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Assessing river embankment stability under transient seepage conditions

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Abstract

The evaluation of riverbank stability is a fundamental problem in flood risk management, representing a critical task for engineering practice. Soil heterogeneity together with initial and boundary conditions are among the crucial issues that should be considered to obtain an accurate solution of the problem. Generally, attention and efforts are mostly devoted to the soil characterization, the hydrometric level forecasts and the estimation of the rainfall intensity, while in situ measurements usually receive less attention. Nevertheless, suction and soil water content have a strong influence on the reliability of seepage and stability analyses. A preliminary study aiming at the design of a monitoring system for the measurement of soil moisture and suction in the unsaturated silty soils of a river embankment has been carried out, with the purpose of linking the collected data to the boundary conditions and hence obtaining a more accurate estimate of the riverbank probability of failure. Furthermore, a general outline of the research project, its methodology and application are presented in the paper.

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Keywords: Unsaturated soil; monitoring; river embankment; stability analysis; transient seepage

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1. Introduction

Riverbank safety assessment is one of the key issues in geohazard prevention. A proper and accurate analysis relies

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on the determination of transient seepage characteristics. On the other hand, these are strongly dependent on the initial and boundary conditions, as well as on the hydro-mechanical soil properties and on their variability, thus requiring a probabilistic approach. In standard engineering practice, attention is mostly devoted to the soil characterization, the expected water level and the estimation of the rainfall intensity, while the in situ water content and the relevant negative pore water pressure distribution usually receive less attention. For this reason, their influence on the probability of global and local failure is typically neglected. A preliminary study aimed at the design of a monitoring system for the in situ measurement of moisture and suction in the unsaturated silty soils of river embankments is presented. The goal is to link the monitoring data to the boundary conditions and hence obtain a more reliable estimate of the failure probability for the riverbank section under investigation. In this paper, soil water retention curves (SWRCs) obtained from laboratory tests and hydrometric and meteorological data measured at the site of interest have been implemented in the analyses to investigate the riverbank instability mechanism induced by soil water content and suction variations due to high water events. In particular, a series of bi-dimensional transient seepage and slope stability analyses has been performed, using a combination of VADOSE/W and SLOPE/W softwares [1,2]. Based on these analyses, the areas of interest for the field sensor installation have been identified.

2. Monitoring system and case study

The embankment cross section considered to design the monitoring system and to perform preliminary numerical analyses, refers to the river Secchia, which experienced a total bank's collapse on 19th January 2014. This flooding event involved approximately 38 million cubic meters of water and caused one casualty and long-lasting damages to a vast surrounding area. The bank cross section is characterized by a 7m high crown from the ground level and a 33° and a 30° slope towards the river and the land, respectively (Fig. 1). The soil stratigraphy is characterized by three main layers: Unit A, Unit B and Unit C. The first unit includes a complex mixture of sands, sandy silts and silty sands forming the artificial riverbank. The second unit, linked to the flood plain environment and mainly consisting of sandy and clayey silts, corresponds to the 7m thick foundation of the riverbank infrastructure. The bottom layer, which was scarcely involved in the analyses, consists predominantly of a clayey unit and can be found from 12m depth. Generally, Unit A and B have similar characteristics, having less than 10% clay and a variable amount of sand, ranging from 20 to 50%. Unlike Unit C, the soil has low plasticity and plastic to semi-solid consistency. More details regarding the geometrical and geotechnical data can be found in D'Alpaos et al [3]. In Figure 1 the blue dotted line having a 1:4 slope represents the saturation line frequently assumed in preliminary design. The hatched area is what would be interested by the monitoring system proposed, above a realistic phreatic blue bold line, as obtained from the analyses that will be described later on. The instruments that will be implemented in situ are based on methodologies widely used in agronomic and geotechnical applications, as Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR) for the soil water content and tensiometers and piezometers for the pore water pressure. More specifically, a number of verticals will be considered in the selected section, located on both the central part of the riverbank and along its sides, installing the monitoring probes at different depths. However, a crucial and novel issue will be the reliable installation methodology of the proposed instruments at depth, in order to reach the whole hatched area of Figure 1. Subsequently, the data collected in real-time could be used, together with forecasted hydrometric levels, to assess the riverbank stability conditions.

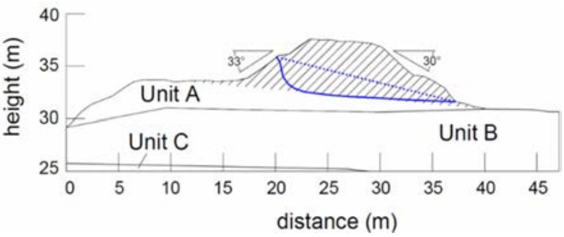

Fig. 1. Schematic stratigraphy and geometry of the riverbank: the area of interest for monitoring is hatched. Blue dotted and full lines represent the phreatic line for preliminary design and a realistic transient seepage condition, respectively.

The hydrometric data used in the following analyses were collected on the Secchia river from the stream gauge at Ponte Bacchello (Lat. 44.747546, Lon. 10.98734) north of the city of Modena, with an hourly sampling frequency; while the relative humidity, temperature and precipitation data were recorded by a meteorological station at Cortile di Carpi (Lat. 44.778387, Lon. 10.971285), about 4.5km away. The strength parameters and the main hydraulic properties of the three units, showed in Table 1, were obtained by a combination of in situ and laboratory tests [3]. More specifically, a number of CPTU and direct shear and triaxial tests was carried out, which allowed an estimate of φ' and its statistical parameters. Furthermore, in situ permeability tests and direct permeability measurements in triaxial and oedometric cells were carried out to estimate the water hydraulic conductivity. This was also indirectly obtained by means of CPTU soundings and dissipation tests. In addition, a few evaporation tests were carried out with the Hyprop device (UMS), which will be described in more detail in the following section.

Table 1. Estimated average values of the most relevant soil parameters. [1] standard deviation in brackets.

	φ' (°)	c' (kPa)	k (m/s)
Unit A	32.0 (1.94)[1]	0	$1.57\cdot10^{-6}$
Unit B	28.8 (3.20)[1]	0	$1.88\cdot10^{-6}$
Unit C	24.9 (2.40)[1]	0	$1.30\cdot10^{-9}$

3. Experimental measurements of permeability

As already mentioned, experimental measurements of the hydraulic conductivity were carried out in several ways, obtaining a range of values considerably different (Fig. 2a), due to a variety of boundary, stress and/or saturation conditions. In addition, the direction of measurement might also have an effect, due to inherent anisotropy. In particular, the values obtained by Lefranc permeability tests compared to those computed from CPTU tests, on the basis of the Soil Behavior Type index proposed by Robertson [4], show significantly higher values. For the purposes of preliminary analyses, k was calculated along the whole CPTU sounding according to Robertson's correlation [4] and the mean value for each unit was taken as the relevant parameter, enabling a statistical distribution analysis. Regardless of the value assumed at saturation, a model describing k vs. saturation is required in the stability analyses proposed. The parameters of the van Genuchten–Mualem model [5] in VADOSE/W were thus calibrated based on the measurements carried out by the HYPROP device (UMS), whose software TENSOVIEW allows to fit the SWRC and k using coupled parameters. In Figure 2b the experimental data and fitting curves can be observed for the SWRC and k of a single test, where four evaporation stages were carried out spaced by wetting phases. In particular, the air entry value ($1/\alpha$) appears to be difficult to identify as the SWRC retains a flatter slope than allowed by the model. The saturated and residual water contents were measured experimentally, but it should be pointed out that they slightly vary with the soil void ratio. As a consequence, n is the only parameter that needs to be estimated, but does not greatly affect the fitting line. If different evaporation cycles are used to estimate the SWRC or k, the parameters slightly change, but overall unique values can be found that describe reasonably well the whole set of evaporation curves. This may not be true when trying to fit a wetting curve.

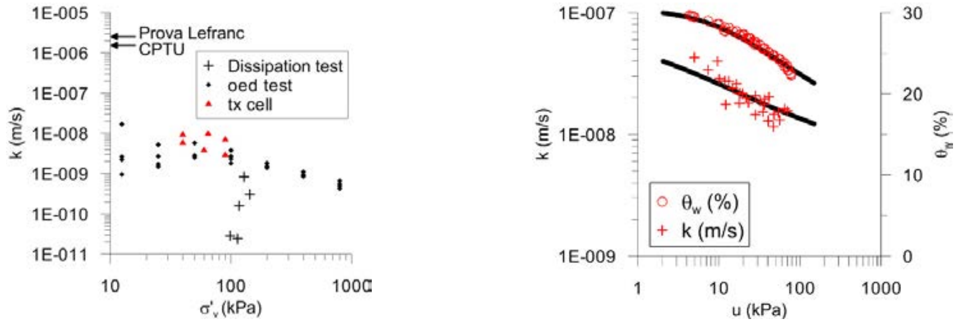

Fig. 2. Experimental values of permeability coefficient: (a) conventional measurements and (b) carried out during evaporation tests.

4. Numerical Analysis

4.1. Seepage modelling

Transient seepage analyses were carried out using VADOSE/W, a Finite Element software capable of solving saturated and unsaturated seepage problems where the soil-atmosphere interaction is involved. The software includes a comprehensive infiltration modeling tool that accounts for precipitation, actual evaporation and transpiration, runoff and storage. The adopted mesh consists of an unstructured assembly of approximately 13500 triangular and quadrangular elements, with an approximate global size of 0.25m. To determine the flow regime for both saturated and unsaturated conditions, the model performs a two-dimensional finite element numerical analysis using the seepage partial differential equations [1]. The Penman-Wilson method [6] is then adopted to compute the actual evaporation as a function of the estimated potential evaporation. The relative humidity of the soil surface is evaluated by simultaneously solving coupled moisture and heat flow equations. It should be pointed out that the effects of wind and vegetation have been disregarded for simplicity and the values of thermal conductivity and volumetric heat capacity of the superficial layer taken from the literature [7], due to the lack of more specific information.

4.2. Initial and boundary conditions

The definition of initial conditions represents a crucial point for transient seepage analyses and the relevant assumptions strongly affect the assessment of the riverbank stability during its lifetime. Nevertheless, direct measurement of soil water content and suction are rarely available in engineering practice and simplistic hypotheses on their distribution (e.g. fully saturated conditions or hydrostatic suction pattern above the phreatic line) can lead to unrealistic predictions of the risk analysis. In the present study, an initial condition was first assigned in terms of suction distribution, assuming the water table at 29m a.s.l. and a hydrostatic suction pattern up to 40kPa. Afterwards, a transient coupled hydro-thermal analysis from 15th July 2013 to 14th July 2014 was performed with VADOSE/W for model spin-up, using the climatic and hydrometric data (Fig. 3) locally measured. The PWP distribution obtained for 15th July 2014, 00:00, was then used as the initial condition for the subsequent seepage numerical analyses. The spin-up time was considered sufficient to erase the effect of different hypotheses on the initial PWP and to provide realistic suction and PWP distribution in the embankment [8,9,10]. In situ measurements, such as those proposed herein, could provide experimental evidence of the results obtained by this numerical expedient. To account for the soil variability, five sets of input hydraulic parameters were used for Unit A, differing for the assumed values of saturated hydraulic conductivity k and α parameters of the van Genuchten soil water retention curve (Table 2). Average constant k values were used for Units B and C, mostly in saturated conditions and not being actively involved in the failure mechanisms. In particular, Set 1 assumes the hydraulic properties equal to the average values estimated during the geotechnical characterization, while in Sets 2 to 5 each considered parameter is in turn modified to account for the estimated site variance. Based on the analyses carried out, the embankment stability was then evaluated for two specific high water sequence events, indicated by the dashed-dot red and blue lines in Figure 3, to highlight the importance of initial conditions.

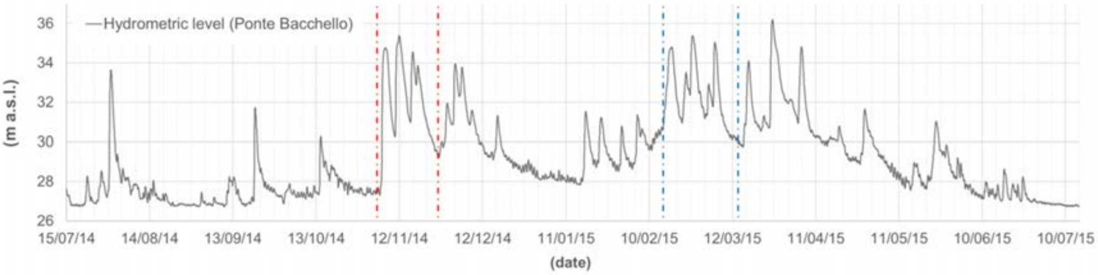

Fig. 3. Hydrometric levels recorded at Ponte Bacchello.

An example of the PWP distribution obtained performing seepage numerical analyses is showed in Figure 4a, obtained with the parameters of Set 1. The increment between two adjacent isolines is 10kPa and the blue bold line indicates the phreatic line. It is easily observed that the PWP gradient is very high along the embankment sides and the phreatic line is rather different from what usually assumed in design practice.

Table 2. Hydraulic parameters for Unit A used in the transient seepage analyses.

	Set 1	Set 2	Set 3	Set 4	Set 5
α (kPa)	6.110	4.905	14.014	6.110	6.110
k (m/s)	$1.57{\cdot}10^{-6}$	$1.57{\cdot}10^{-6}$	$1.57{\cdot}10^{-6}$	$5.80{\cdot}10^{-6}$	$1.36{\cdot}10^{-7}$

4.3. Stability analysis

In order to study the riverbank stability conditions, its evolution and dependency on soil hydraulic properties and suction distribution, a series of limit equilibrium analyses was performed in correspondence of the three main peaks of the hydrometric level for each of the two considered events. Using the PWP distributions obtained by the previous seepage analyses, the stability of the embankment was studied by means of the Morgenstern and Price method [11] and the Vanapalli failure criterion [12] to account for the unsaturated soil strength contribution; detailed analyses focusing on the role of partially saturated soil strength in the stability assessment of the considered embankment can be found in Gottardi and Gragnano [13]. The analyses were performed through Monte Carlo method (100,000 simulations) on critical surfaces defined by specific geometrical properties, to investigate in particular the most critical landward instability mechanisms (Fig. 4b), the minimum slip surface depth being 4m . The results of the stability analyses were quantified in terms of the reliability index (β=(μ_{SF}-1)/σ_{SF}), where μ_{SF} is the mean value of safety factor and σ_{SF} its standard deviation. The values obtained are provided in Table 3, for each input dataset and the six calculation steps, corresponding to the peaks of the hydrometric levels registered during the two considered events. A higher β value represents a lower probability of failure for a given collapse mechanism. With reference to the landward slope stability assessment, the results and their evolution with time show a strong effect of the initial conditions and the hydrometric levels. Although β values are largely positive, the difference between the first peaks of each event results in differences in the probability of failure (Pf) of approximately one order of magnitude for most cases. Set 5 represents an exception, since the lower k value decreases the possibility of water flow through the riverbank during the dry period, characterized by a high suction distribution (e.g. during Event 1 or for the first high water level during Event 2). As a consequence, β estimates clearly show safer conditions when compared to other considered cases. However, the influence of the initial conditions on landward slope stability assessment can be clearly seen when comparing β values at the end of the two events, showed in Table 3. For all the input datasets results highlight that the initial suction distribution assumed can strongly influence the global safety conditions at the end of both transient seepage analyses, here characterized by similar boundary conditions. Therefore, a direct measurement of the initial conditions, both in terms of soil water content and suction, could reduce the uncertainties related to the retention and hydraulic properties determination. Moreover, additional stability analyses have been performed to investigate other failure mechanisms, like along the riverside embankment slope; such results have not been reported here for the sake of brevity, as their interpretation require considering various issues, like the strong influence of the variability rate of water levels, the soil shear strength properties and the specific PWP distribution.

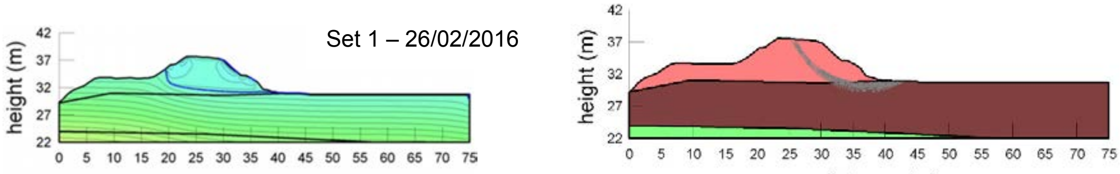

Fig. 4. (a) Pore water pressure distribution for transient seepage analysis: increment between two adjacent isolines is 10kPa and the blue bold line indicates the estimated phreatic line; (b) Slip surfaces obtained by limit equilibrium analyses for the landward slope.

Table 3. Results of the probabilistic stability analyses by means of the reliability index β.

	Date	Set 1	Set 2	Set 3	Set 4	Set 5
		Landward slope				
Event 1	07/11/2014	5.867	5.615	6.460	6.064	6.165
	12/11/2014	5.825	5.594	5.070	4.877	6.127
	16/11/2014	4.654	4.642	4.564	3.984	6.092
Event 2	18/02/2015	4.818	4.908	4.999	4.685	5.957
	26/02/2015	4.024	3.969	4.150	3.736	4.774
	06/03/2015	3.641	3.494	4.081	3.582	4.337

5. Conclusions

The results discussed herein show the importance of initial/boundary conditions and of soil hydraulic parameters in assessing the slope stability of river embankments. In particular, similar high water levels may be more or less critical whether they occur at the beginning of the wet season or afterwards. In addition, numerical expedients and experimental pitfalls with regards to current best practice have been discussed. On the basis of the results obtained, the area of interest for the installation of the monitoring system has been identified, reaching depths beyond 5m. The proposed field sensors, which include frequency and time domain reflectometers and tensiometers, are widely used in agronomy as well as in geotechnical engineering, but they have not been typically used for monitoring riverbanks at multiple depths and in association with the relevant stability analyses. In particular, their proper and reliable installation at the required depth is an especially challenging task, with the final aim of gaining further confidence when dealing with safety of water infrastructures.

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