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Assessing the performance of a versatile and affordable geotechnical monitoring system for river embankments

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Abstract

River embankments stability is a key aspect in geohazard assessment and underestimating its failure risk may result in unexpected and severe damages. Changes in hydraulic and climatic boundary conditions are responsible for transient water flow within the embankments, consequently the related soil water content and pore-water pressure distributions vary with time. Therefore, it is crucial to investigate their hydraulic and retention behaviour in order to assess in a reliable way the safety margins towards instability mechanisms. To obtain a realistic estimate of key variables in time and space, as a function of external conditions, a combination of field measurements, laboratory testing and suitably calibrated numerical analyses should be used. To achieve this purpose, a full-scale monitoring system was implemented on a cross section of an embankment along the river Secchia (Modena, Italy), mainly measuring the pore-water pressure (including suction) and the water content at different depths. A relatively large variety of different sensors have been installed, to compare their performance in terms of robustness and reliability, and collected data have been interpreted with the help of laboratory and field geotechnical characterisation. The article describes such system and the sensors used, their capabilities and the installation techniques, resulting in quite innovative solutions for the specific application. The spatial variability of the monitored variables is also finally presented and discussed. The proposed integrated monitoring system, which aims at making use of cost-effective and commercially available sensors that can be therefore installed along extensive river stretches, appears a fundamental starting point to assess potential risks of such geotechnical infrastructures in real-time and to devise well-balanced related mitigation measures.

Keywords

River embankments, field monitoring, partial saturation, suction, transient seepage

1 Introduction

Risk assessment of river embankments is now receiving great attention worldwide, as a consequence of the severe damages caused by flooding. The key input parameter of slope stability analyses is clearly the soil strength, which may vary with relevant suction and degree of saturation or water content. In the case of river embankments, the value of such state variables changes with transient seepage processes, as induced by weather conditions and hydrometric fluctuations of the river level. In addition, water flow is a function of the soil hydraulic and retention properties, which in turn depend on the same unsaturated soil variables, resulting in an overall quite complex system. For this reason, an accurate determination of the soil hydraulic and retention behaviour and a good estimate of the spatial distribution and temporal fluctuations of the saturation degree and of suction in response to natural climate processes become crucial for a reliable risk assessment of river embankments slope stability.

Several studies have addressed the problem of slope stability in response to climate driven water infiltration (e.g. Toll et al., 2011; Toll et al., 2012; Springman et al., 2013; Bordoni et al., 2015; Pirone et al., 2015; Tang et al., 2018). However, in the case of river embankments, the additional fundamental aspect of water infiltration from the river must be considered. To the authors' knowledge, only few studies have so far considered the use of extensive monitoring data of unsaturated state variables for a comprehensive assessment of river embankments in response to variable hydraulic and atmospheric conditions (Rinaldi et al. 2004, Mayor et al. 2008; Simeoni et al., 2008; Calabresi et al., 2013; Tarantino and El Mountassir, 2013; Pozzato et al., 2014).

This study focuses on a typical earthen water retaining structure in Emilia Romagna (Italy), which - as most similar river embankments - originated from natural levees and was then progressively enlarged starting from the 19th century, becoming a continuous system of linear infrastructures. Limited knowledge is therefore available regarding construction methods and relevant technical guidelines that were followed at the time. However, it is commonly acknowledged that their stability largely relies on the unsaturated soil conditions, which are established in response to typical hydrometric levels, particularly low in dry seasons and characterised by rapid outflows during high water levels. Such regime has so far guaranteed a limited amount of water infiltration, securing the overall embankments stability. However, any future variation of such climatic trend, resulting in more persistent hydrometric levels, can lead to progressive saturation and, eventually, possible failure of the embankments. It is therefore evident that a rational risk analysis should be based on the adequate knowledge of the response of such infrastructures, with special attention to their water retention characteristics. This is especially true if any improvement of their performance can be hardly completed for technical, social or economic reasons.

Within such context, this article describes the design and the implementation of a full-scale prototype monitoring system at a section of the river Secchia (Modena, Italy) embankment. The system was installed with the aim of measuring time and space distributions of the pore-water pressure (including suction) and the water content under transient seepage conditions. The study addresses several issues of designing a system as such, particularly the choice of sensor types among those commercially distributed, their installation techniques and spatial arrangement, taking into account their cost-effectiveness and accuracy. The monitoring data collected up to date were then used to assess the overall system response and to detect the spatial distribution of pore-water pressures at relevant time-steps, which could only be built from suitable field readings. The study provides the starting point for the development of a methodology able to effectively support the field monitoring of riverbanks for the assessment of stability conditions. More in general, it tackles various issues related to the use of sensors typically developed for agricultural applications for the monitoring of geotechnical structures, such as their reliability, implementation, numerical modelling and practical applications.

2 Characterisation of the experimental site

The experimental site is located along the river Secchia (Fig. 1). Together with the adjacent the river Panaro, Secchia is one of the largest right-hand side tributaries of the river Po in the area around Modena (Italy). Its basin covers 2090 km^2, which corresponds to 3% of the entire Po basin, and flows along 172 km from mountainous to plains environments. The hydrological systems are characterised by significant sediment transport and evolving morphology. The catchment is largely linked to the drainage of the Apennines mountain sector, resulting in a rapid response to precipitation. For the period 2021-2050 a variation in the annual cumulative precipitation is expected for the autumn season (+19%), with reductions in winter and spring (-2% and -11%, respectively) (Arpae Emilia Romagna, 2017), with a general amplification of the seasonal cycle according to Pavan et al. (2008). Similarly to the river Enza and the river Panaro, both Emilian tributaries of the river Po, which experienced failures between 2014 and 2017, the river Secchia is continuously confined by embankments in the plain sector, where in January 2014 a catastrophic breach suddenly occurred after a period of intense rainfall in San Matteo, seven kilometres north of the town of Modena. The embankments of these rivers are typically characterized by a considerable height, frequently exceeding 7 m, with a 4 to 6 m wide crest, often open to pedestrian and light traffic. Both river and landward sides are typically sloping at angles above 30° and for the greatest part possible river berms are less than 10 m wide. The area selected for the installation of the monitoring system is about 12 km downstream from the breach experienced in January 2014. The selected representative section is illustrated in Fig. 1, where the position of the closest hydrometer is also indicated. It was chosen to guarantee uniform water infiltration and frequent contact with the hydrometric river fluctuations.

A few piezocone penetrometer tests (CPTU) were carried out in order to characterise the selected area: in particular, one test from the embankment crest to 25 m depth and one from the berm to 15 m depth. Test data are shown in Fig. 2a, in terms of corrected total cone resistance (q_t) and pore-water pressure response u_2. Since the response to penetration can be influenced by unsaturated conditions (e.g. Yang and Russel, 2016) in the upper part and penetrometer tests were carried out in July, normalized Q_t with respect to the current effective stress level was computed considering a linear profile of negative pore-water pressures above the water table (about 9 m from the embankment crest) as obtained from suction measurements in the same dry season (see data in Figure 10, later on). Such value of Q_t was then used for the interpretation of CPTU results in terms of soil behaviour type (SBT_n), according to Robertson (2009), as shown in Fig. 2b, along with the laboratory particle size distribution (PSD) obtained from corresponding soil samples. According to these data, the embankment section was divided in the following soil units (Fig. 3): unit A, sandy silt mix; unit A’, silt mix; unit B, clayey silt mix; unit C, silty sand mix and unit D, clay.

Following a specific topographical survey, the embankment crest is approximately 11 m above the ground level and the landward slope is inclined of 25°. The crest is 4.6 m wide and hosts a light traffic road. Its centre is distant around 38 m from the river centreline. The inner slope is inclined of 30° and ends on a 5.5 m wide horizontal river berm, positioned 5.2 m below the embankment crest. The inner bank at the berm and below is rich in vegetation, especially reeds, with occasional trees that can reach a height of few meters. The elevation of the river bed, 19.4 m above the mean sea level, has been selected hereafter as datum.

3 Details of the monitoring system

3.1 Sensor types

The sensors were selected among those commercially available, taking in due consideration practical and economical aspects. In general, functionality and cost-effectiveness play a crucial role in the choice of the most suitable instruments for the geotechnical monitoring of extended areas, as several installations have to be carried out rather easily and the instruments are not necessarily retrieved.

Most of the selected sensors were first developed for agricultural purposes, where they are now routinely employed in large scale applications, while their use for unsaturated soil mechanics in geotechnical practice and research is relatively new, even if constantly increasing (Nguyen et al., 2010; Harris et al., 2013; Cascini et al., 2014). Four different types of sensors were chosen in the studied case, also for the sake of comparison. They are shown in Fig. 4, while essential details regarding their capabilities are provided in Table 1. The soil water content was measured using GS3 and SM150T sensors, the former being more suitable, as it better combines versatility and cost-effectiveness. In fact, GS3 sensors can be installed at considerable depth with purposely developed tools (Rocchi et al., 2018a), as necessary for this application, and their cost is approximately half or less than SM150T. For this reason, only few SM150T sensors were used and the study is especially focused on the installation and measurements of GS3 sensors. For direct and indirect measurement of suction, T8 tensiometers and capacitive MPS-6 sensors were employed, respectively. Due to the different working principles, measuring ranges and manufactures of these two type of suction sensors, their use is here intended to be complementary rather than alternative. Essential details of these sensors are briefly provided in the following.

The GS3 water content probe has a default accuracy of ±3% (Decagon Devices, 2016a). The instrument is provided with a calibration of the sensor output (i.e. dielectric permittivity) with the water content. In order to improve the accuracy, the manufacturer encourages to perform soil-specific calibrations and so it was done in the present study. SM150T is similar to GS3, although with a slightly different geometry (Fig. 4) and it works at 100 MHz frequency (Delta-T Device, 2016). For this sensor the default calibration was simply adopted.

The T8 tensiometer measures between -85 and +100 kPa pore-water pressure with ±0.5 kPa accuracy (UMS, 2011), allowing for both positive and negative (i.e. suction) pore-water pressures to be measured. A piezoelectric pressure sensor is housed behind a ceramic cup and therefore hydraulic equilibrium with the surrounding soil is necessary. The measurement is relative to the atmospheric pressure taken at the ground level through a membrane. In case of desaturation the ceramic cup can be refilled from the ground surface through a thin metallic tube housed in a 3.5 cm-diameter plastic tube that also contains the sensor cable. The sensor does not require a custom calibration, being supplied by the manufacturer. When the sensor is placed close to the surface and well above the water table, cavitation often arises. This can be assessed by sudden changes in water potential measurements, which are easily detectable in the remote monitoring. If the tensiometers are installed deeper, the re-saturation procedure is less frequently required.

The MPS-6 sensor measures pore-water pressure over a range -9 to -10,000 kPa with an accuracy of ±(2 kPa + 10% of the reading) in the range -9 to -100 kPa (Decagon Devices, 2016b). The actual measurement is the dielectric permittivity of a porous ceramic disc, used to obtain its water content, which is in turn related to the (negative) pore-water pressure via its water retention curve (WRC). The sensors are individually calibrated by the company in specific environments and the measuring range starts from the air entry value of the ceramic cup, which is -9 kPa. Therefore, values very close to saturation are generally missed. However, it should be noticed that at -9 kPa the soil monitored in this study is almost at full saturation and the information provided is still useful for practical purposes, especially when combined with direct measurements from tensiometers. With the exception of shallow depth measurements, the instrument default calibration thus focuses on suction values significantly higher than those typically encountered within a river embankment, as this sensor was developed for agricultural purposes. Therefore, a customised calibration within the suction range relevant to the case study was performed according to the procedure described in Section 3.2.

3.2 Sensor calibration

Sensor calibrations were all carried out at the laboratory of Structural and Geotechnical Engineering of the University of Bologna, using the soil collected at the site to such purpose. In particular, GS3 and MPS-6 sensors were subjected to custom procedures. A schematic drawing of the calibration setups is shown in Fig. 5 and the results obtained are reported in Fig. 6. As soon as a good contact is ensured between the metallic prongs of the GS3 and the surrounding medium, as illustrated in Fig. 5a, reliable data can be collected and it is not required for the sensor body to be completely buried. unless the sensor head is exposed to direct UV radiations because this may degrade the vinyl surface and influence the electrical resistance and conductance of the sensor circuits, thus potentially altering the electrical signal interpreted and collected by data logger (Decagon Devices, 2016a).

For the GS3 sensor, the probe was placed in a 105 mm diameter and 120 mm high soil sample, prepared at a known water content and void ratio in a glass beaker (Fig. 5a). The top of the beaker was sealed with a plastic film fixed to its top edge until the sensor reached equilibrium with the surrounding soil. A known amount of water was then repeatedly added from the top, after which the beaker was sealed again until equilibrium was reached. The mass of the beaker, filled with the soil and the sensor, was measured each time. Overall, this procedure was repeated four times. Upon dismantling the setup, a soil sample next to the sensor was taken and used to assess the final water content by mass. Two different GS3 sensors underwent this procedure, one having 6.5 cm long prongs (default length) and the other 4.5 cm, labelled P1 and P6 respectively (consistently with the data logger connection ports used for data acquisition). The reduced prong length (4.5 cm) has been tested and implemented in the monitoring system (see Section 3.3) for installation with their horizontal orientation in the borehole shaft so that the investigated soil was disturbed less by drilling operations. In fact, due to the dimensions of the installation tools (Rocchi et al., 2018a), an acceptable compromise among ease of installation, soil disturbance and measurement accuracy has been reached reducing the prong length. This reduction does not significantly affect the measurements in the field, thanks to the specific sensor calibration carried out with reduced prong length. Figure 6a illustrates the two sensors recordings and the water content measured during the tests. Based on the collected data, a user calibration equation for each sensor - referred to the specific soil type and density - was formulated. The comparison highlights that the calibration parameters are a function of both geometry and soil type.

The experimental setup designed and developed in the laboratory in order to calibrate the MPS-6 sensors consisted of a plastic cylindrical cell of 17.8 cm diameter and 20 cm height (Fig. 5b), initially resting in a plastic box 40 cm long and 100 cm wide. The cell was filled with the embankment soil up to a height of 14.4 cm, using the moist tamping technique to target a void ratio e=0.7. Two MPS-6 sensors (labelled P2 and P4, again consistently with the data logger connection port used for data acquisition) and a laboratory mini-tensiometer (similar to T5) were buried at the same depth in the soil column, approximately 3 cm from the top surface. A good contact to all ceramic surfaces were ensured for the sensors, according to the manufacturer's specifications. The soil sample was initially saturated from the base by filling the plastic box with water. Following saturation, the base was made an impervious boundary by replacing the porous base with a solid one and evaporation was induced in stages at the top of the sample by using a fan. After suction started to develop, the cylinder was sealed at the top. When equilibrium was achieved in the instruments through the soil column, the sensor readings were recorded and the evaporation was re-established. Full equilibration times spanning from 3-5 hours to a full day were observed for MPS-6 measurements, moving from low to high values in the suction range of interest (10 to 60 kPa), similar to other instruments requiring equilibrium of the porous cup with the surrounding soil (e.g. tensiometer). Starting from saturated conditions, the procedure was repeated drying the sample in nine consecutive steps up to a maximum suction value equal to 60 kPa. Figure 6b correlates the MPS-6 raw readings with the corresponding suction values measured using a laboratory tensiometer (circular and triangular markers). For comparison, readings from default calibration are also plotted in Figure 6b (cross markers). Consistency is observed in the whole set of measurements for the two sensors. The scatter between the user and the default calibration best fit lines progressively reduces as suction increases and tends to coincide when extrapolated at high values, as expected from the sensor accuracy declared by manufacturer. At the end of the procedure, the MPS-6 sensor P4 was left in the soil column until suction values above 1,000 kPa were recorded. During this phase, soil specimens were progressively taken from the soil column and suction measured using a chilled mirror device (WP4, Decagon Device, 2007). The MPS-6 raw readings with the corresponding WP4 values of suction are also plotted in Fig. 6b for a qualitative assessment of the calibration trend at higher suction values. However, even if consistent with low suction measurements, these data were not used to infer the custom calibration due to a possible disturbance produced by the specimens collection and to the contribution of the osmotic suction, which is measured by the WP4, not by the MPS-6. It has to be noticed that the procedure followed in the calibration of MPS-6 sensors has been performed starting from saturated conditions, therefore following the drying branch of the hysteresis loop. Nevertheless, wetting and drying tests performed by the manufacturer on MPS-6 probes highlighted that the magnitude of the error linked to hysteresis is less than 10 kPa in the −20 kPa to −100 kPa range (Decagon Devices, 2016b). As a result, data collected as the soil wets up can generally be expected slightly drier than the actual degree of saturation (i.e. higher suction is measured). For the present case, the overall resulting error, which can be detected due to the presence of tensiometers in situ, is considered to be acceptable. Note that tensiometers do not suffer from hysteresis and therefore they allow a critical evaluation of direct and indirect suction measurements.

3.3 Design and implementation

The system was designed to obtain the monitoring of representative data of a single cross section. This is about ten meters long and includes the embankment crown and berm, extending from the soil surface to a maximum of 8 m depth. The instruments were installed in boreholes purposely executed from the crown and from the berm. Twelve boreholes were drilled, either to host a single sensor (single point SP, seven boreholes) or more than one sensor (multipoint MP, five boreholes). Horizontal or inclined boreholes were avoided because they may lead to preferential flow paths in the embankment and thus increase the through-seepage process, particularly when drilled from the river side.

Multiple installations within a single borehole enable to reduce the total number of boreholes, thus mitigating the impact of the monitoring system on the earthen structure, with further beneficial effects on the overall installation costs. Multiple installations also enable to couple water content and suction measurements at the same point, allowing for the identification of the field water retention curves (e.g. Bordoni et al., 2017). However, it is worth noticing that multiple sensor installations within a single borehole are at risk of "cross-talk", as water may leak along the cables running from one installation to the other, particularly if installed by unsuitably trained personnel. For this reason, at certain depths the WRCs were also inferred using the data from adjacent single point boreholes (e.g. SPC1, SPC2 and SPC3).

GS3 sensors were either installed at the bottom of a borehole, using a rod assembly that can thrust the prongs into the undisturbed soil, or at its sidewall using a specific steel arm, through which the sensor is lowered to the required depth and then thrusted into the soil. SM150T sensors were installed only at the bottom of the borehole because of their design, using the same rod assembly of the sensors.

The T8 tensiometers were installed in 50 mm diameter boreholes drilled to the monitoring depth. At the bottom of each borehole a further 200 mm were excavated with a hand auger, having a smaller diameter than the instrument ceramic cup, in order to ensure a good soil contact when pushing the sensor in. A plastic casing was placed to support the borehole and its top was then closed to ensure protection from heating and solar radiation.

The MPS-6 could not be inserted directly in the undisturbed soil due to the relevant depth of installation, as the ceramic disc of the sensor is fragile and is suitable to penetrate only very soft soils. Therefore, these sensors were placed in the borehole within a pre-compacted "soil cake" prepared in the laboratory prior to installation, using the soil sampled on site at the installation depth (Rocchi et al., 2018a).

Each permanent installation (i.e. all except for T8 tensiometers) was backfilled with the excavated soil for approximately 20 to 30 cm. Subsequently, hydrated bentonitic pellets were placed for 20 to 30 cm to create a hydraulic seal and to avoid preferential water flow along the cables. The borehole was then backfilled with the excavated soil, either until the next installation or to 0.5 m depth from the ground level. The remaining 0.5 m depth was finally sealed again with bentonitic pellets to avoid preferential water infiltration from the ground surface.

Twenty sensors were deployed in total (three T8, eight MPS-6, seven GS3, two SM150T), whose full details are given in Table 2, where the borehole name, sensor type, installation depth and date of installation are provided. In Table 2 the following notation is used: label MP stands for Multi Point, SP for Single Point and T for Tensiometer. According to the location, B stands for Berm and C for Crest or Crown. According to this notation, the monitoring system lay-out is illustrated in Fig. 7, where a comprehensive overview is given in a three dimensional sketch (Fig. 7a), plan view (Fig. 7b) and longitudinal cross sections (Fig. 7c). Further details of the innovative procedures for deep installation of GS3 and MPS-6 sensors can be found in Rocchi et al. (2018a).

Two T8 tensiometers were installed from the embankment crest at 4.7 and 8 m depths (TC1 and TC2), and one from the river berm, at 4.9 m depth (TB1). Five MPS-6 were installed from the embankment crest between 1.2 and 7 m depths and three from the river berm between 0.9 and 2.7 m depths. Five GS3 were installed from the embankment crest between 1.4 and 7.1 m depths, while two from the river berm at 0.7 and 2.2 m depths. Finally, only two SM150T were installed, both from the crest at 1.5 and 7.1 m depths. Notice that only in a couple of cases the installation was modified with respect to initial design due to local unexpected problems (see Table 2 for details). The whole monitoring system was completed in four rounds of installations and each sensor has been operational for at least one year.

4 Interpretation of monitoring data

A comprehensive overview of the monitoring data is given in Fig. 8-11 in terms of relevant time histories for a two-years period starting in October 2016. In particular, the monitoring data include the hydraulic river level and rainfalls (Fig. 8a and 8b, respectively), which are the most important boundary conditions, the water content (Fig. 9a-c) and the pore-water pressure (Fig. 10a-c), also expressed as hydraulic heads (Fig. 11). Aiming to assess the performance of each installed sensor and the monitoring system as a whole, data have been grouped and discussed in separate sections, having as primary concerns the redundancy and coherence checks. Sensor measurements at similar depths are so plotted in distinct figures, focusing on the effect of river level and climatic conditions on water content and pore-water pressure. Furthermore, water retention properties of the riverbank materials are depicted in Fig. 12, where field WRCs are compared to laboratory results, assessing the combined values of pore-water pressure and water content. Finally, profiles of the unsaturated state variables in the riverbank (i.e. pore-water pressure and water content) are shown in Fig. 13 assessing the measurement of pore-water pressure in comparison with the phreatic surface.

During the observation time, various high-water events were observed as recorded at Ponte Motta's hydrometric station, five of which exceeded 8 m height above datum (i.e. the river bed). During these events, the river submerged the berms, causing water to easily infiltrate both berm and embankment. In addition, more than ten events were registered having water levels between 5 and 7 m above the river bed, which produced a significant response in the sensors (especially TB1). However, only two events combined high hydrometric levels to peak persistence: in December 2017 (13/12/17), with a maximum level of about 10 m above the datum and water persistence above the berm for about one week, and in March 2018 (14/03/18), with a maximum level of about 9.5 m above the datum and water persistence above the berm for about two weeks. As discussed later on, they caused significant seepage processes in large parts of the embankment.

4.1 Comparison of SM150T and GS3 sensors for water content measurement

Figure 9 shows the values of water content for installations from the embankment crest and berm. Specifically, responses of deep (below 6.0 m depth), intermediate (between 2.0 and 5.0 m depth) and shallow (above 1.5 m depth) sensors are plotted in Figure 9a, 9b and 9c respectively. Deep sensors (SPC2, SPC3 and MPC3) exhibit slight variations during the year and a significant change only in response to persistent high-water levels, i.e. December 2017 to May 2018, consistently with the pore-water pressure values measured in the same periods (Fig. 10a). The response of GS3 sensors (SPC2 and MPC3) appears here consistent, with a limited increase in water content after the hydrometric peak in December 2017 and a water content near the saturation level in March 2018 (i.e. around 0.40 m^3/m^3, similar to the values derived from sensor calibration). Isolated high water events with limited hydrometric peak and low persistence, as those occurred until November 2017 (when only GS3 sensors were installed), did not cause any appreciable change in water content at depth below the embankment (Fig. 9a and 9b), thus highlighting a good water retention efficiency of the main infrastructure. However, during the same events the sensors installed in the berm (e.g. MPB1 in Fig. 9c) rapidly reached a near saturation state, with water content equal to 0.40-0.43 m^3/m^3. Values recorded within the embankment central core (MPC1 in Fig. 9b) generally do not show significant variations since the beginning of measurements, evidencing that initial conditions tend to persist in the area.

Figure 9c shows the values of water content for installations placed above 2 m depth, where empty symbols are used for sensors installed from the embankment berm. The water content values of the shallowest installed sensor (MPB1) tend to remain higher in response to continued actions. This sensor also shows an impulse response to the events between November 2016 and March 2017, consistently with the hydraulic level variations. A similar behaviour is observed after the event of December 2017. The decrease is more gradual after April 2018, due to the larger volume of soil wetted during winter. On the other hand, MPC2 and MPC3 show a different response than corresponding deep installations, probably due to water infiltration from precipitations. In fact, had it been a result of water content redistributions within the embankment, the effects would have been observed also in the sensors installed in the central core. In general, shallow sensors show a greater variation in response, when drying and wetting processes are induced by soil transpiration (i.e. MPB1 from March to October 2017) and intense rainfalls infiltration (i.e. MPC2, MPC3 and MPB1 from March to April 2018). Note that no installations shallower than 2 m depth at the embankment crown were available in 2016/2017.

When considering Fig. 9a and 9c, the SM150T sensors indicated with dotted lines (SPC3 and MPC2) exhibit greater excursions compared to GS3 sensors. In particular, SPC3 (i.e., SM150T at 7.1 m depth from the embankment crest) provides values lower than 20% in terms of volumetric water content (θ) prior to March 2018, which do not appear reliable if compared to direct measurements of water content in the laboratory. These low values could be somehow connected to installation, occurred in November 2017, as measurements from such sensor become meaningful following the first significant hydraulic input (March 2018), differing only 4 to 8% (in terms of θ) from those provided by SPC2 (GS3 sensor at the same depth from the embankment crest). Similar differences are observed in Fig. 9c for shallow sensors (MPC2 and MPC3). Although the main difference between the two sensor types is in the installation direction (horizontal for the GS3 and vertical for the SM150T), others like the sensor electronics and a lack of user calibration for the SM150T are considered to be the reason for such discrepancy.

4.2 Comparison of T8 and MPS6-6 sensors for suction measurement

The response in pore-water pressure terms is showed in Figure 10. Consistently with Figure 9, the responses of deep (below 6.0 m depth), intermediate (between 2.0 and 4.5 m depth) and shallow (above 1.5 m depth) sensors are respectively plotted in Figure 10a, 10b and 10c. Due to the large excursion in suction at shallow depths, the values in Fig. 10c are presented on a logarithmic scale. Furthermore, the capacitive sensors marked by dotted lines cannot measure pore-water pressure above the air entry value of the MPS-6 porous disk, resulting in a constant small suction value when this is saturated. These values are showed in light grey as they are not representative. Similarly, values for TC1 affected by water infiltration at the head of the installation during Spring 2018 are shown in grey in Fig. 10b.

The values within the embankment are generally rather stationary and vary just a few kPa in suction, unless significant hydrometric peaks are experienced, as those registered in December 2017 and in March 2018, when deep sensors (SPC1, MPC3, TC2) show a visible reduction in suction. A very consistent response is registered by such sensors (Fig. 10a), where the largest and fastest response is exhibited by the deepest sensor, gradually reducing towards the core of the embankment. In particular, with reference to the high water event occurred in December 2017, the tensiometer installed in TC2 (8.0 m depth) measures a variation in suction values from -16.5 kPa (28/12/2017) to about -6 kPa (06/02/2018), with a maximum daily rate of variation equal to 1.1 kPa/day (06/01/2018). The MPS-6 sensor installed in SPC1 (7.1 m depth) responds to the same event with a variation in suction from -20.7 kPa (28/12/2017) to about -13 kPa (07/02/2018), with a maximum daily rate of variation equal to 0.5 kPa/day (08/01/2018) while the MPS-6 sensor installed in MPC3 (6.2 m depth) responds with a variation in suction from -21.3 kPa (28/12/2017) to about -15 kPa (15/03/2018), with a maximum daily rate of variation equal to 0.2 kPa/day (15/01/2018). Following the high water event occurred in March 2018, the tensiometer installed in TC2 reaches a peak value for pore-water pressure equal to about +7 kPa (22/03/2018) with a maximum daily rate of change equal to 2.3 kPa/day (14/03/2018), soon after the maximum hydrometric peak; in the same period, the MPS-6 installed in SPC1 reaches the limit values for the sensor (-9 kPa on 15/03/2018) with a change of 3.6 kPa within one day, while the MPS-6 installed in MPC3 responds with a variation in suction up to about -9.7 kPa (27/03/2018), with a maximum daily rate of variation equal to 1.5 kPa/day (23/03/2018). Even considering the differences in installation depth and initial suction values, MPS-6 and T8 have thus comparable response time, indicating that the MPS-6 is as prompt as T8.

Furthermore, TC2 provides data consistent with the MPS-6 placed at 7 m (SPC1), whose measurements have a maximum difference (when equilibrium is reached) of about 10 kPa, which can be related to the difference in installation depth between the two. In Figure 10b it can be also observed that measurements from T8 (i.e. TC1) and MPS-6 (i.e. MPC1) at around 4.5 m depth from the embankment top provide a nearly stable value around 30-35 kPa for a long time (May 2017 to February 2018). This firstly guarantees that the core of the embankment is not significantly influenced by external conditions (rainfall and hydrometric fluctuations) during the monitoring period. Moreover, these observations proved that the measurements by direct and indirect sensors are in good agreement, as also observed in the laboratory. As already mentioned, in some cases infiltration occurred inside the PVC tube protecting the sensor shaft of the tensiometer installed in TC1 and thus its data are not always representative of the deep seepage process (values in light grey in Fig. 10b from March to May and June to July 2018). It is worth noticing that data observed during the whole 2-year monitoring period do not evidence the need for tensiometers re-saturation, which was not therefore performed.

Shallow measurements of suction (Fig. 10c) evidence a sharp increase, with values exceeding thousands of kPa upon drying (i.e. from April to September 2017 and from May to October 2018), while impulsive reductions are recorded when high water events (e.g., November 2016, December 2017, March 2018) and intensive rainfall impact the embankment (e.g. February 2018), consistently with water content measurements at the same depths (Fig. 9c).

4.3 Assessment of pore-water pressure measurement vs river level

Tensiometers data and dielectric measurements from the embankment are plotted in terms of hydraulic head in Fig. 11, in addition to data from the piezometer installed a few meters from the monitoring section at 17 m depth from the embankment crest. Hydraulic heads and river water levels are then referred to the same datum for a coherence check, focusing on the time period from December 2017 to May 2018. It can be first observed that hydraulic heads tend to decrease with depth along the same vertical, as a consequence of suction values (i.e. negative pore-water pressure) inside the embankment, which do not follow a hydrostatic trend above the saturation line.

The piezometer in the deep aquifer (PZ1) and the tensiometer in the berm (TB1) (Fig. 11a and 11b, respectively) are the only sensors that move more or less synchronous with the water level. In case of rising river water level, like in March 2018, both tensiometers located at approximately the same elevation (i.e. same position head). TB1 and TC2 clearly follow the trend, but show a decrease in total hydraulic head when moving from the berm to the embankment core, in agreement with the seepage flow generated during the event. On the other hand, sensors above 4.5 m depth in the embankment (MPC1) remain uncorrelated to the changing river level and are not influenced by the atmospheric conditions, whereas the hydraulic head in deeper sensors (MPC3, SPC1 and TC2) move with some significant delay with respect to boundary conditions.

4.4 Assessment of pore-water pressure vs water content measurement

For those sensors installed in the same borehole at close depths or in two separate boreholes at the same depth, data could be coupled to trace the soil-water retention behaviour in situ (WRCs, Fig. 12). Solid symbols have been used for GS3, while empty symbols for SM150T; all of them are coupled to MPS-6 suction sensors. For useful comparison, laboratory WRCs were also determined by drying recompacted samples using a combination of evaporation tests and Dew Point method. The experimental data obtained following main drying paths are showed as grey crosses in in Fig. 12a and 12b, while the relevant interpreted curves for the embankment material have also been added as dashed lines. The curves in Fig. 12a were obtained on soil sampled at 2.8 m and 4.8 m depths from the embankment crest and recompacted at a void ratio ranging from 0.62 to 0.75, representative of in situ conditions, while in Fig. 12b similar tests were carried out on soil sampled at 2.1 m and 2.3 m depths from the berm with a void ratio ranging from 0.48 to 0.52. Further related details can be found in Rocchi et al. (2018a), Rocchi et al. (2018b) and Gragnano et al. (2018).

Regarding the behaviour along a vertical under the embankment crest (Fig. 12a), measured data plot within a rather narrow band, which can be considered to identify a single soil water retention locus despite the difference in depth and some heterogeneity in the particle size distribution. Data are also in quite good agreement with laboratory results, thus confirming the overall reliability of the monitoring data. The slopes of the field retention paths in Fig. 12a and 12b appear similar for the various installations. In particular, they tend to plot below the main drying curves obtained from evaporation tests, probably due to some hysteretic field response along wetting-drying paths. A distinct steeper wetting path is shown by retention data obtained from the SM150T sensor at 7 m depth (SPC3), which starts from unrealistically low water content values. An apparently greater reliability is achieved in the response of GS3 water content sensor at a similar depth (SPC2), when coupled to the same suction sensor MPS-6 (SPC1), as it plots closer to laboratory curves. Analogous observations hold true for the other SM150T sensor in Fig. 12a (MPC2) with respect to the corresponding GS3 (MPC3) when coupled to the MPS-6 in MPC2.

The behaviour of sensors installed close to the river (Fig. 12b) appears significantly different from those in the embankment core. Due to shallow installations that have been in operation for longer time, a greater range of suction is here displayed and this enables to identify a greater portion of field WRC. For MPB1 two full cycles of drying and wetting can be compared, one right after installation and the other a year later. In general, the soil achieves saturation rapidly as the river water reaches the berm level, making it even more difficult to interpret the behaviour on wetting, because indirect measurements of pore-water pressure are restricted to suction above -9 kPa. It should be noticed that the field retention curves traced by these sensors plot considerably higher than in the embankment core, when the low suction range is considered. This is consistent with a distinction between Unit A and Unit A’ introduced in the model of Fig. 3. Furthermore, many field data in Figure 12b plot above the laboratory main drying curves, particularly in the wet-end parts: this may be due to the void ratio tested in the laboratory (0.48 – 0.52), probably lower than the actual site value due to sample disturbance.

4.5 Assessment of pore-water pressure vs phreatic surface

Based on the data just presented, which represent discrete points, comparison along the two verticals (i.e. from the crest and from the berm) was performed in order to infer general trends. In particular, the profiles of pore-water pressure and water content measurements with the installation depth are presented in Fig. 13a and 13b, respectively, with reference to two significant events, namely 01/12/2017 and 14/03/2018. Furthermore, the ranges corresponding to the maximum and minimum values ever measured at each single location during the whole monitoring period are also presented in Fig. 13.

Both pore-water pressure and water content profiles show rather constant values at intermediate depth and the distributions pivots around this point, which however occurs at different depths for the two parameters. The values of pore-water pressure generally change smoothly with depth indicating continuous profiles, with the exception of MPC2 (1.2 m depth). Suction measurements exhibit a nearly linear profile with depth. In particular, the slope of such profile is close to hydrostatic up to approximately 1 m above the water table (6.1 to 8 m), while it reduces in the central part of the embankment (3.1 to 6.2 m depths) and then shows strong variability and sensitivity to the atmospheric conditions, when approaching the ground surface. Furthermore, as already mentioned, some inconsistency is observed between the two water content sensors installed at 7 m depth (SPC2 and SPC3), where SPC2 behaviour appears to fit better the overall response observed along the profile with respect to SPC3, which again highlights the need for a user calibration of SM150T sensors.

The same parameters show a significantly different behaviour closer to the river, particularly the pore-water pressure (Fig. 13a). However, any picture is hidden by the inability to measure positive pore-water pressure with capacitive sensors. Furthermore, the water content profile is less well defined due to the presence of only two sensors successfully installed, instead of the three originally planned.

5 Mapping the distribution of unsaturated soil state variables

Although comparison of water content and pore-water pressure measured profiles can help to understand general trends, a major challenge remains in extending the quantification of such variables to the entire 2D domain of interest, i.e. to the whole monitored section. Furthermore, knowledge of spatial variability and related uncertainty becomes crucial for subsequent seepage and slope stability analyses. In this regard, geostatistical algorithms can be introduced as they are capable to spatially extend distributed discrete data. Geostatistical methods have been already extensively applied in geotechnical and environmental engineering (Davis, 2002; Lenz and Baise, 2007; Li et al., 2009; Asa et al., 2012), in order to create realistic models based on punctual or limited sources of information. For the present case, the Kriging method was considered (Krige, 1951) for the spatial interpolation of monitoring data, as it is widely implemented in several numerical codes for the interpretation and computation of geotechnical data. In essence, Kriging is a regression technique minimizing the estimation from a fitted covariance model, determining a minimum error variance estimate at a location where the actual value is unknown. This procedure involves fitting a discrete function onto a series of spatially distributed discrete points, as suitable for the case of direct measurements of soil water content or pore-water pressure. In addition, there is the possibility to include weighing coefficients in the calculation, which can be then used to compute values for any other point in the domain. The same two different time-steps selected in Fig. 13 were considered for the interpretation of site measurements, representative of the beginning and of the middle of the wet season. These are plotted in Fig. 14 using isolines contours, where an increment between two adjacent isolines is 10 kPa. The time-steps considered correspond to 01/12/2017 (Fig. 14a) and 14/03/2018 (Fig. 14b), the first being characterized by low water level and the second by a persistent hydrometric peak.

In details, the input data included in the Kriging interpolation are the pore-water pressure measurements from tensiometers, capacitive sensors and Casagrande piezometers. It should also be noted that shallow measurements of suction (MPC2, SPB1 and MPB1) can often be misleading for a reliable spatial interpolation, as they may show extreme values at given times of the year. Therefore, their values were considered only when in the range of a hydrostatic increment from deeper suction measurements. Even though it would be beneficial to include the whole set of measurements in the shallow zone of the embankment (above 1.5 m depth, for the present case) in order to investigate soil-atmosphere interaction processes, a simpler approach was used here as such processes were deemed less important with regards to the water flow within the embankment. River levels were also included as boundary condition of pressure head values on the left side of the riverbank, substituting MPS-6 measurements on the river berm during high-water events. In the landward area a hydrostatic distribution with depth was assumed, with the groundwater table either as from pore-water pressures measured during the low-water period (01/12/2017) or, alternatively, at the ground level in correspondence of high-water events (14/03/2018). Before implementing monitoring data in the interpolation algorithm, it is therefore crucial to perform a quality check and data reliability assessment. For example, as mentioned, all measurements from shallow sensors (up to 2 m depth), which frequently exceed hundreds of kPa, have been disregarded from the data interpolation with the Kriging method, as they are not representative nor meaningful of the overall suction distribution in the riverbank as a result of changing river levels. Data from the tensiometer installed in TC1 (4.5 m depth from the crest of the embankment) have not been considered when water infiltrated from the top of the installation (e.g. on 15th March 2017 and on 14th December 2017), which do not provide representative data for the seepage process throughout the river embankment.

Through the procedure thus defined, monitored pore-water pressure values (including suction), two groundwater table values, two hydrometric levels and the geometry of the section constituted here a sufficient amount of data for a reliable estimate of related spatial variability, together with the only required further assumption of three suction values at different locations on the ground level, at the top and at the two sides of the embankment (see Fig. 14b). The spatial distribution of pore-water pressure (including suction) could be then obtained as a continuous smooth surface that fits all monitoring points, shown in Fig. 14. This result represents a fundamental source of information for the assessment of actual safety margins of the embankment, while in most cases it is the major source of uncertainty. It can be subsequently used as an input (e.g. to define initial conditions) for seepage and stability numerical analyses. It should be added that the main purpose here for using the Kriging method (1951) when mapping the distribution of unsaturated soil state variables was to find an adequate mathematical tool to properly interpolate site measurements at the riverbank section scale, rather than to extrapolate the missing information to the area not covered by monitoring, the correctness of the final outcome being dependent on the assumptions discussed above.

6 Concluding remarks

Various sensors of unsaturated soil state, together with their installation techniques, used to implement an articulated full-scale monitoring system within a river embankment cross section on the river Secchia have been presented. An extensive description of the experimental work, from field and laboratory investigations to sensor calibration and installation procedure, has been provided. A total of twenty sensors were successfully installed along two main verticals, from the embankment crest and from its berm, including two types of water content dielectric permittivity sensors, tensiometers and capacitive suction sensors. With the aim of monitoring soil depths from up to 8 m from the ground level, the specific choice of sensors was designed to cover the wide range of expected values, from thousands of kPa to zero suction, thus from almost dry to fully saturated conditions, using commercially available and cost-effective solutions. Due to the challenging required depth of installation, the sensors were placed inside purposely drilled boreholes. Multiple installations within a borehole were experimented to limit their impact on the embankment performance and to couple water content and suction measurements at the same point. After a monitoring period of two years, when several high-water events were observed, the monitoring setup proved to be robust and reliable, having suffered only a minimal loss of sensors and/or data and having provided a consistent response from the different sensor types and depths of installation.

In particular, MPS-6 sensors for the monitoring of suction have shown to be able to be successfully installed inside a precompacted “soil cake”, as none of those tested in laboratory conditions and in for site trials have exhibited cracks in the porous stone or damage in the plastic body. The relatively limited cost of these instruments makes their implementation extremely competitive on large scale projects. The sensor time response appears similar to more established tensiometers. A soil-specific and user defined calibration is highly recommended in order to ensure the data reliability in the range from 10 to 60 kPa, which is typically of interest for the present application and corresponds to the zone with the largest error of its default calibration. Possible limitations are due to the fact that these instruments can hardly be re-usable when installed at more than 1 m-depth and that they would best perform in the high-suction range. Furthermore, the porous block has got a hysteretic retention behaviour that can introduce an error up to 10 kPa in the −20 kPa to −100 kPa range, as stated by the manufacturer. As a result, according to the outcome of this investigation, this sensor turns out to be suitable for river embankment applications provided that (1) it is not used in the area close or below the groundwater table (for the present case, a maximum depth of 7.1 m from the embankment crest was selected, which is approximately 2 m above the groundwater table depth during the dry period) and (2) it is combined with more accurate instruments (e.g. tensiometers) for achieving possibly direct and correlated measurements. Finally, user-calibration of sensors has proved to provide a significant improvement to the data reliability of all sensors, as also demonstrated by comparison between GS3 (where a user-calibration was determined) and SM150T (where default calibration was adopted) water content sensors.

In general, the combined use of various sensors as source of complementary information, having different measurement techniques (dielectric measures and tensiometers), observed variables (pore-water pressure and water content) and operating range (from -10,000 to +100 kPa), has proved to be a significant strong point for the implemented monitoring system.

Despite the intrinsic heterogeneity of the soil system investigated, with largely unknown characteristics, continuous profiles of water content and pore-water pressure could be observed along a representative vertical both from the embankment crest and from its berm. As expected, they tend to vary seasonally, as expected, in response to climatic conditions and especially in response to persistent high river water levels. However, data in the berm and in the embankment core show distinct responses and a different retention behaviour.

The largest excursions are observed at the ground surface, but with limited consequences on the embankment stability. On the other hand, the embankment core tends to remain largely unaffected by changing river water levels, thanks to its soil retention characteristics. However, important modifications have been registered at greater depths, in proximity of the water table, and with a significant delay with respect to the hydraulic boundary conditions, highlighting once more how the unsaturated soil states in the embankment, and consequently its available shear strength, are clearly a function of time and initial conditions as well as past history should be taken in due consideration.

To this purpose and to assess the actual soil state in the whole embankment, the discrete field observations from the monitoring system can be used - together with known boundary conditions - to obtain a reliable distribution of pore-water pressure at any time. Such result does represent a realistic - still rarely available - set of information on the unsaturated soil state of the river embankment and thus provides the basis for the development of relevant accurate and suitably calibrated stability analyses, under transient seepage and continuously variable boundary conditions.

The proposed integrated monitoring system, which aims at making use of cost-effective and commercially available sensors that could be therefore installed along extensive river stretches, appears a fundamental starting point to assess potential risks of such geotechnical infrastructures in real-time and to devise well-balanced related mitigation measures.

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List of symbols and abbreviations

e_0 initial void ratio

PSD particle size distribution

q_t corrected total cone resistance

Q_t normalized cone parameter

SBT_n soil behaviour type

u pore-water pressure, subscript 0 and 2 for hydrostatic values and pore-water pressure response measured during CPTU, respectively

θ volumetric water content

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Table 1. Summary of sensor capabilities

Sensor	Variable monitored	Measurement Type	Range	Accuracy (according to manufacturer)	Suitability for multipoint installation
T8	Pore-water pressure	Pressure	+85 – -100 kPa	±0.5 kPa	No
MPS-6		Dielectric permittivity	-9 – -10,000 kPa	±(2 kPa + 10%)	Yes
GS3	Water content		0-60%	±3%	Yes, to 2 m depth
SM150T			0-60%	±3%	Only when installed at the base of the borehole

Table 2. Installation details of the monitoring network.

Borehole	Probe	Installation depth (m b.g.l.)	Measurement	Installation date
MPC1	GS3	2.4	Water content	September 2016
	MPS-6	3.1	Suction	September 2016
	GS3	4.5	Water content	September 2016
	MPS-6	4.6	Suction	September 2016
SPC1	MPS-6	7.0	Suction	September 2016
SPC2	GS3	7.1	Water content	September 2016
TC1	T8	4.7	Pore pressure	January 2017
MPB1	GS3	0.7	Water content	October 2016
	MPS-6	0.9	Suction	October 2016
MPB2[1]	GS3	2.2	Water content	October 2016
	MPS-6	2.7	Suction	October 2016
TB1	T8	4.9	Pore pressure	January 2017
TC2	T8	8.0	Pore pressure	October 2017
MPC2	MPS-6	1.2	Suction	October 2017
	SM150T	1.5	Water content	October 2017
MPC3	GS3	1.4	Water content	October 2017
	MPS-6	6.2	Suction	October 2017
	GS3	6.4	Water content	October 2017
SPC3	SM150T	7.1	Water content	October 2017
SPB1	MPS-6	1.2	Suction	October 2017
	SM150T[2]	1.5	Water content	October 2017