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Abstract

In situ measurements of soil suction and water content in deep soil layers still represent an experimental challenge. Mostly developed within agriculture related disciplines, field techniques for the identification of soil retention behaviour have been so far employed in the geotechnical context to monitor shallow landslides and seasonal volume changes beneath shallow foundations, within the most superficial ground strata. In this paper, a novel installation technique is presented, discussed and assessed, which allows to extend the use of commercially available low cost and low maintenance instruments to characterise deep soil layers. Multi-depth installations have been successfully carried out using two different sensors to measure the soil suction and water content up to 7m from the soil surface. Preliminary laboratory investigations were also shown to provide a reasonable benchmark to the field data. The results of this study offer a convenient starting point to accommodate important geotechnical works such as river and road embankments in the traditional monitoring of unsaturated soil variables.

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Notation

A	activity index
e_0	initial void ratio
n_{VG}	pore size distribution parameter
PI	plasticity index
PSD	particle size distribution
w_n	natural water content
w_P	plastic limit
α_{VG}	residual reciprocal of air entry value
θ	volumetric water content
θ_r	residual volumetric water content
θ_s	saturated volumetric water content

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Introduction

The evaluation of negative pore water pressures plays a crucial role in the description of the stress state of an unsaturated soil. Negative pore water pressures directly relates to soil suction, particularly the matric suction component, which influences soil water content. The soil suction is typically given as a function of soil water content, through the Soil Water Retention Curve (SWRC), which sets the foundations for unsaturated soil mechanics. The SWRC can be measured either in the laboratory or in the field. However, *in situ* measurements of SWRC may differ from that determined in the laboratory, due to different boundary and stress conditions in the field (Bordoni et al., 2017). Field measurements enable larger soil volume to be investigated and allows for accounting the time and spatial variability of water content and soil suction. As a result, field measurements of these unsaturated soil variables play a crucial role in identifying the initial stress state at a specific site and provide relevant monitoring data, complementing the laboratory data in the development and validations of unsaturated soil models (Fredlund, 2006).

The most widespread tools for *in situ* evaluation of soil water content are based on electro-magnetic indirect methods such as frequency, time or amplitude domain reflectometry and capacitive sensors (Bittelli, 2011). Water-filled tensiometers are, on the other side, the most widely used instruments for *in situ* measurement of suction in the lowest range (i.e. less than -100kPa). Since the pioneering work by Ridley and Burland (1996), know-how regarding high capacity tensiometers (HTC) capable of measuring in excess of 1MPa, has advanced considerably (Lourenço et al., 2008), but only recently designs specific to field applications were developed (e.g. Toll et al., 2011). Nonetheless, the use of HTCs in situ has so far been limited to research applications. In addition, their installation has to provide the possibility of removing the instrument, as conditioning is necessary before installation and upon air entry. Thermocouple psychrometers and heat dissipation sensors, which can determine either the water content or the soil water potential and extend the range of measurement compared to tensiometers, are also used frequently. These instruments generally require lower economic and maintenance efforts compared to the more advanced HTCs, leading to the possibility of extended monitoring system with relatively low operation costs. However, HTCs allow to measure positive values of pore pressure, while this is not possible with indirect methods. Degré et al. (2017) have recently given an essential summary of these instruments along with an accurate overview on the performance of new sensors like polymer tensiometers (POTs), MPS probes or pF meters.

Significant contributions to the development of these instruments have come from the agriculture-related disciplines, such as soil science, soil physics, and agronomy, as the SWRC essentially governs the amount of plant-available water influencing deeply irrigation management procedures. For applications as such, special attention is paid to evapo-transpiration process, atmospheric coupling and interaction with vegetation. Since their developments, these instruments have also found utilisation in some geotechnical problems. Most commonly in the field of monitoring landslides (e.g. Springman et al., 2013; Cascini et al., 2014; Bordoni et al., 2015; Pirone et al., 2015) or changes in the soil volume due to seasonal variations of water content for the purpose of foundation design (Nguyen et al., 2010; Harris et al., 2013) and river embankments (Casagli et al., 1999).

For these applications, the instruments were installed within the first few meters below the ground surface, up to maximum depths of 2 to 3m. To the authors' knowledge, only few studies have considered so far deeper soil layers. In these studies soil suction was measured and HTCs were used, in single installations (Ridley and Burland, 1996) or multiple installations in a single borehole (Mendes et al., 2008). More recently, attempts have also been made to mount HTCs along the sleeve of a penetrometer to allow for measurement at depth (Tarantino et al., 2016).

Simultaneous measurements of soil suction and water content in deep soil layers still offer an experimental challenge and may open the way to a wide range of applications, such as road and river embankments, for which partial saturation conditions may easily extend well beyond 5m from the ground surface (Gottardi et al., 2016; Gottardi and Gragnano, 2016). Throughout the lifetime of these geotechnical works, soil suction and water content are subjected to variations as function of changes in the hydraulic and meteorological conditions. A continuous monitoring of these variables during wet and dry periods becomes then crucial towards the development and assessment of seepage and stability analyses.

To the scope, the study presented in this paper, focuses on the development of a new methodology for deep measurements of soil suction and water content. The idea was to devise a cost-effective, non-invasive, repeatable technique, whose implementation into monitoring systems could be carried out rather easily over wide areas, ensuring accurate measurements and low maintenance operations.

The experimental procedures were tested, for the first time, at the crown of a river embankment in Emilia Romagna, Northern Italy, where dielectric water potential and water content sensors, selected as they offered a cost-effective and low-maintenance solution, were installed up to 7m depth.

In this paper, special attention is given to the tools, procedures and applications of the installation procedures, highlighting practical issues and solutions. Monitoring data collected during installation and up to equilibrium with the boundary conditions are presented and discussed. In addition, preliminary laboratory investigations on soil retention behaviour are shown to provide a benchmark to the field data. The technological contributions described herein might provide the starting point to extend the traditional monitoring of unsaturated soil state variables to deeper soil layers, which would enable to cover a wide variety of geotechnical applications.

Details of the soil properties at the test site

The study has been carried out at an 8m high embankment, at a suitable site in Emilia Romagna, Northern Italy. Prior to the installation, core samples were taken at the site, at depths between 1.8m and 6.8m from the embankment crown. In particular, the natural water content, the particle size distribution and the consistency indexes, were determined by means of laboratory testing. According to these data, the artificial embankment consists of a single heterogeneous unit, about 6m thick, characterised by a complex alternation of silt and sandy silt. Figure 1a shows the main soil fractions obtained from the grading curves plotted along the embankment depth. The main fraction is silt, ranging between 45 and 70%, while sand varies between 25 to 50%. The clay fraction ranges between 10 and 25% and has plasticity index, PI, of about 10%, as depicted in Fig.1b.

The natural water content, w_n, measured on the core samples, was close to the plastic limit, w_P, and increases from the embankment crown up to 4m depth (Fig.1b). The soil is classified as a low plasticity clay on the Casagrande chart (Fig.1c), with the data points plotting above the A-line as characteristic of illite. The mineralogy was also confirmed by the activity index A, which is close to 0.7.

Details of the soil suction and water content sensors

The soil suction sensors used were MPS-6 sensors (Decagon Devices, 2016a), which were recently assessed as having a good performance by Degré et al. (2017). The instrument uses the water content of a porous ceramic disc to calculate the water potential (soil suction) through a highly reliable water retention characteristic curve of the disc, which is the actual monitoring point. The water content itself is obtained through calibration with its dielectric permittivity, which is the quantity directly measured. Assuming hydraulic equilibrium between the ceramic disc and the surrounding soil, the soil suction is measured indirectly. The instrument accuracy is ±10% of the reading + 2kPa, over a range -9 to -100kPa, while the measuring range extends to dry conditions (-100MPa). The sensors were installed at depths between 3m and 7m, as detailed in Table 1 and depicted in Fig. 2.

As the ceramic disc constitutes a fragile element of the probe, special care was taken in the installation phase. To avoid possible damages associated by simply pushing the instrument to the required depth, a specific procedure was developed. The idea underpinning the installation procedure is to secure the suction sensor in a "soil cake" prepared in the laboratory prior to installation. The suction sensor is then in contact with the borehole through the soil cake. Upon

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installation, if the initial conditions of the soil cake differ from those of the surrounding soil, a transient flow is established between the soil cake and the surrounding soil until the hydraulic equilibrium is reached in correspondence of a unique value of soil suction. The soil used was sampled at the site and had a particle size distribution slightly finer than that found at the installation depth. While filters around piezometers should have a higher permeability (i.e. coarser particle size distribution) than that of the surrounding soil, the opposite is true when measuring suction, as this guarantees a high air entry value and therefore avoids that hydraulic continuity between the soil and the sensor is lost. For this reason, jet-fill and flushable piezometers are sometimes buried in cement bentonite mixtures. However, this might cause a considerably larger delay in the sensor response than when using soil of the same or similar composition as in situ. In particular, Toll et al. (2011) found that HTCs measured a lower value when placed in the grouting mixture than in the intact soil. For this reason, a comparison between direct and indirect measurements of suction in a soil volume at the laboratory scale was carried out, developing a specific calibration for the sensor.

The cake was formed using a cylindrical bucket having the same diameter as the boreholes hosting the sensor (10cm), as depicted in Fig.2a. A plastic tube having a short longitudinal slot was placed vertically inside the bucket while preparing the cake (Fig.2b) to channel out the cable of the host sensor and/or of sensors installed deeper (Fig.2d-e), as in the case of multiple-points installations. As seen in Figures 2c and 3a, the sensor was placed with the ceramic disc oriented upwards to ease air discharge and reduce air entrapment. As the natural soil water content was generally close or below its plastic limit, water was added to ensure workability. However, the water content was kept below the liquid limit to avoid the formation of cracks while curing the cake to approximately the initial water content. This latter step ensured safe handling of the cake as it was left to dry until self-sustaining and shorter time to reach equilibrium with the field conditions. These preparatory operations carried out in the laboratory with controlled conditions provide a series of soil volumes each containing a soil suction sensor (Fig.2f) and allow a highly repeatable procedure. Figure 3 shows a final sketch of the soil cake and its conditions prior site installation.

The soil water content sensors used were the GS3 (Decagon Devices, 2016b). The sensor consists in a plastic body from which three parallel steel needles having a slightly tapered end (prongs) are protruding at a right angle, which allow direct installation into the intact ground. The sensor measures the dielectric permittivity of the medium in which its prongs are placed by generating a 70MHz electromagnetic field across them. The dielectric permittivity measured is calibrated against the water content of the soil surrounding the sensor prongs (≈160cm^3). This calibration depends on the type of charge, soil lithology and prongs length and to improve the default accuracy (±3%), user calibrations taking into account all these factors were carried out. Depths of installation on site were between 2.3m and 7.1m. Because of the geometry of the sensor prongs, it was possible to install it directly in the soil surrounding the host borehole without risking damaging it. This aspect is crucial, as the water content distribution and, more generally hydraulic, properties are highly dependent on the particle arrangement of the soil.

Details of the installation procedures

The suction sensors and water content sensors were installed within boreholes carried out to the scope, in a single or multiple arrangement as depicted in Fig.4. The installation of different sensors within the same borehole offers the advantage to minimise the number of excavations, avoiding preferential water flow paths to be established at the site, which could bias the measurements and locally damage the embankment integrity with possible consequence on its stability. The multiple point type of installation also facilitates the identification of the field SWRC, as suction and water content sensors can be combined at the same depth in the same borehole.

Single point measurements were also designed and implemented, where one sensor only was installed within a given borehole. This procedure, which is comparatively simpler to execute, was followed for the deepest installations (7m). Details are provided in Table 1, where the type of installation, either multiple (M) or single (S) is given along with the depth at which each sensor (MPS-6 and GS3) was installed with respect to the embankment crown (C). The installations herein described were executed in three boreholes, of which one was a multiple point installation with 4 sensors (MPC1), while the other two single point installations hosted one sensor each (SPC1 and SPC2).

For the installation of the water content sensors a different experimental technique was developed. As already mentioned, the GS3 sensor is equipped with three prongs shaped electrodes that can be installed directly in the intact soil, either at the borehole base or sidewall, as illustrated schematically in Fig.5 (installation 1 and 2, respectively). The installation procedure involves pushing the prongs into the soil until a full contact between the sensor body and the borehole shaft is achieved. The geometry of the GS3 allows the process to be carried out quite easily, ensuring no damage during installation and keeping the soil disturbance at a minimum.

To install the GS3 at the borehole base (1 in Fig.5a), the sensor body was positioned in a "U" shaped cradle, as shown in Fig.5b, to keep its prongs vertical during installation. Two thin plastic wires were employed to hold the sensor in place while lowering the assembly down the borehole. These were removed after ascertaining a successful installation by means of changes in the transducer's readings and/or video inspection (Fig.5c). In Figures 5c and 5e, the plastic body of the sensor is outlined and, despite the rather poor quality of the images, the sensor prongs are not visible having entered the ground, hence confirming that the instrument was correctly installed.

For the sidewall installation of the GS3 (2 in Fig.5a) a different procedure was developed that made use of a prototype instrument provided by Meter Group, called Quick Borehole Installation Tool and hereinafter referred to as Q-BIT. The tool is made of a series of telescopic pipes that thrust the instrument's head forward in a horizontal direction and push the GS3 prongs in the soil. As depicted in Figure 6, the Q-BIT consists of three main parts: the carriage, the shaft and the handle actuator. The sensor is placed in a plastic housing (cradle), which is mounted on the carriage. Figure 6 shows the carriage in the retracted mode hosting a GS3. The carriage features a three-leg jack mechanism to convert vertical into a horizontal force, therefore pushing the sensor prongs through the soil of the borehole shaft. If the Q-BIT is held perfectly vertical,

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the mechanism forces the sensor to proceed on a straight line during horizontal displacement, thus assuring a perfect contact between electrodes and soil. This results from identical, yet opposite vertical displacement of the two carriage slides. These are, in turn, actuated by the symmetrical levers in the handle actuator, which control two concentric shafts moving in opposite directions. A third external shaft connects carriage and actuator and provides the sufficient stiffness to the system.

Thanks to the mechanical advantage offered by both the actuator levers and the jack mechanism, in addition to the sharp prong tips, very little force is required to install the sensor in either soft or comparatively harder soils. As a successful installation relies on the integrity of the sensor, presence of gravel might be problematic. If the user has enough sensitivity in the handles, it is possible to recognize when a rock is being hit by the sensor. In this case, the installation procedure can be interrupted, and the sensor recovered by gently pulling on the cable.

By means of these techniques, one MPS-6 sensor and one GS3 sensor were installed at the base of borehole SPC1 and SPC2, respectively. The borehole MPC1 was instrumented with 2 water content sensors and 2 suction sensors as follows. Upon completion of the borehole to the prescribed depth (about 4.6m), the first soil cake was lowered to the borehole base with the aid of a metallic tube, as already described. Afterwards the water content sensor (GS3) was installed right above on the borehole sidewall (configuration 2 in Fig.5a). For the installation, the Q-BIT was lowered into the borehole until its head was resting on top of the soil cake (about 4.5m). As already mentioned, the Q-BIT uses the borehole sidewall as a contrast to push the sensor prongs into the soil. Once the sensor was installed, the carriage was retracted, leaving the sensor in place,

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and the Q-BIT was retrieved from the borehole. Attaching a miniature camera to the Q-BIT it was possible to confirm the inspection as shown in Fig.5e. Completion of the operation was also confirmed by changes in the data recorded, which were monitored while installing the sensors as a warning. The first installation was then sealed filling 0.5m of the borehole with bentonite hydrated pellets, while soil retrieved on site was used to fill the borehole up to the depth of the second installation (about 3m from the soil surface). Another soil cake hosting an MPS-6 was then lowered into the borehole and a second GS3 was installed.

Figure 7 shows the monitoring data collected during and right after the installation phases. The MPS-6 measurements start from suction values generally higher than in situ, which is due to having dried the soil cake prior to installation. Equilibrium with the surrounding soil can be reached in one day to several weeks, when no significant external actions occur (as experienced on the monitoring site); the duration of this process is, however, strongly dependent on the initial and boundary conditions of the transient seepage existing between the soil cake and the surrounding soil. The equilibrium time for the GS3 is rather similar for all the sensors installed and it is less than one day. At the end of the equalization process, measured suction values were consistently between 35-60kPa, while volumetric water content values were between 0.21-0.32m^3/m^3.

Soil retention behaviour

Soil water retention curves (SWRC) were also investigated in in the laboratory on a set of remoulded samples taken at the installation site at various depths. The experiments were run using the Hyprop (UMS, 2015), which measures the water loss due to evaporation by weighing continuously an initially saturated soil sample. During the evaporation test, two tensiometers measure the matric suction at depths equal to 0.75 and 0.25 times the sample height. At the end of the test, the sample dry density can be calculated by oven drying the sample at 105°C. The main advantage of this method is that the hydraulic properties are obtained during transient flow, similarly to what happens naturally in the subsurface, thereby estimating highly representative hydraulic properties of the porous medium under study (Romano and Santini, 1999).

The main limitation of the instrument is the maximum suction that it can measure accurately, which is limited to a threshold value of 80-100kPa, above which tensiometers start to cavitate. For this reason, values at higher suction were obtained coupling the evaporation test to the Dew Point Method (DPM), using the WP4 (Decagon Devices, 2007). This method is based on the measurement of the relative humidity in a closed chamber containing the soil sample. When equilibrium is reached between the vapour in the chamber and the liquid phase in the soil, Kelvin's equation is used to calculate the water potential from the relative humidity. This is a reference method for determining the soil hydraulic potential (Gee and Or, 2002).

Using both instruments, a series of six evaporation tests was carried out on remoulded samples of disturbed soil taken at about 2.8m depth from the embankment crown (Sample 1) and at 4.8m depth (Sample 2). Various initial void ratios were used, reflecting the range observed in the field (e_0=0.57-0.91). After completing the third evaporation test for each sample at suction values higher than 100kPa and prior to oven drying, a subsample was collected for each sample and measurements at higher suctions were carried out with the WP4. Discrete measurements of suction and water content were, then, performed following the progressive desaturation of the

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soil specimens. Through this procedure, and with the aim to obtain the main drying characteristic curves for a wide suction range, the WP4 measurements were thus combined to retention data resulted from the relevant evaporation test results for both samples. Figure 8 shows the soil water retention curves obtained from these tests, where the curves interpolate the experimental data using the well-known van Genuchten model in eq.(1) (van Genuchten, 1980).

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

Best fit parameters, obtained using a least square regression, are listed in Table 2. While the water content at saturation θ_S varies slightly with e_0, which changes in the order ±0.05, the dry part of the path tend to be more independent of e_0. The experimental data were fitted so as to capture accurately the knee of the curve, which is reflected in n_{VG} and α_{VG}. The first parameter is mainly a function of the pore size distribution and does not change significantly across the different tests, while α_{VG} is the reciprocal of the air entry value and varies nearly an order of magnitude, starting from a few kPa due to the rather coarse nature of the soil. Generally α_{VG} reduces with increasing e_0, as the pore size of the sample increases.

Figure 8 also shows the soil suction and water content values measured in field after equilibration with the surrounding environment for a specific location, i.e. MPC1 at 4.5m-4.6m depth. The coupled values of soil suction and water content recorded in situ plot below, but reasonably close to the main drying curves identified from laboratory test, showing that the installation techniques used provide reliable results. The discrepancy could result from a number of reasons, even given the same soil composition. For example, the reconstituted samples have a slightly higher e_0 than measured in situ for that depth and the particle arrangement would not be

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as that of the intact soil. An additional reason is that the soil retention behaviour experienced in wetting or drying process differs (i.e. hydraulic hysteresis) and water content can be consistently coupled to suction values lower than those encountered along the main drying curve, although monitoring data for a much longer period would be needed to confirm this. Several researchers emphasised that a reliable estimation of soil retention parameters fully representing wetting and drying paths is essential for a complete definition of soil mechanical hydraulic behaviour (Topp and Miller, 1966; Jaynes, 1984; Kool and Parker, 1987; Likos et al., 2014), being particularly crucial when frequent fluctuation in water content occur with seasonal or daily periodicity, e.g. embankments, streambanks and riverbanks. For this reason, a comprehensive suite of laboratory experiments and site monitoring is required for a proper unsaturated soil characterisation and for the determination of stability and seepage conditions of the earthen structures during their lifetime.

Concluding remarks

The paper has presented the experimental aspects of a new technique for the field measurements of soil suction and water content in deep soil layers, with potential applications in the field of monitoring of road and river embankments. A first set of installations was implemented and assessed at the crown of a riverbank in the Emilia Romagna region, where instruments were successfully installed up to 7m depth. The paper presents the essential features of the field activities and first measurements along with the results of preliminary laboratory data as obtained by soil samples taken at the site. Special emphasis was given to the tools and the field installation procedures, focusing on practical issues and solutions that were suitably devise to:

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- enable coupled measure of soil suction and volumetric water content at the same depth, allowing for tracking the evolution of the field SWRC with time,
- record data at different depths while minimising the infrastructure disturbance,
- ensure a good balance between accuracy and cost-effectiveness of the instruments,
- allow for simple maintenance operations following the installation phase,
- guarantee the procedure simplicity and repeatability.

These key aspects provide the basis for the development of a monitoring system, which might extend over wide areas involving the use of several sensors, for which cost-effectiveness and repeatability plays a crucial role.

The initial monitoring data show that the techniques adopted were successful in achieving good quality measurements and demonstrated that the time required to reach equilibrium with the boundary conditions was rather short, however acceptable for various geotechnical engineering applications. Furthermore, the combination of suction and water content data was used to calculate the retention state in situ, which was then compared with preliminary retention curves obtained in the laboratory. The results looked promising, although further work is required, involving longer monitoring time, comparison with direct measurement methodologies and laboratory determination of retention curves over an extended range based on intact samples. The results of this study provide a convenient experimental starting point to extend the monitoring of the soil retention behaviour in river and road embankments.

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Table 1. Details of the installation scheme for suction and water content sensors within the embankment

Borehole	Sensor	Installation depth (m)
MPC1	GS3	2.4
	MPS-6	3.1
	GS3	4.5
	MPS-6	4.6
SPC1	MPS-6	7.0
SPC2	GS3	7.1

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Table 2. Estimated soil main retention properties, initial void ratio and sampling depths

Sample	depth (m)	e_0 (-)	Θ_r (m^3/m^3)	Θ_s (m^3/m^3)	α_{VG} (kPa^{-1})	n_{VG} (-)
		0.616	0.00	0.375	0.092	1.172
1	2.7-2.9	0.684	0.00	0.385	0.084	1. 265
		0.724	0.01	0.385	0.186	1.267
		0.646	0.00	0.373	0.027	1.204
2	4.7-4.9	0.668	0.00	0.351	0.033	1.237
		0.755	0.00	0.404	0.185	1.164

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Figure 1. Soil classification at the installation site: (a) Particle size distribution, (b) plasticity index and natural water content with depth and (c) Casagrande chart.

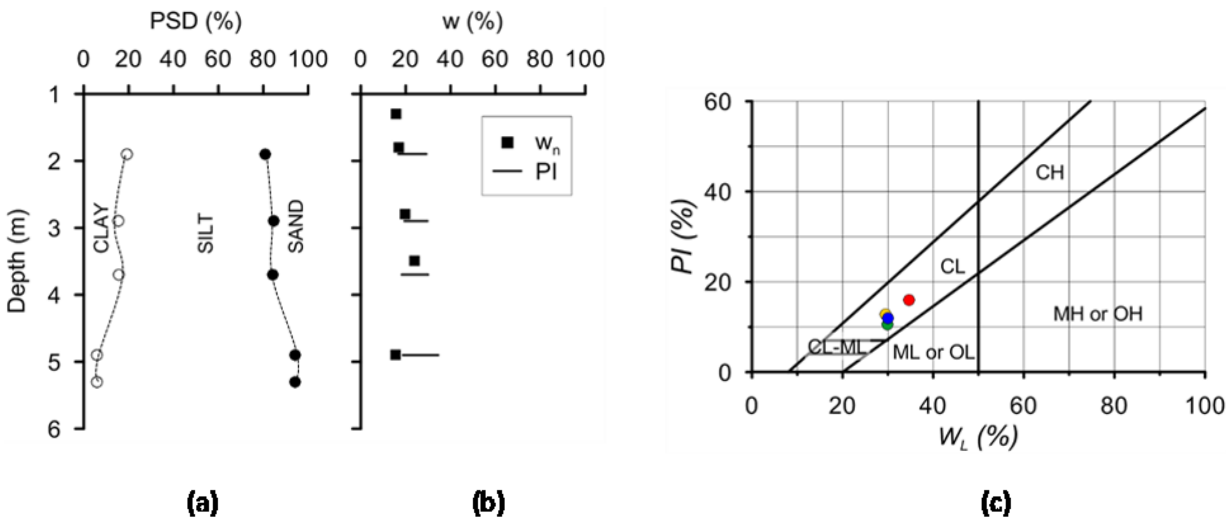

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Figure 2. Phases of the laboratory preparation of the "soil cake" used for installing the suction sensor.

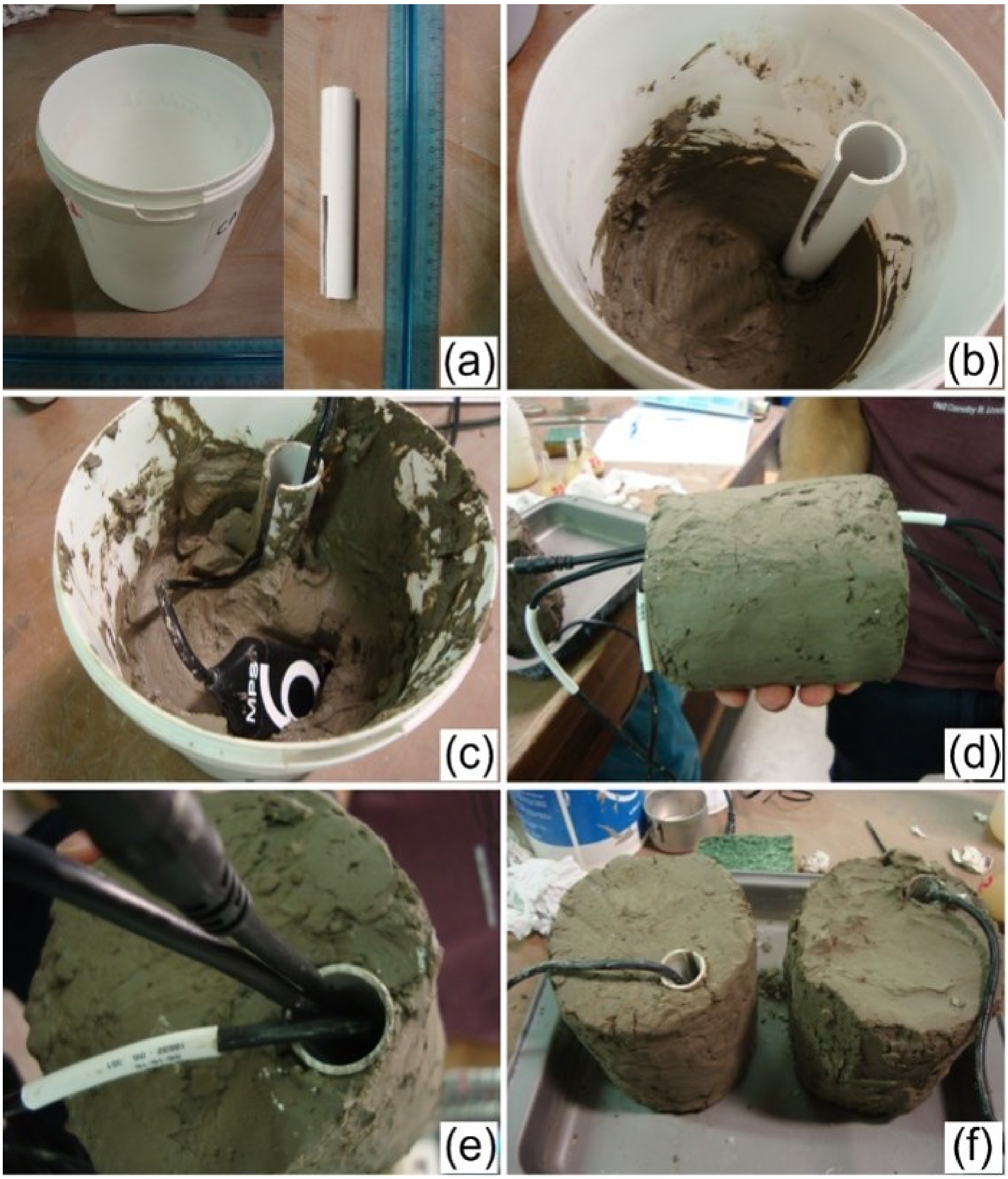

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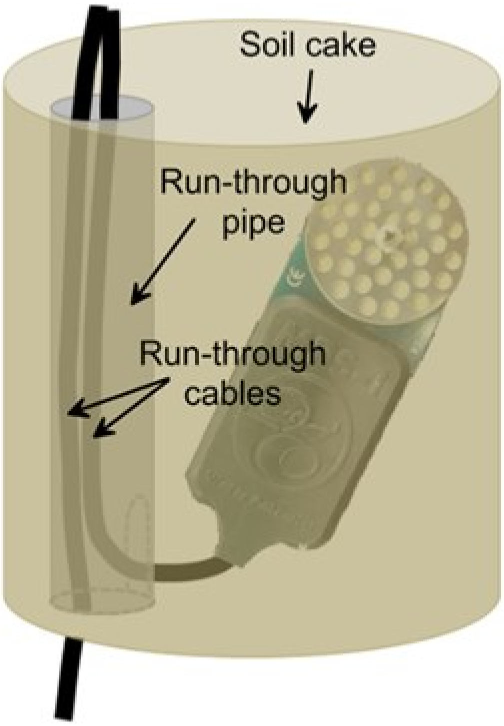
Figure 3. Schematic of the "soil cake" used for installing the suction sensor (a) drawing and (b) photo taken at the site prior to the installation.



(a) (b)

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Figure 4. Scheme of the sensors installation: a) cross-section with likely hydrometric levels and b) longitudinal section.

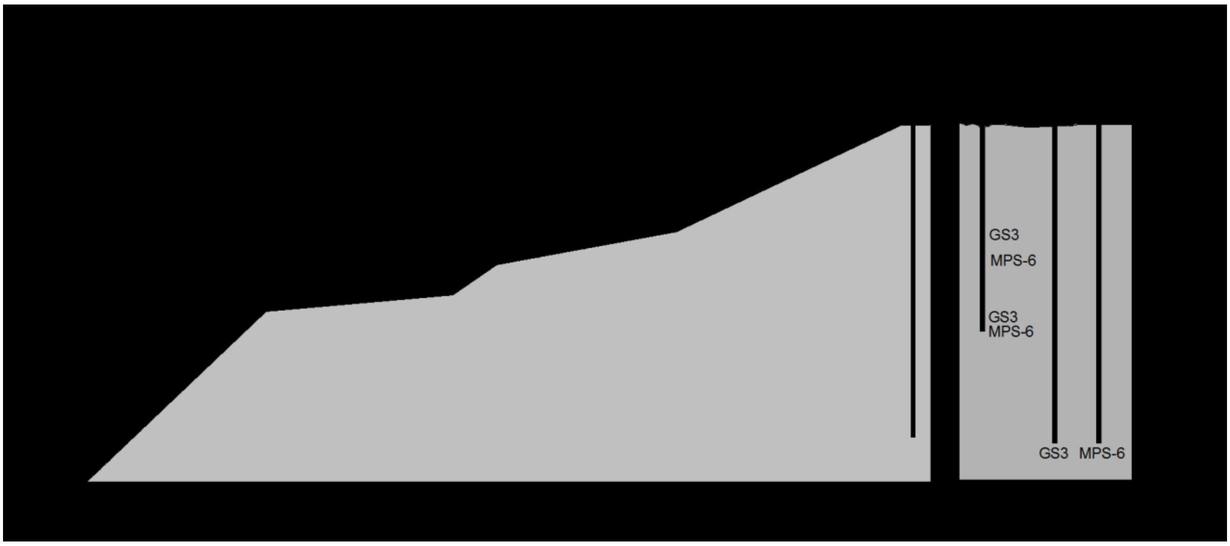


Figure 5. Schematic of the installation of a water content sensor: a) at the borehole base (1) and sidewall (2); details of installation 1, b) U shaped cradle and c) video inspection; details installation 2, d) Q-BIT entering the borehole and e) video inspection.

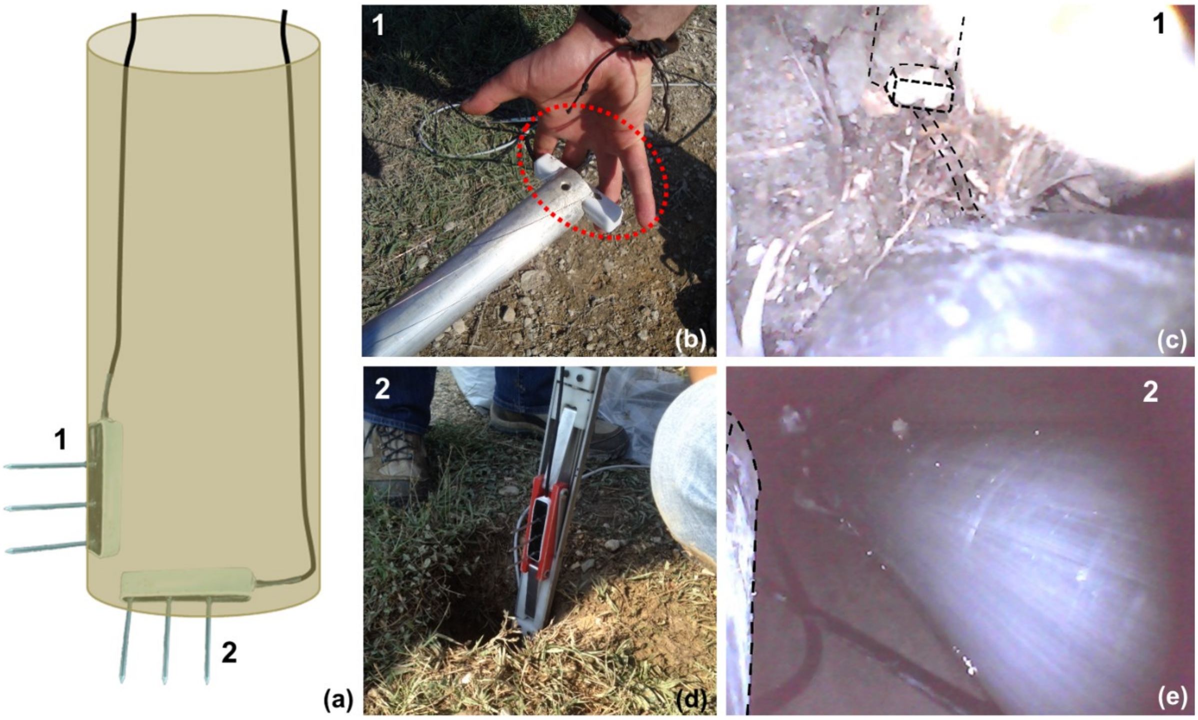
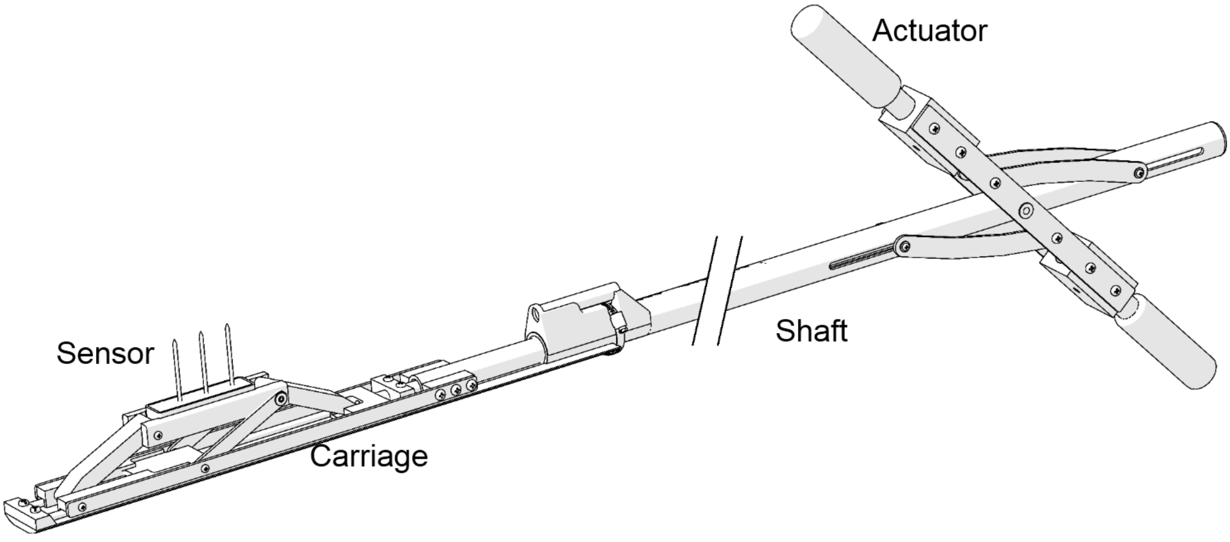


Figure 6. Three-dimensional view of the Quick Borehole Installation Tool (Q-BIT).



doi: 10.1680/jgere.17.00012

Figure 7. Monitoring data collected right after the sensors installation.

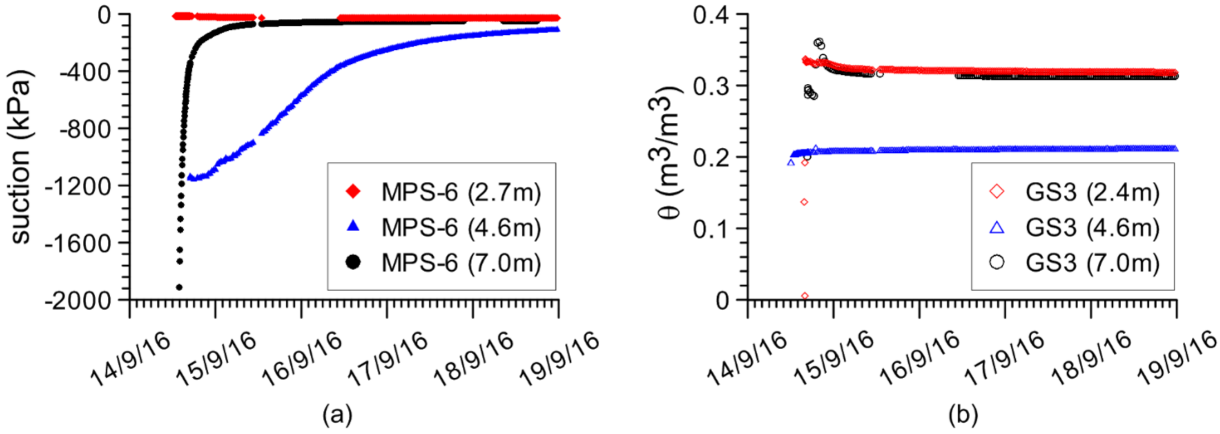


Figure 8. Soil water retention curves for the main drying paths obtained by means of evaporation tests on remoulded soil sampled at 2.8m (left) and 4.8m (right) depth from the surface. Field values (filled circle) at 4.5m-4.6m depth are plotted when equilibrium is fully reached (31/01/2017).