Laboratory measurement of the mechanical and retention properties of a river embankment silty soil in partially saturated condition

C.G. Gragnano & G. Gottardi
Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Italy

M. Moscariello, S. Cuomo
Department of Civil Engineering, University of Salerno, Italy

I. Rocchi
Department of Civil Engineering, Technical University of Denmark, Copenhagen, Denmark

ABSTRACT: The unsaturated condition is a significant feature to be taken into account for the reliable evaluation of seepage and stability characteristics of river embankment during their lifetime and especially in the periods of high river water levels, as this has strong influence on the mechanical and hydraulic behavior of the soil. However, this is not specifically considered under the standard assessment procedures and current design guidelines. Accounting for unsaturated soil condition, actual stress states and hydraulic paths representative of in situ conditions would eventually lead to more reliable safety analyses and optimized design criteria. In this context, an extensive specific experimental programme has been carried out on intact specimens sampled from a riverbank, aiming at comprehensively characterizing the unsaturated soil behavior. The present study focuses on the laboratory devices used and the investigation methodologies, which included suction-controlled oedometer, direct shear and evaporation tests. Relevant data interpretation and comparison are also briefly presented and discussed. The main purpose of this contribution is to underline the practical implications of the use of advanced laboratory tests in the stability analysis of river embankments.

1 INTRODUCTION

Safety assessment of river embankments represents a significant problem in geohazard prevention and land-use planning, due to high variability in time-space domains and significant sources of uncertainties. These earthen infrastructures, for all their lifetime, are generally in partially saturated condition, which plays a key-role in the hydraulic and mechanical behaviour of filling materials (Jommi & Della Vecchia 2013). Substantial differences in suction and water content values are encountered at different times and locations beneath the ground surface. These result from variable boundary conditions impacting the system (e.g. hydrometric water level rise and drop, water table fluctuation and atmospheric coupling), possibly with heavy consequences on seepage and stability characteristics (Calabresi et al. 2013; Cuomo et al. 2014; Liang et al. 2015; Gottardi & Gragnano 2016).

The determination of the actual suction and water content distributions in the field, as the unsaturated soil behaviour under site stress conditions, represents a key-point for reliable and accurate riverbanks and slopes safety assessment. However, since the pioneering studies by Ng and Shi (1997), this problem is still a demanding task for both standard and research applications in geotechnical studies, often requiring a suitable combination of site monitoring and advanced laboratory testing (Hughes et al. 2009; Toll et al. 2012; Pirone et al. 2014; Tarantino et al. 2016; Moscariello et al. 2016; Cuomo et al. 2017).

With the aim to gain a clear knowledge on the unsaturated conditions of soil and its time variability, a full-scale riverbank section has been extensively instrumented using different probes for soil water content and suction measurements. Combined to site monitoring, advanced laboratory tests have been performed for the interpretation of data collected in situ and to reach a comprehensive confidence with physical, hydraulic, retention and mechanical parameters of soils of interest for seepage and stability characteristics of the riverbank. Specifically, the influence of site-stress conditions on soil retention behaviour have been studied through suction-controlled oedometric tests for undisturbed soil sampled at specific depths of interest. Then, a series of direct shear tests were completed under controlled suction values, aimed to investigate the soil stress-strain behaviour. The experimental results were compared to both the data collected in situ and the results obtained from simpler tests, performed at null net stress for estimating the soil water characteristic curves. Such comparison highlighted the importance to consider the site-specific saturation and stress conditions for a truthful geotechnical characterization. The preliminary results and observations achieved from the laboratory activities and monitoring campaign are hereafter presented and discussed, with the final purpose to be implemented and used for the determination of riverbank seepage and stability characteristics.

2 MATERIALS AND METHODS

2.1 *Experimental site and monitoring system*

The riverbank section considered for the experimental investigations is part of the river Secchia (Po tributary) retaining water infrastructure, North of Italy. The specific bank cross section has an 8.5 m high crown, referred to the ground level, an average 25° slope towards the river and 31° towards the land. The river longitudinal profile is locally straight and a morphologically quite flat ground surface surrounds it, at an altitude of about 24 m a.s.l.. Site investigation involved the execution of cone penetration tests including pore-pressure measurements (CPTU) running up to a 15-25 m depth. In addition, disturbed and undisturbed soil samples were taken at depths between 1.8 m and 6.8 m from the embankment crown. The riverbank was selected, among the most critical spots in the area, also due to its geometrical and filling material characteristics, which guaranteed the possibility to implement a deep monitoring system and partially saturated conditions in the riverbank. Concerning the monitoring of the experimental site, here briefly presented and sketched in Figure 1, the soil suction sensors used are the MPS-6 (Decagon Devices 2016a) and T8 (UMS 2011) by Meter Group, while the GS3 probes (Decagon Devices 2016b) are adopted for the soil water content. 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 berm. A couple of suction and soil water content probes were placed, at each depth considered, with the exception of the measuring point at 4.6 m depth from the river berm, consisting of a single tensiometer able to monitor water pressure in the range -85 kPa to +100 kPa. Different vertical boreholes were instrumented by single and multiple points of measure. Further details on the installation methodologies and monitoring system are available in Rocchi et al. (2018).

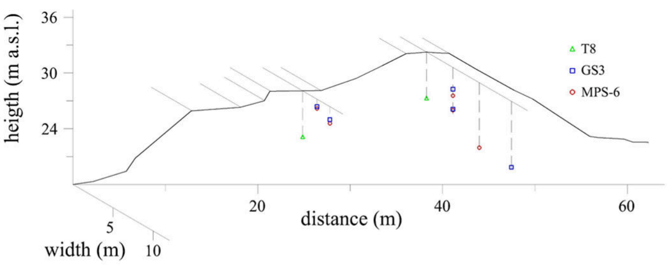

Figure 1. Layout of the monitoring system implemented in the river embankment.

2.2 *Testing devices for unsaturated soils*

The experimental programme for soils characterization in partially saturated conditions combined standard and advanced laboratory devices, with the aim to investigate both soils mechanical and retention properties under various stress-states and hydraulic boundaries conditions.

Evaporation Tests (ET) were performed to estimate the retention characteristics of soils in transient flow conditions at zero net stress (Wendroth et al. 1993; Romano & Santini 1999). The experiment consists in drying an initially saturated soil sample, while measuring the water loss due to evaporation from the top of the sample by continuously weighing the sample. The matric suction in the sample is simultaneously monitored at two depths within the soil sample by means of tensiometers measuring at 1/4 and 3/4 of the specimen height. At various stages during the ETs, wetting paths were imposed by adding controlled quantities of water, which was assumed to infiltrate downward vertically, and considering as representative the soil suction measured when hydraulic equilibrium was reached in the sample.

Hydraulic and shear strength properties in unsaturated conditions were measured also by means of advanced laboratory test, i.e. Unsaturated Direct Shear (UDS) apparatus and Suction Controlled Oedometer (SCO). One of the main features of these devices is the ability to control the influence of both the net stress ($\sigma - u_a$) and the matric suction ($u_a - u_w$), where σ is the total stress, u_a the pore air pressure and u_w the pore water pressure. The UDS apparatus (Evangelista et al. 2003; Cuomo et al. 2016) is here used to test samples contained in prismatic shear box, housed in an air-pressurised chamber, allowing independent regulation of pore-water and pore-air pressures. The axis translation technique is used to measure and apply the matric suction to the soil specimen. Pore-air pressure is controlled by the air-pressurised chamber, while free drainage of air from the specimen is ensured by a standard porous stone located in the top platen. Pore-water pressure can be applied to the bottom of the specimen through the water drainage system using a ceramic porous stone preventing air flows into the drainage system up to the air-entry value. The net vertical load is transmitted through a vertical pneumatic loading frame equipped with a load cell. Shear load is transferred to the soil specimen through a horizontal ram, and recorded by a load cell installed inside the chamber. Displacements are measured through an external (horizontal) and internal (vertical) linear variable differential transformers. The variation in the specimen water content is measured directly through comparing the volume exchange between the specimen and two external burettes, linked to a differential pressure transducer, one set as a reference level and the other connected to the water drainage circuit of the specimen.

The SCO (Aversa & Nicotera 2002; Bilotta et al. 2006) used here tests standard oedometric samples. Axis translation technique is again used to control/measure matric suction. Pore water pressure (u_w) is controlled at the base of the sample through the water drainage system, using a ceramic porous stone preventing air flows into the drainage system up to the air-entry value (i.e. 1 bar). A low air-entry value porous stone is used to control the air pressure (u_a) at the top of the sample and, hence, the pore air pressure corresponds to the cell pressure. The total vertical stress is applied to the sample through a computer controlled pneumatic press acting at the base of the oedometric cell. Axial strains are calculated based on the axial displacements measured by an external LVDT. The water content variations, as for UDS apparatus, are measured by two burettes, one working as a reference level and the other connected to the drainage circuit of the sample.

2.3 *Soil characterization and test setup*

Based on CPTU tests interpretation, the embankment filling material mainly consists of a single heterogeneous unit, about 7.0 m thick, characterised by a complex alternation of silt and sandy silt. Furthermore, soil classification was carried out by standard laboratory testing, determining natural water content, specific gravity, particle size distribution, Atterberg limits and organic content. The sand content varies from 25 to 50%, while silt accounts for 40 to 70%. The fine-grained fraction is around 5% - 18% (Fig. 2a), with a PI generally lower than 15% and natural water content always lower than w_P (Fig. 2b). The specific gravity was measured in the range 2.60 – 2.69, while the organic matter is negligible (1.5%). The main physical properties are showed in Figs. 2a-b and listed in Table 1.

Table 2 summarises the mechanical and hydraulic tests carried out on both remoulded and intact samples, i.e. 2 evaporation (ET), 2 suction-controlled oedometer (SCO) and 3 unsaturated direct shear (UDS) tests. Samples from three depths were tested, having initial void ratio in the range 0.53-0.86. Undisturbed samples collected at 5.0-5.5 m from the embankment crown were tested in SCO and UDS, where the experiments were run keeping the net stress ($\sigma_v - u_a$) constant during the test, under lithostatic stress conditions. This reflects the conditions in the riverbank, where the soil is mainly subjected to variations in soil suction rather than in lithostatic stress. Wetting paths by water exchange were performed both in UDS and SCO tests, while drying paths were only performed in SCO tests. Evaporation tests were carried out on remoulded samples taken at 2.8 m and 4.8 m and carried out under no net stress.

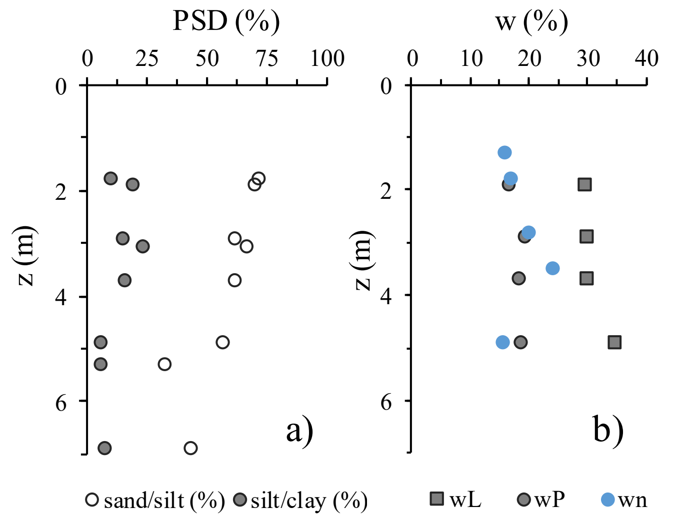

Figure 2. Soil classification at the installation site: (a) Particle size distribution, (b) plastic limit (w_P), liquid limit (w_L) and natural water content (w_n) with depth.

Table 1. Soil particle size main parameters.

Depth (m)	D_{50} (mm)	w_n (%)	w_L (%)	w_P (%)	Gs (-)	Cu (-)	Cc (-)
1.3	-	15.7	-	-	-	-	-
1.8	0.032	17.0	29.4	16.7	2.71	133	2.4
2.8	0.021	19.9	29.9	19.3	2.57	23	0.2
3.6	0.045	24	-	-	2.71	9	0.2
3.8	0.073	-	30.0	18.1	2.67	20	5.6
4.7	0.079	15.5	34.7	18.7	2.60	57	5.6
5.1	0.125	-	-	-	-	18	3.4
6.9	0.087	-	-	-	2.65	24	5.2

D_{50}= median diameter; w_L= limit liquid; w_P= plastic limit; Gs= specific gravity; Cu= uniformity coefficient; Cc= curvature coefficient

Table 2. Test details of the testing programme for hydraulic and mechanical characterisation.

Depth (m)	Test type	Test ID	Soil sample	e_0 (-)	s_0 (kPa)	$\sigma_v - p_a$ (kPa)	e_c (-)
5.1	SCO	SCO01	Intact	0.859	>100	90	0.794
5.4	SCO	SCO02	Intact	0.608	>100	5	0.679
5.2	UDS	UDS01	Intact	0.530	>100	90	0.547
5.3	UDS	UDS02	Intact	0.679	>100	90	0.641
5.5	UDS	UDS03	Intact	0.508	>100	90	0.489
2.8	ET	ET01	Remoulded	0.594	0.1	0	0.597
4.8	ET	ET02	Remoulded	0.605	0.1	0	0.610

s_0= initial suction; e_0= initial void ratio; $\sigma_v - p_a$= net vertical stress.

In Table 2 are also listed the values of void ratio (e_c) resulted at the end of the consolidation stage for SCO and UDS test and at the end of evaporation stage for ETs.

3 RESULTS AND DISCUSSION

3.1 *Drying and wetting paths*

The soil retention and hydraulic properties were first investigated through a series of evaporation tests performed on remoulded specimens obtained from samples taken at various depths varying the initial void ratio e_0 from 0.594 to 0.605, which partially overlaps with the values determined for in situ state at the considered depths (e_0=0.57-0.62). Figure 3 shows the results obtained from ETs performed on remoulded samples from two depths, 2.7-2.9 m (a) and 4.7-4.9 m (b), both expressed from the river embankment crown. These experimental data were interpreted using the well-known van Genuchten model (van Genuchten 1980) expressed in Eq. 1:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + \left(s \cdot \alpha_{VG} \right)^{n_{VG}}} \right]^{1 - \frac{1}{n_{VG}}} \qquad (1)$$

where θ, θ_r and θ_s are the current, residual and saturated values of volumetric soil water content respectively, s is the suction, α_{VG} and n_{VG} are model parameter mainly determining the inflection point and the shape of the retention curve respectively.

The best-fit parameters for main drying paths, obtained using a least square regression, are listed in Table 3. In addition, a series of wetting-drying flow paths were carried out during the evaporation test to study the effect of hysteresis on retention properties. These focused on suction varying from 10 to 100 kPa, which include the most representative site conditions. The experimental data and the fitting lines obtained through the van Genuchten model are also plotted in Figs. 3a-b (continuous and dashed lines, respectively), where each hydraulic path is indicated with arrow and different color (black for main drying paths, red for wetting scanning paths, yellow for drying scanning paths). During these tests, slow evaporation rates were imposed to ensure a linear suction distribution in the soil, as results of a constant rate of evaporation along the sample height, which generally leads to a higher average soil suction being measured. Differently, when evaporation is unrestricted, the vertical tension profile is strongly nonlinear, particularly at the dry top. Even for this latter case, laboratory tests and numerical simulations evidenced that linearization would lead to minor errors (Peters & Durner 2008; Schindler et al. 2010). However, the procedure has been considered in order to properly identify wetting and re-drying cycles with average suction and water content measurements.

From the results of Sample 1 (Fig. 3a), significant differences can be observed in the wetting-drying paths resulted from the scanning curve obtained at value of suction at approximately 90 kPa. Differently, the size of the various hysteretic cycles is approximately unchanged for Sample 2 (Fig. 3b), if more than one scanning curve is carried out starting from the same suction and it appears similar even when starting from different suctions within the range investigated. In fact, the wetting-drying paths determined show only moderate hysteresis.

The mechanisms behind the observed hysteretic responses can only be roughly identified at this stage, but could certainly include the inkbottle effect arising from non-uniformity of the interconnected pores cross-sections, potential differences in solid-liquid contact angles during drying and wetting and entrapped air. Clearly, the importance of hysteretic pathways depends on the soil properties such as texture and structure. All these features are generally more pronounced at lower values of saturation and this can be confirmed comparing the values of the two samples prior to wetting, which were 84% and 80% for Sample 2 and 60% for Sample 1. Figure 3b shows that the hysteresis is greater when the degree of saturation at which rewetting is initiated is lower.

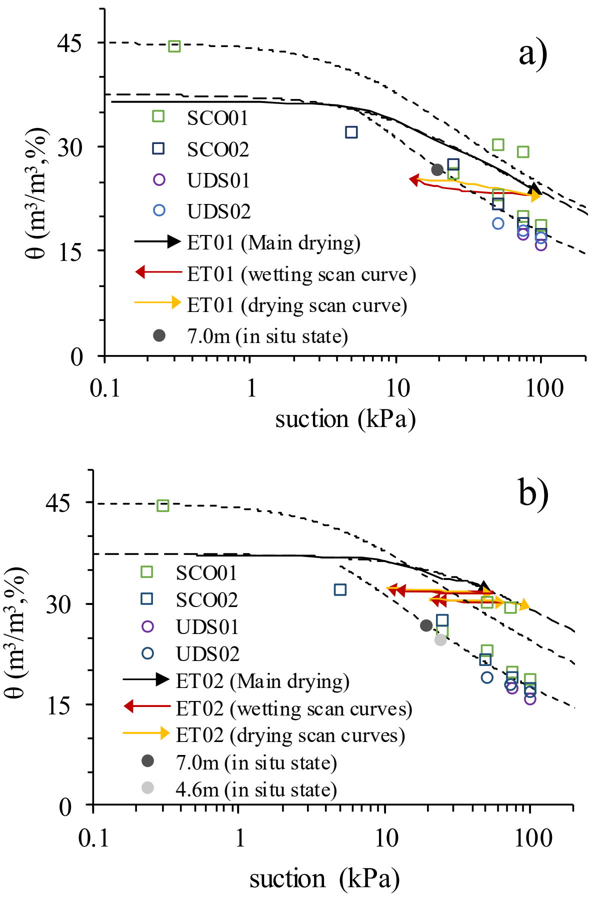

Figure 3. Soil water retention data obtained from various laboratory procedures; results are referred to SCO test (squared dots), UDS test (unfilled rounded dot) and evaporation test (continuous line, red and yellow paths are referred to wetting and drying scanning paths, respectively). Field values (filled circle) at 4.6 and 7.0m depth are plotted once equilibrium is fully reached after installation (31/01/2017).

Table 3. Estimated soil main retention properties, and sampling depths.

Hydraulic path	Depth (m)	θ_{sat} (m^3/m^3)	θ_r (m^3/m^3)	α_{VG} (kPa^{-1})	n_{VG} (-)
Drying	2.7 – 2.9	37.5%	0	0.092	1.172
Drying	4.7 – 4.9	37.3%	0	0.027	1.204
Drying	5.0 – 5.1	45.0%	0	0.149	1.667
Wetting	5.1 – 5.5	43.0%	0	0.264	1.272

Several researchers also emphasized that hysteresis can be interpreted as a material characteristic (e.g. Kool & Parker 1987; Likos et al. 2014) and observed that it is more limited in cohesive soils (well-graded and containing a higher percentage of fines) than in cohesionless soils (poorly graded and predominantly coarse-grained). It could be here also observed that Sample 2 is slightly coarser graded and less plastic than Sample 1, but the physical properties seem to influence hysteresis less than the saturation at the time of wetting, as greater hysteresis is observed for Sample 2, as already mentioned.

Retention data (coupled values of suction and water content) achieved from both UDS and SCO test in wetting paths are consistent among the different experiments performed (Fig. 3a and 3b), with a maximum difference in θ values of about 4% experienced for suction equal to 50kPa among the various test. The characteristic curve obtained fitting these data also evidence a similar slope of those from ET on both samples in main drying paths. These results, considering also that wetting paths obtained on ET01 and ET02 mainly relies to scanning curves, could lead to consider that results obtained from UDS and SCO nearly evidence the main wetting curve of soil for the considered. Moreover, it has to be noticed that retention data obtained from UDS and SCO are following hydraulic paths characterized by lower values of saturation prior to wetting (less than 40%), if compared to wetting paths in ETs. Nevertheless, this value should not be interpreted as the saturation state in situ, which is generally higher; this difference is practically due to water loss in soil during samples conservation and configuration. Furthermore, experimental results evidence that water content values at saturation obtained from suction controlled mechanical test are higher than those obtained considering a null net stress (Table 3), which could also be related to the higher value of e_0 and the slight differences existing in particle size distribution evidenced among the various considered depths.

Soil suction and water content values measured in situ are also shown in Figure 3. These data are referred to depths equal to 4.6m and 7.0m from the top of the riverbank and could reasonably be referred to the equilibrium state reached after the sensors installation. It can be here observed that site retention states plot approximately on the wetting paths evidenced by the UDS (01 and 02) and SCO (01 and 02) test, which is possible for the time considered for monitoring data (31/01/2017). This turn to confirm the reliability of retention data obtained through the use of SCO and UDS test, highlighting the importance of properly considering the actual stress states and hydraulic paths representative of in situ conditions for a comprehensive unsaturated soil characterization.

3.2 *Unsaturated soil behaviour upon shearing*

The shear testing procedure under suction controlled aimed to reproduce stress-strain variation experienced by riverbank soil on failure under typical site conditions. As already mentioned $(\sigma_v - u_a) = 90$ kPa at all times, corresponding to a depth of about 5.5m from the crown of the embankment, while $(u_w - u_a)$ was 75, 50 and 60 kPa for test UDS01, UDS02 and UDS03, respectively, which was also kept constant during the shearing stage. The results in terms of axial strain (ε_a) with respect to nominal shear strain (γ) during shear are plotted in Figs. 4 for the three UDS tests. Both UDS01 an UDS03, having $e_c = 0.547$ and $e_c = 0.489$, respectively; are dilative while UDS02, for which $e_c = 0.641$, is contractive. Related to that, the volumetric water content (θ) measured during the shear stage is plotted in Figure 5 against suction. The observed retention behavior is mainly related to void ratio variations induced by the contractive or dilative soil response during shear stage at constant net vertical stress and suction.

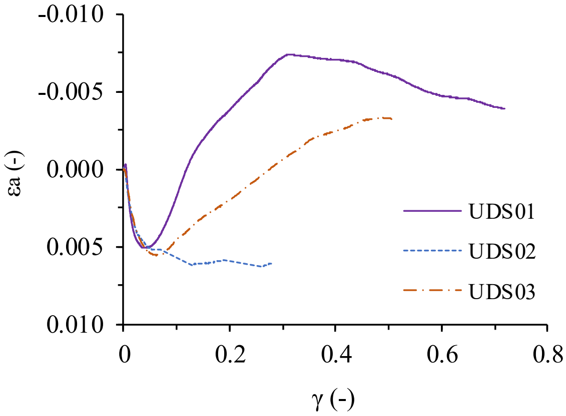

Figure 4. (a) Axial strain (εa) and (b) volume of water exchanged between the specimen and external reservoir (Δw) against shear strain (γ) during the shear stages in suction controlled conditions for test UDS01, UDS02, UDS03.

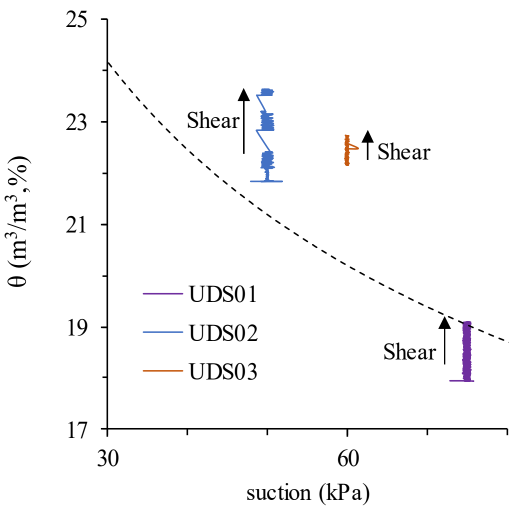

Figure 5. Volumetric water content (θ) variations against suction during shear stages for UDS01, UDS02 and UDS03, dashed line main wetting curve.

In particular, due to negative axial deformation in shear stage (e.g. soil volume increases, as for UDS01 and UDS03), θ would tend to change. In this new configuration, higher quantities of water can be retained in the aggregate for a constant value of suction, at equilibrium, leading to water absorption from the external reservoir (Fig. 5). An inverse process would be plausible for contractive soils. This process, evolving with time, could be considered as partial explanation of data showed in Figure 5. However, for a complete overview of stress-strain paths in shear phases an extended discussion and visualization of results is required, which is beyond the aim of this contribution.

4 CONCLUSIONS

The use of various experimental methodologies for the determination of mechanical and retention behavior of a river embankment silty soil in partially saturated conditions was described presenting the soil hydraulic properties and characteristic curves. Retention features were compared in different stress conditions and hydraulic paths. In addition, the evolution of strain (ε_a) and physical parameters (θ) upon shearing and under suction controlled was showed. The procedures, methodologies and applications here above described are all part of a wide research project focused on the analysis of the response of an instrumented riverbank under variable boundary conditions. Future work will cover comparison between in situ and laboratory soil water retention curves and an extended mechanical characterization to assess the embankment seepage and stability.

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