



# Multidisciplinary Analysis and Modelling of a River Embankment Affected by Piping

Giulia Bossi<sup>1</sup>, Silvia Bersan<sup>2</sup>, Simonetta Cola<sup>2(✉)</sup>, Luca Schenato<sup>1</sup>,  
Fabio De Polo<sup>3</sup>, Celeste Menegazzo<sup>2</sup>, Jacopo Boaga<sup>4</sup>,  
Giorgio Cassiani<sup>4</sup>, Fabiano Donini<sup>4</sup>, and Paolo Simonini<sup>2</sup>

<sup>1</sup> National Research Council,

Research Institute for Geo-Hydrological Protection, Rome, Italy

<sup>2</sup> Department of Civil, Environmental and Architectural Engineering,

University of Padova, Padua, Italy

simonetta.col@unipd.it

<sup>3</sup> Dam Office, Autonomous Province of Bolzano, Bolzano, Italy

<sup>4</sup> Department of Géosciences, University of Padova, Padua, Italy

**Abstract.** The paper presents a multidisciplinary analysis carried out for the characterization and monitoring of a levee in Bozen Province, North Italy. The study treats a small section of the Adige river embankments, interested in the recent past by moderate piping phenomena and subjected to some subsequent interventions for the risk mitigation. The data acquired with an Electrical Resistivity Tomography (ERT) investigation and an optical fiber distributed temperature sensing (DTS) are compared to boreholes information, laboratory tests and piezometers measurements. They provided a multi-dimensional characterization of the levee and of the close subsoil water-meadows, possible piping preferential paths. Since the presence of more permeable lenses within the silty matrix characterizing the levee foundations, the subsequent 2D seepage analysis was carried out with the Boolean Stochastic Generation (BoSG) method, which randomly generates lenses with specific rheological properties within a matrix with another set of parameters. The soil configurations that are more congruent with the monitoring data were selected within a pool of 360 simulations, providing information about the probable seepage mechanism within the levee and the reliability of the interventions.

**Keywords:** Embankment · Piping · Fiber optic sensor  
Electrical resistivity tomography · Stochastic modelling

## 1 The Test Site

The study concerns a levee on the Adige River in Bozen Province (Fig. 1), North Italy (46°14'11.0"N 11°10'52.8"E). In the long history of the Adige valley, several anthropic interventions were performed in the area. Particularly, in the 19th century straight embankments were realized to confine the river that was before free to migrate along the narrow alluvial plan. Therefore, a complex sedimentological environment with point-bar structures and paleo-channels characterizes the subsoil system. In the recent past, moderate piping phenomena and flooding affected a 350 m long segment of the

right levee (Fig. 1). To reinforce the protection system and avoid internal erosion the embankment was recently reinforced with a 10 m deep jet-grouting diaphragm. Nevertheless, moderate piping phenomena still persist in the area when the water level in the river is high.

In order to identify the areas more prone to internal erosion a multidisciplinary survey was carried out. It consisted of boreholes and penetrometer tests, laboratory tests and a monitoring performed with electrical piezometers installed in boreholes. The in-site investigation was completed with several Electrical Resistivity Tomographies (ERT) executed along the river and in the neighbour area and the monitoring system was integrated with a fiber optic based system installed in a shallow trench at the bank base on the landside. All the collected data were used as input for the realization of an innovative stochastic seepage model. Of course, for a lack of space, only some results of the in-situ investigation and preliminary output of the stochastic model are reported in this work.

## 2 The Monitoring Network

Since many years, the measurement of temperature inside levees is extensively investigated as a tool for identifying abnormal filtration flows across the dam. The basic principle at the basis of the detection by temperature sensing consists in assuming that when normal flow regime exists, temperature fluctuations are driven by heat conduction from the air and 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 way too significant. On these premises, only a measuring campaign performed over a long time and with sufficient spatial resolution can detect any relevant change.

In the Salorno test site, we installed both optical fiber cable and traditional sensors in order to assess the potentiality of distributed sensing with fiber optics for detecting local heterogeneity in seepage rate.

### 2.1 Traditional Sensor Network

As Fig. 1 depicts, two cross sections of the levee were equipped with piezometers and spot temperature sensors. One Casagrande piezometer was placed on the riverside to indirectly record the river water level. Other two piezometers were deployed on both sides of the barrier as to assess its efficacy and evaluate its influence on the seepage pattern. Lastly, a two-level piezometer is located below the landside berm.

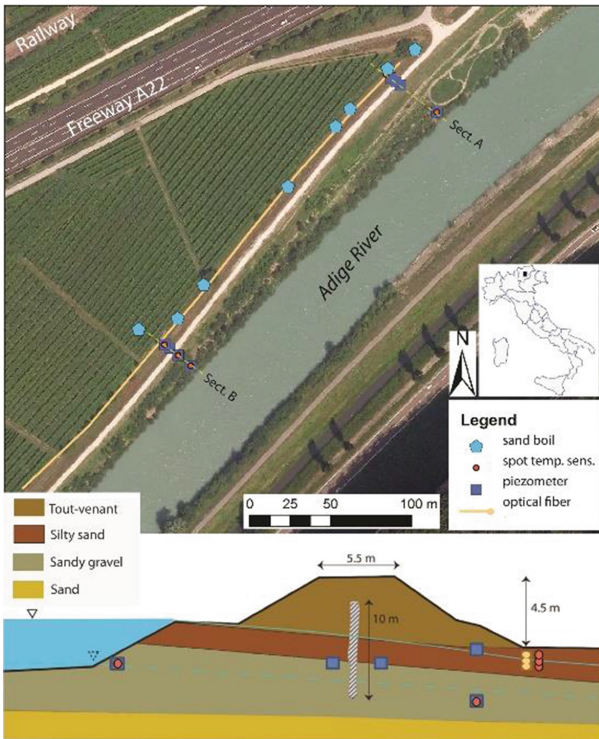
A spot temperature sensor was deployed along Adige bank, to control the temperature of the river water. Another one is located on the deeper level of the piezometer below the berm and three were placed near the trench that would accommodate the optical fiber.

All traditional sensors work in real-time, acquiring every hour and sending data to a remote server. Data acquisition started in June 2016. As the monitoring system is finalized to identify the presence of anomalous seepage paths and not as an early-warning system, the acquisition time step of 1 h was considered enough short to find a relation among observations in the subsoil and the water level in the river.

### 2.2 Distributed Temperature Sensing by Optical Fiber Sensors

Distributed fiber optic sensing (DFOS) is the only available contact sensor technology, capable of providing the measurement of temperature with sufficient spatial resolution in soil over a long length (Schenato 2017). Remarkably, the first applications of DFOS to embankment temperature monitoring are dated to the middle of the 1990s (Albalat and Garnero 1995). In particular, the DFOS exploiting Raman-based distributed temperature sensing (DTS) technique is the mostly used optical fiber sensor in this kind of application and also employed in this specific study.

According to DTS, when a fiber is probed with an input light signal, due to the molecular bonds' inhomogeneity of the fiber material two signals are generated and back propagated along the fiber. Namely, they are the Stokes signal at a higher wavelength and the anti-Stokes one at a lower wavelength. Only the intensity of the anti-Stokes signal is temperature-dependent, while the Stokes one is temperature insensitive. Therefore, the ratio between the anti-Stokes and the Stokes light intensity generated all along the fiber is quantitatively related to the local temperature. By probing the fiber with pulsed light and by measuring the roundtrip propagation time, it is straightforward to determine the position at which those back propagating signals have been generated.



**Fig. 1.** Study area (*above*) and section of the levee (*below*) with the deployed sensor network.

Depending on the specific implementation, spatial resolution in the order of one meter or less can be achieved over a length of several kilometres. Temperature resolution may easily reach few tenths of a Celsius degree or even less, with a measurement time of few minutes. In our application, we used the interrogator Oryx SR DTS by Sensornet, characterized by 1 m spatial resolution and 0.1 °C temperature resolution of over 2 km, with 30 s of measurement time. The temperature accuracy is limited to 0.5 °C.

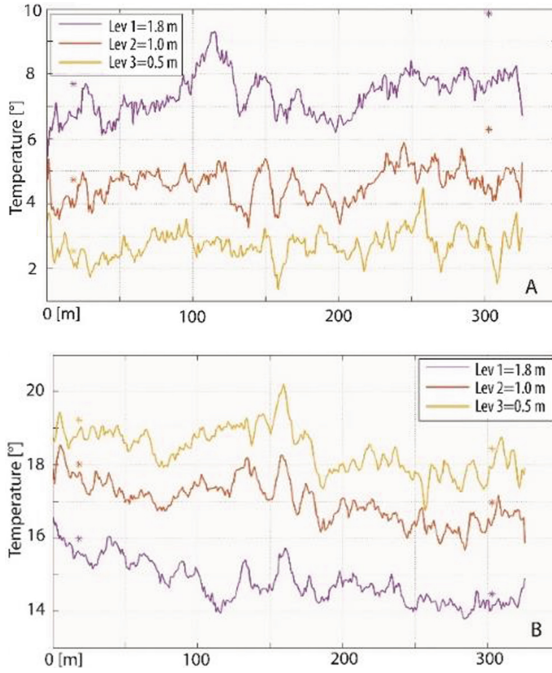
Despite the features of DTS, one of the main challenges of the thermometric approach is the identification of distinctive “signatures” of seepage (regarding time rate, amplitude, spatial gradient, etc.) from the raw temperature field data. Several factors other than those related to existing filtration flows can affect the temperature dynamics in the embankment. To address this issue, an alternative method, the so-called “heat-up” or “active” thermometric method, has been proposed. This method consists of using a hybrid cable embedding an optical fiber and one or more electrical wires, used to heat the cable via the Joule effect. The temperature dynamics during the heating and cooling phases, i.e. the time to reach a final stable temperature, are correlated to different thermal conductivity ascribable to abnormal filtration flows. This approach has been proved efficacious in those embankments with small seasonal temperature variations of the reservoir water or with very small temperature gradients between the water and the measurement point in the soil, and it has also been applied to the embankment here addressed.

Here an optical fiber cable was installed in a 350 m-long trench longitudinally excavated at the toe of the embankment. The fiber has been deployed at three levels, at depths of approximately 50, 100 and 180 cm, and it has an overall length of 1100 m. In this application, a hybrid cable, embedding an optical fiber and four copper wires, has been used to possibly enable also the active thermometric measurement of the dam.

Of course, the excavation of the trench could interfere with the undisturbed groundwater seepage paths, but we adopted every possible action to minimize the negative effects: the trench was kept as narrow as possible, also with respect to the horizontal size of the embankment; the fiber was deployed near the trench wall and the filling soil was adequately compacted to prevent vertical flows inside the trench.

Plots of Fig. 2 show two examples of the temperature field along the fiber at the three depths, taken in summer and winter respectively. Seasonal fluctuation differently affects the temperature at the three layers. In particular, the mean temperature decreases from the lower level to the upper one during winter, while it behaves oppositely in summer, when the temperature decreases with depth.

Moreover, one can observe that the temperature at the three levels in each plot shows a common trend, with localized spikes and dips at precise locations. We believe that these features are ascribable to the local characteristics of the soil (e.g. lenses with different permeability). Unfortunately, high water discharge events did not occur during the monitored period and we had not the possibility to record the soil temperature during an intense seepage phenomenon. Further investigation are currently on going, as it will be see in the section about the stochastic modelling.



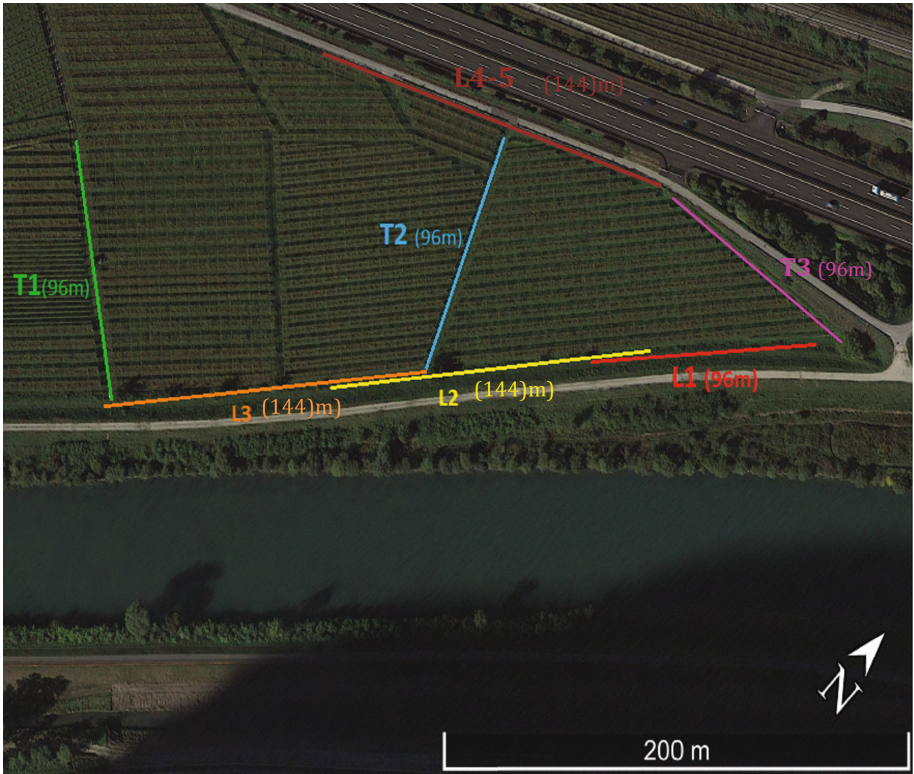
**Fig. 2.** Temperature along the three levels of the fiber cable in winter (A-above) and in summer (B-below).

### 3 Electrical Resistivity Tomography

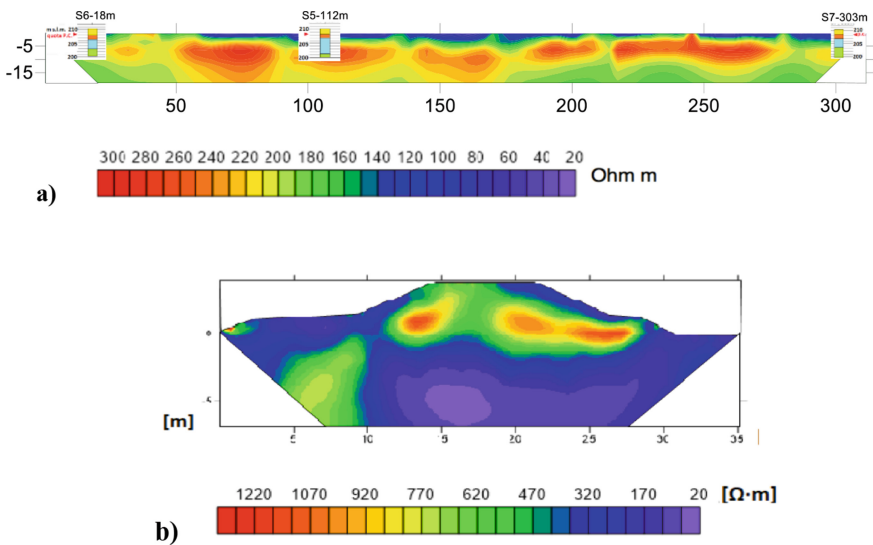
Electrical resistivity tomography (ERT) can provide meaningful, high-resolution images of the subsoil electrical conductivity (Binley and Kemna 2005). In the context of embankment investigation this results in very detailed information concerning the levee structure (e.g. Niederleithinger et al. 2012; Perri et al. 2014; Weller et al. 2006, Busato et al. 2016), particularly when the fine-grained sediments (clay and silt), which are generally more electrically conductive than coarse materials, constitute the core of a well-built embankment. ERT is also very flexible in terms of scaling and resolution, so it is particularly suitable for this type of investigation.

At this site, several ERT surveys were applied in different configurations, in order to vary depth of investigation, resolution, and explore longitudinal and transverse sections of the embankment and the closer areas. The ERT surveys consisted of N.48 or N.72 channels, with variable electrode spacing from 0.75 m to 2 m. The ERT lines are divided in L (longitudinal) and T (transversal), as reported in Fig. 3.

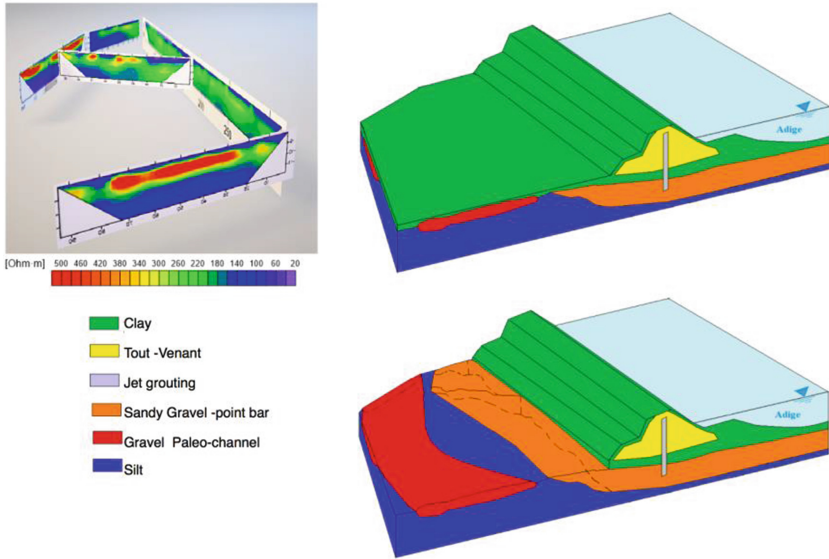
We adopted the acquisition scheme dipole-dipole skip-4, which provides the best lateral resolution for our aims. Figure 4 shows as example the longitudinal ERT (L1-L3) along the levee compared to the simplified stratigraphy of boreholes S6, S5 and S7 and a transversal ERT across the levee. As it can be seen, ERT results are in very good accordance with the borehole information highlighting the presence of coarse and fine materials.



**Fig. 3.** Map of the ERT lines acquired in the Adige embankment.



**Fig. 4.** Longitudinal ERT along the levee compared to boreholes information (yellow and orange: clay and silty clay; light blue gravel) (a). Transversal ERT across the levee highlights the more resistive coarser core of the embankment (b).



**Fig. 5.** The ERT results collected in the Adige areas and the 3D geological model of the paleo-channels as derived by the ERT information and the historical geomorphological map.

Figure 5 summarizes the ERT results coupling longitudinal and transversal lines in a homogenized scale. More resistive levels are clearly visible, representing the coarser sandy ad gravel levels. These resistive bodies were interpreted as the paleo-channel deposits that interest all the right side of the river, as already pointed out in some geomorphology studies (internal reports of Bolzano Province; ETSCH 2000 Proc.; Zen et al. 2016). The right panel presents a paleo-channel geological 3D model reconstructed on the base of ERT results, borehole information and the historical geomorphological maps. The ERT results, coupled with the geotechnical information, provided the input for the 2D seepage models.

#### 4 The Stochastic Model

To investigate the seepage in the levee foundation, in light of the ERT analysis coupled with monitoring data and stratigraphic evidence, the effects of the presence of lenses with different permeability, originated from the fluvial depositional process, was analysed using the method called Boolean Stochastic Generation (BoSG) method (Bossi et al. 2016).

BoSG method randomly generates lenses with specific rheological properties within a matrix with another set of parameters. The procedure integrates scripts in Matlab® and numerical simulations with the geotechnical software FLAC (Fast Lagrangian Analysis of Continua) to generate a large number of possible dispositions of lenses. The pool of the resulting configurations is then analyzed in order to evaluate the effect of different configurations of lenses and select the configuration giving the most reliable response in comparison with the monitored data.

For the Salerno case study, 120 soil configurations in a bi-dimensional model of section A were generated: particularly, 30 configurations with 3, 6, 9 and 12 lenses respectively, were analysed. To each soil configuration, three different values of permeability, namely lens A, B and C, were associated to the lenses, bringing the grand-total of the simulations to 360. The horizontal extension of the lenses and their position are randomly assigned, while the thickness is assumed constant and equal to 20 cm. The disposition of lenses was kept horizontal to mimic the fluvial depositional process that formed them.

An example of a soil configuration with 9 lenses is shown in Fig. 6. The soil parameters for the model are indicated in Table 1. They were obtained on the base of results of laboratory tests executed on undisturbed samples during the boreholes and trench excavation.

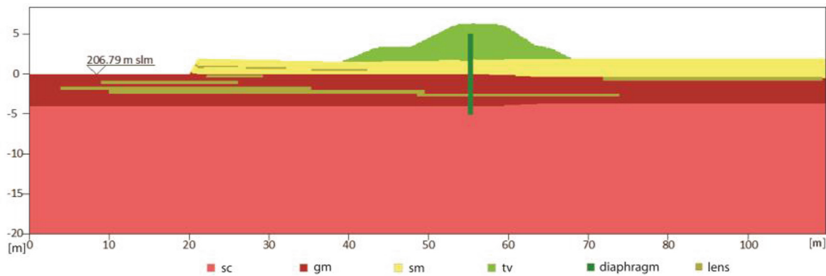


Fig. 6. Example of a modelled section with 9 randomly generated lenses (configuration #9-19).

Table 1. Soil parameters assumed for the soils and the generated lenses.

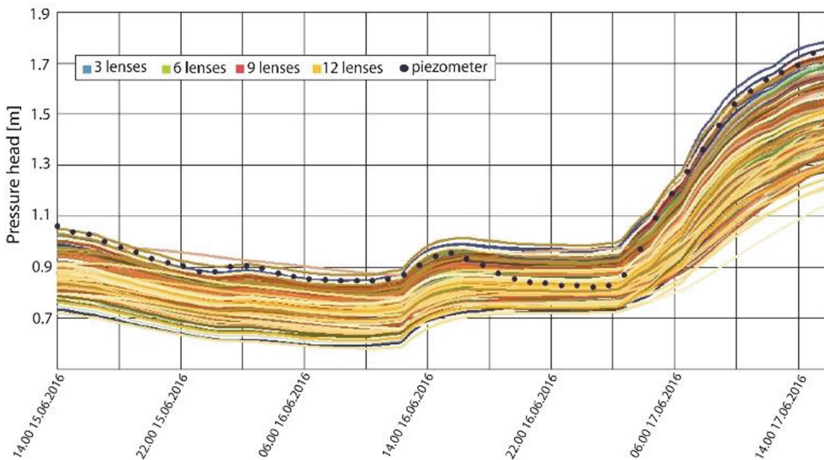
Material	$\rho$ [kg/m <sup>3</sup> ]	$\Phi$ [°]	$c$ [kPa]	$M$ [MPa]	$\nu$	$k$ [m/s]
tv*	1936	34	0	69.7	0.30	9.70E-07
sm	1985	27	50	34.8	0.35	9.77E-06
gm	1936	33	0	83.6	0.40	2.10E-05
sc	1936	35	0	55.7	0.40	6.29E-06
lens A	1936	33	0	83.6	0.40	6.29E-05
lens B						1.25E-04
lens C						2.10E-04

(\*) tv = tout-ventant, well graded soil, sm = silty sand, gm = silty gravel, sc = clayey sand.



The stochastic model was tested on data from a modest flood event recorded in the 16th and 17th June 2016. The transient effect induced on pore pressure on the 360 soil configurations were confronted with data from the piezometers, checking within the pool of results those that were more congruent with the monitoring data. For instance, in Fig. 7 all the pressure head vs time curves, obtained with the numerical model for the set “lensA”, are reported and compared with the data recorded at the piezometer PA03. In Fig. 8 the best and the worst fitting curves selected among the simulation obtained for set “lens C” are compared with data recorded at PA03.

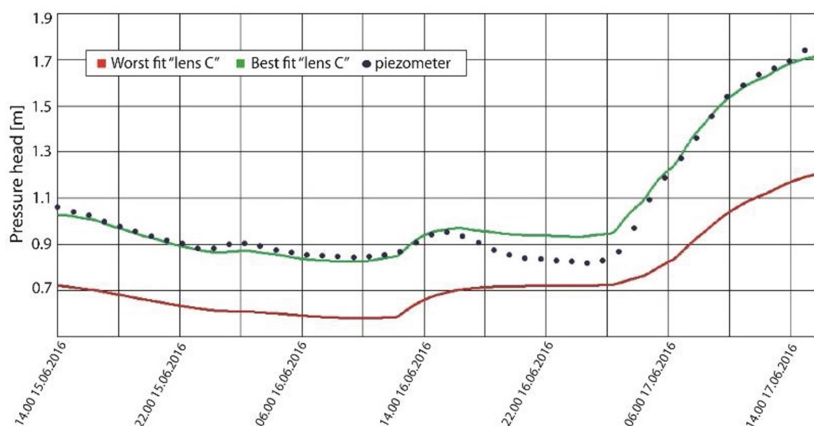
The stochastic generated configurations in average better represent the seepage mechanism within the levee than the configuration without lenses. This means that there is indeed an influence of layers with higher permeability in the dynamic of the section. In particular, our first results show a greater influence of permeable layers located on the riverside.



**Fig. 7.** Pressure head curves predicted at piezometer PA03 located near the diaphragm on the landside by all the configurations with permeability values “lens A” and compared with in-situ measures.

## 5 Final Remarks

The paper presents the preliminary results of a comprehensive multidisciplinary study carried out on 350 m-long portion of the right levee of the Adige River in Salorno. Different and advanced techniques (i.e. ERT and Raman-based DTS) were coupled to traditional techniques to investigate the embankment foundation and the neighbor farmland. Particularly, a very detailed ERT survey permitted to point out the subsoil structures and evidence the presence of paleo-channel sediments intercepting the levee



**Fig. 8.** Best and worst predictions for the pressure head vs time curve, among all the configurations “lens C”, compared with the trend recorded at piezometer PA03.

constructed in the last 50 years, while the DFOS gave detailed information on the soil stratigraphy below the landside berm. The in-situ and laboratory data permitted the reconstruction of a seepage model on which a BoSG procedure is applied to study the influence of soil heterogeneity on the subsoil seepage and the efficiency of flooding protection.

Unfortunately, even if the monitoring system was installed in March 2016, up to now no significant flooding has occurred and DFOS could not be applied during a high seepage rate occurrence. For the same reason the stochastic seepage model was calibrated on data from a modest flood event recorded in June 2016 and the results obtained up to now cannot be considered sufficient to give final conclusion of the work. Moreover, a 3D seepage model will be constructed in the next future and different heterogeneities, i.e. heterogeneity of the waterproof barrier, will be analyzed to complete the study.

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