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Experimental study on a partially saturated soil of a river embankment

Études expérimentales sur un sol partiellement saturé d'une berge

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ABSTRACT: River embankments are usually designed as earthen structures to retain hydrometric level fluctuations. Filling materials generally adopted are intermediate soils, consisting of natural silty soils with limited sand and clay content, compacted during construction process for both ensuring their mechanical stability and limiting the water flow through the embankment itself. The evaluation of time-dependent seepage and stability characteristics of riverbanks, which represents a crucial step for their vulnerability assessment, is strongly influenced by the unsaturated soil behaviour. Within this framework, a comprehensive experimental study has been carried out to explore the mechanical and retention properties of a river embankment silty soil under partially saturated conditions. Oedometric and direct shear suction-controlled tests have been carried out on soil sampled from a field instrumented riverbank section, where an extensive monitoring system with suction and water content measurements has been recently implemented. The results of laboratory investigations are presented and discussed. Comparisons with monitoring data and similar laboratory tests performed in saturated conditions are also provided, in order to highlight the importance of an accurate characterization of the unsaturated soil behaviour for a realistic estimate of the river embankments stability and for the relevant reliable safety assessment.

RÉSUMÉ: Les berges rivières sont souvent conçu pour contenir les fluctuations du niveau de la rivière. En général, le matériau de remplissage employé est un sol intermédiaire, composé par sol limoneux naturel avec faible teneur de sable et argile. Ces matériaux sont compactés pendant les processus de construction de la berge fluvial tant pour assurer la stabilité de la berge que pour réduire la circulation de l'eau au sein de la berge. Les matériaux de remplissage de la berge sont caractérisés par leur état partialement saturé, qui a une signifiante influence sur les propriétés mécaniques et hydrauliques du sol et qui peut avoir évolutions spatiales et temporels.

En ce papier, un étude expérimentale a été effectué pour examiner les caractéristiques hydromécaniques d'un sol limoneux partiellement saturé de la berge et a été exécuté sur essaies intacts au travers de appareils œdométriques et de cisaillement direct a succion contrôlée. Les essais ont étés rassemblés sur une section de la berge instrumentée avec détecteurs de mesure de la succion et du contenu d'eau. Les résultats sont décrits et examinés ici. Une comparaison entre les résultats expérimentales obtenus dans le laboratoire et in situ est aussi proposée afin de souligner que une caractérisation rigoureuse du comportement du sol partialement saturé est vital pour une estimation réaliste de la stabilité et de la sécurité d'une berge.

Keywords: River embankment; unsaturated soil; laboratory testing; suction measurement; retention curve.

1 INTRODUCTION

Flood events represent an important source of risk for European hydraulic protection systems, producing significant distresses and damages wherever they occur. It has been estimated that, from 1998 to 2009, more than 1100 fatalities and the evacuation of around half million people have been caused by the combination of flooding from rivers, estuaries and sea (Feyen and Watkissy, 2011).

Another critical value is the estimated annual damage (EAD), which for the period 1980 – 2011 has increased from an average of €6 billion per year to around €20 billion per year (Kundzewicz et al., 2013), revealing a warning trend in the last decades. Flooding consequences significantly depend on local and socio-economic conditions, including protection measures (e.g., levees, dams, river management, dredging, flood warning systems), geomorphology and climatic conditions.

The use of earth-filled embankments to retain river and water courses, in general, represents a typical solution of land-use planning. These linear infrastructures are designed to limit the seepage process induced by hydrometric fluctuation and to ensure adequate margins of safety, during their lifetime, towards the possible occurrence of local or global collapses. Being the embankment design actually based on the maximum expected water level for a given return period, a significant volume of the filling material is typically in partially saturated conditions, thus characterized by suction values variable with time and depending on initial and boundary conditions. These aspects play a crucial role in the hydraulic and mechanical response of the river embankments, directly influencing seepage, stress-strain and strength soil behaviour (Gottardi et al., 2016).

An efficient and reliable analysis of the performance of these infrastructures requires both a careful characterization of the unsaturated properties for the filling materials and extended measurements of soil suction and water content in situ (Rinaldi et al., 2004; Hughes et al., 2009; Mendes, 2011; Calabresi et al., 2013; Toll et al., 2016). Unfortunately, these investigations are largely neglected in standard engineering practice, the former being generally performed only for research applications and the latter rarely available in real cases. This lack of knowledge often produces strong and undefined uncertainties in risk assessment procedure, due to the large use of simplified assumptions in seepage and stability analysis of riverbanks (Gottardi and Gragnano, 2016).

Aiming at extending the applications of unsaturated soil mechanics to practitioners and national guidelines, an experimental study has been implemented on a specific section of a riverbank system in Northern Italy, which included field monitoring of the main properties affecting seepage and stability (e.g. soil suction and water content).

In this framework, various laboratory tests for hydraulic and mechanical soil characterization have been carried out, both in saturated and unsaturated conditions. The results obtained from both site and laboratory activities are then compared to highlight the importance of specific experimental investigations for a reliable soil characterization and the subsequent suitable assessment of riverbank seepage and stability.

2 METHODOLOGY

2.1 Study area and monitoring system

The experimental site selected for the present study has been presented in previous publications and is here only briefly described. An embankment section of the Secchia River, near Modena (Italy) was highly instrumented using capacitative sensors for indirect measurement of soil suction (Meter Group, 2016a), frequency domain reflectometer for indirect measurement of water content (Meter Group, 2016b), temperature, included in both the previous sensors type, and pore water pressure with Casagrande piezometers and tensiometers. The principal aim is to achieve a realistic and up-to-dated estimates of the margins of safety using monitoring data as key information (Rocchi et al., 2018a).

The embankment geometry can be roughly represented by its maximum height of more than 10m from the ground level, riverside slope of about 30° and land side slope of 25°. The berm width ranges from 5 m to 10 m, so that the embankment structure - relatively to its height - appears rather small and therefore the hydrometric fluctuations can frequently induce changes in suction and water content inside the embankment body through seepage processes.

This aspect can maximize the variability of unsaturated soil state parameters induced by high-water level. An important detail of the monitoring system is represented by the coupled measurement of soil water content and suction.

This target was achieved installing both suction and water content sensors (e.g. MPS-6 and GS3) at closer depth in the same or in adjacent boreholes (namely, multiple and single point installation, MP and SP). A sketch providing an example of of both single and multiple instrumented verticals is shown in Figure 1.

Details on installation methodologies and procedures can be found in Rocchi et al. (2018b). For the present case it was possible to obtain site-specific information on retention soil properties and water characteristic curves, which are also dependent on soil porosity and net stress (σ_v - u_a), i.e. difference of total vertical stress and pore air pressure. The information collected during installation and preliminary monitoring data were useful to set up a laboratory programme, which also included direct shear and oedometric tests in suction-controlled conditions, consistent with the research purpose and representative of the actual site conditions. Monitoring data and experimental results have been, then used for comparison and soil characterization.

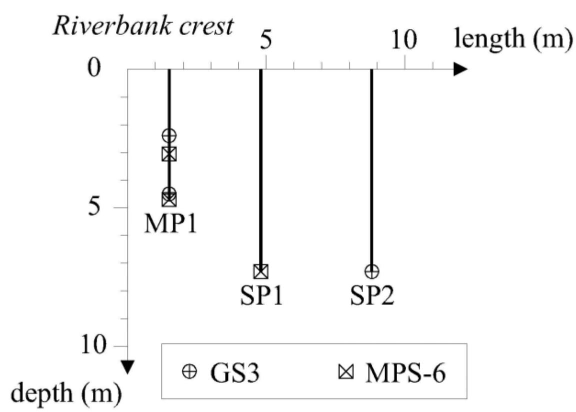

Figure 1. Example of sensor coupling for measurement of SWRC in situ, within single and multipoint installation configurations.

2.2 River embankment material

The design of the monitoring system and the execution of suction-controlled laboratory tests have been planned after preliminary soil classification and physical characterization carried out through site investigations and conventional laboratory test. The embankment material, in particular, mainly consists of a single heterogeneous unit, about 8.0m thick, characterized by a complex alternation of silt and sandy silt, having a sand content varying from 25 to 50%, while silt accounts for 40 to 60%.

A series of 14 particle size distributions are plotted in Figure 2 as obtained on samples collected at depth ranging between 1.5 m and 6.9 m from the embankment crest. The curves exhibit large variation of both curvature coefficient (between 0.1 and 5.6) and uniformity coefficient (between 9 and 133). Intrinsic heterogeneity has been observed from grain size analysis, deriving from the construction process of the specific riverbank sector, which relied on progressive compaction of site-available natural soils.

A series of four CPTU were executed in the study area during the dry season, both from the top of the embankment and berm, with investigation depth ranging from 15m to 25m from the berm and the crest, respectively. Results obtained from site and laboratory investigation generally provide consistent description for riverbank soil unit.

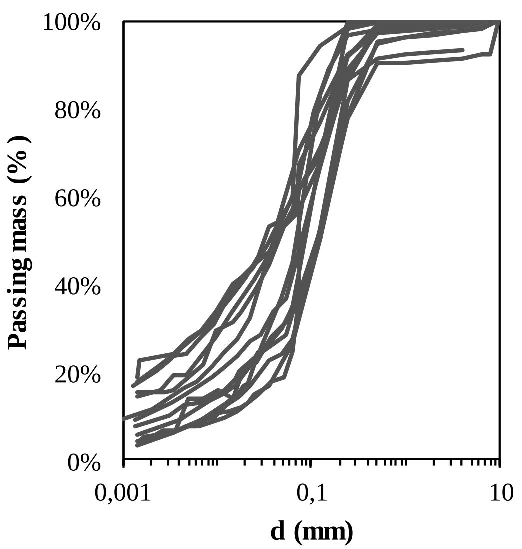

Figure 2. Particle size distribution of filling material.

2.3 Testing programme

The experimental program on the river embankment silty material was aimed at investigating mechanical and hydraulic soil behaviour, both in saturated and unsaturated conditions.

Various types of testing devices were used, measuring variables of interest in different laboratory-controlled conditions. A series of three Direct Shear tests (DS) under saturated conditions were performed at vertical stress in the range 50 kPa – 120 kPa, on intact and remoulded specimens sampled at depth ranging from 4.05 m to 4.25 m from the embankment crest. Aimed at the study of the soil retention behaviour up to suction of about 85 kPa, two Evaporation Tests (ET) (Wendroth et al. 1993; Romano & Santini 1999) were performed on both intact and remoulded specimens and sampling depth of 4.3 m and 4.8 m.

In addition, suction-controlled oedometer and suction-controlled Direct Shear tests were performed on intact specimens sampled at depth ranging from 5.0 m to 5.5 m. All the tests were performed keeping the vertical net stress constant and equal to 90 kPa, which is representative of the in situ stress conditions at the sampling depth, almost constant during the life of the structure. Suction values ($u_w - u_a$) considered for the tests varied from 50 kPa to 75 kPa, which represent an upperbound for the study case. Both wetting and drying paths were performed in Unsaturated Oedometer device (UOE), while only wetting paths were considered in Unsaturated Direct Shear device (UDS) (Gragnano et al., 2018). Retained water content at the prescribed values of suctions were determined at site-specific (UDS and UOE) and null net stress (ET) conditions, representing a useful source of information for interpreting monitoring data. Furthermore, results achieved from DS and UDS were used to compare shear strength behaviour. The laboratory setup and details are summarized in Table 1.

Table 1. Laboratory tests and relevant setup

Depth (*m*)	**Sample state**	**Test type and ID**	$\mathbf{e_0}$ (-)	$\mathbf{\sigma_v - u_a}$ (*kPa*)	$\mathbf{u_w - u_a}$ (*kPa*)
4.3	I	ET01	0.626	0	0-100
4.8	R	ET02	0.675	0	0-100
4.3	I	DS01	0.732	70	0
4.1	R	DS02	0.913	50	0
4.1	R	DS03	0.669	120	0
5.5	I	UDS00	0.470	90	0
5.2	I	UDS01	0.530	90	75
5.3	I	UDS02	0.679	90	50
5.5	I	UDS03	0.508	90	60
5.1	I	UOE01	0.859	90	0-100
5.4	I	UOE02	0.608	90	0-100

R = Remoulded; I = Intact; e_0 = initial void ratio; σ_v - u_a = vertical net stress; $u_w - u_a$ = matric suction

3 DISCUSSION OF RESULTS

3.1 Soil retention behaviour

Soil suction and water content measurements from laboratory test are together plotted as the Soil Water Retention Curve (SWRC). Figure 3 shows the results obtained in drying paths in the laboratory tests, specifically ETs and UOE.

The differences observed in retention curves obtained from ET1, ET02 and UOE01 are mainly due to differences in e_0, which result in higher saturated water content and lower air-entry value with increasing e_0. Similar slope of SWRCs, however, are evidenced for test performed on intact samples. Black lines plot the SWRCs obtained from an interpretation of the laboratory data by means of the van Genuchten-Mualem model (van Genuchten, 1980) as continuos, dashed and dashed-dot for ET02, ET01 and UOE01, respectively.

In Figure 4 the experimental data obtained from laboratory and site measurements are compared, where the latter are obtained plotting values of soil suction and water content at the same depth.

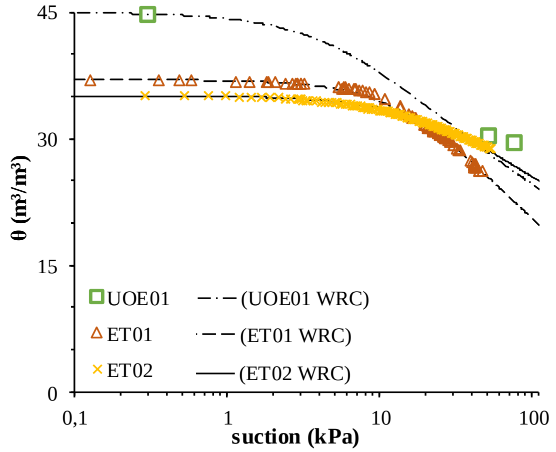

Figure 3. SWRCs from drying paths through ET and UOE laboratory test.

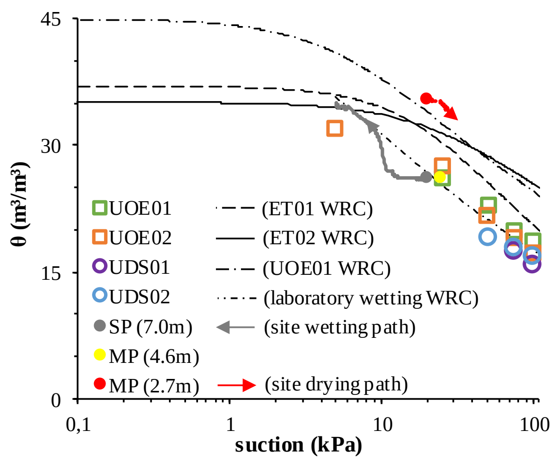

Figure 4. SWRCs from wetting paths through suction-controlled laboratory tests and monitoring data.

The data refer to the period December 2017 – February 2018. Specifically, wetting paths are evidenced for soil at 7.0 m depth and drying paths at about 2.7 m depth for the same period.

At greater depth, the riverbank filling material is influenced by changes of the in situ water table conditions.

On the contrary, at shallower depth, smaller variations in the drying path are measured, mainly due to soil-atmospheric interaction. Stable measurements are collected at 4.6 m depth. It can be here observed that site retention states plot approximately on the drying and wetting main paths evidenced by the UOE and UDS test, confirming the reliability of the retention data obtained considering the stress states and hydraulic paths representative of in situ conditions.

3.2 *Stress and strain behaviour in shear*

Test UDS01, UDS02 and UDS03 were performed at constant suction of 75, 50 and 60 kPa, respectively. This testing strategy was aimed at characterizing the soil strength behaviour at site-specific conditions. In addition, using the same testing device, an additional direct shear test was performed under suction approximaly equal to zero (test UDS00).

The results are interpreted using Bishop's Effective Stress (1959) for partially saturated soils. The shear stress measured are, then, plotted in Figure 5. Most of the tests showed an hardening behaviour and the peak resistance is only evidenced in specimens with high suction and low initial void ratio (e.g. UDS01).

Figure 6 plots results obtained from various tests in terms of variation of saturation degree (ΔS_r) and void ratio (Δe) at increasing horizontal displacement (Δx), normalised with respect to the effective base length of the sample (b′). The specimens at suction 50 kPa and 75 kPa exhibit dilative behaviour, while the specimens UDS00 (nil suction) and UDS03 ($u_w - u_a = 50$ kPa) exhibit contractive behaviour. Only limited variations in degree of saturation are generally measured using water exchanged between the specimen and external reservoir.

The specimen UDS02 showed largest variation of degree of saturation (ΔS_r<10%), while the absolute ΔS_r of other specimens are lower than 2%. Insignificant variation of saturation degree were observed upon shearing. Two shear strength envelopes have been obtained (Figure 7) for saturated (black dashed line) and unsaturated (red dashed line) specimens.

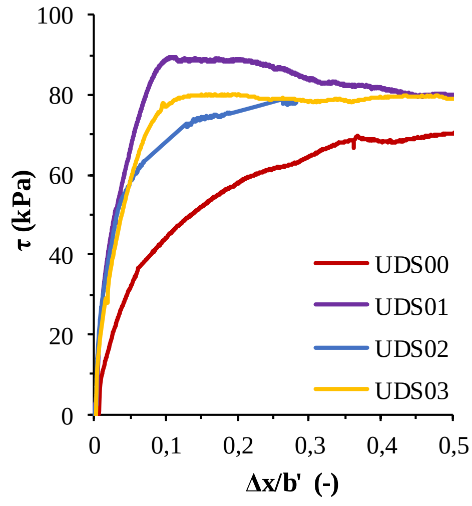

Figure 5. Stress-strain soil behaviour in shear stage under suction-controlled conditions.

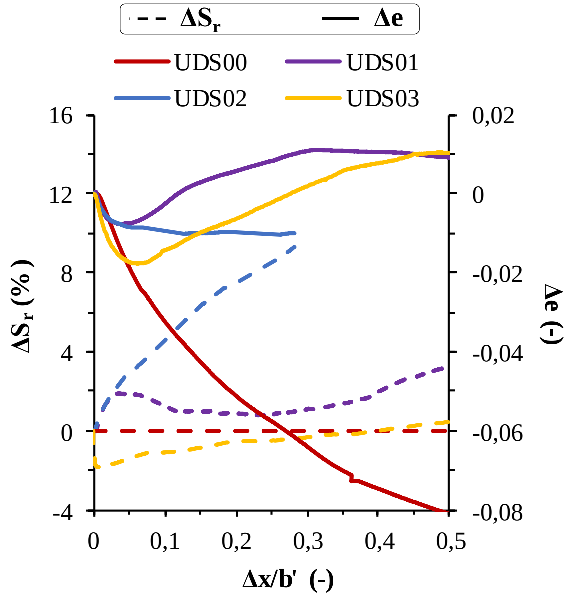

Figure 6. Hydraulic and volumetric soil behaviour in shear stage under suction-controlled conditions.

Two friction angles were evaluated at saturated (φ'=35.4°) and at unsaturated conditions (φ'=35.0°).

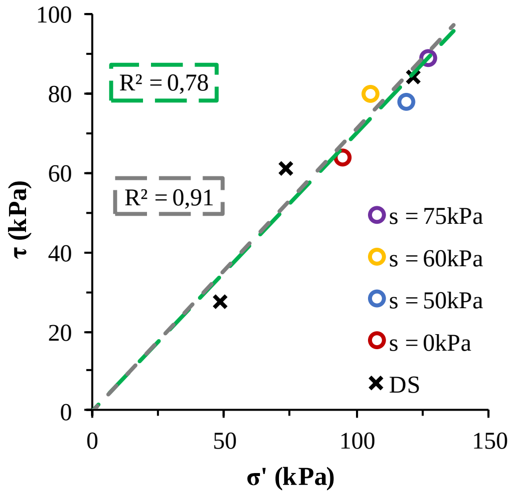

Figure 7. Failure envelope for the embankment filling material from DS tests in both saturated (grey dashed line) and unsaturated (green dashed line) conditions.

Although the difference between the two angles is only 0.4°, which can be consider negligible, the difference between the two coefficients of variation (R^2) is silgthly higher. However, linear relationship for τ(σ′) is here sufficient to represent soil shear strength properties, with vertical intercept (effective cohesion) set equal to zero.

4 CONCLUSION

An extensive experimental study on a river embankment material has been here presented and preliminarily discussed. Various methodologies of analysis have been considered, including field measurement of suction and water content at different depths and laboratory tests. These included both saturated and unsaturated tests, also performed under suction-controlled conditions. Consistent comparison of results showed the importance of properly considering site-specific conditions (in terms of net stress and hydraulic paths) for a reliable interpretation of monitoring data. The use of standard interpretation (e.g. Bishop's Effective Stress formulation) of suction-controlled shear tests evidenced an acceptable agreement with similar data obtained from tests carried out in saturated conditions, providing a significant reliability to the experimental outcomes, performed with different devices and methods. Further analyses and discussion are necessary for an advanced interpretation of soil mechanical and retention properties, which would require a more comprehensive laboratory testing programme to account for different stress and hydraulic conditions and to include soil heterogeneity in the study case.

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