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Soil thermal behavior in different moisture condition: an overview of ITER project from laboratory to field test monitoring

Eloisa Di Sipio[1] · David Bertermann[1]

Abstract

The thermal properties of soils can be considered one of the most important parameters for many engineering projects designing. In detail, the thermal conductivity plays a fundamental role when dimensioning ground heat exchangers, especially very shallow geothermal (VSG) systems, interesting the first 2 m of depth from the ground level. However, the determination of heat transfer in soils is difficult to estimate, because depends on several factors, including, among others, particle size, density, water content, mineralogy composition, ground temperature, organic matter. The performance of a VSG system, as horizontal collectors or special forms, is strongly correlated to the kind of sediment at disposal and suddenly decreases in case of dry-unsaturated conditions in the surrounding soil. Therefore, a better knowledge of the relationship between thermal conductivity and water content is required for understanding the VSG systems behavior in saturated and unsaturated conditions. Key challenge of ITER project, funded by European Union, is to understand how to enhance the heat transfer of the sediments surrounding the pipes, taking into account the interactions between the soil, the horizontal heat exchangers and the surrounding environment. In detail, changes of soil moisture content in the same climatic conditions and under the same thermal stress for five different soil mixtures have been monitored in the ITER test site. The relationship with precipitation and natural/induced ground temperature variations, reaching also water freezing point, are here discussed.

Keywords Soil · Water content · Soil freezing · Thermal conductivity · Very shallow geothermal energy · Geothermal helical heat exchangers

Introduction

Shallow geothermal energy is a promising renewable resource, especially for the space conditioning of residential and industrial buildings. Since the subsurface temperature is steady through the year, the basic principle is to exploit the heat stored in the ground during winter, when outside air temperature is lower, and reinject it in summer time, when the ground is cooler, by means of ground-source heat pumps

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(GSHPs) (Omer et al. 2008; Florides and Kalogirou 2007; Casasso et al. 2017).

Among all the geo-exchange systems configuration, linking the heat pump to the underground to allow extraction (or injection) of heat from (into) the ground, ITER project (Improving thermal efficiency of horizontal ground heat exchangers, http://iter-geo.eu/) focuses on very shallow geothermal systems (VSGs), as horizontal collectors or special forms, interesting the first 2 m of depth from ground level (Di Sipio et al. 2016). VSG systems become increasingly attractive on the market, thanks to their low installation costs, easy maintenance over time and less legal constraints compared to the vertical borehole heat exchangers and are open to technical improvements, as the reduction in the pipe length, less use of the surface and a better efficiency over time (Self et al. 2013; Congedo et al. 2012). The main thermal recharge for all horizontal systems is provided by the solar radiation to the earth's surface and is strictly related to the kind of soil locally available. Therefore, the surface above the ground heat collector must not be covered

(Florides and Kalogirou 2007). Moreover, an improvement in heat conductivity transfer is expected when the soil water content is increased and/or when a small amount of natural additive (i.e., clay) is added to a coarse soil (i.e., sand) (Farouki 1981; Smits et al. 2010; Nikolaev et al. 2013; Bertermann et al. 2014, 2015). In general, in the same saturation condition, sand shows better thermal performance than clay, silty clay and silty loamy material, due to the high thermal behavior of its main component, quartz. However, well-graded soils can retain a greater amount of water, a very important condition if higher thermal conductivities are desired over time (Saxton and Rawls 2006; Smits et al. 2010; Di Sipio and Bertermann 2017a).

In the first meters of depth below the ground level (bgl), the heat transfer in soil is led mainly by conduction, a process driven by temperature gradients and dependent on thermal conductivity, in turn a property strictly related to water content (Gonzales et al. 2012; Song et al. 2014). Except for very high groundwater levels it can be assumed that (i) the water content of the soil only depends on the average precipitation quantity and (ii) the heat transfer by convection does not occur. However, when phase changes, such as condensation/evaporation and freezing/melting, take place due to a sudden drop of air or ground temperature, the heat transfer can substantially increase (Farouki 1981). Recent studies on vertical borehole heat exchangers (BHE) proves that cyclic thermal stress, as that induced by BHE running in extreme conditions (freeze–thaw cycles), can affect the mechanical properties of sediments and grouting material surrounding the exchangers, favoring consolidation process or vertical cracks occurrence (Diersch 2014; Anbergen et al. 2014; Dalla Santa et al. 2016). In ITER project the heat pump runs in heating mode for a very long time, forcing the ground temperature to drop below 0 °C (Di Sipio and Bertermann 2017b). However, even if the effect of freeze–thaw (FT) cycles on the geotechnical behavior of soil interested by VSG systems is highly likely, ITER project is devoted to highlight the soil thermal variation in different soil bodies related to the moisture content change.

In the first meter of depth bgl, soil moisture shows diurnal and seasonal variability related to climatic factors, as surface albedo, solar radiation, precipitation, evaporation. Usually very low and stable content are typical of the dry season, while an increase in value is noticed as the rainy season begins (Guan et al. 2009; Liu et al. 2008). Variations in rainfalls determine variation in soil moisture content, even if the effects can be delayed over time. In agreement with the physical–mechanical properties of the soils (i.e., higher or lower porosity, grain size…), the influence of precipitation on soil moisture can be observed also on a daily or weekly basis. In addition, the water content changes linearly with depth near the ground surface, showing a decrease in amplitude with increasing depth (Hinzmann et al. 1991; Roxy

et al. 2010). The effect of evaporation and wind speed on soil water content is limited to earth's surface (circa 0.55 m) and does not interest the typical installations' depth of horizontal collectors, where long-term changes are more effective (Wu et al. 2010; Song et al. 2014).

As known by the literature, the thermal conductivity (λ) of soils surrounding a VSGs, depending especially on water content and temperature of the ground, has a significant effect on the thermal performance of the system (Farouki 1981; Congedo et al. 2012). Usually, during simulations, this parameter is considered constant and uniform over time, but a variable value seems better to characterize the unsaturated/saturated condition of the soil (Wu et al. 2010, 2015). For example, once a VSG system is running in heating/cooling mode, a significant decrease/increase in soil temperatures compared to the undisturbed condition is registered around the earth collectors. As consequence, the soil moisture content changes, influencing the thermal properties of the surrounding soil and so the performance of the system (Leong et al. 1998; Neuberger et al. 2014).

If the soil temperature is decreasing below freezing point (0 °C), due to low air temperature during winter/early spring or to stressful operating conditions, the water starts to freeze and non-conductive heat transfer mechanisms must be taken into consideration. During ice formation and related phase change process, the release of latent heat occurs, overcoming momentarily the heat conduction (Farouki 1981; Kane et al. 2001; Hinkel et al. 2001). Combined moisture and heat transfer processes are also noticed. On the one hand, the conversion of soil water into ice is gradual and limited to a temperature range of 0.0 and − 6.0 °C. On the other hand, the ice formation, drying away water from the pores, is responsible for the moisture content's decrease in soil, so the effect of freezing on the ground is analogous to the drying process and produces a substantial reduction in unfrozen soil thermal properties (Hinzmann et al. 1991; Hinkel and Outcalt 1994; Wu et al. 2015).

In addition, the effect of ice in soil thermal conductivity depends mainly on the kind of soil at disposal and on the degree of saturation. In coarse-grained materials, all water can turn rapidly into ice, while in fine-grained ones' a certain amount of unfrozen water is always present and guarantees the thermal contact between the soil skeleton and the ice. At the same temperature, soils with greater specific surface areas have higher amounts of unfrozen waters (Ryden 1986). Stated that the $\lambda_{ice} > \lambda_{water}$ (2.25 > 0.58 Wm^{-1} K^{-1}), the thermal conductivity of frozen soil is greater than that of unfrozen soil when high degree of saturation are present, smaller in case of low saturation degrees (Kane et al. 2001). Moreover, during the liquid-to-ice conversion, (i) a larger water content in a soil means a greater amount of latent heat to be extracted (greater latent heat storage capacity), (ii) the temperature remains constant and (iii) the time required

to expand the freezing front in the surrounding ground increases (Xu and Spitler 2011). Once the phase change is completed, the continual removal of heat results in a further temperature reduction (Hinkel et al. 2001; Neuberger et al. 2014).

When low temperatures are recorded, the unfrozen soil moisture is reduced up to 5–10% in volume, with lower values belonging to sand material, and remains fairly constant until meltwater produced during thawing enter the soil body increasing the volumetric water content (VWC). During thawing, any excess of water is rapidly dispersed in coarse-grained soils, while causes oversaturation in the fine-grained ones, contributing to a rapid increase both in soil moisture and ground temperature, once the latent energy releases ended (Ryden 1986; Hinzmann et al. 1991; Hinkel et al. 2001).

However, few monitoring data on real case studies are available and, on this regard, ITER project will contribute to a better understanding of in situ parameters changes providing moisture data variations collected continuously on five different soil mixtures in the same environmental conditions from 03/11/2016 to 07/02/2017.

The aim is to understand the interactions between soil, horizontal heat exchangers and the aboveground environment. To obtain reliable data for modeling, an interdisciplinary approach is used. The physical–thermal properties of five different mixtures are monitored in the ITER project case study (Eltersdorf, Germany), where five geothermal helical heat exchangers are installed in horizontal trenches. The collectors available for ITER have been provided by REHAU AG & Co company, project partner, and from now on they are indicated with their trade term "helix" (REHAU 2012; Zarrella and De Carli 2013; Di Sipio and Bertermann 2017b). A monitoring system allows to record every 5 min, by means of devoted sensors, values related to ground temperature (undisturbed, inside and outside each helix), volumetric water content at 0.20 and 0.60 m depth and climatic data. Then, the physical–thermal parameters of the mixtures are tested also in laboratory under different water content percentages and different consolidation degree.

The main results here presented show the variation of volumetric moisture content for five different materials recorded in the same meteorological conditions and under the influence of a running GSHPs.

Materials and methods

ITER test site in Eltersdorf

The ITER project case study, hosted on the property of REHAU AG & Co company, is located in Eltersdorf, 6 km SW from the city of Erlangen (Bavaria, Germany)

(Fig. 1a). Five sectors of the same size ($1.2 \times 5.0 \times 1.1$ m), thermally isolated by outer and intermediate walls made of XPS (extruded polystyrene, 2 cm thick, $\lambda = 0.035$ Wm^{-1} K^{-1}), cover a total earth volume 6.0 m wide, 5.0 m long and 1.1 m depth (Figs. 1b, 2a) (Di Sipio and Bertermann 2017a, b). As backfilling material, a different soil mixture is used for each trench, and, from north to south the horizontal heat exchangers in helical shape are surrounded by (Fig. 1b):

- loamy sand (SC);
- sand 0–5 mm + 15% bentonite (s15B);
- a commercial product (GeoSolid 240HS) in direct contact with the Helix, covered with sand 0–5 mm (s);
- fine sand 0–1 mm with 15% bentonite (fs15B);
- fine sand 0–1 mm (fs).

According to the grain size analysis, performed by (i) sieving the sand fraction (< 63 μm) of each mixture (DIN 18123 2011), (ii) using the Sedigraph III Plus 5125 for the remaining fine particles (Syvitski 2007) and (iii) adopting the United States Department of Agriculture textural soil classification system (USDA 1987), the mixtures in Eltersdorf are defined as sand (fs, s) loamy sand (SC) and sandy loam (s15B, fs15B). The particle size distribution curves identify poorly graded soils, differentiated in "uniform soils," in which most particles have the same size (fs, s, B), and in "gap graded soil," where intermediate sizes (silt fraction) are missing, typical of fs15B and s15B, the mixtures with bentonite (Fig. 1c). A detailed discussion of the physical–thermal properties of ITER mixtures can be found in Di Sipio and Bertermann (2018).

The loamy sand (SC) is the original quaternary sediment available on site and shows a very high content of silicon oxide and clay minerals (i.e., illite, smectite). The GeoSolid 240HS (GS) is an enhanced thermal material ($\lambda = 2.4$ Wm^{-1} K^{-1}) commercialized by Fischer Spezialbaustoffe Gmbh as grouting for borehole heat exchangers, while a gray white fine sand (fs) and a reddish coarser sand (s) are natural sediments characterized by a mineralogical phase dominated by quartz and feldspar. Both sand bodies are commonly used in constructions and have a grain size ranging between 0–1 mm and 0–5 mm, respectively. Finally, two mixtures obtained by mixing the pure sand materials with bentonite (15% of the total weight) fill in sectors 4 and 2.

The five helices are coupled hydraulically as Tichelmann, showing the same flow over 24 h, and are connected to an absorber, able to stress the working condition in heating/cooling mode. From November 2015 till May 2017, the system runs in heating mode three times (16/03–19/04/2016, 10–29/11/2016 and 02/03–22/05/2017), while in the remaining period the heat carrier fluid is mainly recirculated in the
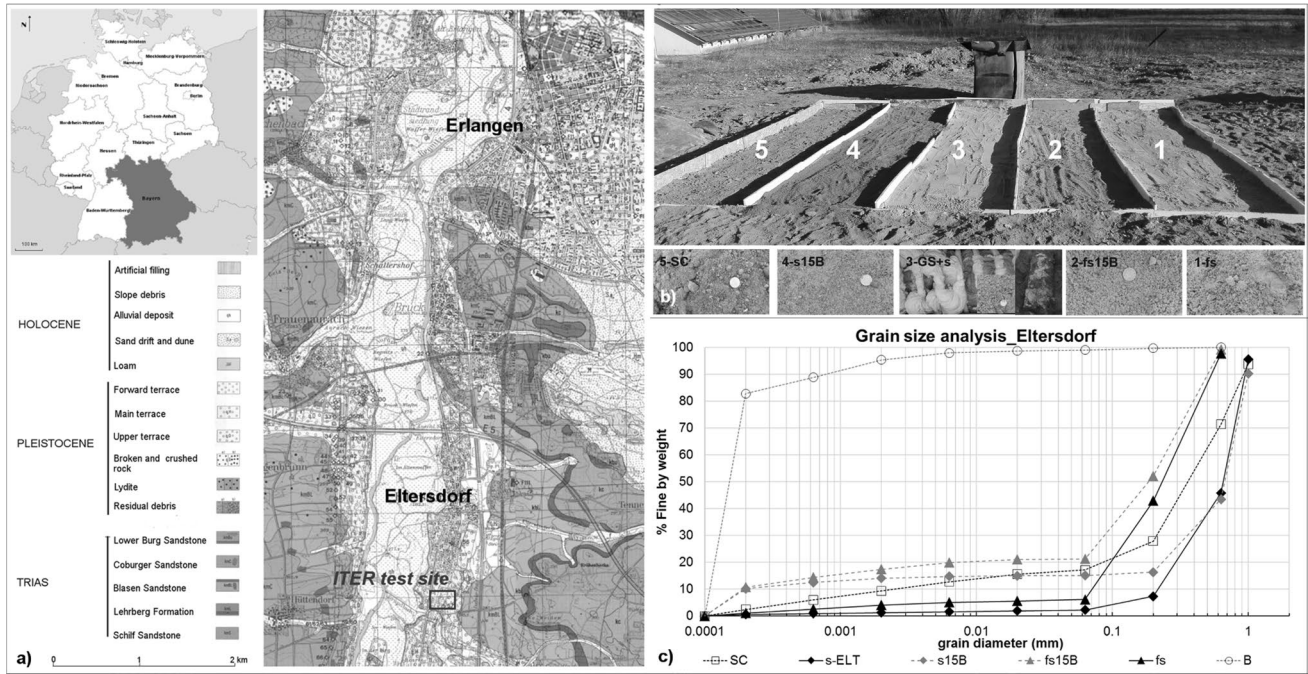
Fig. 1 ITER project test site location in Eltersdorf, Bavaria, Germany: **a** location and geological characterization of the area (modified by Bayerischen Geologischen Landesamt 1971); **b** the 5 backfilling materials covering the helix probes (SC = loamy sand; s15B = sand + 15% bentonite; GS + s = commercial products surrounded by coarse sand; fs15B = fine sand + 15% bentonite; fs = fine sand); **c** grain size curves for the five mixtures used in Eltersdorf
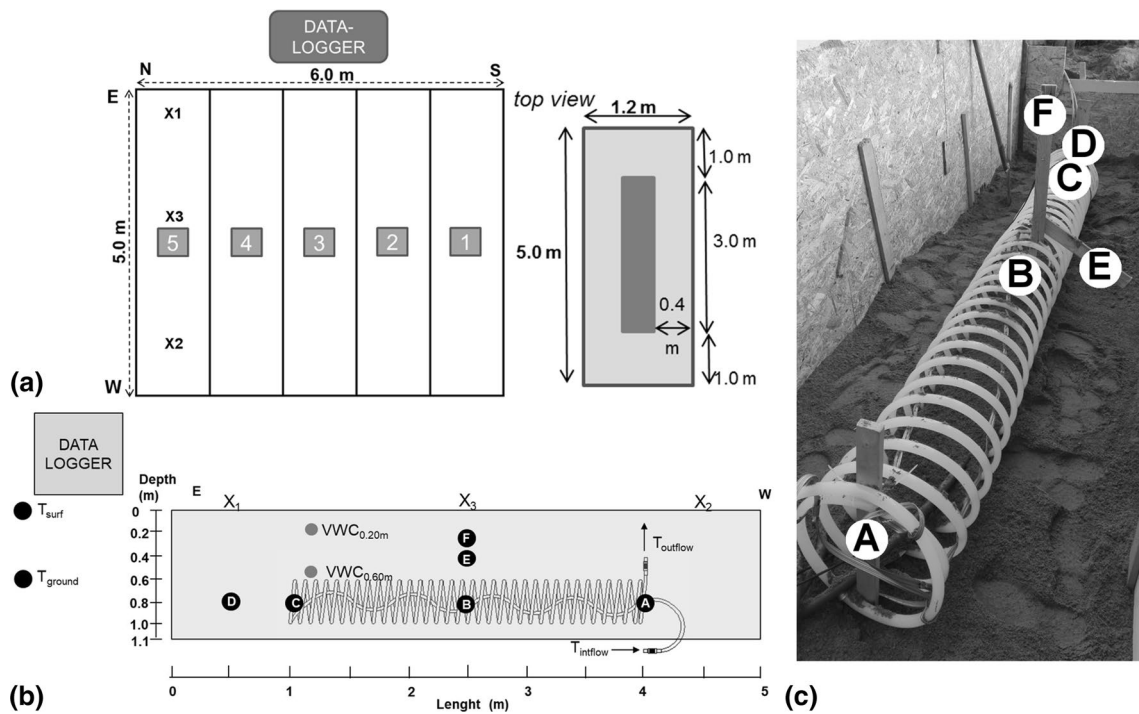

Fig. 2 ITER project test site schematic description: **a** top view of the whole test site, comprehensive of surface sampling measurements points (X_1–X_2–X_3) and data-logger unit, and of helix location inside each trench; **b** cross section of one sector showing temperature (A–B–C–D–E–F–D–T_{surf}–T_{ground}) and moisture (VWC) sensors location; **c** overview of temperature sensors distribution inside and outside a horizontal heat exchanger

helix heat exchangers without any heat extraction (or heat injection) from (into) the ground.

The monitoring system, since November 2015, collects data directly from (i) the helix system, (ii) the surrounding environment and (iii) the backfilling material on surface. A detailed description of factors influencing the thermal efficiency of horizontal ground heat exchangers, especially when the heat pump is running in heating mode for a very long time, together with an evaluation of the recovery time needed to re-establish undisturbed ground temperature conditions inside and outside the helices can be found in Di Sipio and Bertermann (2017b). This paper, instead, focuses on the interactions between ground temperature, volumetric water content (VWC), precipitation and thermal conductivity data, so only the technologies and methods related to these parameters are here described.

In detail, ground temperature data are recorded every 5 min by Pt-1000 class B resistance thermometers (accuracy of $\pm (0.30 \, ^{\circ}\text{C} + 0.005 \times$ the reading temperature)) placed inside and outside each helix (Fig. 2b, c). In each sector, at different depths (0.80, 0.40 and 0.20 m bgl) and at different distance (0.5, 1.0, 2.5, 4.0 m) from the eastern margin, 6 temperature sensors (A–B–C–D–E–F) are used, while outside the test site the surface and the undisturbed ground temperature (T_{surf}, T_{ground}) are recorded on surface and at 0.60 m depth as shown in Fig. 2b, c.

The ground temperatures are monitored from the beginning, both during the switching on and off of the heat pump. In this way, an extensive database has been collected, comprehensive of undisturbed ground temperature data used as reference (T_{surf}, T_{ground}) and ground temperatures variations inside and outside each helix modified by the different VSG system working phase.

Volumetric water content (VWC) is measured continuously (every 5 min) in all the five sectors since November 2016 at 0.20 and 0.60 m depth by two different soil moisture devices, the 10HS sensor (Decagon Devices Inc., range 0–57%, precision of $\pm 0.5\%$) and the MAS-1 sensor (Decagon Devices Inc., range 0–100% VWC, precision of $\pm 6\%$), respectively. The VWC data are collected continuously during both the switching on and off of the heat pump, so it is interesting to check how the VSG operation phases influences this parameter.

Precipitation values, acquired every 10 min, are provided by a meteorological station belonging to REHAU, located 250 m SW from ITER test site and 3 m above the ground. Furthermore, measurements collected at the nearby weather station in Nuremberg airport (about 10 km toward SE) by the Germany National Meteorological Service have been used to validate the hourly and monthly measurement acquired in situ (Deutscher Wetterdienst 2016).

The time and date attributed to the data are always related to the solar time and all instruments adopted were tested and calibrated by the manufacturers. In the helix monitoring system, the hourly and the daily averages are calculated based on 12 measurements per hour and 288 measurements per day, respectively. In the meteorological station, the hourly and daily cumulative rainfall is determined based on 6 measurements per hour and 144 measurements per day. Unfortunately, ground temperature data for sensors E and B in sector 5 (E5 and B5) are missing, respectively, since February and May 2016 due to technical reasons (Fig. 2b, c).

In addition, since November 2015 till June 2017 monthly measurements of thermal conductivity and moisture content are collected in each sector by thermal properties analyzer (KD2Pro apparatus, Decagon Devices, Inc.) and time domain reflectometry (TDR) device (TRIME IMKO GmBH) in the first 10 cm below the ground surface. However, from November 2016 till February 2017, the presence of frozen soil related to prolonged period of air temperatures below 0 °C prevented the execution of reliable thermal conductivity (λ) measurements, while in September 2016 the data have not been measured, due to the non-availability of the devices. Since July 2016, surface soil samples have been collected in order to determine the bulk density and volumetric water content of the mixture, according to DIN 52102 and DIN 18121. The same procedure was used in laboratory on the five soil mixtures used in Eltersdorf (SC, s15B, s, fs15B, fs) to determine their physical–thermal property variations according to soil moisture and load changes (Di Sipio and Bertermann 2018).

The volumetric water content monitoring systems

Given the availability of two different kind of sensors for VWC determination, made by the same manufacturer (Decagon Devices Inc.) but characterized by different declared accuracy, an in situ calibration under the same environmental conditions and in the same type of material was carried out between 4/11 and 15/11/2016 (Decagon Device Inc 2016a, b).

On this purpose, six 10HS sensors and one MAS-1 sensor have been placed in coarse sand (sector 3), oriented perpendicular to the surface of the soil in order to minimize effects on downward water movement, at a depth of 6 cm from the ground surface and at a distance of approximately 3 cm one from the other (Fig. 3).

The 10HS sensors are assembled into 2 groups of 3 sensors each, connected by cables to two data-loggers (sensors 1–2–3 to Box 1 and sensors 4–5–6 to Box 2) powered by solar panels, able to provide power to the system and to record data on MiscroSD card. The MAS-1 sensor (M), representative of all five MAS-1 sensors used in the test site, is connected directly by cable to the main data-logger, recording also all temperatures registered in the five test field sectors (Fig. 3a).
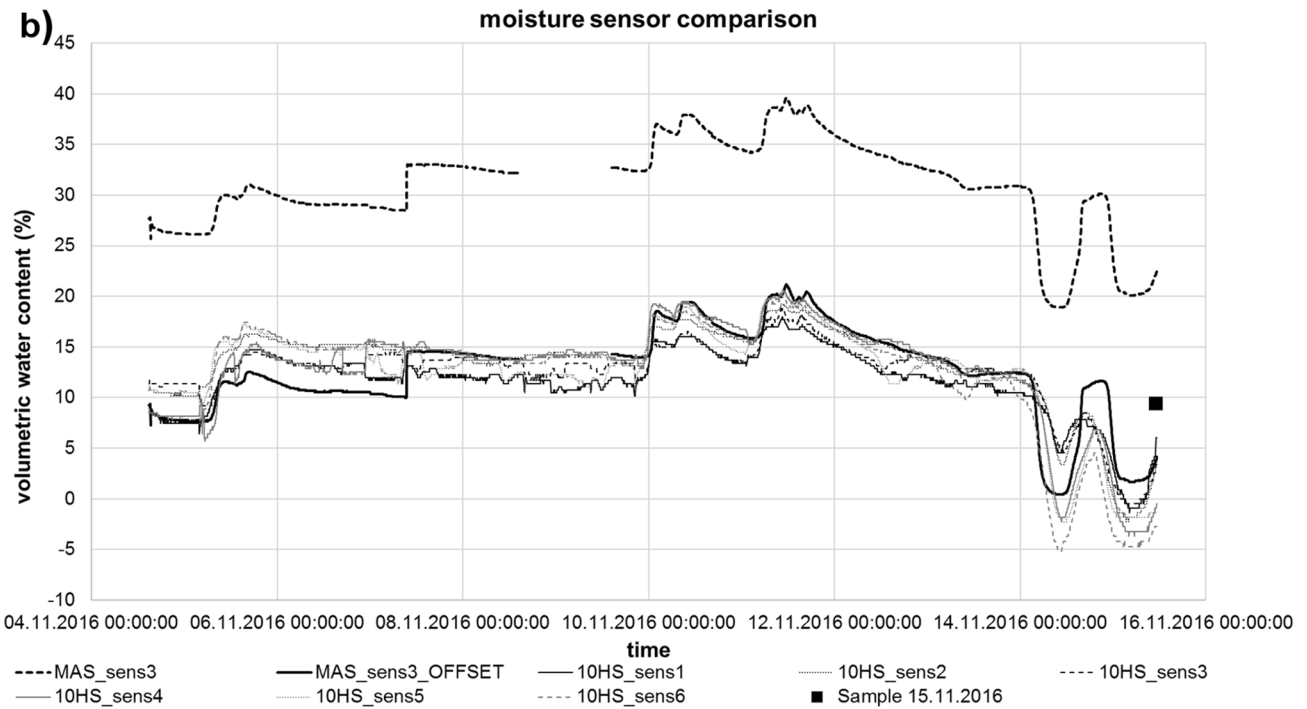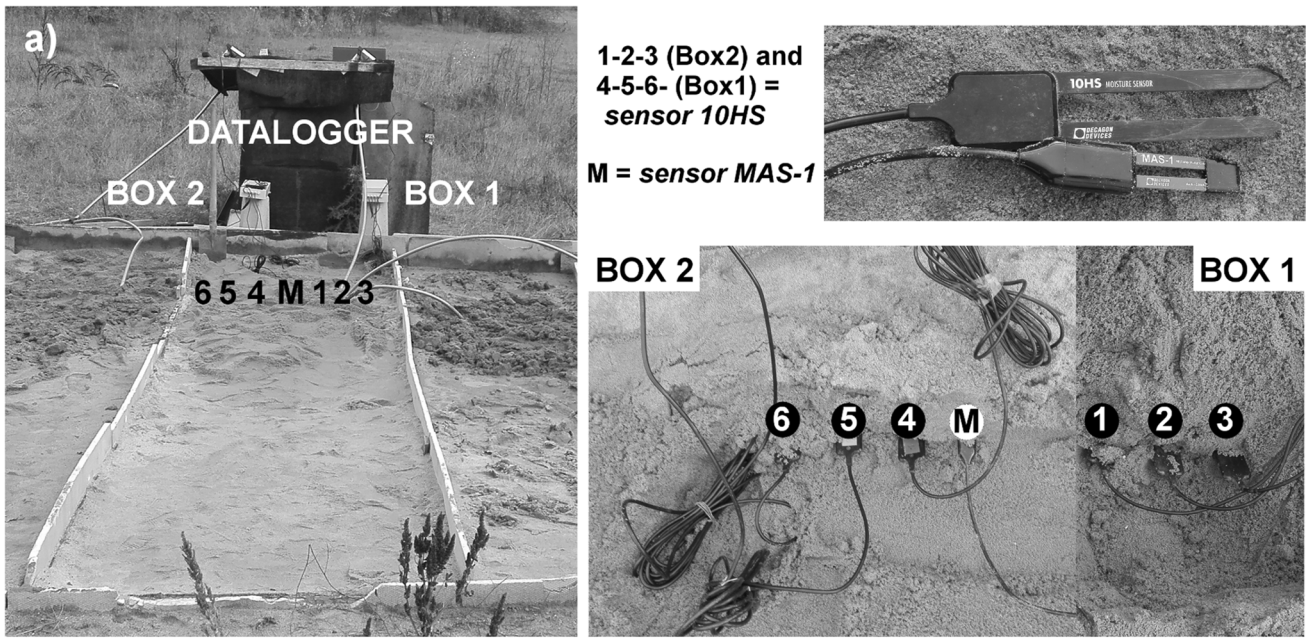
Fig. 3 In situ calibration for VWC sensors between 4 and 15/11/2016: **a** placement of six 10HS sensors and one MAS-1 sensor of Decagon Device Inc. in the coarse sand material (sector 3); **b** VWC measurements of the 10HS and MAS-1 series during the calibration period, showing the systematic errors between the two series (10HS and MAS-1) and the correction of MAS-1 values according to the calculated offset

The data have been recorded every 5 min, for a total of 3127 measurements for each device. However, some technical problems occurred on November 4 for 15 min and on November 8–9 for MAS-1, so in these days a gap in the corresponding data recording is observed.

On 15/11/2016, a soil sample of coarse sand has been collected at the installation depth of the sensors to determine in laboratory the volumetric water content and the bulk density (DIN 18121-1 1998; DIN 52102-2 2006). A

VWC content of 9.5% has been measured and it is used as reference value (Fig. 3b).

The results of the observation period reveal the presence of a systematic error between the two kinds of sensors (Fig. 3b). The 10HS series show high trueness of the data, due to the closeness of their average VWC values (ranging from 11.63 to 13.34%) to the laboratory VWC accepted as reference value (ISO 1994). In addition, they have also a high precision (σ is in the range 3.5–5.9): there is an agreement between the independent measurements made by each sensor under the same environmental and operating conditions, even if small differences in the recordings during the test can be related to random errors and inhomogeneity in the soil (i.e., compaction, exposition to solar radiation) that could lead to changes in the soil moisture content. The MAS-1 series, instead, is characterized by a low trueness (average VWC value about 31.0%) and a high precision ($\sigma = 4.7$) (ISO 1994; JCM 2008). Therefore, a correction of the MAS-1 series is necessary to reduce the systematic error observed. In detail, the difference between MAS-1 and each 10HS value is determined and the average offset calculated is about 18.4 ($\sigma = 2.7$). Reducing the MAS-1 values by this quantity, their trueness is improved (Fig. 3b).

At the end of the calibration period, five 10HS and five MAS-1 sensors are installed at 0.20 m and 0.60 m depth, respectively, 1 m away from the east margin in every sector of the test site in Eltersdorf (Fig. 2a, b). In addition, a sixth 10HS sensor is placed outside the trench, at the same depth and 1 m away from the data-logger near the northern side of the test field, to collect information on the original material available on site, used also on sector 5. The correction defined during the calibration period is then applied to all the values registered by the MAS-1 sensors over the entire observation period, from 03/11/2016 to 07/02/2017.

Only one sensor is used to monitor soil moisture content at each depth. Due to the spatial variability of the soil moisture content, the related measurements may not be entirely representative of each sector, but they can provide an indication of the overall differences in the amount of water between the different soil profiles (Gonzales et al. 2012).

Result and discussion

The relationship between thermal conductivity and volumetric water content of soils, as well known by the literature, shows a decrease in λ as VWC decreases. In general, for all soils, a VWC content (i) below 12.5% determines a sudden decrease in thermal conductivity, affecting negatively also the heat pump performance; (ii) between 12.5 and 25–30% presents maximum values of λ; (iii) above this limit has no substantial effect on increasing the thermal properties of the material (Tarnawsky and Gori 2002; Leong et al. 1998).

Therefore, a correct evaluation of VWC changes in the ground could provide a preliminary information about the possible performance of the heat exchangers.

At first the relationship between soil moisture changes (hourly average) and precipitation (hourly cumulative amount) between 3/11/2016 and 07/2/2017 for the five different mixtures available on site is presented (Figs. 4, 5). Then, the relationship between VWC, surface temperature and ground temperature variations is taken into consideration. During the entire observation period, at first the VSG system is set in heating mode forcing the heat extraction up to reach freezing condition (between 10 and 28/11/2017), then it is switched off until the end of December 2016 and finally 14 alternating period of heat pump operations (generally 2 days on, 2 days off) are artificially induced to observe the reaction of the different kinds of soils to prolonged intermittent thermal stress conditions.

At 0.20 cm depth, the coarse sand (s), thanks to its high hydraulic permeability, show a sudden increase in the VWC content when a meteoric precipitation peak is observed (i.e., 16 and 19/11) and a rapid decrease during dry periods. However, in three timeframes during December 2016 and January 2017, data gaps are present, when the lower detection limit of the instrument is reached (0%) and the material is completely dry (Fig. 4b). In the coarse mixture with bentonite (s15B), the effects of rainfall variations seem delayed and smoothed over time. In addition, the VWC values on average are greater for (s15B) (17.4%) than for (s) (11.8%), favored by the greater porosity of the material (Fig. 4b).

The loamy sand (SC) in sector 5 and outside the trench (out) follows in both cases the (s) trend, showing a quick response to precipitation events (in this case delayed by few hours) compared to the meteoric peak. The VWC average content is lower outside (14.2%) than inside (20.9%) sector 5, probably due both to different consolidation degree and vegetation cover (Fig. 4c).

The behavior of fine sand (fs) and fine sand mixture (fs15B) reflects those of (s) and (s15B). The occurrence of precipitation increases quite immediately the VWC content in (fs), while seems to have a delayed and damped effect on (fs15B). The bentonite mixture shows soil moisture values always greater than the pure fine sand (30.2 versus 15.8%), thanks to the greater ability to retain water (Fig. 4d).

Anyway, at 0.20 m depth, from November to February, all the five mixtures reveal a gradual trend in decreasing the water content values, not directly related to precipitation.

At 0.60 m depth, all the materials, apart the coarse sand, seem not affected by precipitation event. The trend of (SC), (s15B), (fs15B) and (fs) is similar and can be described in three main phases: (i) a sudden decrease and subsequent fast recovery of VWC values when the VSG system is switched on and off (U shape), (ii) an increase in values during the recovery time, (iii) a quite constant trend
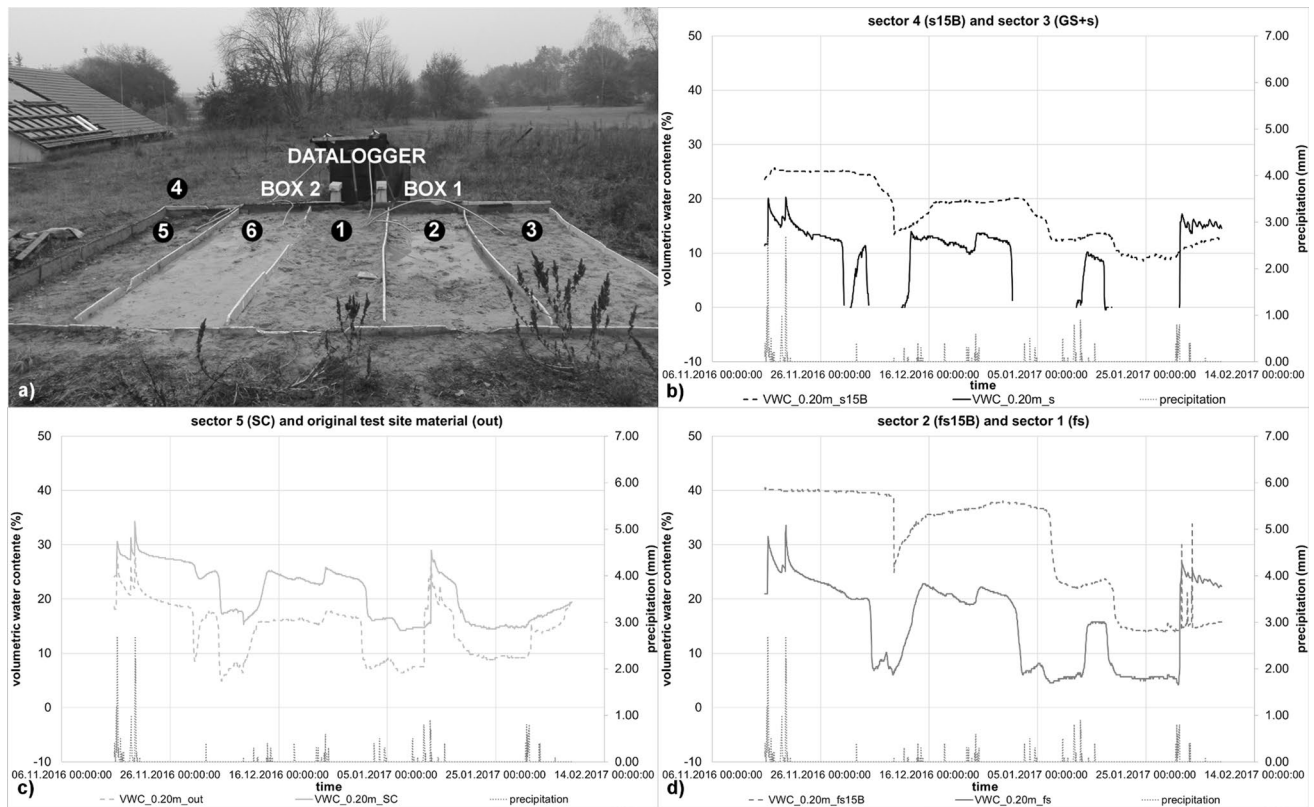
Fig. 4 Relationship between VWC measurements at 0.20 m depth and precipitation from 03/11/2016 to 07/02/2017: **a** installation of six 10HS sensors; VWC and precipitation variation over time for (**b**) sec-tor 4 (s15B) and 3 (GS + s), **c** sector 5 (SC) and the original test site material (out); **d** sector 2 (fs15B) and 1 (fs)

up to the end of the observation period (Fig. 5b–d). The mean VWC values over the whole period are about 10.1, 12.2, 25.8, 6.2% for (SC), (s15B), (fs15B) and (fs), always lower than the corresponding values at 0.20 m.

In the pure coarse sand, instead, a delay of about one day is observed between the occurrence of the main pre-cipitation event and the corresponding peak in the VWC content. In addition, the VWC variations over time are less pronounced than those observed at 20 cm in depth, even if the average VWC values seem unchanged (12.1%). In fact, in sector 3, the sand is not directly in contact with the helix system, surrounded entirely by the commercial products, and so it is not directly affected by the VSG system (Fig. 5b).

In addition, the changes of soil moisture content are extremely sensitive to natural and induced temperature vari-ations (Fig. 6). During winter (October to March), the aver-age daily air temperature in Eltersdorf is about 3–4 °C and values below 0 °C are common. Taking into consideration the average hourly temperatures registered during the whole observation period at ground surface (T_{surf}), at 0.30 m depth (F1) and at 0.60 m depth (T_{ground}), three different patterns are recognized (Fig. 6a):

- T_{surf} shows oscillations typical of day/night alternation and a decline in values from November (maximum of 5.8 °C) to January (minimum about -8.8 °C), with the soil temperature near the earth's surface dropping below 0 °C in January 2017;
- the sensor at 0.30 m depth (i.e., sensor F1 located in sec-tor 1) shows T fluctuations in agreement with T_{surf}, with average, minimum and maximum values around -0.6, -7.7 and 7.3 °C, respectively;
- at 0.60 m depth the amplitude of the T waves is already reduced (T_{ground}), due to the high thermal inertia of the ground and, as expected in the colder months, $T_{ground} > T_{surf}$ (1.7 > -1.5 °C on average); minimum and maximum values for T_{ground} are -1.5 and 6.6 °C, respec-tively.

In each sector, when the soil temperature is decreasing below freezing point (0 °C), the water starts to freeze and non-conductive heat transfer mechanisms must be taken into consideration. The moisture content changes at 0.20 m depth are related to this phenomenon. From the beginning of November, a progressive reduction in VWC is observed in each soil mixture, following the T drop below 0 °C recorded
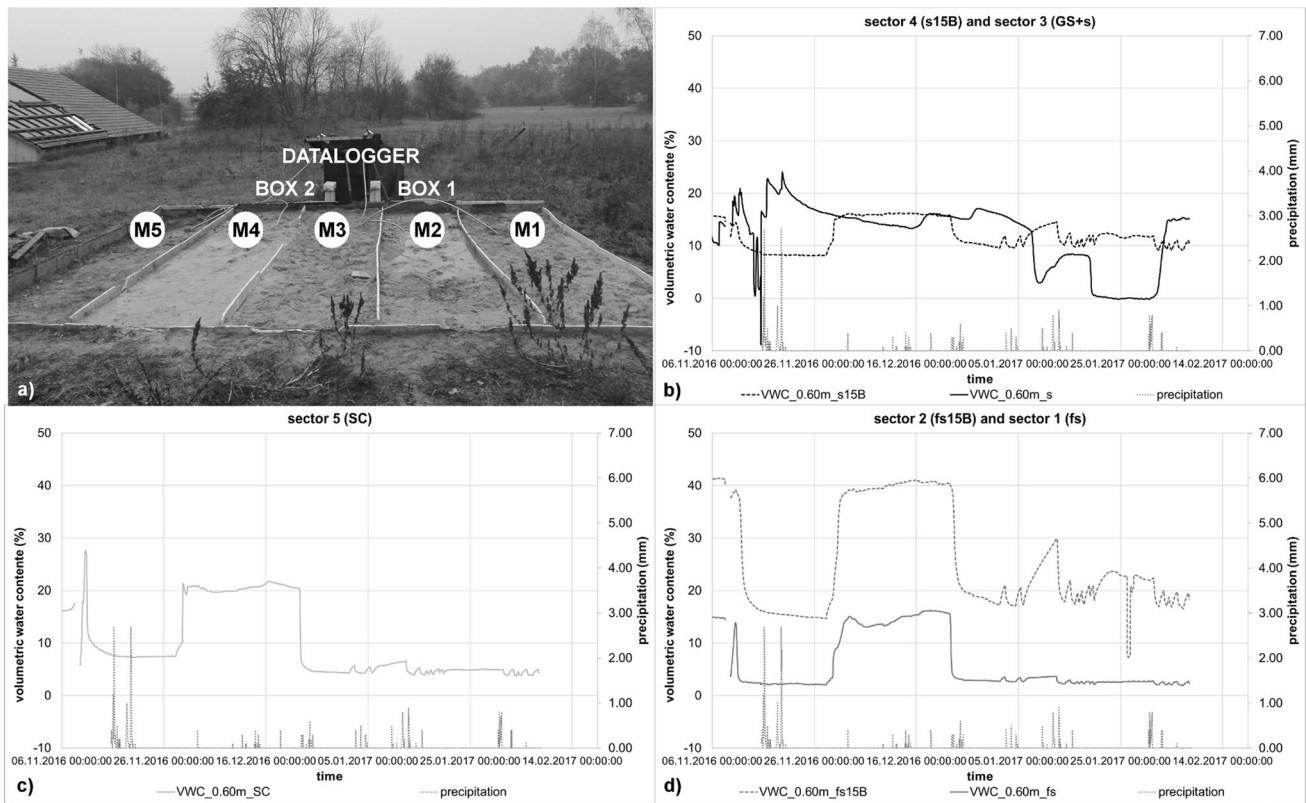
Fig. 5 Relationship between VWC measurements at 0.60 m depth and precipitation from 03/11/2016 to 07/02/2017: **a** installation of five MAS-1 sensors; VWC and precipitation variation over time for (**b**) sector 4 (s15B) and 3 (GS + s), **c** sector 5 (SC) and the original test site material (out); **d** sector 2 (fs15B) and 1 (fs)

at 0.30 m depth by the F sensor (Fig. 7a–c–e–g–i). In detail, VWC content in November and January varies on average as follows: from 19.9 to 10.8% in (out), from 27.7 to 16.9% in (SC), from 25.1 to 12.5% in (s15B), from 14.2 to 7.0% in (s), from 39.9 to 22.5% in (fs15B) and from 24.2 to 7.9% in (fs). The uptake of water to form ice crystals is the highest at the end of January (20–30/01/2017), according to the lowest measured temperatures. However, at this depth, precipitations are still affecting the moisture content, being responsible for the VWC peaks observed in (SC), (s) and (fs) (Fig. 4). The drying effect in the soil, related to extreme temperature reduction, is more pronounced in the coarse sand, where, as stated by the literature, the greater grain size allows to convert all the available water into ice, leaving no unfrozen water in the pores.

When the VSG system is running in heating mode (24 h/day for 18 days), forcing freezing conditions, a significant decrease in soil temperatures compared to the undisturbed ground condition is registered around the earth collectors (Fig. 6b). For example, considering the sensors located above (i.e., F1, 0.30 m depth bgl), on top (i.e., E1, 0.40 m depth bgl) and in the middle (i.e., B1, 0.80 m depth bgl) of the helix in sector 1, it is possible to notice

that temperatures at 0.30 m depth are still influenced by air temperature variation while at 0.40 and 0.60 m depth the trend is completely regulated by the switching on/off of the heat pump and it is no more related to the expected undisturbed pattern already observed in T_{ground}. At 0.40 m depth bgl (sensor E), when the VSG system is running in heating mode, a decrease in temperatures between 0 and -2 °C is noticed and a gradual recovery of temperature above 0 °C is observed few days after the shutdown of the heat pump.

The soil temperature in close proximity to the helix reacts relatively instantly to any increase in heating demand, showing an abrupt decrease of T values. As consequence, the soil moisture content changes, influencing the thermal properties of the surrounding soil and so the performance of the system (Fig. 7).

In detail, when the system is switched on (10/11/2016), a sudden decrease in temperatures below the freezing point is observed, followed between 16 and 28/11/2016 by a constant temperature pattern at around -6.0 °C for (fs), (fs15B), (s15B) and -5 °C for (GS + s) and, finally, by a recovery of the temperature above 0 °C (01/12/2016) started with the shutdown of the heat pump (28/11/2016). The entire process
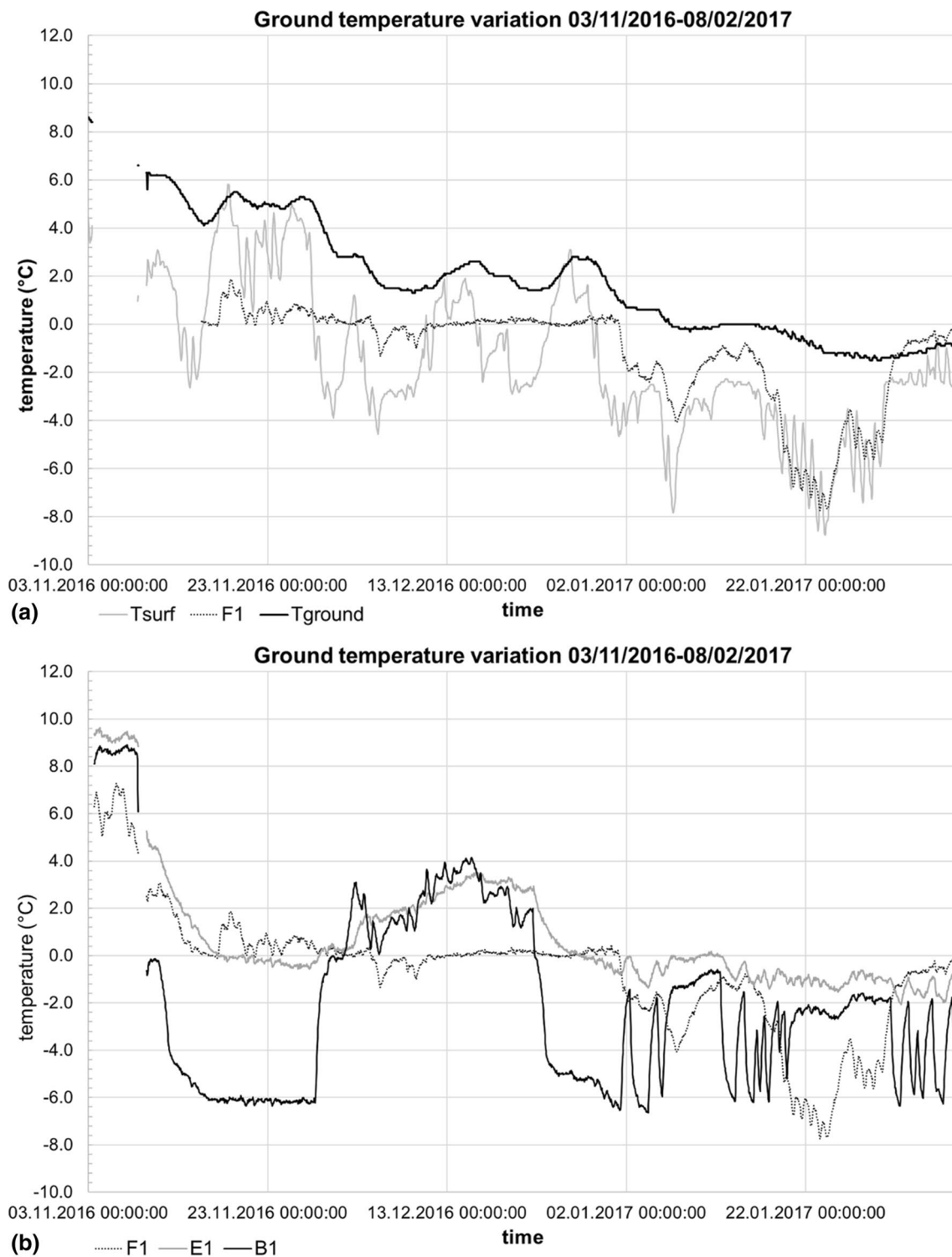
(a)

(b)

Fig. 6 Temperature variations recorded between 03/11/2016 and 07/02/2017: **a** surface (T_{surf}) and undisturbed ground (T_{ground}) temperature recorded outside the test site compared with T at 0.30 m depth above the helix (i.e., sensor F1); **b** temperature changes at 0.30, 0.40 and 0.80 m depth bgl (sensor F-E-B) for sector 1, selected as representative, influenced by the VSG system running in heating mode

is characterized by a "U shape" form of the temperature trend (Fig. 6b).

When the temperature is decreasing, in the range between 0.0 and −6.0 °C, the conversion of soil water into ice is gradual and allows the release of latent heat related to the phase change process. When the temperature remains constant ("U shape base"), the phase change process is still ongoing, and the removal of heat can continue without any further temperature reduction. Finally, after the shutdown of the heat pump, thawing occurs and the melting water released from the ice crystals enters the surrounding soil increasing the VWC content. The rapid increase both in soil moisture and ground temperature, observed especially in fine-grained material during thawing, is strictly related to the oversaturation condition created by the excess of water rapidly dispersed in the ground, made available again after the complete melting of ice (Hinzmann et al. 1991; Hinkel et al. 2001; Gonzales e t al. 2012).

Therefore, during the "U shape" phase, all the soil mixtures tested in ITER project at 0.60 m depth show at first a sudden decrease in moisture content related to the ice formation, able to dry away water from the pores. Then, the VWC values remain quite constant during the phase change process and finally rise again during thawing (Fig. 7b–d–h–l). The sequence just described provides approximately the following VWC average values for the ITER soil mixtures:

- 16.4–8.2–19.9% for (SC) (Fig. 7b);
- 15.4–8.7–15.6% for (s15B) (Fig. 7d);
- 40.7–17.3–38.0% for (fs15B) (Fig. 7h);
- 13.9–2.4–13.7% for (fs) (Fig. 7l).

However, the coarse sand material (s) used in ITER does not respect this scheme: it is not affected by T variations recorded at 0.80 m depth, inside the helix, because the commercial compounds (GS) surrounding the collector acts as an impermeable thermal insulator. Therefore, in sector 3, no tangible effects on sand VWC content at 0.60 cm depth can be attributed to the heat pump activation (Fig. 7f).

During the "U shape" phase, the release of energy (0.33 MJ kg^{-1}) as latent heat is dominant. The heat conduction contribution of the unfrozen soil plays a minor role, but substantial variations of thermal conductivity are associated to the water content oscillation. In detail, considering the laboratory results of ITER project for the five mixtures used in situ under different degrees of saturation, as shown in Table 1, the average thermal conductivity for the unfrozen part varies as follows:

- 1.33–0.67–1.33 Wm^{-1} K^{-1} for (SC);
- 1.43–0.59–1.43 Wm^{-1} K^{-1} for (s15B);
- 1.96–1.19–1.96 Wm^{-1} K^{-1} for (fs15B);
- 1.15–0.31–1.15 Wm^{-1} K^{-1} for (fs).

A quite complete recovery of pre-freezing heat transfer properties seems possible if the complete freezing of the soil is not reached and enough time for thermal recovery is left to the material.

The thawing process seems quite fast and, once the temperature rises again over 0 °C, the VWC remains quite constant during the whole recovery timeframe (1 to 22/12/2016).

In the following period, from 22/12/2016 to 07/02/2017, the heat pump is switched on again in heating mode.

However, this time, prolonged intermittent thermal stress (14 cycles), always forcing the system up to freezing, are artificially induced in the different kinds of soils for short periods (generally 2 days on, 2 days off) (Fig. 6b). The reaction of the soil mixtures over time is quite interesting. Following the first temperature drop below 0 °C, the soil moisture content changes reaching, after a while, a nearly steady state, with average value of about 4.9, 11.3, 20.8, 2.8% for (SC), (s15B), (fs15B), (fs), respectively. Only during two timeframes (6–18/01/2017 and 19–31/01/2017), when the heat pump is switched off, the recovery period lasts long enough to notice an increase in VWC, more pronounced in (s15B) and (fs15B), the soils characterized by the highest initial moisture content.

Given that the ground temperature inside the helix from 22/12/2016 on is always below 0 °C in each sector (very likely even in sector 5, though sensors B and E are not working due to technical problems), the moisture content presents the typical trend observed in the already called "U shape base," when the temperature remains constant, the phase change process is still ongoing, and the removal of heat can continue without any further temperature reduction.

The amount of latent heat available for the helix during the liquid-to-ice conversion depends strictly on the amount of water stored in the soil, directly related to the grain size of the material. Among the ITER soil mixtures, the higher amount of unfrozen water, related to a greater latent heat storage capacity, belongs to the fine sand with 15% bentonite (fs15B). This fine-grained material before, after and during freezing conditions shows always a volumetric water content equals or greater than 25%, corresponding also to the ideal amount of water to reach the maximum thermal conductivity for a given material. In addition, a greater latent heat storage capacity allows to limit the expansion of the freezing front around the helix.
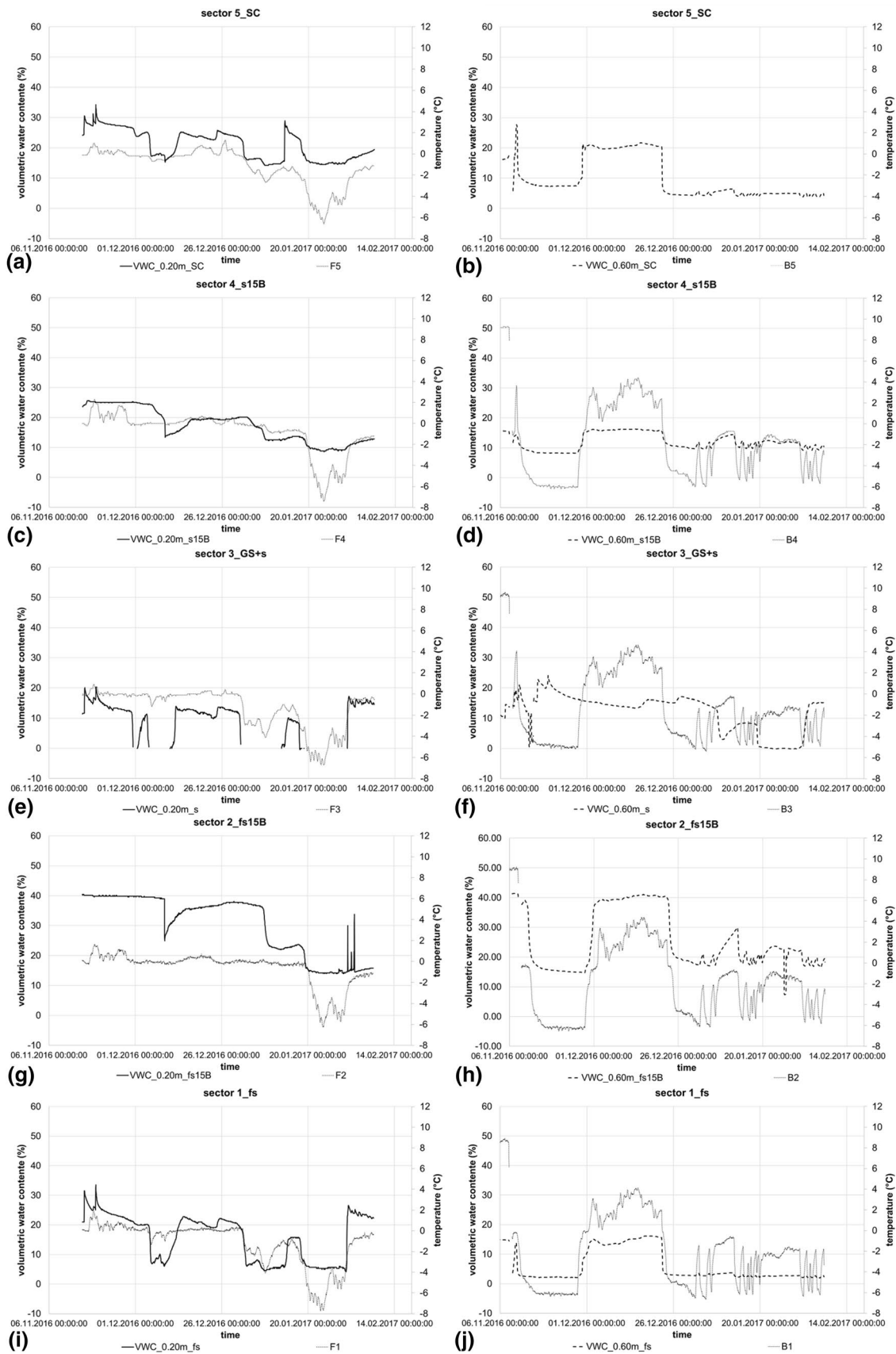
(a) sector 5_SC — VWC_0.20m_SC · F5

(b) sector 5_SC — VWC_0.60m_SC · B5

(c) sector 4_s15B — VWC_0.20m_s15B · F4

(d) sector 4_s15B — VWC_0.60m_s15B · B4

(e) sector 3_GS+s — VWC_0.20m_s · F3

(f) sector 3_GS+s — VWC_0.60m_s · B3

(g) sector 2_fs15B — VWC_0.20m_fs15B · F2

(h) sector 2_fs15B — VWC_0.60m_fs15B · B2

(i) sector 1_fs — VWC_0.20m_fs · F1

(j) sector 1_fs — VWC_0.60m_fs · B1

◀**Fig. 7** Relationship between VWC and temperature measurements at different depths at the ITER test site: VWC at 0.20 m depth and T variations at 0.30 m depth for SC (**a**), s15B (**c**), GS + s (**e**), fs15B (**g**) and fs (**i**); VWC at 0.60 m depth and T variations at 0.80 m depth for SC (**b**), s15B (**d**), GS + s (**f**), fs15B (**h**) and fs (**l**)

Conclusions

In this paper, the changes of soil moisture content, one of the main parameters influencing the thermal properties of the soils, have been monitored in the ITER test site in the same climatic conditions and under the same thermal stress for five different soil mixtures. The data collected highlight the relationship with precipitation and natural/induced ground temperature variations.

Precipitation and outside air temperature are affecting the soil moisture content in the first 20–30 cm depth below the ground level, while in depth (at 80 cm bgl) the main changes are related to the temperature variations induced by running the VSG system in heating mode.

When temperature drops below 0 °C, especially between 0 and − 6 °C, the VWC is noticeably reduced and the soil is dried out. However, even if the thermal conductivity of the unfrozen soil decreases, the helix takes advantage from the release of latent heat during the phase change process. If complete freezing is not reached, that is, if a further drop in temperature does not occur, once the heat pump is shutdown the soil may recover quite the same water content as before. The recovery time needed to re-establish undisturbed T_{ground} conditions, when the helix has a low burial depth of installation and a heat pump operating for a very long time (about 20 days–24 h/day) forcing the ground temperature to drop below 0 °C, has been estimated about 1 week along the vertical profile and 2 weeks along the cross section of a helix (Di Sipio

and Bertermann 2017b). In this way, when conduction comes back as prevalent heat transfer process, thermal conductivity values similar to pre-freezing operation can be regained. Anyway, periods of not operating condition must be respected to allow soil to regenerate its thermal energy content and thermal properties. The recovery of thermal conditions linked to VWC variations is essential to guarantee the long-term performance of a VSG system. However, the running of the system in critical conditions favoring ice formation in the surrounding soil leads to new enquires about the possibility to exploit the latent heat developed during phase change transitions as heat source and push forward the known limits for the exploitation of VSG systems.

In this framework, fine-grained soil as (fs15B) characterized by greater specific surface areas, lower hydraulic conductivity and greater capillary action, can host a high water content, able to significantly improve the thermal conductivity and, above all, the latent heat storage capacity. In detail, the latent heat storage capacity is really promising if the ground temperature falls below 0 °C, because the majority of the extracted heat able to satisfy the peak load demand is obtained from the solidification of the soil water. Once the peak load utilization ends, the ice melts quite fast and the soil slowly recovers its thermal properties. In case only coarse-grained soil is available on site, in freezing condition its ability to hold unfrozen water can be improved by adding a small percentage of a fine material, as bentonite (s15B).

In addition, the geothermal helical heat exchangers used as horizontal collectors are a really promising technology that can be exploited worldwide: A single helix, if stretched, has a total length of about 40 m, comparable with that of standard horizontal collectors, but it is easy to transport and install. Therefore, the installation costs can be sensibly reduced.

Table 1 Average thermal conductivity (Wm^{-1} K^{-1}) for different VWC classes according to ITER project laboratory results for the soil mixtures used in situ

	Volumetric water content (%)							
	0–5	5.01–10	10.01–15	15.01–20	20.01–25	25.01–30	30.01–35	35.01–40
sector5_SC	0.23	0.67	1.12	1.33	2.05	2.58	–	–
sector4_s15B	0.31	0.59	0.90	1.43	1.09	1.47	2.07	2.37
sector3_GS*	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
sector3_s	0.60	1.52	1.70	–	–	–	–	–
sector2_fs15B	0.22	0.43	0.74	1.19	1.29	1.45	1.96	1.96
sector1_fs	0.31	0.85	1.15	1.54	1.75	1.97	–	–

–λ values are missing because saturation limit of the material is reached

*λ value for GS is considered invariant with a constant value of 2.4 Wm^{-1} K^{-1}, as declared by the producer

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