



# Investigating the Effects of Water Levels Measured in Two Nearby Rivers on Groundwater Pore Pressures Regime

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**Abstract.** The paper analyzes the groundwater regime in the embankment foundation of the artificial Gorzone channel located in the Po Plain near Venice, North Italy, under the conditions imposed by the hydraulic regime of the Gorzone itself and the nearby Adige river. Sand boils and blow-outs phenomena occur both at and beyond the levee toe, as the dam located some kilometers downstream is activated to keep the channel water level high for irrigation purposes in spring and summer. In order to design proper interventions, the seepage under the embankment has been investigated and the groundwater regime has been monitored for 2 years. The acquired data revealed that pore pressure regime in the deeper layers is not completely consistent with the Gorzone water level variations; it seems influenced also by the hydraulic regime of the nearby Adige river, that here flows parallel to Gorzone, at the distance of 180 m from the opposite levee.

The paper presents the results of some FEM analysis carried out to better investigate the groundwater regime under the influence of Adige and other local forcings. After a calibration based on the acquired pressure data, the model was used to analyze the levee seepage regime under different boundary conditions. The numerical results highlight that the sand-boils and blow outs are probably caused by a seepage confined in the upper high-permeability deposit induced by Gorzone water level, while the deeper pore pressures are mainly related to the Adige hydraulic conditions and to the activity of some extracting wells in the area.

**Keywords:** River embankment · seepage · groundwater pore pressure · FEM analysis

## 1 Introduction

Since many years, at Boscochiario village (Cavarzere, Venice, Italy) several sand-boils and blow-out phenomena occur at the toe of the left levee of the Gorzone channel, that here flows parallel to the Adige river at a distance of about 180 m. The context is typical of a lowland area, at about 15 km from the sea. The stratigraphy is characterized by a continuous alternation of sandy and silty-clay alluvial deposits hosting a multilayer

aquifer, with the water table laying 1 m from the ground level. The Gorzone fluvial regime is dual: in winter, under normal runoff, the free surface is affected also by the tidal fluctuations imposed by the nearby sea, resulting in a mean water level almost at the same elevation of the countryside; in spring and summer, the dam of Buoro, located at about 3 km downstream, is activated in order to keep the channel water level at a constant level that is 1 m higher than the natural one, to ensure the supply of irrigation canals. In this condition, on the left embankment countryside, numerous sand boils and water blow-outs appear at the embankment toe and within the small ditches.

To understand the causes of these phenomena and in order to support the design of proper interventions, on January 2020 a monitoring system was installed at the landside embankment toe to study the pore pressure regime. The monitoring system consists in pressure and temperature sensors inserted in the ground at the depths corresponding to the most permeable levels, previously identified by boreholes, CPTU and geoelectrical surveys. In the same section at the embankment toe, also a Distributed Fiber Optical Sensor (DFOS) cable was inserted in the ground to measure the temperature along three vertical profiles. In addition, a probe for the combined measure of water pressure and temperature was installed inside the Gorzone channel water.

The use of temperature as a tracer of seepage through the embankment is proposed some years ago by the researchers of the University of Padova and Deltareas [1, 2]. The basic principle is to assume that in plain areas under normal flow regime characterized by very low water filtration velocity, the soil temperature within the embankment body and its foundation is determined only by heat exchange with air and residential water mainly by conduction, thus registering a variation only on a daily and seasonal basis. In contrast, in case of a sudden water level rising or to a flood, the consequent abnormal seepage flows induce higher temperature variations due to the rapid arrival of water at different temperature, associated with an increased heat exchange among water and soil particles due to the increased thermal gradient and to the increased advective heat exchange. To this aim, the application of DFOS to detect and track the temperature variations in the soil can be very interesting to integrate traditional field monitoring, as they allow high spatial resolution measurements over large distances and with high sampling frequency [3]. On the base of this principle, some experimental studies were recently carried out [4, 5].

In this case study, the data provided by the monitoring system, associated with those obtained from the previously geotechnical investigations, revealed that water pore pressure regimes were not completely consistent with the Gorzone water level variations. No variations were captured in the pressures data at the artificial alteration of the fluvial regime, as well as no alteration of the natural vertical temperature profile was detected by the DFOS when the blow-outs occurred [6]. Therefore, a finite element model was developed by using the FeFLOW DHI code, to better investigate the seepage conditions and the underground temperature regime.

## 2 Monitoring System

Over the past 30 years, sensors using the optical fiber technology have experienced considerable development and diffusion in the engineering fields, thanks to the greater opportunities that this technology offers if compared to traditional sensing. A DFOS

provides high spatial and temporal resolution measurements, as it is sensitive along its entire length. By means of a proper interrogator, the fiber is stimulated with a laser signal that is refracted along its entire length depending on the characteristics of the medium in which the cable is deployed (the subsoil, the water, etc.). This way, depending on which component of the refracted wave is analyzed (Stokes / anti-Stokes, Raman, Brillouin or Rayleigh components), it is possible to measure the temperature or the deformations of the medium over the entire cable length; the data spatial and temporal resolution depend on the fiber optic cable type and on the used interrogator [3].

In the considered test site, the DFOS cable (BRUsens DTS STL cable) has been arranged in 3 verticals down to a depth of 20 m. In each vertical the cable is installed with a U-shaped configuration, with a descending and an ascending span and a 180° bend at the bottom. The connecting sections have been buried in a small trench [6]. The verticals are 3 m spaced along a line parallel to the toe of the landside embankment (orange point in Fig. 1). Special attention was paid to the installation methodology: the 20-ton static penetrometer used for the installation was equipped with a disposable drill bit, designed and manufactured on purpose, to protect the cable while drugging it deep into the underground. This methodology was developed to achieve a good thermal contact between DFOS and soil with a minimal disturbance, which is crucial in the filtration-affected soil temperature monitoring. In addition, it is a fast installation methodology [6].



**Fig. 1.** Map of the investigated area. The orange symbol indicates the position where DFOS and pressure/temperature sensors are installed; the blue one indicates the location the diver for channel water level and temperature monitoring. The red ellipse identifies the downstream dam. The black line represents the section represented in the FE model. The green symbol represents the extracting wells in Adige floodplain.

The cable is interrogated with a Sensornet's Oryx SR DTS instrument in Raman mode, which can provide a spatial resolution of 1 m and temperature measurement accuracy of 0.5 °C, up to a maximum cable length of about 2 km and with an acquisition time of about 2 s. The measurement campaign is performed on a monthly basis.

Previous geotechnical investigations indicated that the subsoil stratigraphy is characterized by a continuous succession of sandy and fine alluvial deposits, closely linked to

the transport and deposition actions of the Adige river flowing nearby. Previous geotechnical surveys reveal that, in the monitoring system location, after a first superficial layer of silty clay constituting also the levee body, a fine sandy deposit hosting a superficial phreatic aquifer lays among the depth of  $-2.0$  and  $-3.0$  m a.s.l., while a deeper sandy layer lays between  $-3.05$  and  $-3.8$  m a.s.l.; the two aquifers are separated by an impermeable level of grey clays. Thus, in addition to the DFOS cables, in the same location, 2 pressure and temperature sensors have been installed at the depth of 10 m and 18 m, corresponding to the more permeable layers, in order to monitor the pressure field and the temperatures in the embankment foundation soils. They provide data with hourly frequency and a precision of  $\pm 0.05$  kPa or  $\pm 0.1$  °C. Finally, a diver was installed for continuous acquisition of the level and water temperature in the channel (Fig. 1).

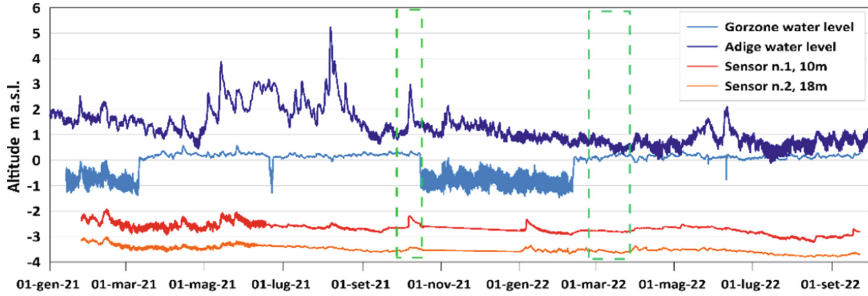
### 3 Experimental Results

Figure 2 compares the total head measured from 25/1/2021 to 30/09/2022 at the depths of 10 m and 18 m with the water levels measured both in the Gorzone channel and in the Adige river. The following observations can be pointed out:

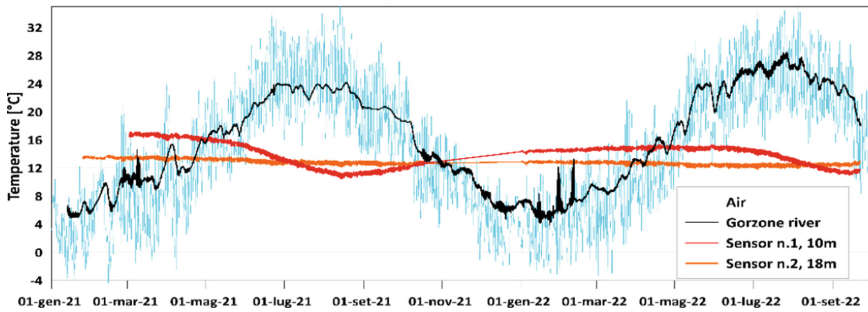
1. It is evident the seasonal behavior of Gorzone water level (black line), that is affected by tidal excursion in autumn-winter and remains quite constant in spring-summer.
2. The total heads measured both at the depths of 10 and 18 m are lower than the channel water level. This indicates that the blow-out observed in the countryside, close to the levee, are not caused by a pressure rising occurring in the deep aquifers associated to seepage in the levee foundation [6].
3. The piezometric heights measured at the depth of 18 m are always lower of 80–120 cm than that measured at 10 m. This indicates the hydraulic separation among the two aquifers, that is provided by the 4 m thick gray clay layer. In addition, it points out that the expected hydrostatic pore pressure distribution is altered, probably due to water extraction in some wells in the area.
4. The total heads variation in the sandy layers are not consistent with the Gorzone fluvial regime, given that no significant changes are recorded when the downstream dam is activated and the Gorzone water level increases of about 1 m. This observation suggests that the aquifers hosted in the sandy layers are not in close hydraulic connection with Gorzone channel.
5. The observed blow-outs are more likely ascribable to seepage in a thin superficial sandy layer confined at the embankment base, strictly caused by the water level rising and disconnected by the pore pressure regime in the deeper layers.

Even the registered temperature data shown in Fig. 3 supports these observations, given the discordance between the temperatures measured in the channel water and the ones registered by the two probes installed in the sandy layers. While the river water varies in temperature from 5 to 25 °C over the whole year, the soil temperature at the depth of 10 m shows only a light and delayed seasonal temperature variation, complying with the installation depth. Consistently, the temperature sensor at higher depth (18 m) displays a constant temperature equal to 12.5 °C. Also, the temperature vertical profiles captured by the DFOS during the monthly campaigns are mainly affected

by the penetration in the ground of the seasonal air temperature variation thus indicating a substantial temperature stability starting from the depth of 10 m. Consequently, in this case, temperature measurements are not able to capture sudden changes that can be addressed as seepage fluxes indicators.



**Fig. 2.** Water levels and total head measured by the monitoring system; the boxes indicate the periods reproduced with the FE model.



**Fig. 3.** Temperature dataset: the air temperature (light blue) is compared with the Gorzone water temperature, and with the temperatures measured at the depths of 10 and 18 m, in the sandy layers.

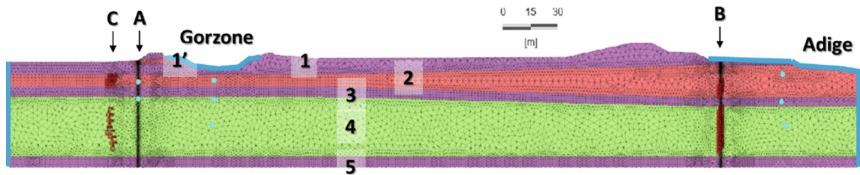
## 4 Hydro-Thermal Modelling

To verify these hypotheses, supported by the experimental data, a FE model was implemented by using the FeFLOW software to represent the Gorzone embankment in the section corresponding to the monitoring system and its extension to the nearby Adige river, in order to evaluate the relations among the recorded pressures and the Adige fluvial regime (Fig. 1). The stratigraphic sequence provided by the local geotechnical investigations (vertical A in Fig. 4) have been recognized in other available boreholes carried out in the nearby Adige floodplain (vertical B in Fig. 4) to realize a group of water extraction wells. The wells have been inserted in the model as boundary condition. Figure 4 depicts the model section, reporting the location of the significant elements (boreholes, wells, boundary condition, etc.).

Permeability, porosity and thermal properties of each layer were initially estimated from field investigations or assumed from tabled values. In a second time, they have been optimized (Table 1) through the model calibration performed by using the monitoring dataset registered from 23/2/2022 to 24/3/2022 (Fig. 2). In this phase, it was observed that the only way to match the pressure data recorded in vertical A is to assume the presence of some additional (undeclared) extraction wells located next to the monitoring system (supposed in vertical C), probably serving a nearby garden center. In fact, only an additional water extraction of almost 0.8l/s can justify the measured groundwater pressure regimes under the observed forcing water levels.

**Table 1.** Main characteristics of the layers represented in the model stratigraphic sequence.

Layer	Soil classification	k [m/s]	n
1	Silty clay	$10^{-9}$	0.2
1'	Fine sand	$10^{-5}$	0.3
2	Fine sand	$10^{-5}$	0.3
3	Gray clay	$10^{-9}$	0.2
4	Medium sand	$5 * 10^{-5}$	0.3
5	Silty clay	$10^{-9}$	0.2

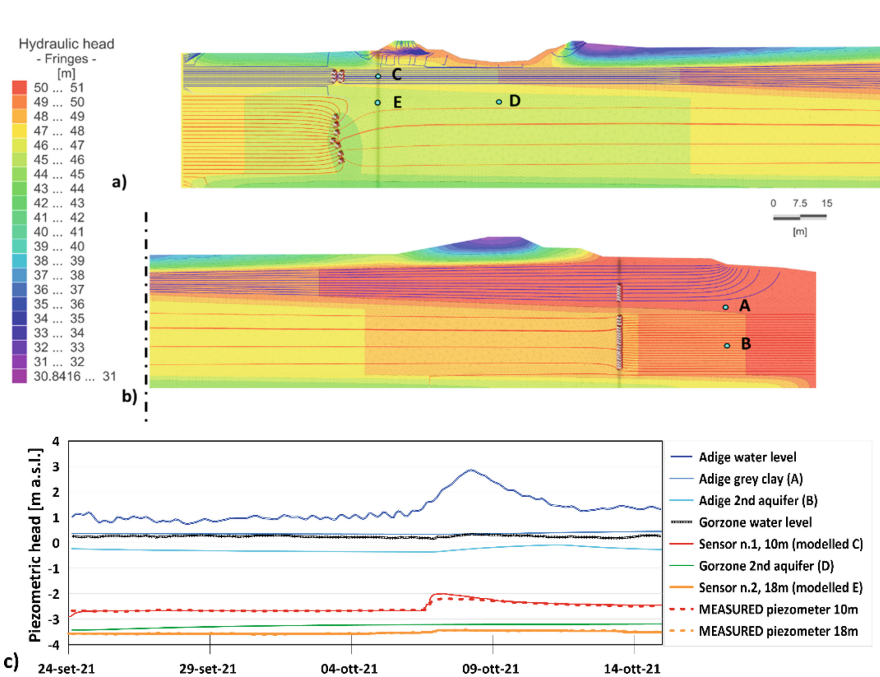


**Fig. 4.** FeFLOW model. There are indicated the layers (characteristics listed in Table 1), the applied hydraulic boundary conditions (blue lines), the verticals where stratigraphic data are available (A, B), the control points (light-blue points) and the identified extracting wells (B, C).

The calibrated model was used to reproduce the seepage regime in the period 24/9/2021–15/10/2021 and verify the hydraulic interconnection among the pressure distribution in the sandy aquifers, the Adige river and the extracting wells. In that period, the Gorzone water level was kept high by the dam, while the Adige water level registered an increase of about 2 m due to a small flood. In the meanwhile, the piezometric head at the depth of 10 m registered a sudden and steep increase, while the one at 18 m displays only a very slight variation. In the model, the imposed hydraulic boundary conditions are represented by the measured water levels and, in the far field, the water table was congruent with the water level in the ditches (1 m deep from the ground).

Figure 5 shows the obtained modelling outputs in terms of flow lines and piezometric head distribution (referred to the model local zero, equal to 50 m above sea level). Also in this situation, the only way to match the model outputs with the pressure regime recorded

by the sensors during the flood event is to assume that the extraction wells suddenly interrupted their activity, restarting the day after. In fact, the water level increase due to the flood registered in the Adige river is not sufficient to justify the steep and sudden groundwater pressure alteration, that, moreover, slight anticipated the flood arrival. The interruption of the pumping activities may be justified by the non-necessity of irrigation water for the garden center, thanks to the occurrence of the rain.



**Fig. 5.** Model outputs at the end of the period 24/9/2021–15/10/2021, a) in the Gorzone embankment section and b) in the Adige river section. Blue and red lines represent the flow lines in the upper and deeper sandy layers respectively. In c) the piezometric heads measured by the sensors are directly compared with the model outputs.

## 5 Conclusions

The combination of pressure and temperature datasets acquired by the monitoring system, data from on-site geotechnical investigation and FEM simulations outputs permit to have a better comprehension of the hydraulic phenomena occurring in this singular area and to draw the following conclusions.

1. It can be assumed that there is no direct connection among the observed blow-outs at the toe of the Gorzone embankment and the seepage in the deeper aquifers. It is more likely that the blow-outs occur as a consequence of a more superficial connection

between the channel and the countryside, probably due to the presence of a thin sandy layer at the levee base. As a consequence, possible interventions can be limited to the construction of a diaphragm wall crossing the levee body.

2. The observed alteration of the natural hydrostatic pressure trend expected in low plain areas, as the case study location, can be ascribable to the operations of several extracting wells: in addition to the declared extracting wells located in the Adige floodplain, it is very likely the presence of other extracting wells in the vicinity of the monitoring section, probably for irrigation purposes.
3. Temperature data and vertical profiles provided by punctual sensors and DFOS are in accordance with a natural seasonal penetration of air temperature in the subsurface. Nevertheless, in this case study, the temperature measurements did not provide useful information to localize seepage fluxes, probably because here the seepage fluxes are limited to the localized superficial sandy layer and so constrained that the DFOS spatial resolution (1 m) could be not sufficient to detect them.

Further studies are planned to analyze the effectiveness of DFOS temperature measurements to detect underground seepage and seepage in levee. Experimentally, the DFOS will be tested by applying a new measurement technique that uses hybrid fiber-optic cables and involves heating the cable at the beginning of the measurement campaign, as it is usually done to evaluate thermal properties of soil layers [7] by recording the temperature deployment over time along the cable, thus localizing seepage flows identified by more rapid temperature decreases. In addition, further modelling activities will be developed to analyze how geometric and hydraulic conditions as well as soils permeability and thermal properties may affect the effectiveness of DFOS in detecting subsurface seepage through temperature measurements.

## References

1. Bersan, S., Koelewijn, A.R., Simonini, P.: Effectiveness of distributed temperature measurements for early detection of piping in river embankments. *Hydrol. Earth Syst. Sci.* **22**, 1491–1508 (2018). <https://doi.org/10.5194/hess-22-1491-2018>
2. Bossi, G., et al.: Multidisciplinary analysis and modelling of a river embankment affected by piping. In: Bonelli, S., Jommi, C., Sterpi, D. (eds.) *Internal Erosion in Earthdams, Dikes and Levees: Proceedings of EWG-IE 26th Annual Meeting 2018*, pp. 234–244. Springer, Cham (2019). [https://doi.org/10.1007/978-3-319-99423-9\\_22](https://doi.org/10.1007/978-3-319-99423-9_22)
3. Schenato, L.: A review of distributed fibre optic sensors for geo-hydrological applications. *Appl. Sci.* **7**, 1–42 (2017)
4. Cola, S., Girardi, V., Bersan, S., Simonini, P., Schenato, L., De Polo, F.: An optical fiber-based monitoring system to study the seepage flow below the landside toe of a river levee. *J. Civ. Struct. Heal. Monit.* **11**(3), 691–705 (2021). <https://doi.org/10.1007/s13349-021-00475-y>
5. Fabbian, N., et al.: Innovative and traditional monitoring system for characterizing the seepage inside river embankments along the Adige River in Salerno (Italy). ISFMG, London (2022)
6. Dalla Santa, G., Fabbian, N., Schenato, L., Tedesco, G., Cola, S.: Misure di temperatura con fibra ottica e sensori tradizionali per modellare il regime di filtrazione arginale: il caso studio del fiume Gorzone. *Incontro Annuale dei Ricercatori di Geotecnica (IARG)* (2021)
7. Dalla Santa, G., Pasquier, P., Schenato, L., Galgaro, A.: Repeated ETRTs in a complex stratified geological setting: high-resolution thermal conductivity identification by multiple linear regression. *J. Geotech. Geoenviron. Eng.* **148**(4), 04022007 (2022)