temperature remains quite constant and equal to the mean annual temperature of the external air of the considered site (Cunat et al. 2009).

Due to the thermal inertia of the ground and the particular meteoric conditions occurring each year, the point of maximum warming could be in 1 day of the summer: for instance, in the 2 years here presented, the maximum temperature is recorded at the 25th of June 2021 and at the 5th of August 2022. For the same reasons, the coldest time is at the end of winter or in early spring. In the series here presented, we have not captured the absolute minimum profile: the lowest observed temperatures are on the 7th of April 2022, which still showed a temperature gradient positive in the first 3–4 m, thus indicating that the temperature was already increasing and probably the absolute minimum occurred previously that date. For the site under consideration, the mean annual temperature is around 11 °C, as measured in the lowest part of quite all the profiles.

Of course, periodic measurements are essential for ascertaining ground temperature at different moments, as variations in thermal conditions arising from hydraulic anomalies are contingent upon a baseline reference measurement.

Observation during the flooding event on the 5th of August 2021

After the installation of the monitoring system, only one notable flood wave, due to an intense rainfall that occurred north of Bolzano, affected the river on the 5th of August 2021.

In Fig. 5a, the piezometric levels recorded by all the TP are compared with the river water level recorded at the hydrometric station. It can be observed that the flood

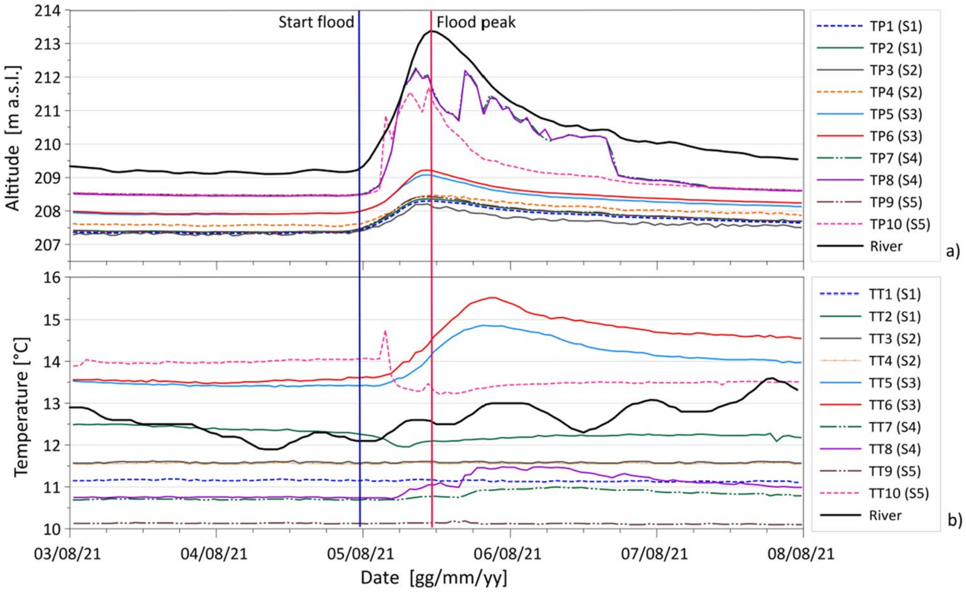


Fig. 5 Total heads (**a**) and temperatures (**b**) registered by traditional sensors during the flood event of August 2021

produced an increase in the water river level of about 4.2 m in only 11 h, reaching the maximum elevation of 213.4 m a.s.l. (about 70 cm below the embankment crest) around 11:00 am on the 5th of August 2021. Meanwhile, numerous springs formed along the landside of the levee. Near the experimental site, four springs of a modest entity were identified; they were characterized by the emersion of clean water, which indicated that the water did not internally erode the embankment.

TP7, TP8, and TP10, located inside the well on the riverside, are most sensible to the river level oscillation: they recorded a variation of about 3–3.8 m, reaching the highest piezometric levels. This behavior was foreseeable for TP10, located at a shallow depth and very close to the riverbed. Conversely, it was less predictable for TP7 and TP8, which are located in the sandy layers no. 5 and no. 7 (see soil stratigraphy in Fig. 2). This appears anomalous if compared with the response of TP9, located at a small horizontal distance in the same layer no. 5. In addition, the piezometric level at TP7 and TP8 began to rise after 1–2 h, which is exceptionally quick when compared to the 4- to 5-h delay showed by the other sensors. This anomalous behavior has to be verified in the future, because it is possible to suppose that it is related to a not correct sealing of the S4 well at the top. The pressure variation registered during the flood by all the other sensors is only 1–1.2 m and seems to reduce its value by moving from the waterside (TP5 and TP6) toward the landside (TP1, TP2, TP3, and TP4).

Starting from the 3rd of August up to flood peak, the water temperature of the river dropped down by about 1 °C, as Fig. 5b shows. Again, only TT10, likely due to its proximity to the riverbed, recorded a comparable drop but localized in time in the rising phase of the water river level, when the flood activated the seepage. On the contrary, TT5, TT6, TT7, and TT8 recorded a temperature increase of about 1.5 °C, with some delay with respect to the passage of the flood wave. This seems ascribable to the migration of warm water previously residing in deeper layers, possibly caused by the activation of seepage between the two levee sides.

Note that in well S3, where TT5 and TT6 are located, the slotted pipe was still empty at that moment, so vertical movements of water and air inside the well are possible. Consequently, data recorded by TT5 and TT6 may be influenced by the external air temperature (about 25 °C at the flood peak time).

Figure 6 illustrates the piezometric line at different times during the flood event in cross-sections S1–S3–S5. As previously observed, the flood wave passage did not significantly affect the water pressure in deep layers, where the piezometric head went above the ground surface only in the central part of the event. This induces the hypothesis that the springs observed on the landside of the levee were induced by a seepage phenomenon that developed entirely within the bank body or at the interface with layer no. 2. They could also be related to some paths locally excavated by animals (e.g., moles or mice), because some small holes attributed to the entrance of animal caves were subsequently found on the landside slope of the levee in the same area.

Figure 7 compares temperature profiles measured with DFOS in boreholes S1 (landside), S3 (center of the levee), and S5 (waterside) during the flood event (5th of August) and 2 weeks before (21st of July), when the water river level was low. Figure 7a shows the temperature profiles; Fig. 7b reports the temperature variations observed in August with respect to July. In the following, the temperature profile recorded on July 21 is assumed as the profile existing just before the rainfall and flood event. This is because the weather in the days before the rainfall had been stable, and it is possible to assume that the soil temperature had not changed significantly.

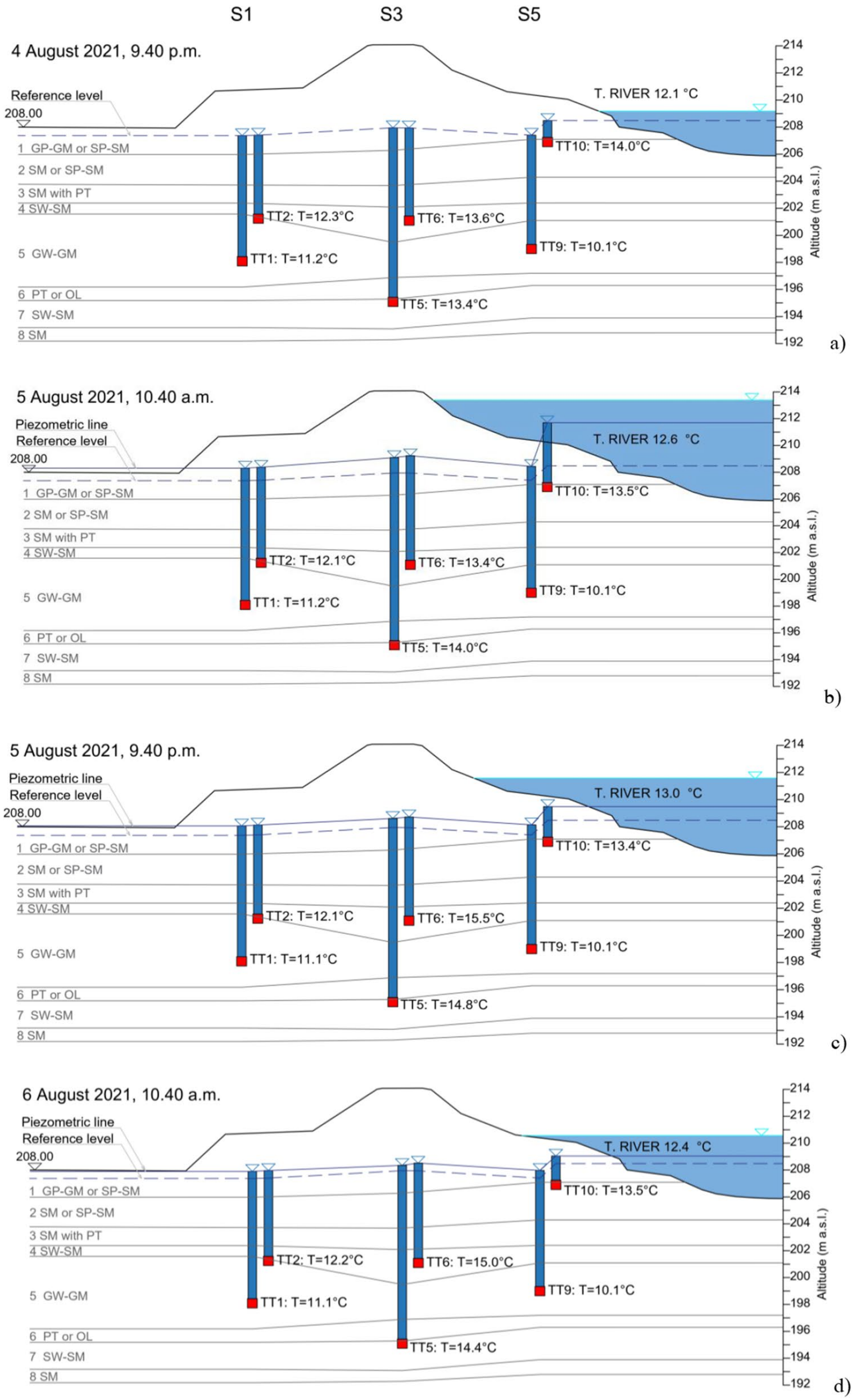
A significant temperature decrease in the upper layers is observed in landside well S1. It should be noted that on the landside, the WT is normally at 207.4 m a.s.l. Therefore, due to solar irradiation and high air temperature (the daily peak of air temperature in summer can arrive higher than 30 °C), in July, the soil temperature above the WT is very high. During the flood, the soil in the shallow 4–5 m saturated rapidly due to the infiltration of cold rainwater, and the soil temperature dropped by about 8 °C. In the waterside well, a similar temperature drop is observed, but only in the first 2–3 m, because the wellhead is only 2 m above WT. Finally, the trend recorded in borehole S3 is completely different, and a small decrease of 2 °C in temperature is observed only in the upper 2 m; this behavior could be explained considering that the soil composing the levee is well compacted and less permeable in the upper part and the rain infiltrates with higher difficulty. Moreover, since the slotted pipe in borehole S3 was still open, the air circulation can affect the temperature recorded inside the well by the DFOS.

In addition, in central well S3, the temperature exhibits a variation of 1 to 2 °C in the deep layers as the flood wave passed. This confirms the trend recorded by traditional sensors. Even if the temperature measured by DFOS is 1 to 2 °C, different from that recorded by the temperature probes, the temperature variations measured with the two monitoring systems are similar.

Discussion

The previous section has presented the data acquired during an important flood event that occurred on the 5th of August 2021. The measurements obtained provided remarkable information. Considering the traditional sensors, it has to be noted that, excluding the sensor located at a small depth below the riverside bank, all the others are in the permeable

Fig. 6 Piezometric lines derived from pressure measurements at **a** 4th August 2021 at 21.40, normal level of the river; **b** 5th August 2021 at 10.40, flood peak; **c** 5th August 2021 at 21.40, 11 h after flood peak; **d** 24 h after flood peak



layers in the levee foundation, at a depth from 12 to 17 m from the levee top and separated by relatively impermeable layers from the riverbed. Despite the significant increment in the river level, the data showed limited pressure increases, suggesting that the deeper layers are not significantly affected by seepage, which probably affected only the levee body and the shallower layers. The same observation can be obtained from the temperature curves; only the sensor

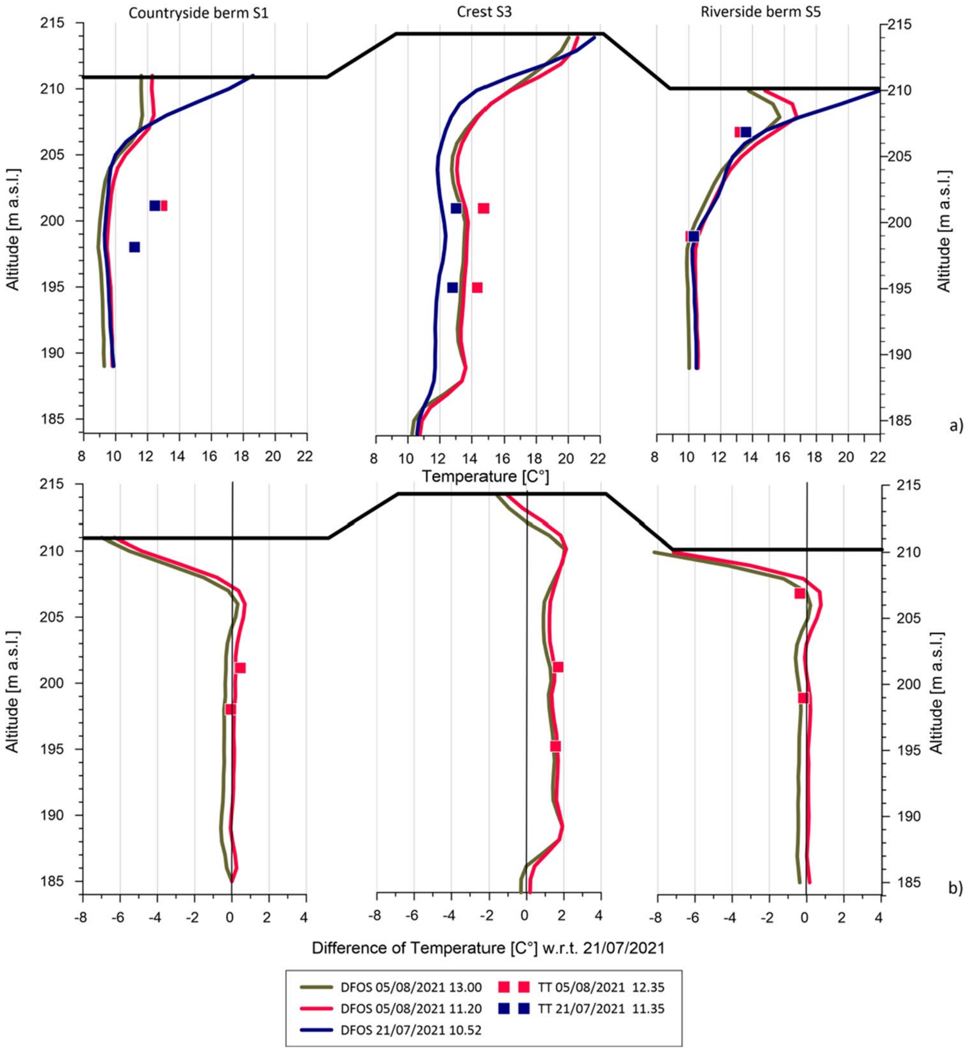


Fig. 7 Temperature (**a**) and temperature variation (**b**) profiles measured by DFOS and temperature probes in boreholes S1 (landside), S3 (embankment axis), and S5 (riverside)

in the riverbank exhibited a temperature change associated with the variation of the river water temperature recorded at the nearby hydrometric station. On the other hand, DFOS in the well at the site corners measured a significant temperature drop limited to the shallower layers above the WT (up to 4 m from the wellhead). Before the flood occurrence, the soil above the WT exhibited very high temperatures, likely due to the high external temperature and seasonality. During the flood, in the wells on the riverside, the temperature decreased from 22 to 13 °C due to infiltration of the river water, which has a temperature of about 12.5 °C. Also, data recorded by DFOS evidenced an analogous decrease in temperature in the landside borehole, in this case also justifiable considering infiltration of the rainwater and the presence of piping observed during the event. No significant decrease in temperature is recorded in the hole located at the center of the embankment; however, the S3 well is not yet clogged and cannot therefore be considered representative of the behavior of the levee. Furthermore, the absence of additional well placements at the central axis of the levee precludes the possibility of a comparative analysis.

In the first attempt of using DFOS for temperature detection during seepage, carried out in a site very close to the one here described (Cola et al. 2021), DFOS was horizontally installed in a trench long 350 m positioned at the toe of an embankment. The measurement carried out in October 2018 during an intense flood event revealed that the flood-induced seepage produced the displacement of the pre-existing water, causing a decrease in soil temperatures toward the temperature of the adjacent river. Thanks to the data acquired with DFOS, an inversion of the temperature gradient observed within a specific section chainage suggested the presence of faster upward seepage flow paths located close to some gravel lenses, with the latter partially discerned during the geotechnical investigation. The interpretation of DFOS data during the flood event presented challenges attributable to the constrained temperature variations and the necessity for an approximate interpretation of the seepage flow dynamics.

In this second attempt, the placement of fibers within vertical boreholes was chosen to have more readily discernible temperature fluctuations with depth. This is clearly observed in the different interrogations performed in the different seasons, but also with the data acquired with the flood event on the 5th of August 2021, when these fibers offer insights into the specific depths at which saturation or preferential filtration pathways manifested.

In this attempt also, the DFOS demonstrated its effectiveness in measuring temperature fluctuations in the soil. A clear outcome of this investigation is that the seasonal temperature fluctuations in the first few meters of soil are not negligible, so periodic measurements are necessary in order to establish a reference measurement in the case of flooding. On the other hand, the soil temperature variations induced by seepage are very small especially in the deep layers. Consequently, for future installations, it could be better to concentrate the attention on the upper layers (levee body and the first two layers in the foundations).

Further measurements and analyses will be carried out under different flood conditions in the future, in order to better understand the possibilities of using DFOS in monitoring embankment structures, which can be more accurately evaluated.

Conclusions

The article has presented the results of a comprehensive study carried out on a section of the right levee of the Adige River near Bolzano (north-east of Italy). In order to evaluate the health state of the levee and the presence of seepage phenomena in the subsoil and, moreover, to test new methods of investigation and monitoring, a test site was realized. In a 20-m-side square area, straddling the embankment, conventional sensors along with DFOS for measuring pressure and temperature evolution were installed in 5 boreholes with the aim of detecting the layer in which the seepage occurs. In addition, a very detailed characterization carried out on-site and on the collected samples permitted the reconstruction of the subsoil stratigraphy and identification of the more permeable layers.

This study has allowed assessment of the applicability of this system and, in particular, the approach of monitoring deep soil temperatures to detect seepage flow from the river. In particular, the vertical profiles of temperature acquired with DFOS clearly showed that both the rain falling to the ground and water infiltrating from the river advanced inside the embankment, but not significantly in the deeper layers. This process is also confirmed by the data temperature acquired with traditional sensors. In fact, water pressure variations observed in the deep layers are quite low and seem to indicate that no significant seepage phenomena are activated in the deep layers.

Additionally, some preliminary conclusions on the adopted system can here be drawn. Thanks to breakthroughs in DFOS in recent decades, it is now possible to obtain high spatial coverage and spatial resolution. This possibility avoids having to previously choose the precise location of each sensing point, as happens for traditional probes. For example, in the analyzed case, by monitoring the temperature vertical profile of DFOS, one can detect the depth at which seepage occurs. This detection is more difficult to obtain through punctual sensors given the need for numerous sensors, and moreover, their positions must be determined in advance. Undeniably, the combination of different sensors provides more detailed information on the levee behavior, and the data acquired by one sensor is useful to validate data recorded by the others and vice versa.

With respect to conventional sensors that provide the temporal evolution of temperature and pressure in some single predetermined points, DFOS presents the advantages of both directly measuring temperatures along vertical wells during the field campaign and being economically convenient, if one considers the ratio between cost and amount of acquired data. Furthermore, DFOSs have no moving parts and no required maintenance and have an expected lifespan of more than 20 years. On the other side, if a safe and temperature-controlled structure for hosting the fiber optic interrogator is not available, measures with DFOS require the presence of an operator, which strongly reduces the possibility of having detailed information over time. Moreover, the interrogator has a great impact on the cost of the overall system, which requires a large investment or must be shared between several sites to reduce costs.

With regard to the positioning of DFOS, to evaluate the presence of local more permeable water paths that permit the migration of water from waterside to landside, optical fibers must be on the path of water. In other words, both cable positions and the installation technique play a crucial role. Generally, a dense distribution of the fiber cable is needed to monitor the full section of the levee body. This can be achieved by installing a zigzagging cable with appropriate spacing between parallel and horizontal lines on the landside portion or by installing the fiber inside a series of vertical holes. The installation of the cable can become a complex and invasive problem, especially when being used to test already existing embankments. However, optical fibers can be a very efficient and cost-effective solution for monitoring new earth structures, where optical fibers can easily be installed during construction.

Of course, temperature variation is an indirect proxy of seepage, and it is better to use DFOS in combination with other monitoring techniques (i.e., other temperature transducers and water pressure transducers) in order to have a more precise and detailed vision of what occurs in the soil. Finally, since it is best to carefully calibrate both traditional and DFOS temperature sensors, the thermic bath procedure adopted in this study proved simple yet effective and can be applied both in the laboratory and on-site. The potential for broadening the application of this methodology to substantial constructions like embankments holds significant appeal for the authorities devoted to land control. This is because it can be integrated as an advanced early warning system in addition to visual inspections, enabling swift protective measures to be initiated in response to potential indicators of embankment structural instability.

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Declarations

Conflicts of interest The authors declare no competing interests.

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