In-situ measurements of soil water content and suction to assess river embankments stability under transient flow conditions

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ABSTRACT: The evaluation of river embankments stability is a key aspect in geohazard assessment and underestimating their failure risk can often produce unexpected and severe damages. Time-variable soil water content and suction distributions represent an intrinsic characteristic of river embankments, playing a fundamental role during their stability assessment. To obtain a realistic estimate of these distributions in time and space – as a function of river water levels – a combination of field measurements, laboratory testing and appropriate calibrated numerical analyses should be used in a complementary way. For preliminary analyses, however, the river embankments are typically assumed to be under steady state conditions and this assumption provides overconservative results in terms of global safety at most times. Soil suction and water content were monitored at different depths within the embankment at the test site along river Secchia, north of the city of Modena (Italy), in order to study transient flow conditions and use it as input for probabilistic numerical analyses of the river embankment stability.

1 INTRODUCTION

River embankments and more generally earth retaining structures are characterised by unsaturated conditions during their lifetime. In particular, various hydraulic and climatic boundary conditions are responsible for transient seepage within embankments due to changes in suction. At the same time changes in suction result in variable strength causing significant variations in the stability conditions of these infrastructures. Therefore, an adequate determination of soil hydraulic and retention behaviour is a fundamental step towards a reliable risk assessment (Gottardi & Gragnano 2016).

The capability to assess unsaturated state variables in situ (i.e., suction and water content) has improved considerably in recent years, due to the development of high capacity tensiometers (Mendes et al. 2008) and interdisciplinary research (Bittelli 2011), as many instruments for indirect measurement of soil suction and water content were first developed in agriculture-related disciplines. Field monitoring of landslides (Springman et al. 2013; Cascini et al. 2014; Pirone et al. 2015; Bordoni et al. 2017) or foundations in connection with deformation induced by seasonal variations of water content (Nguyen et al. 2010; Harris et al. 2013) typically monitor the first few meters below the ground surface (2-3 m depth). Measurements of soil suction and water content in deeper soil layers, such as needed to monitor road and river embankments, is still limited to research applications (Toll et al. 2011) and neither installation techniques nor sensors assessment procedures are, at present, well established.

A full-scale river embankment section was heavily instrumented with sensors for suction and soil water content measurements, which vary during transient seepage depending on the hydraulic and atmospheric boundary conditions. Numerical analyses were first used to support the design of the geotechnical investigation and monitoring system and subsequently as a tool for riverbank safety assessment supporting the interpretation of soil suction and water content data collected in situ. This article describes the experimental site and the details of the system designed. Furthermore, some preliminary results both from monitoring and numerical analysis, are presented and discussed. The present research is part of the INFRASAFE project regarding the risk assessment of hydraulic infrastructures.

2 MONITORING SITE

2.1 *Soil characterisation*

The experimental site was selected at a specific embankment section of the Secchia River, tributary of the Po River, North Italy. Part of the embankment downstream of the area selected underwent some remediation works in the recent past (Caleffi & Cerutti 2014) and concurrently a monitoring system was implemented that includes piezometers, water content sensors and inclinometers at the locations marked in Figure 1. Any influence arising from the remediation works was avoided by placing the experimental site upstream of this area, where the embankment is closer to the river and therefore it is also more likely to receive hydraulic stimulations.

A series of four CPTU tests was carried out as part of site investigation and to confirm the soil stratigraphy encountered downstream during the remediation works. Two tests were carried out from the embankment crown and two from its riverbank, reaching approximately 25 m and 15 m depth, respectively. In Figure 2, the normalized cone resistance (q_t) and pore water pressure (u_2) are plotted together with the three main units identified by means of the soil behaviour type index (Robertson 2009). The test results obtained at the two cross sections investigated are overlapped in Figure 2 to provide an overall view. As seen in previous investigations, the stratigraphy consists of relatively coarse-grained material. Unit A makes up the embankment and consists of alternating silt and sandy silt. At approximately 5 m depth from the embankment crown and at a corresponding depth from the riverbank a coarser layer is encountered varying from a sandy silt to a silty sand. The embankment foundation (Unit B) consists of interbedded silt and silty clay with thickness ranging from 6 to 10 m. The top of this layer plunges slightly towards the riverbed. Underneath a clayey layer is found (Unit C) down to the maximum depth investigated. Under the embankment centreline, the top of this layer is deeper, perhaps due to settlements induced by the embankment itself.

As the water table is estimated to be 1.5 m below the ground level of the surrounding area (i.e. 9 m depth from the crown), the embankment body was in highly unsaturated conditions at the time the CPTUs were carried out on July 2016.

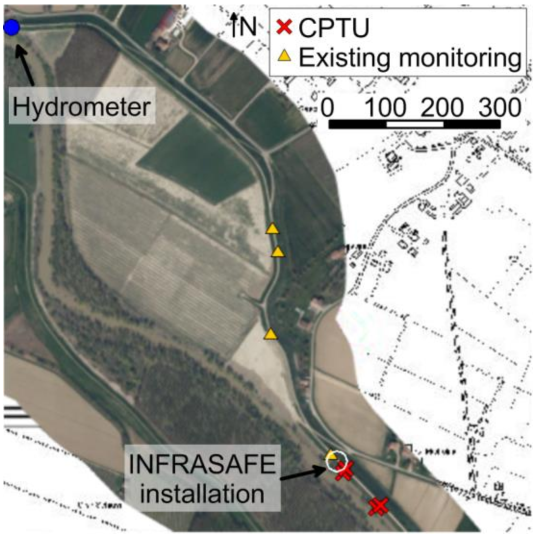

Figure 1. Monitoring area.

This is confirmed by the poor response in pore pressure to approximately 7.5 m depth for the CPTUs carried out from the crown, unlike those measured in the riverbank where lower suction absolute values are expected. Yang and Russel (2016) showed that the tip resistance is influenced by unsaturated conditions and therefore caution should be used when interpreting these tests. Comparison with core description and soil classification tests (Figure 3) confirm the soil stratigraphy obtained from CPTU results. Laboratory and site characterisation were crucial for the design of the monitoring system and, subsequently, the use of numerical model. The hydraulic and retention properties used in the numerical analyses are listed in Table 1. Only the saturated permeability, k_0, based on the CPTU results is provided for Unit B and C, since these units are typically submerged. The retention properties for Unit A were obtained by means of evaporation tests, suction controlled oedometers and Dewpoint method measurements (Gragnano et al. 2018; Rocchi et al. 2018), modelling them through the van Genuchten-Mualem model (van Genuchten 1980).

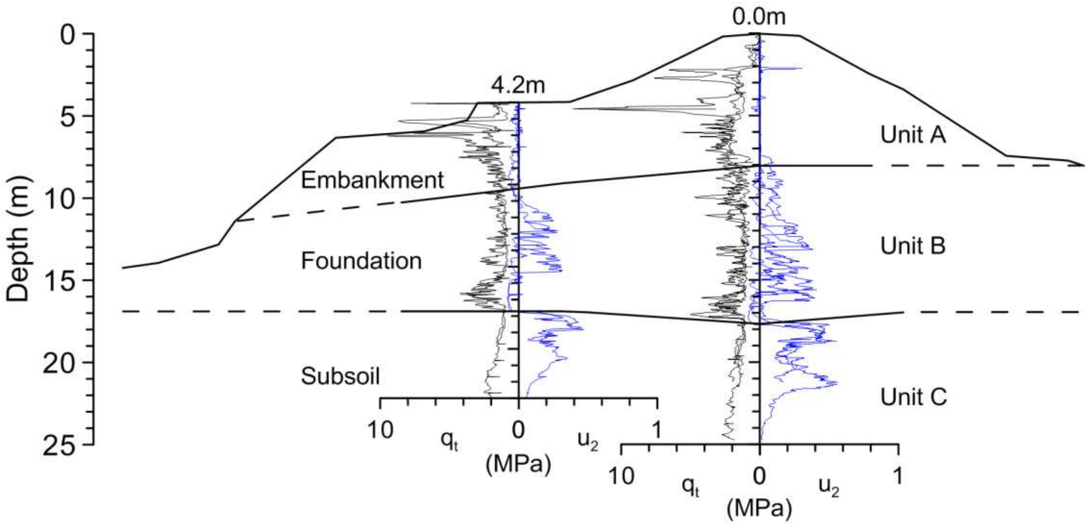

Figure 2. Ground profile.

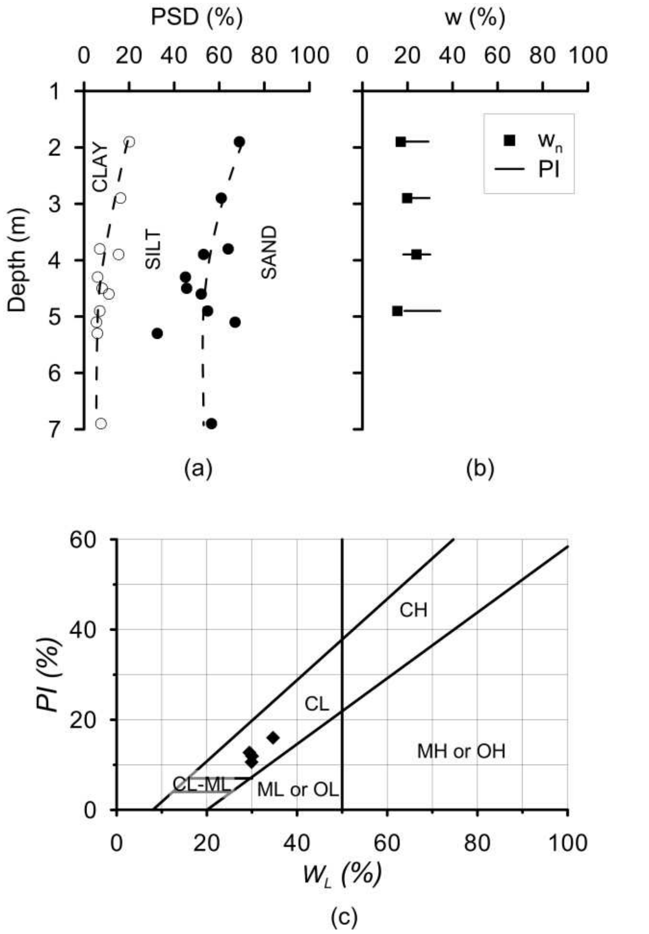

Figure 3. Laboratory classification.

Table 1. Estimated soil hydraulic and retention properties.

Soil unit	k_0 (m/s)	θ_{sat} (m^3/m^3)	θ_r (m^3/m^3)	α_{VG} (kPa^{-1})	n_{VG} (-)
Embankment	1.55×10^{-07}	40.3%	0.01%	0.093	1.298
Foundation	4.81×10^{-09}	-	-	-	-
Subsoil	3.98×10^{-10}	-	-	-	-

2.2 *Monitoring system*

The monitoring system was designed based on the geotechnical investigation and the results of preliminary numerical analyses (Gottardi et al. 2016) and includes both soil suction and moisture probes. The sensors installed are the MPS-6 (Decagon Devices 2016a) and the T8 (UMS 2011) by Meter Group for soil suction and the GS3 probes (Decagon Devices 2016b) for the soil water content. Several vertical boreholes were instrumented by single (SP) or multiple (MP) points of measurement to minimise the number of excavation, which might create a preferential water flow and hence risk compromising the embankment stability or bias the measurements. The installation depths vary in the range 2.3 m to 7.1 m from the embankment crown and 0.7 m to 4.6 m from the top of the river bank and are listed in Table 2. One T8, one MPS-6 and one GS3 were installed at the base of TB1, SPC1 and SPC2, respectively, where T stands for Tensiometer; B for Berm; C for Crown and SP for Single Point.

Figure 4 shows a schematic view of the monitoring system configuration. Two pairs of suction and soil water content probes were installed in MPC1 and a similar configuration was planned for MPB1, but due to stability problems with the borehole shaft, the second pair was installed in MPB2. The purpose of installing the suction and water content sensors together is to measure an in-situ Soil Water Retention Curve. SPC1 and SPC2 are reference installations to verify the reliability of the multi-points (MP) that are more complex. Furthermore, the measuring point at 4.6 m depth from the river bank consisting of a single tensiometer able to monitor water pressure in the range -85 kPa to +100 kPa, was also a single installation. To install the tensiometers 5cm-diameter boreholes were drilled almost to the chosen monitoring depth, while a hand auger having smaller diameter was used for the last 20 cm to ensure a good contact between the ceramic cup and the soil. The remaining sensors were installed using experimental techniques purposely developed to install these sensors at depth, which are further described in Rocchi et al. (2018).

Table 2. Details regarding the monitoring probes installed.

Borehole	Probe	Installation depth (m)
MPC1	GS3	2.4
	MPS-6	3.1
	GS3	4.5
	MPS-6	4.6
SPC1	MPS-6	7.0
SPC2	GS3	7.1
MPB1	GS3	0.7
	MPS-6	0.9
MPB2	GS3	2.2
	MPS-6	2.7
TB1	T8	4.9

3 RESULTS

Figure 5 shows the monitoring data between October 2016 and February 2017. The hydrometric level recorded at the location marked in Figure 1 (Ponte Motta) is presented together with the values for the eleven sensors installed. As seen from Figure 5, the sensors were installed in three phases and only two significant high-water events (November 2016 and February 2017) occurred since the start of monitoring, both soon after an installation campaign, which submerged the riverbank with a low water level and a short duration. The sensors installed from the crown (continuous lines) do not show any significant change, while those in riverbank (dotted lines) record a sudden response, consistent with the external stimulation.

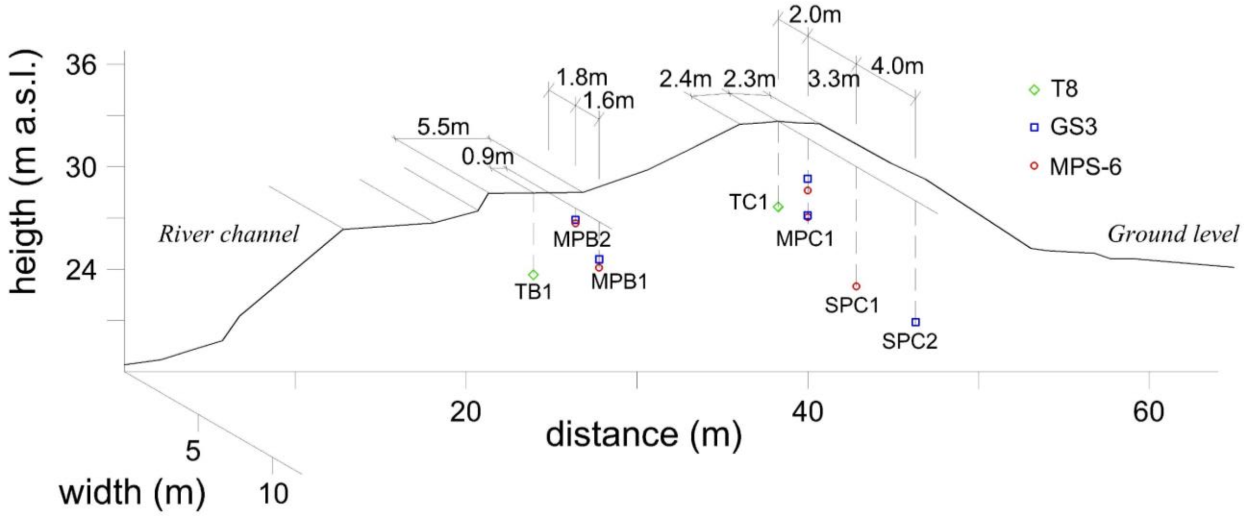

Figure 4. Layout of the monitoring points.

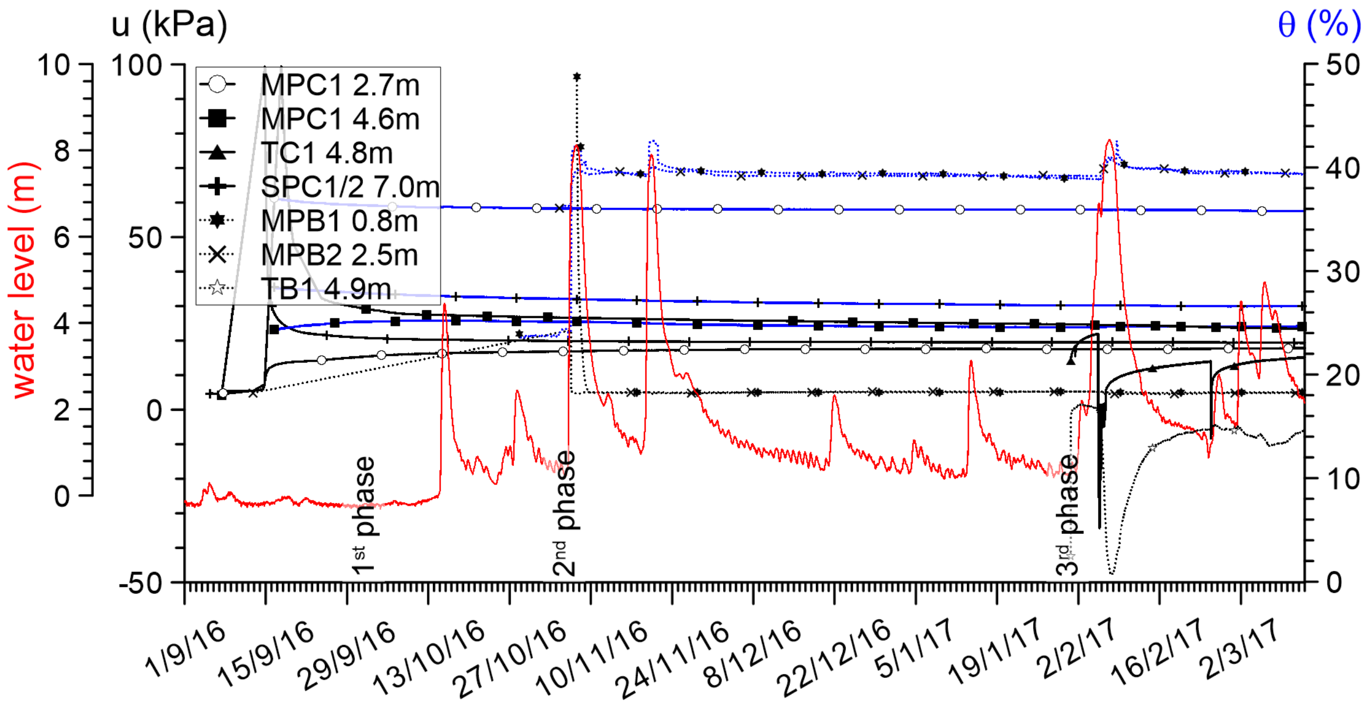

Figure 5. Measurements development with time.

The monitoring data show that the phreatic line is around 1.5 m below the ground level (i.e., 9 m depth from the crown) and the profile keeps a hydrostatic trend above the phreatic line and up to the central part of the embankment, but the suction then reduces towards the soil surface in the vadose zone, which is influenced by the external climatic conditions. The seepage analyses, used for comparison with monitoring data, were obtained using the procedure described in Gottardi et al. (2016) that uses model spin-up to achieve more realistic initial conditions for seepage analysis. For these analyses, initially the phreatic line was taken at 1.5 m below the ground level and the suction distribution was assumed to have a hydrostatic trend up to -5 m pressure head and thereafter a constant value; while the boundary conditions were considered hourly based on those registered since September 2015. Figure 6 shows the pore pressure profiles for 07/02/17 right after the maximum hydrometric level, overlapped with the results from 2D seepage analyses performed using Vadose/W (Geo-Slope International Ltd. 2008). The difference in pressure between two adjacent isolines is 10 kPa and the corresponding profiles at the measuring verticals are plotted as dashed lines. Good agreement is observed between the measurements of the tensiometer (TC1) and the MPS-6 (MPC1), but the absolute value of suction forecasted by the model in the embankment core is slightly higher than observed. In addition, the positive value recorded by the tensiometer in the bank (TB1) is lower than suggested by the model. This highlights the importance of field monitoring to validate the model.

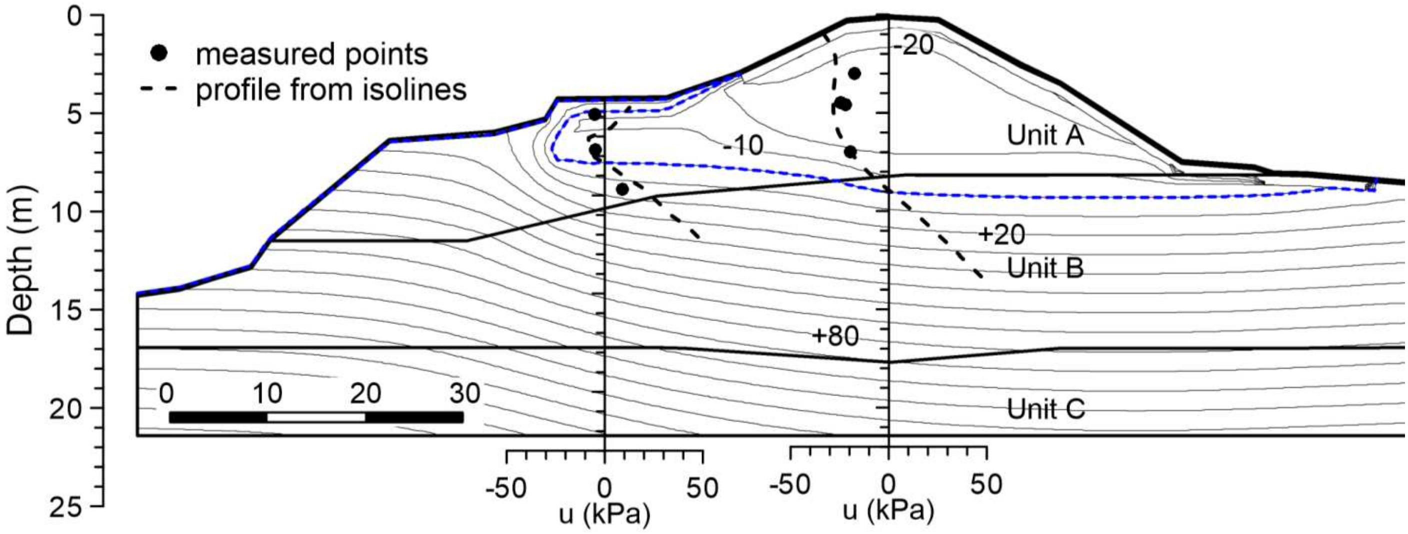

Figure 6. Comparison of pore pressure profile at 07/02/2017 from monitoring data (solid circles) and numerical model (isolines).

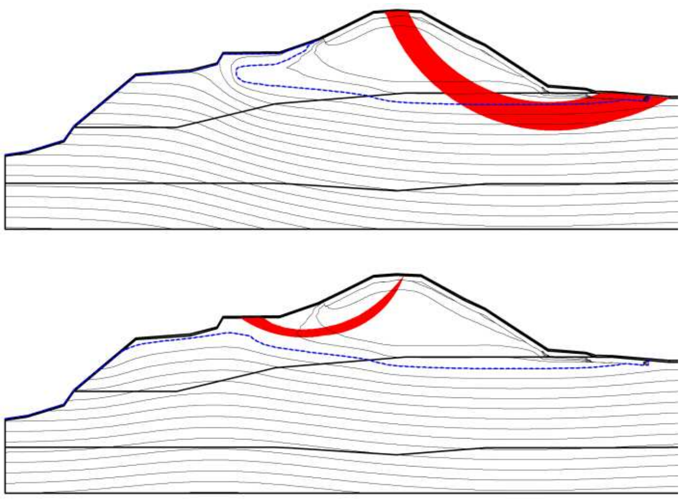

Figure 7. Riverbank safety map for outer slopes and inner slopes critical surfaces (07/02/2017).

Using the pore-water pressure distributions obtained on the previous analysis, stability conditions for the riverbank were studied by means of limit equilibrium analysis adopting the Morgenstern and Price method (Morgenstern & Price 1965). The analysis was performed on critical surfaces defined by specific geometrical constraints (e.g. entry and exit point range; minimum slip surface depth), to investigate the instability mechanisms. No random variables were introduced in the analysis. Figure 7 shows the estimated Safety map, referring to the high-water event registered from 05/20/2017 to 10/02/2017. The area where slip surfaces have the lowest factor of safety are drawn in red.

The stability analysis for the outer slope was performed at the time the hydrometric peak was reached (07/02/2017), because it represents the most critical scenarios for overall stability, while for the inner slope was considered the final part of the high-water event (10/02/2017). A minimum slip surface depth equal to 4 m and 1.5 m was assumed for the outer and inner slope stability, respectively. This provides values of Safety Factor (FS) in the range 1.74-1.94 for the outer slope and 2.92-3.12 for the inner slope. These results highlight a stable condition for the riverbank with respect to the studied collapse mechanisms, coherently to the limited influence of the high-water event on the pore pressure distribution. However, higher and more persistent water levels would cause a considerable reduction of suction and hence stability.

4 CONCLUSIONS

This paper presents the details of full-scale monitoring system at a river embankment cross section of the river Secchia and a set of preliminary monitoring data. The data collected from the site monitoring provide an indication on the unsaturated state for river embankments, representing an important source of knowledge to define seepage and stability characteristic for the structure. However, attention is required for the validation and verification of the collected data, using laboratory measurement for soil suction and water content, as showed by the results. When comparing the pore-pressure profiles within the embankment with results obtained based on numerical techniques, significant differences were observed. A proper interpretation of site measurements, however, requires significant high-water events, which would lead to remarkable variations in soil suction and water content values in the riverbank. The complementary use of laboratory testing, numerical analysis and field measurements represents a key point of this research project. Future work will cover comparison between in situ and laboratory soil water retention curves, calibration of the seepage model based on monitoring data and mechanical characterisation in view of a more accurate and extended assessment of the embankment stability.

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