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Cardoso, Rafaela; Ramon-Tarragona, Anna; Lourenço, Sérgio; Mendes, João; Caruso, Marco; Jommi, Cristina

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Testing and Monitoring of Earth Structures

Rafaela Cardoso, Anna Ramon-Tarragona, Sérgio Lourenço, João Mendes, Marco Caruso, and Cristina Jommi

Abstract Monitoring structural behavior of earth structures during construction and in service is a common practice done for safety reasons, consolidation control and maintenance needs. Several are the techniques available for measuring displacements, water pressures and total stresses, not only in these geotechnical structures but also at their foundations. Materials testing has been used for calibrating models for structural design and behavior prediction, and these models can be validated with instrumentation data as well. Relatively recent investigation on the behavior of these materials considering their degree of saturation focuses on monitoring the evolution of water content or suction as function of soil-atmosphere interaction, necessary to predict cyclic and/or accumulated displacements, and has huge potential to predict

R. Cardoso (✉)
CERIS, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal
e-mail: rafaela.cardoso@tecnico.ulisboa.pt

A. Ramon-Tarragona
Division of Geotechnical Engineering and Geosciences, Department of Civil and Environmental Engineering (DECA), Universitat Politècnica de Catalunya, Barcelona, Spain
e-mail: anna.ramon@upc.edu

S. Lourenço
Department of Civil Engineering, The University of Hong Kong, Hong Kong, China
e-mail: lourenco@hku.hk

J. Mendes
Department of Mechanical and Construction Engineering, Faculty of Engineering and Environment, Northumbria University, Newcastle, UK
e-mail: joao.mendes@northumbria.ac.uk

M. Caruso · C. Jommi
Materials Testing Laboratory, Politecnico Di Milano, Milan, Italy
e-mail: marco.caruso@polimi.it

C. Jommi
Department Geoscience and Engineering, Delft University of Technology, Delft, The Netherlands
e-mail: c.jommi@tudelft.nl

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the impact of climate changes on the performance of existing geotechnical structures. This new need justifies the investment on developing sensors able to be used for in situ monitoring of water in the soils, such as those presented here. Testing and monitoring becomes even more important nowadays when, for sustainability purposes, traditional construction materials are replaced by other geo-materials with unknown behavior and long-term performance (mainly accumulated displacements). Existing experimental protocols and monitoring equipment are used for such cases, however new techniques must be developed to deal with particular behaviors. Three case studies are presented and discussion is made on monitoring equipment used and how monitored data helped understanding the behaviors observed.

Keywords Suction · Climate changes · Non-traditional geo-materials · Monitoring · Accumulated displacements · Chemical properties · Mineralogy

1 Instrumentation of Embankments and Their Foundations

Earth structures such as dykes, dams and road embankments have been built since more than 4000 years and construction techniques have been updated as function of technological development and human needs. Nowadays, monitoring structural behavior during construction and in service is a common practice for safety reasons, consolidation control, maintenance needs, etc. Instrumentation data is also necessary to confirm design assumptions, and also for research purposes. Several are the techniques available for measuring displacements, water pressures and total stresses (Table 1), not only in the geotechnical structures but also in their foundations.

The instruments used for the different applications are being updated along time taking advantage of technological development, improving their accuracy, response time and maintenance needs. Materials testing has been used for calibrating models used in structural design and behavior prediction, and then these models can be validated with instrumentation data as well. Nevertheless, for the most usual earth structures and almost for practical cases, the monitored parameters have remained practically unchanged the last century and their use in many practical cases has been

Table 1 Summary of typical instruments on embankments

Parameter			Equipment
Displacements	Internal	Horizontal	Inclinometers (electric, magnetic)
		Vertical	Settlement plates
			Extensometers
	External	Topographic targets, …	
Total stress		Loading cells	
Pore pressure		Piezometers (electric, hydraulic, magnetic, etc.)	
		Pore pressure cells	

extensively reported. For this reason, this work is not about standard instrumentation or standard applications of such known instruments, but on how the instruments may be used for particular needs illustrated by three case-studies.

Design mechanical and hydraulic properties of the geotechnical materials refer to saturated conditions, although compacted materials are in unsaturated state and their degree of saturation experience cyclic changes due to the exposition to climate actions. Changes on the degree of saturation or water content significantly affect these properties and can be responsible for cyclic and/or accumulated (irreversible) volume changes, compromising structural performance. Relatively recent investigation on the behavior of these materials considering their degree of saturation focuses on monitoring the evolution of water content (or suction) in earth structures, which is necessary to predict such cyclic behavior. In addition, this knowledge has huge potential to be used on predicting the impact of climate changes on the performance of existing geotechnical structures (in the structure itself and also considering changes on water table levels at the foundation). This new need justifies the investment on developing sensors able to be used for in situ monitoring of water presence in the soils in unsaturated states (soil suction sensors), and for this reason a small introduction to existing sensors and working principles is presented here.

Testing and monitoring or earth structures becomes even more important nowadays when, for sustainability purposes, traditional construction materials are replaced by other geo-materials which behavior and long-term performance (mainly accumulated displacements) are unknown. Existing experimental protocols and monitoring equipment are used for such cases, however new techniques must be developed to deal with the particular behavior of these non-standard materials. Some case-studies are presented here to deal with different situations: (i) when non-standard materials for embankment construction are used, such as light weight aggregates, construction residues, lime or cement treated materials, etc.; (ii) when displacements caused by unexpected chemical reactions occur, causing structural damages and forcing the adoption of repair interventions; (iii) when the effects on earth structures of permanent changes in water table levels at their foundations must be quantified. The cases presented here are examples in which standard instrumentation was installed to monitor parameters related with the particular nature of such structures. Monitored data presented helped to investigate instability phenomena and to find solutions for the problems observed.

2 Monitoring Soil-Atmosphere Interaction

2.1 Introduction

Soil structures, such as embankments and excavations, are typically built in an unsaturated state, above the water table and exposed to the atmosphere. Vegetation also plays a critical role, and it often has opposite effects, by providing root reinforcement and contributing to stability or by enhancing drying by evapotranspiration. The ground is subjected to continuous wetting and drying cycles. Under extreme weather events, through excessive rainfall and prolonged droughts, slope instability (creep and slides) and shrinkage (desiccation cracks) endanger the structures leading to significant economic losses. Therefore, approaches to prevent or mitigate the negative effects of soil-atmosphere interactions in soil structures are based on (i) classic engineering (ground stabilization, retaining structures), (ii) new approaches based on bioengineering and (iii) monitoring or sensing of structures. This chapter will focus on the latter.

At the pore scale, soils are composed of three distinct phases: particles, water, and air, forming water menisci in-between soil particles with a negative water pressure. Suction, the difference between pore air and pore water pressure across the menisci, controls soil behavior, by increasing the soil strength and compressibility, controlling the soil volumetric behavior (swelling and shrinkage) including the soil water retention (relation between soil water content and suction). The response of soil structures to atmosphere interactions and its effects can thus be accessed through the monitoring of suction.

This section presents a review of methods to measure suction in the field, with a focus on methods that provide a continuous measurement and that can be installed permanently in the field. At first, indirect methods that rely on the measurement of water content will be presented, followed by methods that measure the pore water pressure, mostly conventional tensiometers and high capacity tensiometers. Finally, field examples will be provided of the monitoring of pore water pressure with high capacity tensiometers, including their sensitivity to soil-atmosphere interactions (speed of response to rainfall events).

2.2 Measurement of Soil Suction

Over the past decades, various techniques have been developed for measuring the different soil suction components (total, matric and osmotic) using direct and indirect methods. Direct methods, as the name suggests, are methods in which the measured value is directly related to the soil suction. Whereas indirect methods are methods in which the soil suction is inferred from the equilibrium between the suction in the soil and a known medium. Although many techniques have been developed for measuring different soil suction components in the laboratory (Total [1–3], Matric [4–9] and Osmotic [10]) and most have been adapted to field use, only a few have been adapted for the continuous measurement of soil suction on a permanent field installation basis. Below is a brief description of different methods that have been adapted for continuous measurement of soil matric suction in the field that are commercially available.

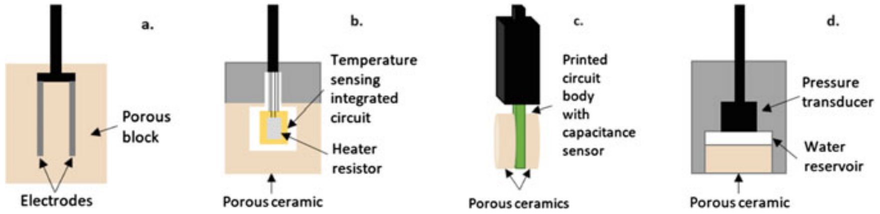


Fig. 1 Schematics of soil matric suction sensors (not to scale): **a** Electrical conductivity [5]; **b** Thermal conductivity [6]; **c** Dielectric permittivity [7]; and **d** High capacity tensiometer [12]

Indirect methods. Indirect methods for measuring soil matric suction include electrical conductivity, thermal conductivity, and dielectric permittivity.

Electrical conductivity sensors infer soil matric suction from the relation that the degree of saturation has with the suction and resistivity of the soil. Because this relation is different for different soil types [5] the measurement of soil suction is, instead, inferred from the electrical impedance on a porous block with known characteristics. The most typical electrical conductivity sensors are the Gypsum Blocks, as shown schematically in Fig. 1a. These sensors are composed of two concentric electric electrodes installed in a permeable block. Each sensor is required to undergo calibration where the electrical impedance is directly related to the water content in the block that, in turn, is indirectly related to soil matric suction. The measurement of soil matric suction is achieved when an equilibrium between the suction in the soil with the suction in the block is reached. These sensors are simple to use and easy to install in the field and can measure soil suctions typically in the range of 30–1500 kPa. However, they are known to underperform when matric suction values are higher than 300 kPa, the measurement is affected by the salt concentration in the soil pore water and the initial equilibration time can be significant (up to two weeks).

Thermal conductivity sensors infer soil matric suction from the water flux into the sensor until suction reaches and equilibrium between the porous medium of the sensor and the soil. Much like the electrical conductivity sensors, a known porous medium must be used due to the variability in the thermal conductivity of soils. The typical schematic for a thermal conductivity sensor is shown in Fig. 1b. These sensors are composed of a temperature sensing integrated circuit and a heater resistor encased in a ceramic porous medium with known porosity. The measurement of soil suction is made indirectly by determining the water content by heating the porous block with the heater resistor and by measuring the temperature increment during heating. These sensors must be calibrated before use for a reliable measurement of soil suction, different readings must be obtained at different degrees of saturation of the porous block varying from fully dry to fully saturated and, if possible, at know values of suctions using, for example, the pressure plate technique [11]. These sensors are relatively easy to use and to install in the field, measurement is not affected by salt concentrations and have a measuring range of 10–1500 kPa. However, these sensors can be very difficult to calibrate due to the heterogenies in the porous medium and tend to be very inaccurate at high values of suction.

Dielectric permittivity sensors (DPS) infer soil matric suction from the dielectric permittivity properties of air, water, and solid particles [7]. While these properties are well defined for air and water, the variability in soil solid particles makes this type of measurement difficult to implement. Thus, a porous medium with known pore size distribution is used where the measurement of soil suction is inferred from the water content in the porous medium when it is in equilibrium with the soil. The typical schematic for a DPS is shown in Fig. 1c. These sensors are composed by a capacitance sensor placed between two ceramics discs with known properties. The measurement of soil suction is inferred from the water content in the porous ceramic discs derived from the dielectric permittivity of the amount of air, water, and solid particles in the ceramic discs. Because the dielectric permittivity is highly dependent on the amount of water an accurate and wide range of the measurement is possible. Factory calibration of these sensors are based on the water retention curve of the ceramic discs and is directly imbued in the sensor circuit board. The measurement is made by submerging the whole sensor (ceramic discs and circuit board) into the soil until equilibrium between the soil and ceramic discs is reached. These sensors are very easy to use and install in the field, have a measuring range of 9–2000 kPa and the factory calibration is reasonably accurate due to the close control on the porosity and pore size dimensions of the ceramic filter during fabrication.

All indirect methods that rely on measuring the water content of a porous medium have the same limitation regarding field installations, the porous medium undergoes hysteresis during wetting and drying cycles that can result in under and overestimation of soil suction in dynamic climatic environments during drying and wetting cycles, respectively.

Direct methods. Direct methods for measuring soil matric suction include conventional tensiometers (CT) and high capacity tensiometers (HCT). Both methods use the same measuring principle where the measurement of soil matric suction is made directly from the hydraulic equilibrium of the pore water in the soil with a pressure transducer or pressure gauge. These sensors are composed of a high air entry value (AEV) porous ceramic filter with known largest pore size, a water reservoir, and a pressure transducer/gauge as shown schematically in Fig. 1d. The main difference between these two methods is in the measuring range, CTs have a measuring range of 100 kPa [8], whereas HCTs have a measuring range of > 15,000 kPa [12]. The difference in the measuring range is due to the smaller largest pore size within the porous ceramic filter used in HCTs which is directly related to the AEV of the ceramic filter and, in turn, related to the measuring range of the sensor [13]. Measurement of soil suction is only possible if the water reservoir and ceramic filter are fully saturated. This is achieved by filling the sensor existing pore space (pores in ceramic filter and water reservoir) with deaired water under pressure that should be above the AEV of the ceramic filter using a pressure controller. Calibration of different sensors is required as the voltage output of the pressure transducer must be converted to pressure values. Calibration is performed on the positive pressure range that is linearly

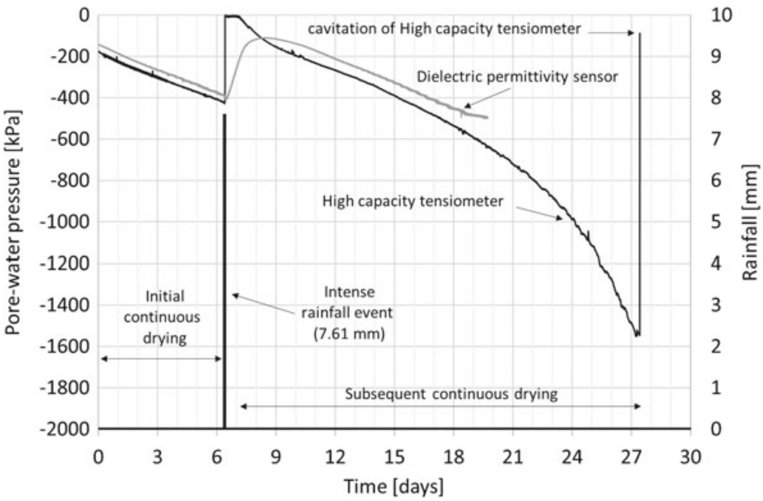


Fig. 2 Comparison of pore-water pressure readings of a DPS versus a HCT during drying-wetting–drying cycle, after [13]

extrapolated to the negative pressure range. The measurement of soil matric suction is then possible, and it can be achieved by placing the CT or HCT in intimate contact with the soil. During measurement, water from the water ceramic filter flows into the soil until hydraulic equilibrium between sensor and soil is reached.

CTs and HCTs, if properly saturated, can react very quickly to changes in suction in the soil, are not affected by hysteresis due to wetting and drying cycles, can be used as a typical piezometer as it measures both positive and negative pore-water pressures, and are the only techniques available that measures soil suction directly. However, these sensors have some important limitations, such as cavitation. Cavitation is the result of tension breakdown within the water reservoir inside the CT or HCT when water is under tension. This is easily identifiable in HCTs by a sudden jump in the reading to values close to −100 kPa, as shown in Fig. 2. When cavitation occurs, the sensor is unable to measure soil suction and must be re-saturated. Thus, to continuously use these types of sensors in the field a more complex installation and maintenance than any of the indirect methods mentioned before is required.

2.3 Soil Suction Monitoring in Soil Structures

Soil structures are typically exposed to dynamic climates where they undergo through multiple wetting and drying cycles influencing the pore-water pressure in the soil. During a dry spell, while evaporation occurs, the suction in the soil will tend to increase; while, during rainfall events, as water infiltrates into the soil, soil suction will tend to reduce. Thus, when choosing which methods to deploy for monitoring soil suction it is important to understand how different techniques respond to dynamic climatic events; especially if future climate and climatic patterns are taken into consideration.

Figure 2 shows the readings of negative pore-water pressure (soil matric suction) measured in the laboratory on a large specimen of fine sand using a DPS (indirect method) and a HCT (direct method), both installed at the same depth, and subjected to drying-wetting–drying cycle [13]. It can be observed from Fig. 2 that, during the initial drying, both sensors were measuring comparable values of soil suction as the sand continuously dried. When a value of soil suction of 400 kPa (−400 kPa of pore-water pressure) was reached, an intense rainfall event was imposed to the sand. The HCT responded with a sudden jump of the pore-water pressure to values close to zero. While, in comparison, the response of the DPS was considerably slower that continued to increase gradually for another 2 days well into the subsequent drying stage. After the DPS reached hydraulic equilibrium with the soil, the readings of pore-water pressure were once again comparable with the readings from the HCT [13].

The observed behavior of the DPS in Fig. 2 can be explained by the measuring principle used in this and other indirect methods of inferring soil suction from the measurement of the water content of a porous medium. During continuous measurement when the soil is drying, and while the sensor and soil are in equilibrium (initial drying in Fig. 2), desaturation of the pores will occur as water gradually flows from the sensor into the soil. However, when the flow is quickly reversed (intense rainfall event in Fig. 2) the hydraulic equilibrium is lost as the intake of water by the porous medium is not sufficient to maintain it. This is because the water flux is controlled by the hydraulic conductivity and the shape of the pores (responsible for the hysteretic water retention behavior) inside the porous medium. The reason why HCTs do not show this behavior is because the porous ceramic filter is required to be fully saturated during measurement. When significant desaturation occurs in the porous ceramic filter the HCTs cavitate and will require to undergo re-saturation.

Thus, when considering which method to employ for monitoring soil suction in the field a mixed approach of direct methods, that have an immediate response to suction changes but can cavitate, coupled with indirect methods should be considered.

3 Some Case-Studies

3.1 Embankment Built with Compacted Marls Sensitive to Water

Description of the case-study. Several embankments from A10 Motorway, in Portugal, were built with fragments of marls in order to reuse the excavated material

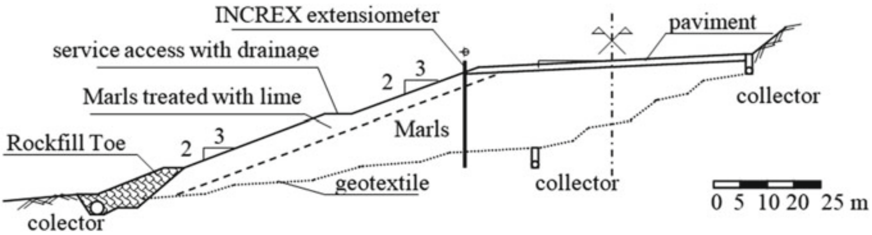


Fig. 3 Schematic profile of embankment AT1 from A10 Motorway (adapted from [14])

from the site. Marls are soft rocks which exhibit evolutive behaviour due to exposition to atmospheric actions (wetting–drying cycles). Crack opening and/or loss of bonding occur on wetting, with negative impact on the strength and compressibility of the material.

Relatively large fragments remained after the compaction processes and their further physical degradation or swelling deformations can have strong effect on global behaviour. For this reason, in the embankment investigated the construction procedure was adapted to add more water than what is usually done in road embankments, and the marls used to build the shoulders were treated with lime. The construction procedure adopted intended to reduce the size of the fragments minimizing the impact on overall behaviour of their eventual volume change. Lime addition would reduce the swelling potential of the marls.

Due to the particular behaviour of this non-traditional material, the vertical deformations and the evolution of the water content in embankment AT1 (simplified profile at Fig. 3) were measured during the construction and in the following two years. The instruments installed during the construction were (i) extensometers, to measure vertical deformations due to wetting and drying, and (ii) electrical resistive sensors to measure changes in water content. Traditional instruments such as inclinometers (operating in the gutters of the extensometers) and topographic targets were also installed, but they will not be discussed here.

Embankment AT1 was selected because it is very high (about 10 m at pavement axis) and was installed in a slope. The material treated with lime was at the shoulders in a layer with 5 m thickness (zoned profile in Fig. 3). Compaction was done in the wet side of optimum (interval [w_{opt}, $w_{opt+2\%}$], energy equivalent to modified compaction effort and minimum of 95% of relative compaction), and using a vibratory sheepstoot roller to promote fragments breakage. Drainage systems were installed in the foundation and at the pavement levels (Fig. 3) to prevent water access, as it is usually done in embankments.

Overall description. The marls used in the construction of AT1 are named as Abadia marls (upper Jurassic) having moderate swelling potential. The main minerals present are carbonates (calcite), quartz, mica, dolomite, feldspar, clay minerals (almost no smectite), expansive minerals such as chlorite and gypsum, and a very small percentage of organic matter (0–2%) [14]. Laboratory tests were performed on

Table 2 Main geotechnical properties of the treated and untreated marls

	Marls (untreated)	Marls treated with 3.5% of lime (after 1 day)
Weight density of solid particles	27.5 kN/m^3	
Liquid limit, w_L	49%	36%
Plasticity index, PI	25%	7%

samples with different weathering degrees to find the main geotechnical properties summarized in Table 2. The treatment with lime (3.5% in weight) reduced the plasticity of the marls (due to the reduction of the w_L thus on PI), improving the workability of the material and changing the classification of the fine fraction from CL to ML. The effect of this treatment on the hydraulic and mechanical properties of the marls was also investigated (details in Cardoso and Maranha das Neves [14] and Cardoso et al. [15]).

Instrumentation. The instruments installed are (i) magnetic extensometers, INCREX [16], on a PCV gutter, to measure vertical displacements, and (ii) electrical resistive sensors, ECH$_2$O [17], for measuring water content. Two vertical sections were instrumented, each having one gutter for measuring displacements (both vertical and horizontal can be done in the same gutter) and seven water content sensors (five in the marls and two in the treated marls, Fig. 4) distributed 1.5 m along height. To avoid interferences between the different instruments, the sensors were installed at 3 m distance (in longitudinal direction) from the INCREX gutters.

INCREX are INCRemental EXtensometers [16] and measure small vertical deformations with large precision. The system required to measure the magnetic field allows a precision higher than the one obtained when standard measuring systems are used (±0.02 mm for INCREX, and ± 0.5 mm for more general measurement equipment). Operation is based on the measurement of relative vertical displacements of magnetic rings spaced exactly one meter in the installation (Fig. 5). The rings are installed outside the gutter and are free to slide along it, but must be connected to the

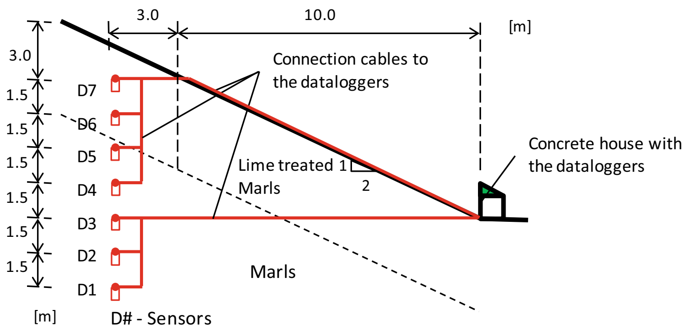
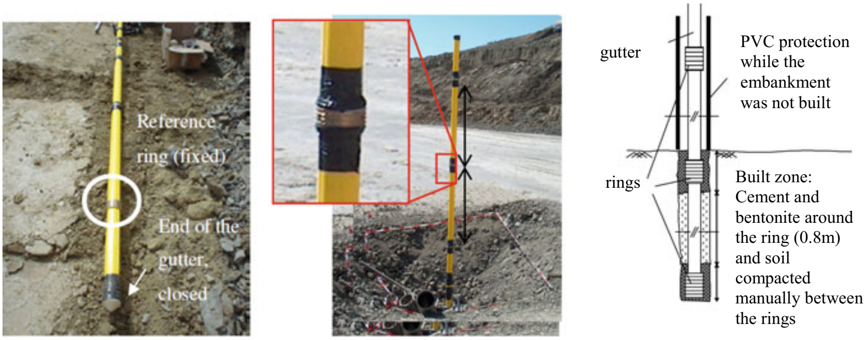


Fig. 4 Profile instrumented with sensors ECH$_2$O



First piece of gutter (3m) with the reference fixed ring

Instrument installed during construction and detail of the magnetic rings

Installation system adopted to fix the rings to the soil

Fig. 5 Gutters and magnetic rings of INCREX instruments

soil to displace with it. This connection was done by creating a thin cement-bentonite layer in the ring zone and a compressible layer made of compacted material between these zones, as illustrated in Fig. 5. Unfortunately, the two gutters were broken during the construction and readings were interrupted. Nevertheless, it was possible to measure the vertical displacements during almost the construction period. They were similar to those from topography readings, showing that the installation system adopted was efficient. In addition, these readings allowed calibrating a finite element model of the embankments used to estimate long-term displacements [18].

Sensors ECH$_2$O (Fig. 6) measure water content and changes in water content, related to suction changes through the water retention curve. These sensors must be in contact with soil and measure its electrical resistivity, which changes in function of changes in water content. The electrical wires had to be protected during sensors installation and the construction of the embankment, to be connected to the dataloggers, also shown in Fig. 6. The dataloggers were stored in a locked case build for that purpose in the access way.

Sensor installed manually

Electrical wire protection

Connection between levels

Connection to datalogger

Fig. 6 Installation of the resistive sensors ECH$_2$0 for measuring water content

Soil resistivity depends on void ratio as well, and therefore sensors calibration had to be done in the laboratory. This calibration consists in the relationship between voltage and water content, so the sensors were installed in samples compacted with known different water contents for the same dry volumetric weight and voltage was measured. The relationship between voltage and water content is presented in Fig. 7 for each dry volumetric weight, where it can be seen that the slope found was independent from dry volumetric weight (average value 19.9). The voltage for null water content increases with the dry unit weight, so the real dry volumetric weight had to be measured in situ to select the proper calibration curve. It was done by measuring the voltage and water content of the soil when each sensor was installed.

Data collected during the construction with the ECH_2O sensors (Fig. 8) showed

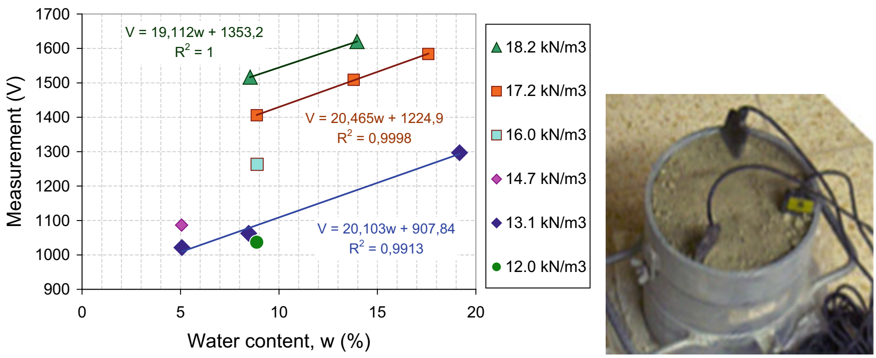


Fig. 7 Calibration of sensors ECH_2O

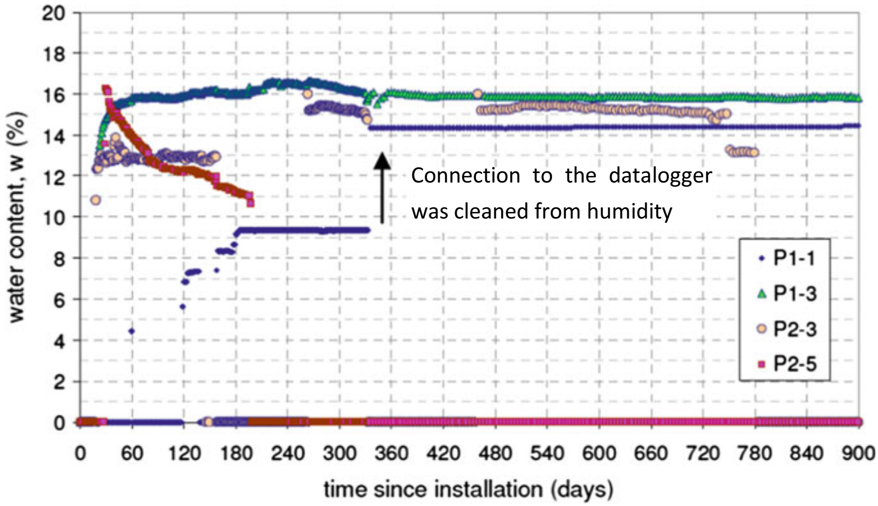


Fig. 8 Evolution of water content with depth and time (after [18])

some malfunction of the sensors, explained by humidity attack in their connection to the dataloggers. Nevertheless, data available allowed identifying an initial period where water content of the soil surrounding the sensor equalized the value of the layer where it was installed (around 15%) after this period. It was possible to detect the homogenization in depth of the water content (between 12 and 16%). No oscillations were detected during the service period monitored, which somehow was expected due to the depth where the sensors were installed. Nevertheless, this result indicates that the drainage system was efficient to prevent water access to the embankment, and therefore the swelling nature of the marls appear not to compromise the performance of the embankment during service.

Final considerations. The instrumentation of AT1 was conceived to monitor the expansive behaviour of the marls. Vertical deformations and displacements were recorded, as a direct measurement of this behaviour, but also its causes were investigated by introducing the water content sensors. This would allowed a more informed decision in case of problems.

Creative solutions had to be implemented to install the instruments used, in particular the INCREX. The location of the dataloggers necessary for recording ECH_2O measurements also requested the construction of a small locked case. Humidity problems caused the malfunctioning of some sensor's connection to the dataloggers. This is a typical problem in long term monitoring.

The need of complementary experimental tests is highlighted when using non-traditional materials. In this case, the sensors had to be calibrated before installation through laboratory testing. Experimental tests were also performed to characterize the hydraulic and mechanical behaviour of the materials, information used in other works.

Unfortunately, the gutters were broken, but no relevant displacements were detected by topographical instruments also installed in AT1. This was in accordance with the lack of significant oscillations on the values recorded for the water content along the exploitation, monitored by the resistive sensors. This showed that water access to the interior of the embankment was not significant, indicating the effectiveness of the drainage system installed.

3.2 Massive Expansions in Compacted Embankments Due to Sulphate Attack

Introduction. Deformations and movements in embankments and fills may result from chemical processes that involve crystal growth. For instance, sulphate attack is at the origin of surface heave developed in cement- and lime-treated soils that contain sulphates or are in contact with a source of sulphated water. This attack induces a decrease in soil strength and has damaged a number of compacted road bases and sub-bases [19–22]). The soil stabilization commonly concerns thin layers of soil.

However, massive sulphate attack can also develop when the treatment encompasses larger masses of soil. This is the case described in this section.

Pallaressos embankments performance. Pallaressos embankments belong to the high-speed rail connection between Barcelona and Madrid in Spain. Their construction finished in 2004. The embankments give access to a bridge 196 m long, Pallaressos Bridge. Alonso and Ramon [23] detail structural characteristics of the bridge. The embankments have a maximum height of 18 m in the vicinity of bridge abutments and its thickness decreases gradually at farther distances from abutments.

The abutment structures are founded directly on a Tertiary hard marl formation. Figure 9 presents the internal design of the embankments. The transition wedge built in the proximity of the abutment guarantees a smooth transition from the compacted fill to the rigid structures of the abutment and bridge. The design specifications of the embankments defined the construction of the wedge closest to the abutment with a cement-soil mixture As-built data obtained during construction showed that the compaction was in general on the dry side of optimum. The origin of the compacted material of the embankments core was a previous excavation in a nearby Tertiary natural formation of gypsiferous claystone with limestone and sandstone interstratified layers. The extreme expansive problems that suffered Pont de Candí Bridge [24, 25] and Lilla tunnel [26, 27] also involved this geologic formation.

Railway administration detected heave development of the tracks located above the embankments, in the vicinity of abutments, a short time after the end of construction of the embankments. Periodical rail leveling revealed a maximum vertical displacement rate ranging from 4.0 to 4.5 mm/month at the beginning of 2006.

The measured heave rates did not decrease and a grid of jet-grouting columns 1.5 m in diameter was carried out in each embankment (Fig. 10) in October 2006. The distribution and length of the columns resulted in an enlarged transition zone in both embankments. The reinforcement treated the central part of the embankments along an approximate length of 30 m. The application of the treatment was more intense in the proximity of abutments. The implementation of the reinforcement was

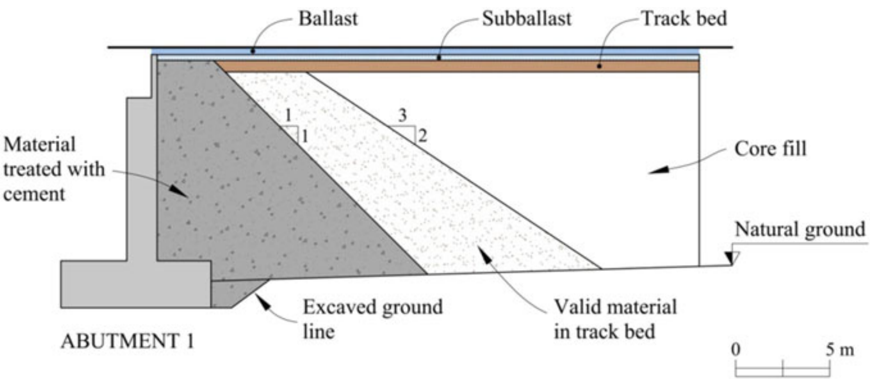


Fig. 9 Longitudinal section of pallaressos embankment

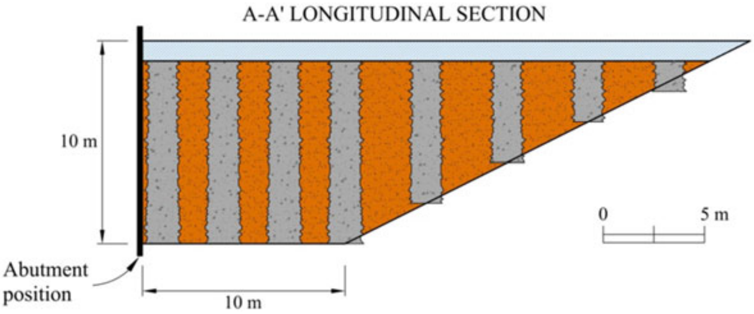


Fig. 10 Longitudinal cross section of the jet-grouting treatment applied at both embankments

justified by the weakness and disintegration easiness of the cement-treated soil in the embankment material, and also by the expected poor wedge design observed from boreholes drilled through the two embankments.

Despite of this treatment solution the embankment heave continued. In addition, heave rates measured after the treatment accelerated to values up to 6.5 mm/month in some positions.

Embankments monitoring. An monitoring campaign was launched to investigate the extension and origin of expansions. The full operation of the railway line posed challenging difficulties for the field investigations.

A monitoring of the surface of embankments by means of topographic marks identified the sustained development of vertical and horizontal surface displacements. The surveillance indicated relevant horizontal movements in the transverse direction (perpendicular to rail tracks). A topographic mark installed 10 m away from the abutment structure of one embankment showed an accumulated horizontal transverse displacement of 150 mm and an accumulated heave of 59 mm during the first 18 months of monitoring. Surface topographic control provided also longitudinal horizontal displacements. However, the values were significantly lower than the displacements measured in the other two directions. Maximum values of 22 mm towards the structure of the abutment developed during the same period along the first 10 m from the position of the abutment.

The distribution of transverse horizontal movement and heave measured at both embankment surfaces followed the pattern indicated in Fig. 11. The maximum displacement in both embankments occurred at a position 10–13 m far from the abutments and no development of significant movements occurs at distances more than 30 m away from the abutments. Topographic monitoring outside the embankments, on the natural ground surface, did not detect any displacement.

Recorded heave rate was not constant in time. In fact, rainfall events seemed to have an influence on the development of heave. The comparison between measured heave and precipitation indicated that heave rates increased immediately after significant rainfall events.

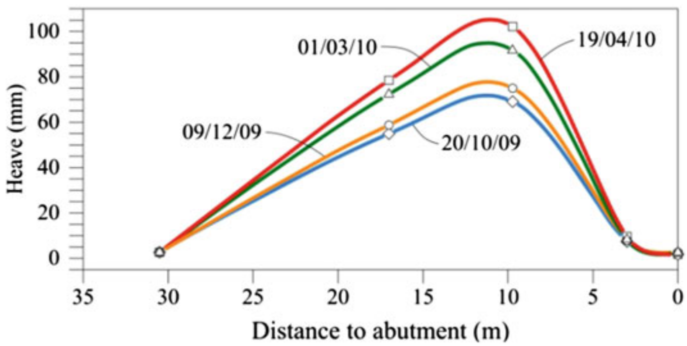


Fig. 11 Distribution of surface heave along the distance from abutment position. Initial topographic measurement: 26 May 2008

Several high precision (±0.003 mm/m) vertical continuous extensometers (sliding micrometers [28]) installed in boreholes allowed investigating the vertical strains of the embankments along depth. The extensometers crossed the whole embankment and reached the natural stratum under the embankments. The instruments were installed at different distances from the abutments. Records showed that vertical expansions develop along the first 8 – 10 m and smaller compressive deformations occur within the deeper part of the embankments over time (Fig. 12). Micrometers

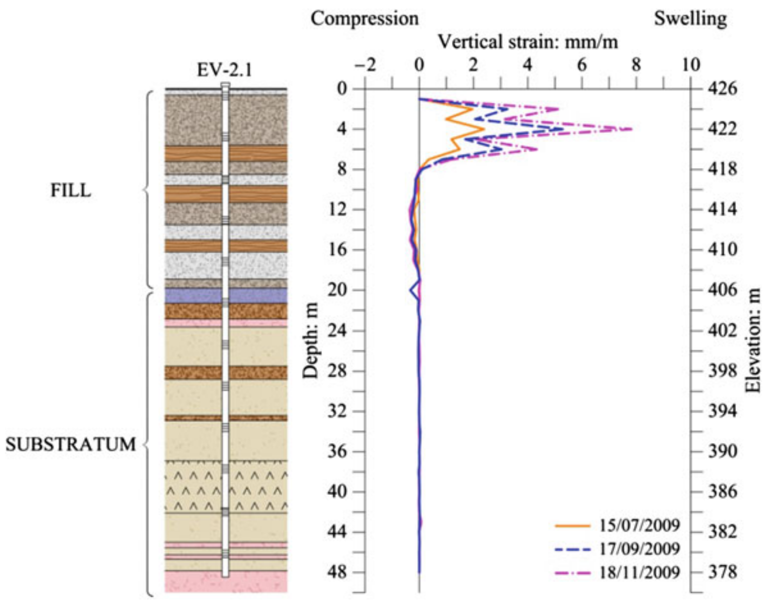


Fig. 12 Vertical strains measured in a sliding micrometer installed at a distance of 8 m from abutment. Initial recording: 20/05/2009

installed 40 m far from abutments measured only a small compression. The pattern of strain records remained invariable over time. The upper expanding layer did not enlarge downwards.

The integral of deformation measured along depth in each micrometer was consistent with the surface vertical displacement in topographic records. This verification is important because it shows that the extensometer length covered the whole “active” expansive zone that originates the heave observed at surface level.

Inclinometer measurements identified the development of horizontal movements in depth along mainly the first 8–10 m of boreholes. Inclinometers recorded a horizontal movement about 9–12 mm in the transverse direction in 2.5 months of monitoring. The horizontal measurements indicated that the embankments were swelling also in a lateral direction.

The combination of the recorded three-dimensional expansion of the embankments and the reduced deformation measured in longitudinal direction suggested that the internal swelling may result in the development of high horizontal loads against the abutments and, therefore, against the bridge structure. In fact, an examination of the structure showed the existence of spalling damage and fissures at the contact between the abutment and bridge structural elements, a displacement of the abutment structure towards the deck of the bridge and relevant damage in the drainage and communications conduits. In addition, forces generated from confined displacements were acting against both sides of the bridge, which agrees with a bending-induced cracking pattern observed at the lower part of the pillars.

The reduced longitudinal strain also pointed out to the risk of occurrence of a passive failure on the upper part of the embankments due to the development of strong passive stresses at the upper level of the embankment, in the longitudinal direction. A finite element analysis simulated well the expansion and heave measured in the embankment and verified the development of a dangerous state of passive stresses at the upper 8–10 m of the embankment. The model estimated a total thrust of 2.32 MN/m against bridge abutment.

Laboratory testing. The material recovered from different depths in the boreholes drilled for the monitoring campaign was investigated in detail. Test results suggest an overall heterogeneous distribution of properties along the depth of the embankments. Identification tests showed that the fine fraction of the compacted fill is a low-plasticity clay and that water content within the embankment does not reach the plastic limit. Heterogeneity was also observed in the wide ranges of the grain size fraction contents found in different samples: fines (7–69.3%), sand (10.5–35.1%); and gravel contents (18.6–62.1%). Some boulders larger than 100 mm were scattered within the compacted material. Figure 13a) shows the aspect of the material at the upper meters of the embankments at the exposed surface excavated during the underpinning works described later. The presence of gravels and boulders immersed in the reddish clay matrix is appreciated in the photo. Also, two columns of jet-grouting treatment and some masses with cement-treated soil can be observed. A detail of a cement-soil mixture recovered from the cut surface is shown in Fig. 13b.

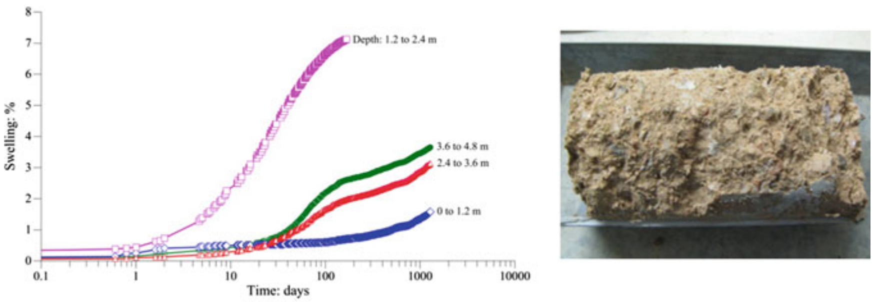
(a) (b)

Fig. 13 **a** Upper meters of the compacted fill of one of the embankments. Exposed surface excavated during the underpinning works; **b** detail of a cement-soil mixture found at the cut surface

An important outcome of the laboratory tests was the distribution of soluble sulphates in the soil along depth. Contents range from 2.0 to 2.5% in the upper 8 m and drop to values lower than 0.5% at increasing depths. Presumably, the existence of two different source areas for the material used for the construction of the embankment may explain these findings.

The heterogeneity in the compacted fill pose difficulties to investigate in the laboratory the reasons for the expansions observed in the field. Large free swelling tests on compacted samples approximated the embankment conditions. The preparation of representative samples involved two steps: firstly, the homogenization of the material recovered in boring lengths of 1.20 m and, secondly, the compaction to the standard Proctor energy with a water content of 10%. Four representative samples were prepared to test the five upper meters of one embankment. The compacted unloaded samples, 160 mm in height and 120 mm in diameter, remained partially submerged in water and at a constant temperature of 8 °C during the tests.

The samples developed a significant long-term swelling that cannot be explained by a possible mechanism of clay minerals hydration (Fig. 14a). Expansion evolved



(a) (b)

Fig. 14 **a** Vertical swelling strains measured in free swelling tests (boring S-2.1B); **b** Sample aspect after test dismantling (1.20–2.40 m deep) throughout 11 months with no signs of stabilization. Figure 14b shows the aspect of the sample exhibiting larger expansion (built from material recovered at depths ranging 1.20–2.40 m). The mineralogical investigation of the sample by means of scanning electron microscopy (SEM) observations and X-ray diffraction analyses revealed thaumasite ($Ca_6[Si(OH)_6]_2(CO_3)_2(SO_4)_2{\cdot}24H_2O$) and ettringite ($Ca_6[Al(OH)_6]_2(SO_4)_3{\cdot}26H_2O$).

Samples of poorly cemented soil–cement mixtures or pure cement grout, recovered from different locations in the embankment and which had a wet-muddy consistency (Fig. 14b), also showed the presence of thaumasite and ettringite in its mineralogical composition. The analysis identified calcite, dolomite, gypsum, illite, kaolinite and quartz in the clay matrix.

Interpretation and final remarks. The mineralogical composition pointed out to the origin of expansions. Sulphate attack in treated soils results in the precipitation of the minerals ettringite and thaumasite and produces the destruction of the strength of the cement paste and a relevant expansion starting from inside the material. Note the high proportion of water molecules in these chemical compositions.

Mohamed [29] describes the development of both minerals in lime-stabilized soils throughout a complex process. The highly basic environment created after the hydration of lime triggers the attack. High pH favors the dissolution of sulphate minerals (i.e., gypsum) and clay minerals. Then, the combination of aluminum released from clays, calcium from cement or lime and sulphates with water molecules results in the precipitation of ettringite. Thaumasite precipitates after the dissolution of calcite in the presence of carbonic acid in the pore water.

Monitoring records identified in a conclusive manner that volumetric expansions extend along the upper 8–10 m of the embankments. The content of sulphates in this region (2.5%) is high enough for the occurrence of sulphate attack. In fact, Puppala et al. [21] identified very low threshold values (0.3%) to trigger the attack. A chemical simulation of the coupled hydraulic and chemical processes taking place at soil–cement interface verified that sulphate attack can develop within the jet-grouting treated volume of the embankments [27]. The distribution of expansions and heave along the embankment axis agrees with the extension and intensity of jet-grouting treatment. The confinement offered on one side by the abutment structure and by the non-treated embankment at the other side also explains the heave profile.

The chemical composition of the embankments and the availability of water from rainfall set up a scenario for future unlimited development of expansions. The risks of an increase of the damage generated to the bridge and a development of a worse passive state of stress motivated the excavation of the upper 6 m of the embankments along the stretch affected by sulphate attack. The remedial measures also included the construction of a new structure, founded on piles on both sides of the embankment, to support the rail tracks.

Lessons learned. Topographic investigations and the measurements of movements and deformations by means of sliding micrometers and inclinometers carried out in the site of Pallaressos embankments suggested that a volumetric swelling affected both embankments. Expansion derived in the generation of a passive state of stress, menacing the rail tracks. Swelling also resulted in high thrusts applied against the structure of both abutments that were damaging the bridge. A massive active sulphate attack agreed with the observed swelling. The treatments containing cement that were implemented at transition wedges joined with the high contents of sulphate at the upper 8 m of the compacted fill set a dangerous scenario for the development of sulphate attack. The availability of the necessary chemical components for sulphate attack was unlimited in the compacted soil (alumina, silicates, sulphates, calcium and water) and suggested that the formation of thaumasite and ettringite and, consequently, strains in embankments would continue if no comforting measures were built.

3.3 Monitoring Infrastructures and Their Foundations

Infrastructures and their foundations at Mestre (Italy). The area around Venice is undergoing remediation and protection works, to address the environmental concerns coming from high water in the Adriatic Sea and pollution from the chemical industrial area sitting on the onshore at Marghera. Besides the mobile barriers in the lagoon, which started functioning in 2020, extensive remediation of the industrial area includes the construction of continuous sheet-piles, which are designed to protect the lagoon from the discharge of polluted water coming from the industrial area.

The design of the sheet-piles has been accompanied by an extensive study on their impact on groundwater hydrology. The sheet-piles will act as a hydraulic barrier, preventing direct groundwater flow into the lagoon. Pumping wells have been designed to capture the groundwater ahead of the old industrial area and compensate for the reduced discharge into the sea. The groundwater hydraulic gradients are locally changed due to these remediation works, and concerns arose about the local water mass balance and pore pressure distribution in the ground, which may affect the intense network of existing infrastructures, including roads, highways and railways.

Besides a hydro-geological study on the entire watershed, which addressed the study at the regional scale, the water mass balance at the local scale of the specific infrastructure was investigated by monitoring the hydraulic response in the upper unsaturated soil and using the monitoring data to calibrate and validate a comprehensive numerical model.

Soil classification. In spite of the extension of the area and local heterogeneities, the topsoil grain size distribution is well defined, and consists of silty and clayey materials, having different percentages of sand. Typical grain size distributions are plotted in Fig. 15b and the relevant geotechnical properties are given in Table 3.

The retention properties were investigated in the laboratory in a pressure plate extractor, which was modified to apply appropriate vertical stresses [30]. The data allowed drawing lower and upper bounds for the retention curves expected in the area (Fig. 15b). The unsaturated hydraulic conductivity was assumed to be represented

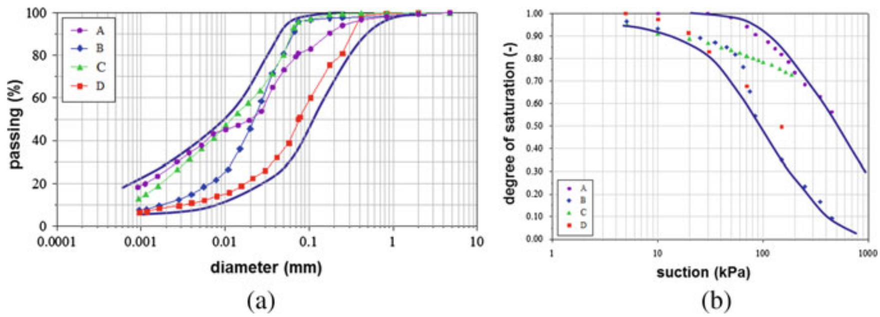


Fig. 15 Topsoil properties: **a** grading size distribution curves; **b** water retention curves

Table 3 Relevant geotechnical properties of the topsoils

Property	Topsoils
Specific gravity, Gs	2.74
Liquid limit, w_L, range	30–50%
Plasticity index, PI, range	10–25%
Average porosity	0.40
Saturated hydraulic conductivity, k	$10^{-6} \div 10^{-8}$ m/s

by the power function $k_r\ (S_r) = S_r^{\ 5}$, which was chosen after careful and extensive assessment of the most common predictive functions [31].

Research questions. The laboratory and numerical investigation aimed at answering a number of research questions, including: (i) Quantifying the local net water recharge over one year, as a function of the depth of the water table; (ii) In case of exceptional design flood having 1 m height above the ground surface would affected the area, estimate the time needed for the subsoil and the embankments to get saturated; and (iii) given paradigmatic soil profiles, estimate the depth of the soil affected by water exchanges due to soil-atmosphere interaction. These questions were addressed with numerical models, implemented in the CODE_BRIGHT finite element platform [32]. The numerical model was calibrated and validated with the data from the field described and discussed as follows.

Choice of the instrumentation. The instrumentation had to be chosen in order to be effective in a variety of soils, from rather impervious clayey silts to more pervious sandy silts. Multiple monitoring depths were needed over a depth encompassing the unsaturated topsoil above the water table, located from −1 m to −4 m depth from the ground surface. Moreover, the monitoring period had to last over one year, with limited possibility for direct inspection and control.

Ideally, both water content and suction were of interest. However, given the previous constraints, it was decided to invest on monitoring water content changes, and use the retention curves to infer the changes in suctions, which are needed in the geotechnical analysis of the infrastructures and foundations. Among the available

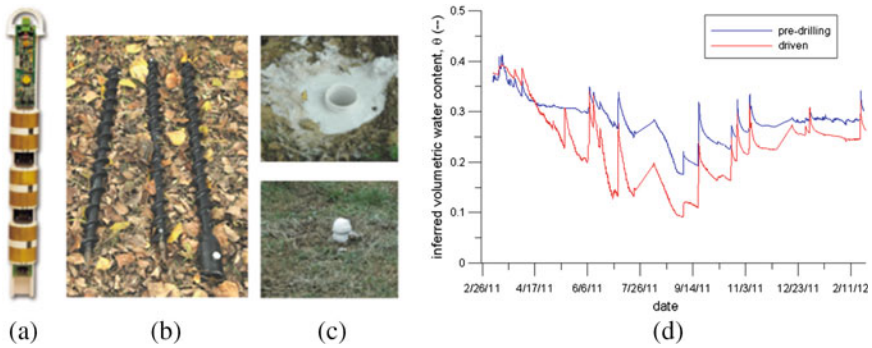


Fig. 16 Installation of the sensors: **a** sensor slide (from Sentek®); **b** drilling tools; **c** fluid filling and final configuration at the end of installation; **d** Comparison between two twin measurement installed with and without pre-drilling

possibilities, capacitance sensors were chosen, which could be installed at various depth interval on the same vertical section, and are less sensitive than comparable ones to the chemical composition of water, which is highly variable over the investigated area. The capacitance sensors are mounted on a plastic slide (Fig. 16a), inserted in an access tube, which was designed to be installed in the ground by pushing. However, the original design allowed to reach a depth of −1.0 to −1.5 depth only. To increase the installation depth of the sensor, pre-drilling was implemented, using specifically designed drilling tools (Fig. 16b). The pre-drilled hole was filled with a fluid mixture of kaolin and cement, to provide continuity between the sensors and the surrounding ground (Fig. 16c).

Calibration of the sensors. Typically, a reference calibration curve is provided for commercial sensors. One of the advantages of the capacitance sensors is that their calibration curve is rather insensitive to the type of soil, due to the limited contribution of the water chemistry at the input frequencies used in the measurement.

However, it was found that the installation procedures have a relevant influence on the measurement, as shown in Fig. 16d, where the results are reported from two twin sensors installed by driving and pre-drilling at a small distance from each other. The comparison in the figure shows that the kaolin-cement mixture at the interface between the access tube and the soil, which is chosen to keep saturated over a wide range of water content to guarantee optimal contact with the soil, partly shadows the water content changes in the surrounding ground, especially during the dry seasons. The calibration curves can be refined, by simulating the electric field in a numerical model, able to include the disturbance due to the different installation procedures. The numerical model adopted for the calibration refinement is shown in Fig. 17. Figure 18 presents the calculated electric fields in the soil accounting for installation disturbance (Fig. 18b), to be compared to the ideal field (Fig. 18a), aiming to evaluate the measurement dispersion. The analysis allowed to define calibration curves as a function of the installation procedure (Fig. 18c).

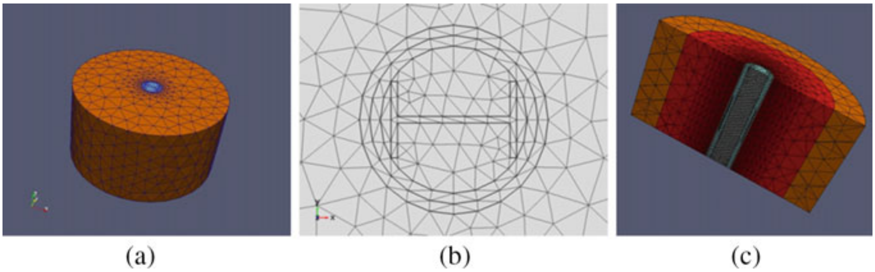


Fig. 17 Numerical model: **a** complete view; **b** top view, showing the instrumentation components; **c** cross section including variable properties to simulate installation effects

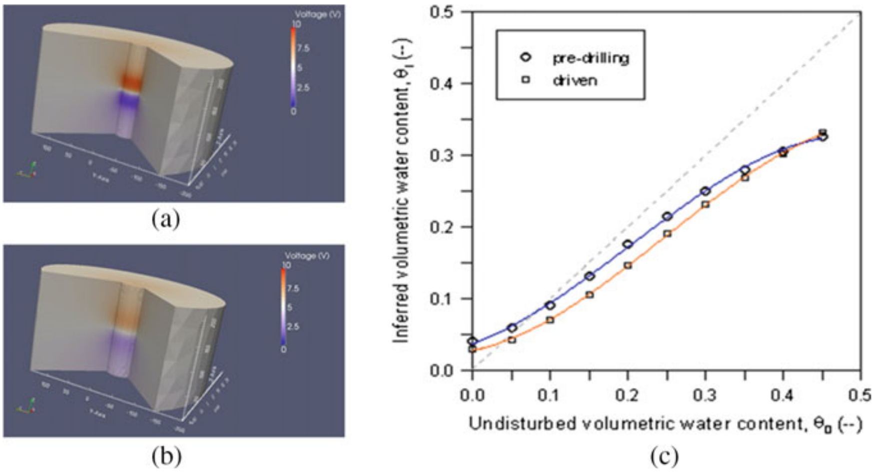


Fig. 18 Correction of the calibration curves to consider disturbance during installation: **a** numerical simulation of the electric field for ideal conditions; **b** numerical simulation of the electric field with disturbance from installation; **c** resulting calibration curves

Results. A number of vertical sections were investigated in the Mestre area. Among them, the data from a highway embankment and from the surrounding foundation soil are presented and compared in the following. Whenever possible, embankments are constructed with the soils locally available nearby, to reduce the construction and environmental costs. Thanks to the composition of the foundation soil, a good clayey and sandy silt, this was the construction choice for the tested embankment, which is part of the highway bypassing the area of Mestre in the E-W direction. Figure 19 presents selected results over two vertical sections nearby the embankment, showing the response of the natural soil profile to the climatic history. The soil profile presents a 50 cm cover, rich in organic matter, which clearly acts as a buffer over time for the deeper layers. The lower clayey silt has a hydraulic conductivity of about 10^{-7} m/s, which is low enough to avoid any significant change in the water content over time,

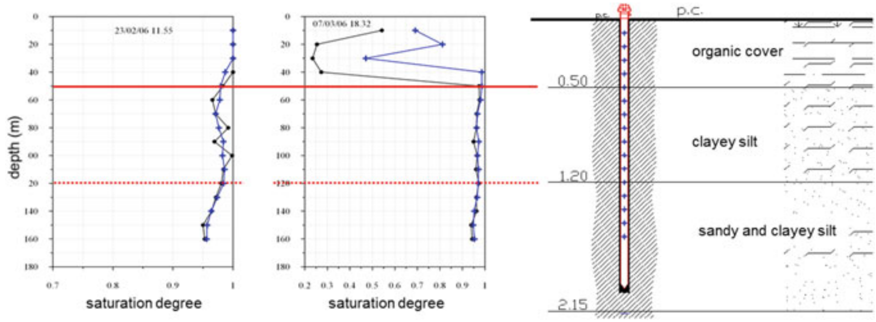


Fig. 19 Variation of the degree of saturation over time in the foundation soil

given the shallow position of the groundwater table. However, the behaviour of the same clayey silt used in the construction of the embankment is clearly different due to two concomitant effects. On the one hand, digging and compaction operations change the texture of the material, which results in an increased hydraulic conductivity. On the other hand, the absence of the protecting organic cover reduces the buffering effect and allows water exchanges to affect higher depths.

Final comments. the calibration of the numerical model on laboratory data showed to be reliable to simulate the response of the natural soil, hence of the foundation. When the same soil is used in compacted earth constructions, a wider pore size distribution is expected due to compaction of lumps, which typically cannot be reproduced in a standard laboratory investigations. Calibration of numerical models takes great advantage from the back-analysis of field data, as shown, e.g., in [33]. Finally, is worth mentioning that defects in sensors installation, like air pockets, would affect the measurement dramatically, as investigated and extensively discussed in a dedicated study [34]. Therefore, they must be avoided to get reliable data.

4 Conclusions

Monitoring soil suction, or the evolution of water content in earth structures, is necessary to predict deformations caused by wetting and drying cycles such as those from soil-atmosphere interaction, or by changes on water table levels at their foundations. This has huge potential to be used on predicting the impact of climate changes on the performance of existing geotechnical structures and is already a concern for all entities connected to infrastructures design, operation and maintenance. Novel working opportunities are expected for Geotechnical Engineers to deal with aspects related with unsaturated soils behavior.

As when traditional instruments are installed, the choice of the proper sensors to monitor water content or soil suction must consider their compatibility with the type of soil, the expected range of operation, accuracy and sensitiveness, response speed, calibration needs, installation and technical knowledge for their operation, and their durability and maintenance needs. For such sensors, the response to dynamic climatic events is very important if climatic patterns are taken into consideration.

The three case-studies presented are non-conventional cases where standard instruments were installed to help understanding problematic behaviors, expected or in progress. The lessons learned and some common features to all cases (also common to traditional earth structures), can be highlighted: (i) the choice of standard instruments is tailored for each case considering the expected behavior and its main causes; (ii) the displacements are the most relevant information to collect because they occur due to deformations, and therefore are liked to stress state by material mechanical constants; (iii) displacements allow identifying ongoing mechanisms and define adequate interventions to stop them; (iv) complementary instrumentation can also be installed to investigate the causes of the deformations, such as soil suction sensors; (v) creative solutions may have to be implemented to install the instruments and sensors, especially when they need to operate in different materials; (vi) disturbance affecting calibration must be considered; (vii) sensors need calibration, usually done through experimental tests in laboratory; (viii) laboratory tests can also be performed to characterize the hydraulic and mechanical behaviour of the materials, necessary to calibrate numerical models to simulate the behaviour observed; (ix) calibration of numerical models takes great advantage from the back-analysis of field data; (x) the behaviour predicted by the model can also help defining instrument location; (xi) instrumentation can be broken or malfunctioning, so it should be redundant by duplication or installing different instruments for cross information; (xii) monitored data also must be redundant and obtained by different type of instruments for validation.

To conclude, testing and monitoring earth structures requires instrumentation and sensors which are being continuously updated by technological advances and many new will be invented, always seeking for environment-friendly and sustainable solutions. New sensors and many interesting case studies are expected in the future.

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