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Estimating moisture content and hydraulic properties of unsaturated sandy soils of Tiber River (Central Italy): integrating data from calibrated PR2/6 probe and hydraulic property estimator

Stima del contenuto d'acqua e delle proprietà idrauliche dei terreni sabbiosi non saturi del bacino del Fiume Tevere (Italia centrale): integrazione dei dati della sonda PR2/6 e di un estimatore di proprietà idrologiche

Sofia Ortenzi[a] , **Martina Mangoni[a]**, **Lucio Di Matteo[a]**

[a]Dipartimento di Fisica e Geologia, Università di Perugia, Via Pascoli snc, 06123 -Perugia, Italy. - email: *sofia.ortenzi@studenti.unipg.it* - email: *martina.mangoni@studenti.unipg.it* - *lucio.dimatteo@unipg.it*

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Correspondence to:
Sofia Ortenzi
sofia.ortenzi@studenti.unipg.it

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Riassunto

La corretta valutazione dell'umidità del suolo è essenziale nella gestione dell'acqua e nella stima delle proprietà idrauliche dei suoli non saturi. L'uso delle sonde capacitive multi-sensore (MCAP) è in crescente aumento; i dati acquisiti non sarebbero realistici, e quindi di nessuna utilità pratica, senza un'accurata calibrazione. Il lavoro presenta curve di calibrazione della sonda PR2/6 per sabbie di diversa natura (diversa mineralogia) utili ad ottenere dati affidabili di umidità. All'aumentare del contenuto di ossidi di ferro nelle sabbie del bacino del Fiume Tevere, la pendenza delle equazioni di calibrazione aumenta, permettendo la comprensione delle diverse risposte elettromagnetiche dei materiali. In analogia con gli studi su terreni simili, le sabbie ad alto contenuto di ossidi di ferro mostrano una superficie specifica relativa più alta rispetto a quelle quarzose o calcaree; la formazione di acqua di adesione incrementa i valori di permittività (pendenza della retta di calibrazione più elevata). I dati sul contenuto d'acqua, integrati con quelli derivati da uno stimatore di proprietà idrologiche dei suoli, permettono la stima della conduttività idraulica del non saturo. L'applicazione dell'equazione della ditta produttrice al posto di quelle specifiche può sovrastimare i valori di conducibilità idraulica fino a due ordini di grandezza, interpretando quindi in maniera non corretta i fenomeni che avvengono nella zona insatura.

Abstract

The correct estimation of soil moisture data is essential in soil-water management and estimating the hydraulic properties of unsaturated soils. The increased use of Multi-Sensor Capacitance Probes (MCAPs) requires careful calibration. Without accurate calibration, the use of MCAPs leads to incorrect water content estimation, making them of no practical use. This work presents the specific calibration equations for the correct use of the PR2/6 profile probe on sands of different nature. As the iron oxides content of the Tiber River basin sands increases, the calibration lines slope increases, allowing the understanding of the different electromagnetic responses. As for other sands worldwide, sands with high iron oxides content show a relative high specific surface than quartz or calcareous sands, responsible for more adhesive water (e.g., high permittivity values). The water content data are integrated with a hydraulic property estimator allowing the estimation of the hydraulic conductivity of soils. Applying the manufacturer equation of the PR2/6 profile probe instead of the specific equation leads to an overestimation of the hydraulic conductivity values up to two orders of magnitude, making therefore rather incorrect the understanding of the phenomena occurring in the unsaturated zone.

Introduction

The monitoring of soil water content is mandatory in different fields to understand processes involving the unsaturated zone (e.g., infiltration, groundwater recharge, migration of pollutants, etc.) (Nielsen et al. 1986; Daly and Porporato 2005; Zhang and Schilling 2006; Lee et al. 2008; Mathias et al. 2017). As reported by United Nation Sustainable Development Goals (UN SDGs), especially ns. 6 and 14, an accurate water content estimation contributes to sustainable water management (Russo et al. 2014). This topic is particularly important considering the ongoing climate change and growing of agriculture water demands, i.e., the water for irrigation represents about 70% of global water withdrawals (Chartzoulakis and Bertaki 2015). Although several factors govern the groundwater recharge (e.g., Balek 1988; de Vries and Simmers 2002), according to Hodnett and Bell (1986), the role of physical and hydraulic properties of the soil and the antecedent moisture content contributes to defining the direct vertical percolation through the vadose zone (direct recharge, de Vries and Simmers 2002). A soil moisture balance can be helpful to estimate the potential recharge towards the water table (e.g., Lee et al. 2008). As the soil moisture increases, the hydraulic conductivity increases reaching its maximum value for fully saturated soils. Therefore, reliable soil moisture measurements are required for modelling the moisture profile, degree of saturation and hydraulic conductivity of unsaturated soils (Leong and Rahardjo 1997). Nowadays, soil moisture profiles can be obtained in real-time through electromagnetic devices (e.g., capacitance probe), helping calibrate and validate hydrologic models. Although these instruments are increasingly used, especially in irrigation scheduling to enhance water use, to obtain reliable water content data a proper probe calibration is mandatory (Muñoz-Carpena 2005; Evett et al. 2006; Walker et al. 2004, Di Matteo et al. 2018). Among the electromagnetic devices, the Multi-Sensor Capacitance Probes (MCAPs) allow the estimation of the volumetric water content through measurement of the dielectric properties of soil. The PR2/6 device (Delta-T Devices) belongs to the MCAP family, allowing the volumetric water content estimation at different depths, up to 100 cm. The problem of the calibration of low-frequency devices (such as the PR2/6 probe) was reported by several studies in the literature by investigating different soil types, often comparing the moisture content values with those obtained by other devices (Kargas and Kerkides 2008, Schmutz and Namikas 2011, Dhakal et al. 2019). Vaz et al. (2013), evaluated the calibration functions for eight electromagnetic soil moisture sensors in seven well-characterized and texturally varying soils. Recently, Di Matteo et al. (2018, 2021) investigated the performance of the PR/6 probe on some sands, showing how the use of the manufacturer equations leads to an overestimation of the water content with practical implications (e.g., slope stability, understanding of infiltration and runoff processes, etc.). Studies on the calibration of low-frequency probes have dealt marginally with the role of mineralogical characteristics of materials, which can influence estimates of soil permittivity and, therefore, water content. As suggested by Kargas et al. (2020), the presence of iron oxides affects the response of MCAPs instruments, inviting further studies to explore this topic. In this framework, the present study aims to improve the performance of PR2/6 probe by investigating sandy soils of different nature outcropping in the Tiber River basin in Central Italy. Calibration curves for the PR2/6 probe are presented and discussed, considering the mineralogical characteristics of the selected soils and investigating their effects on estimating the hydraulic conductivity and degree of saturation values of unsaturated soils.

Soils characteristics

A sandy soil sample from Central Italy (Tiber basin) was selected: the sample (S_C) was collected from an outcrop belonging to the Santa Maria di Ciciliano Unit (SMCU). The SMCU (early Pleistocene) was deposed in an alluvial system characterized by a wide floodplain and prevalently meandering rivers. It is composed of alternations of sand organized in tabular bodies rarely gravelly, and of clayey-silty deposits; the former due to channel deposits and the latter to floodplains (Basilici 1997; Di Matteo et al.2008; Baldanza et al. 2018).

Five other non-plastic sandy soils are also considered; two from the Tiber River basin (Central Italy) (Di Matteo et al. 2018; Di Matteo et al. 2021) and three from the UK, previously investigated by Robinson et al. (1999). The chosen soils have similar characteristics in terms of fine fraction (lower than 17%) and organic matter (lower than 2.5%). These materials have been selected to increase the database of sandy soils having different mineralogical compositions. The three soils taken from Robinson et al.(1999) are quartz sands (S_1, S_2 and S_4 with a percentage of sands higher than 93%) with organic matter (OM) ranging from 0.36% to 2.06%.

Figure 1 shows the location of samples of Tiber River basin; the soils are named S_A, S_B and S_C, where A, B, and C indicate the name of sampling sites. Figure 2 illustrates the sampling site of S_C soil.

Materials and methods

Geotechnical and mineralogical tests

The main geotechnical properties of sands are obtained by means ASTM standards (ASTM D422-63(2007)e2; ASTM D2974-20e1; ASTM D698-12e2). Laboratory tests were carried for ascertaining grain size distribution, organic matter (OM), Specific gravity (Gs), Maximum Dry Unit Weight (MDUW) and Optimum Moisture Content (OMC) by standard Proctor. The mineralogical composition of S_A, S_B and S_C samples has been obtained by Quantitative X-Ray Powder Diffraction analysis (XRPD, with powder diffractometer system PW1800 Philips) and Scanning Electron Microscope analysis (SEM, model Philips 515 with an Edax Falcon).

PR2/6 probe

The PR2/6 capacitance probe (Delta-T Devices, UK) allows the estimation of soil volumetric water content (θ)

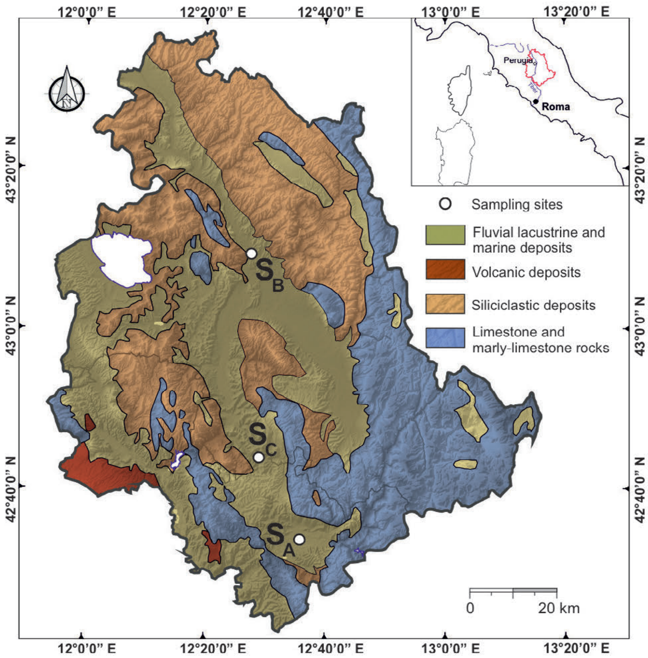

Fig. 1 - Location of the selected sampling sites.

Fig. 1 - Localizzazione geografica dei siti di campionamento delle sabbie selezionate.

Fig. 2 - Detail of the outcropping of SC soil.

Fig. 2 - Dettaglio dell'affioramento del sito di campionamento SC.

at different depths. θ is the ratio between the volume of water (V_w) and the total volume of soil (V); this parameter is directly proportional to the gravimetric water content (θ_g) and to the ratio between the dry unit weight of soil (γ_d) and the unit weight of water (γ_w). The device works with a 9-volt battery that generates an electromagnetic field (frequency of 100 MHz) which is applied to six pairs of sensors placed at different depths, from 0.10 to 1.00 m b.g.s. The probe is installed in soil with an access tube that does not affect the electromagnetic field. Sensors transmit the electromagnetic field extending about 100 mm into the soil/air/water mixture. A data logger records the voltage output (mV) that is empirically related to the square root of soil dielectric-permittivity (√ε) by a six-order polynomial function (e.g., Qi and Helmers 2010). According to Topp (1980), the dielectric property of a wet soil is a complex number (ε*) made by a real part (ε') and an imaginary part (ε''), the latter associated with dielectric losses (eq. 1).

$$\varepsilon_r^* = \varepsilon_r^{'} + j\cdot\varepsilon^{''} = \varepsilon_r^{'} + j\left[\varepsilon_{rel}^{''} + \left(\sigma_{dc} / \omega\cdot\varepsilon_o\right)\right] \quad (1)$$

where:

ε_r^* = complex relative permittivity;
$\varepsilon_r^{'}$ = real part of the permittivity;
$\varepsilon^{''}$ = imaginary part of the permittivity;
j = $j=\sqrt{-1}$
$\varepsilon_{rel}^{''}$ = relaxation component;
σ_{dc} = zero-frequency conductivity;
ω = angular frequency;
ε_o = free-space permittivity.

The real part of the permittivity ($\varepsilon_r^{'}$) is related to the solid, the free water and the hygroscopic or adhesive water (Robinson et al. 2002). Most soil sensors measure the apparent permittivity (ε_a, eq. 2) that mixes together the real and imaginary permittivity (Logsdon et al. 2010).

$$\sqrt{\varepsilon_a} = \sqrt{\frac{\varepsilon_r^{'}}{2}\cdot\left(1+\sqrt{1+\left(\frac{\varepsilon^{''}}{\varepsilon_r^{'}}\right)^2}\right)} \quad (2)$$

In general, for many soils, the effect of electrical loss is minimal; in this way, the instrument records an apparent relative permittivity (ε_a, eq. 2) which is very close to real part of the permittivity $\varepsilon_r^{'}$ (e.g., Topp 1980). The $\varepsilon^{''}$ can be affected by several factors such as the water salinity and temperature, influencing the water content estimates. Regarding the salinity, for effluent waters having electrical conductivity values higher than 1500–5000 µS/cm this problem is not negligible (Rüdiger et al. 2010; Sevostianova et al. 2015). The PR2/6 device has a very low intrinsic sensitivity to the salinity of effluent water when it is about an order of magnitude lower than that reported by the above reference studies (Di Matteo et al. 2018). Moreover, the probe has a very low intrinsic sensitivity to changes in temperature (Delta-T Devices 2017).

According to Kizito et al. (2008), soil water monitoring devices require a laboratory calibration for a range of soil types prior to field deployment. As reported by Topp (1980), there is a simple linear relationship between (√ε) and θ (eq. 3).

$$\sqrt{\varepsilon} = a_o + a_1\theta \quad (3)$$

Equation 3 contains two parameters, a_0 (soil offset) ad a_1 (slope), the values of which are specific to the soil type as they are affected by physical-chemical and mineralogical characteristics of the soil. In this framework the PR2/6 probe needs to be calibrated. As already reported for soil S_A and S_B by Di Matteo et al. (2018), the calibration was performed in a soil column in the laboratory by using repacked soil samples. Volumetric water content values were calculated from the dry unit weight and the gravimetric water content following the procedure reported by Gardner et al. (1998) and Di Matteo et al. (2021).

Soil Water Characteristic Curve

Soil Water Characteristic Curve (SWCC) is the relationship between matric suction (the difference between pore air pressure, u_a, and pore water pressure, u_w) and volumetric water content. Laboratory tests methods can be carried out to determine the soil parameters required for modelling unsaturated soils, which are often costly and time-consuming (Lu and Likos 2004). In this framework, a soil hydraulic property estimator (Soil Water Characteristics – SWC software, Fig. 3) is used to determine some essential hydrological soil properties of the unsaturated zone (e.g., residual, θ_r, and saturated volumetric water content, θ_s), including the hydraulic conductivity (k). The SWC software has been developed by USDA (United States Department of Agriculture). It requires some input parameters such as the texture class, gravel fraction, organic matter, salinity and compaction (bulk density). The software uses the model developed by Saxton and Rawls (2006) for the computation. θ, θ_r, and θ_s values allow the calculation of the effective degree of saturation (S_e, eq. 4); S_e can be assumed equal to the degree of saturation (S_r) when θ_r is negligible (Bordoni et al. 2018).

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

The SWC software has been used to estimate the hydraulic properties of all the selected sands of the Tiber River basin (S_A, S_B, and S_C).

Results

Geotechnical and mineralogical properties

Results of geotechnical analyses on S_C sand are reported in Figure 4, together with those taken from Di Matteo et al. (2018, 2021) who investigated the other two sandy soils of Tiber basin (S_A and S_B,). Figure 5 shows the results of XRPD analysis of S_A, S_B and S_C samples. The mineralogical composition of soils is different: soil S_A is mainly composed of carbonates; soil S_B is a typical flyschoid sand; soil S_C is composed of several minerals, indicating a more complex sedimentary environment (e.g., Ambrosetti et al. 1995). Table 1 shows the main oxides of the investigated sands as obtained by SEM analysis.

Tab. 1 - Mean weight percentage of oxides obtained by SEM analysis.

Tab. 1 - Percentuale in peso media di ossidi nelle sabbie ottenute al SEM.

Oxides	Mean weight (%)		
	S_A	S_B	S_C
Na_2O	0.57	1.75	1.93
MgO	1.11	3.24	2.06
Al_2O_3	3.53	12.29	11.40
SiO_2	30.8	49.98	59.58
K_2O	1.16	2.45	3.72
CaO	60.97	23.34	10.81
FeO	1.85	6.24	10.51
TiO_2	-	0.70	-

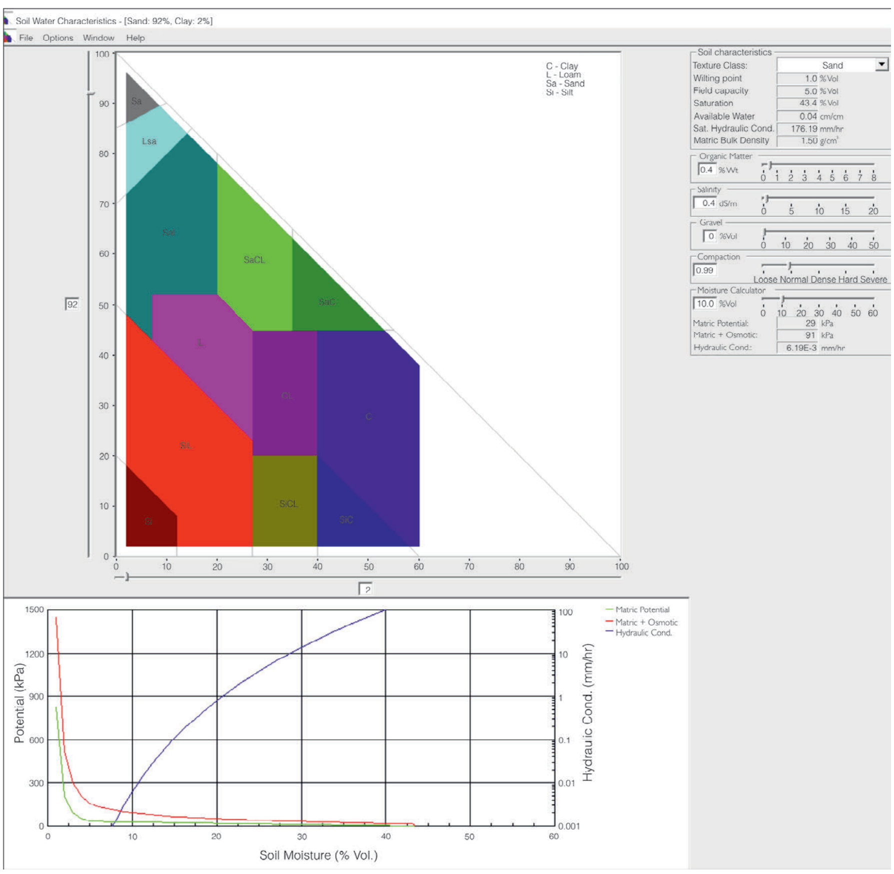

Fig. 3 - Main screen of SWC software.

Fig. 3 - Schermata principale del software SWC.

Soil	Gs	Compaction properties		OM (%)	DUW (kN/m³)
		MDUW (kN/m³)	OMC (%)		
S_A	2.67	14.80	20.0	0.37	14.30
S_B	2.66	17.50	13.2	1.53	14.33
S_C	2.67	17.55	10.0	0.70	15.70

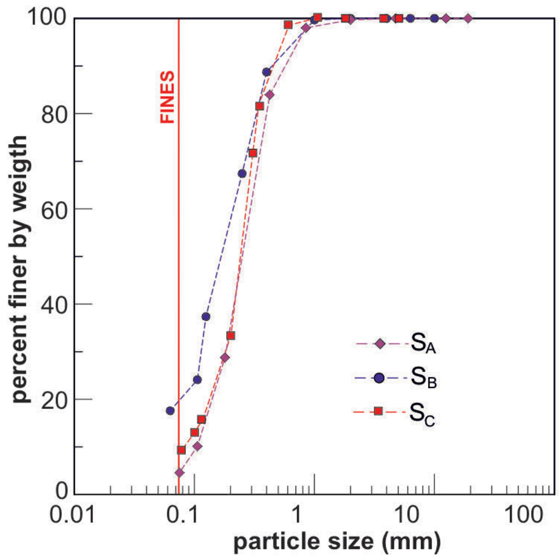

Fig. 4 - Main geotechnical properties of soils of Tiber basin. Gs – Specific gravity; MDUW – Maximum Dry Unit Weight (standard Proctor); OMC – Optimum Moisture Content; OM – Organic Matter; DUW – Dry Unit Weight (in situ).

Fig. 4 - Principali caratteristiche geotecniche delle sabbie del bacino tiberino. Gs – Gravità Specifica; MDUW – Peso di volume secco massimo (Proctor Standard); OMC – Contenuto d'acqua ottimale (Proctor Standard); OM – Sostanza organica; DUW – Peso di volume secco in sito.

Calibration of PR2/6 probe

Following the procedure of Gardner et al. (1998) and Di Matteo et al. (2021), it was possible to obtain the calibration curve for soil S_C useful for reliable estimates of soil water content. Linear regression is performed on the $\sqrt{\varepsilon} \div \theta$ data. Figure 6 shows the comparison of the calibration curve for soil S_C with other sandy soils; it is confirmed that the linear equation proposed by the manufacturer for mineral soils (MS) tends to overestimate the water content for all the soils investigated. Among the sands studied for the Tiber River basin, the calibration line of the S_C sand shows a higher slope than the others, slightly higher than that of the S_B sand. Moreover, it can be seen that the calibration line of the calcareous sands (S_A) and quartz sands (Robinson et al. 1999) almost overlap. For these sands, the overestimation made by the MS equation is of few percentage points. This result agrees with previous studies, highlighting the need to calibrate probes working at a low frequency such as the PR2/6 (Robinson et al. 1999; Logsdon et al. 2010; Di Matteo et al. 2018; Di Matteo et al. 2021). Table 2 reports the synthesis of the calibration equations obtained for the different sands considered.

Tab. 2 - Calibration equations of different sands of Tiber basin (Central Italy) with the Mineral soils line (MS) suggested by the manufacturer.

Tab. 2 - Curve di calibrazione della sonda PR2/6 per alcune sabbie del bacino del Tevere (Italia centrale) insieme a quella Mineral soils (MS), suggerita dalla ditta produttrice.

Soil	Equation		Source
MS	$\sqrt{\varepsilon} = 1.6 + 8.4\,\theta$	5)	Delta-T Devices (Mineral Soil, manufacturer)
S_A	$\sqrt{\varepsilon} = 1.7 + 9.5\,\theta$	6)	Di Matteo et al (2018)
S_B	$\sqrt{\varepsilon} = 1.9 + 10.6\,\theta$	7)	
S_C	$\sqrt{\varepsilon} = 2.0 + 11.2\,\theta$	8)	Present work

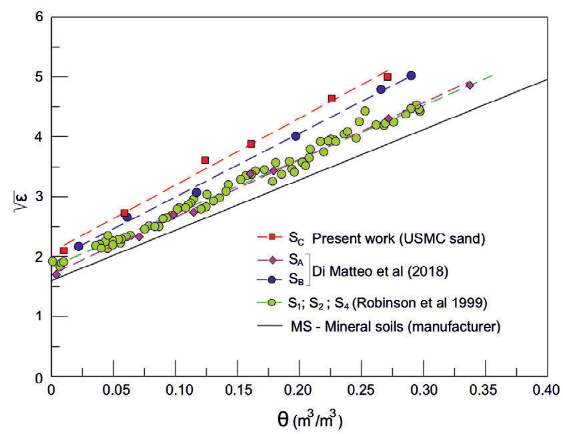

Fig. 6 - Calibration Curves of PR2/6 probe for sands with different mineralogy. Robinson et al.(1999) data are obtained with the Theta probe (Delta-T Devices) working at the same frequency as the PR2/6 device.

Fig. 6 - Curve di calibrazione della sonda PR2/6 per sabbie con caratteristiche mineralogiche diverse. I dati di Robinson et al. (1999) sono stati ottenuti mediante la sonda Theta probe (Delta-T Devices) che lavora alla stessa frequenza della PR2/6.

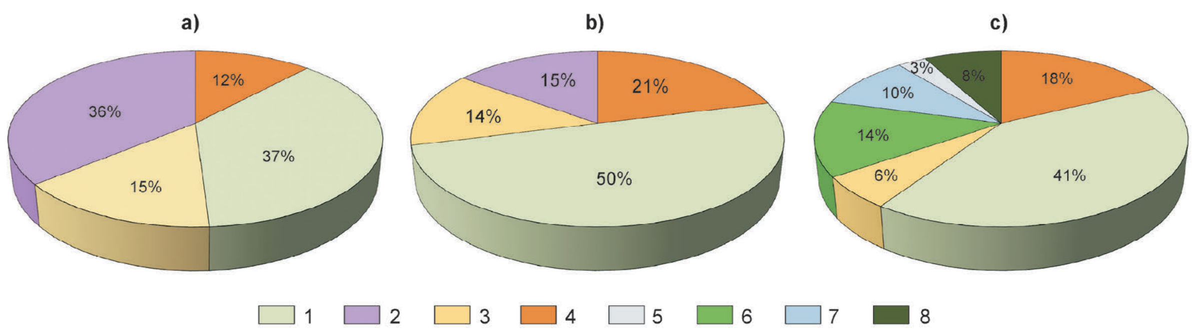

Fig. 5 - Mineralogical composition of the sandy soils S_A (a), S_B (b), and S_C (c). 1 - Quartz; 2 - Calcite; 3 - Orthoclase; 4 - Albite; 5 - Chamosite; 6 - Phengite; 7 - Microcline; 8 - Augite. Data for S_A and S_B are made available by Gubbiotti, University of Perugia (unpublished data 2019).

Fig. 5 - Composizione mineralogiche delle sabbie S_A (a), S_B (b), e S_C (c). 1 - Quarzo; 2 - Calcite; 3 - Ortoclasio; 4 - Albite; 5 - Chamosite; 6 - Phengite; 7 - Microclino; 8 - Augite. I dati di S_A and S_B sono stati ripresi da Gubbiotti, Università di Perugia (dati non pubblicati 2019).

The reliability of water content estimation by profile probes affects the assessment of hydrological properties of unsaturated soils. As presented in the materials and methods section, physically-based methods can be used to predict the unsaturated hydraulic conductivity of soils. In general, as the moisture content decreases, the available pathways for water flow in an unsaturated soil decrease. In this way, the SWCC can estimate the hydro-mechanical behaviour of unsaturated soils, including the hydraulic conductivity (Fredlund 2000). Figure 7a shows the hydraulic conductivity curves for the different sands of the Tiber River basin (S_A, S_B and S_C) at the Maximum Dry Unit Weight conditions (MDUW, optimum Proctor), as estimated by the SWC software. As expected, the sands experience a high hydraulic conductivity decrease because they can retain less water under high suctions (e.g., for low volumetric water content values). Among the sands, maximum hydraulic conductivity values are reached – for all the volumetric water content range – by sand S_A, characterized by an MDUW of 15% lower than soils S_B and S_C. Moreover, soil S_A shows the highest sand fraction content and contains less than 5% fine fraction (Fig. 4). Figure 7b compares hydraulic conductivity values at MDUW with those obtained for the in situ Dry Unit Weight values (DUW). As reported in Figure 4, MDUW for S_A (14.8 kN/m^3) is very close to DUW (14.3 kN/m^3); thus, points tend to along the equality line (1:1 line).

Discussion

The calibration of the PR2/6 probe is critical for the correct estimation of soil water content. As presented in Figure 6 the equations for water content estimation of sandy soils from the Tiber basin differ from that proposed by the manufacturer. The calibration equation of sand S_A is similar to that obtained by Robinson et al. (1999) on quartz sands by using a device similar to the PR2/6 (Theta probe of Delta-T Devices working at 100 MHz). For these types of materials (calcareous and quartz sands), the θ values obtained using the MS equation (eq. 5) are slightly overestimated for a defined $\sqrt{\varepsilon}$ value. On the contrary, both a_0 and a_1 coefficients of soils S_B and S_C (eqs. 7-8 in Table 2) are higher than S_A (eq. 6 in Table 2) and MS (eq. 5 in Table 2). The mineralogical properties of soils can help the explanation of this behaviour. According to SEM analyses (Table 1), iron oxides increase from S_A to S_C, moving from about 1.85% to about 10.5%. As recently presented by Kargas et al. (2020), the amount of iron oxides in the sand affects the calibration parameters and, therefore, the estimation of θ values. In this way, the a_0 parameter tends to increase as the iron oxide fraction increases, as the latter increase the $\varepsilon_r^{'}$. For humid soils, the differences highlighted with the a_0 parameter become more critical when examining the a_1 parameter of the different sands. Although three points are analysed, a positive linear correlation between a_1 parameter and iron oxides percentage occurs (Fig. 8).

By means of SEM investigations, several studies have shown that iron-oxide minerals have a larger specific surface than quartz grains due to relatively rough surface texture (Frank 1981; Smart and Tovey 1981; Welton 1984; Van Dam et al. 2002; Logsdon et al. 2010). These roughnesses allow the presence of adhesive water (not considered in the θ value since it refers only to free water) that increase the $\varepsilon_r^{'}$ values. In other words, for the same θ value, the permittivity of sands having high iron oxides content (high specific surface) is higher than that of quartz or calcareous sands (low specific surface). The corresponding slope ($\Delta\sqrt{\varepsilon}/\Delta\theta$) is much higher for soils S_B and S_C than S_A or quartz sands of Robinson et al. (1999).

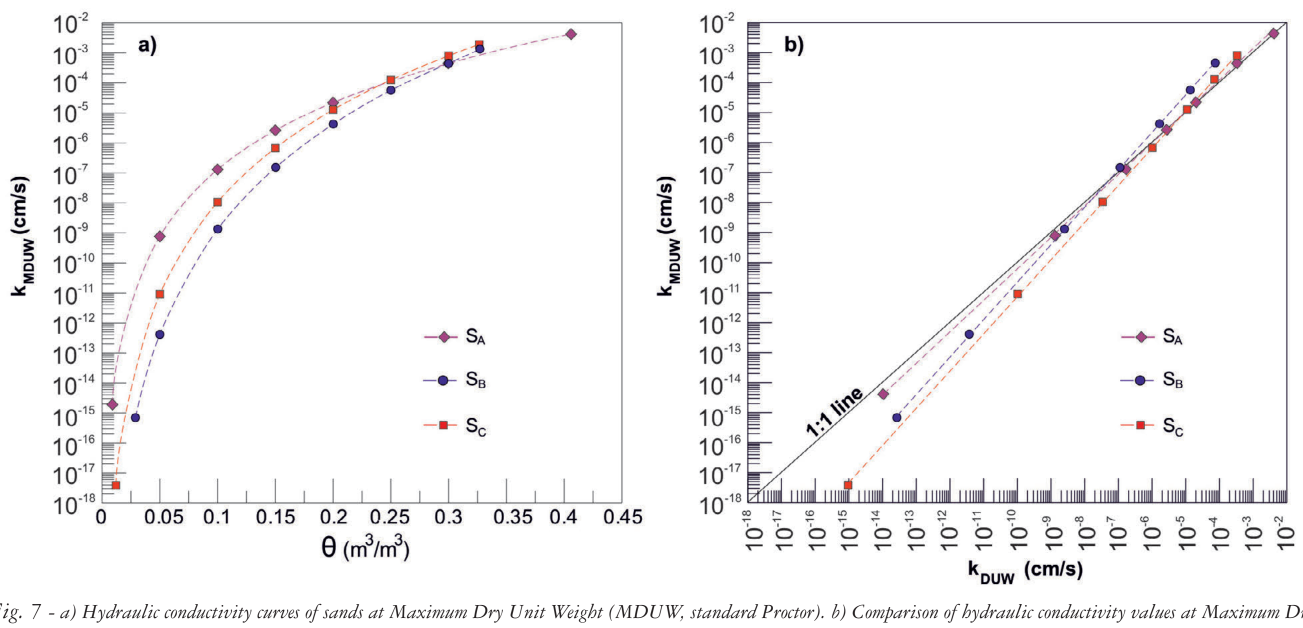

Fig. 7 - a) Hydraulic conductivity curves of sands at Maximum Dry Unit Weight (MDUW, standard Proctor). b) Comparison of hydraulic conductivity values at Maximum Dry Unit Weight (MDUW) vs. in situ Dry Unit Weight (DUW).

Fig. 7 - a) Curve di conducibilità idraulica delle sabbie alle condizioni di addensamento massime (MDUW, Proctor standard). b) Valori di conducibilità idraulica delle sabbie alle condizioni MDUW verso quelle di addensamento in sito (DUW).

Tab. 3 - Hydraulic conductivity values (k) and effective degree of saturation (S_e) of different unsaturated sands obtained with the SWC software. Volumetric water content data are obtained by applying the calibration equations and that of Mineral soils (MS) suggested by the manufacturer.

Tab. 3 - Coefficiente di permeabilità (k) per diverse sabbie non sature ottenute attraverso il software SWC. I valori di contenuto d'acqua sono stati ottenuti mediante le curve di calibrazione specifiche e quella Mineral soils (MS) suggerita dalla ditta produttrice.

Soil	Equation		θ for √ε = 3 (m^3/m^3)	k (cm/s)	S_e (%)
S_A	$\sqrt{\varepsilon} = 1.6 + 8.40\,\theta$	5)	0.17	$6.64 \cdot 10^{-6}$	37
	$\sqrt{\varepsilon} = 1.7 + 9.50\,\theta$	6)	0.14	$1.66 \cdot 10^{-6}$	29
S_B	$\sqrt{\varepsilon} = 1.6 + 8.40\,\theta$	5)	0.17	$6.36 \cdot 10^{-7}$	45
	$\sqrt{\varepsilon} = 1.9 + 10.6\,\theta$	7)	0.10	$1.32 \cdot 10^{-9}$	21
S_C	$\sqrt{\varepsilon} = 1.6 + 8.40\,\theta$	5)	0.17	$1.00 \cdot 10^{-6}$	45
	$\sqrt{\varepsilon} = 2.0 + 11.2\,\theta$	8)	0.09	$1.64 \cdot 10^{-8}$	21

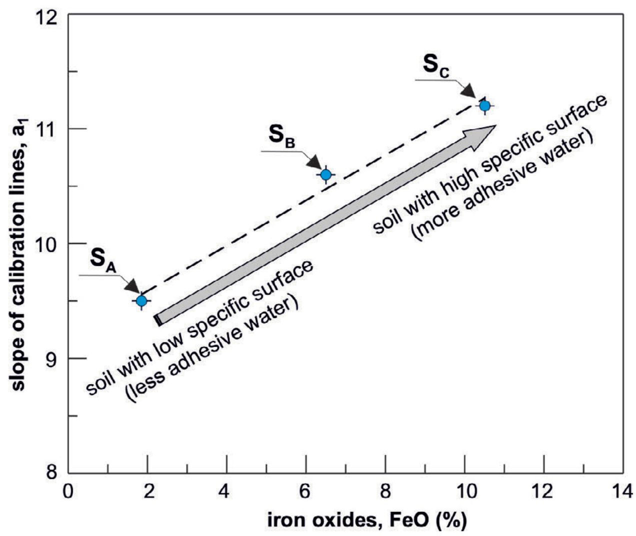

Fig. 8 - Slope of calibration line (a_1) of sands S_A, S_B, and S_C vs. iron oxides content (Tab. 1).

Fig. 8 - Pendenza delle equazioni di calibrazione (a_1) delle sabbie S_A, S_B, and S_C in relazione al contenuto di ossidi di ferro (Tab. 1).

The calibration of the PR2/6 probe and the mechanisms behind the different equations obtained on sandy materials of different nature affects the θ estimation and, therefore, the hydraulic conductivity estimation of unsaturated soils (k) derived by the hydraulic parameters estimator (SWC software). By way of example, Table 3 shows the assessment of k and S_e by considering an $\sqrt{\varepsilon} = 3$. For soils with medium to high iron oxides content (soils S_B and S_C), the k values estimated for the θ value obtained by the calibration equations (eqs. 7-8) are two orders lower than that obtained by using eq. 5 (MS, manufacturer). The effective degree of saturation (S_e) is also overestimated by using θ values obtained with eq. 5, reaching values approximately twice as high as those obtained from eqs. 7-8.

Conclusions

The study investigated the hydraulic properties of unsaturated sandy soils focusing on the reliability of water content estimation of some sandy soils of Tiber basin by the PR2/6 probe. The mineralogy of sands deeply affects the parameters of calibration equations (soil offset and slope). This finding indicates that for the same volumetric water content value (free water), a higher permittivity is measured in sands with high iron oxides content. In other words, the permittivity registered by the PR2/6 probe contains an additional component linked to the adhesive water, which is negligible in quartz or calcareous sands. It is again emphasised that the calibration equations for the sands of the Tiber River basin differ from that suggested by the manufacturer for mineral soils. If the presented specific equations are not applied, the hydraulic conductivity values are overestimated up to two orders of magnitude. In other words, the fraction of water occupied by free water into voids is much higher if the manufacturer equation is used (i.e., high hydraulic conductivity values). The increasing use of profile probes working at a low frequency than Time Domain Reflectometry (TDR) requires detailed studies to improve soil-water management and validate remote sensing data and hydrological soil models.

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Competing interest

The authors declare no competing interest.

Author contributions

Collection of data, Mangoni M, Di Matteo L; data processing, Ortenzi S, Di Matteo L; interpretation of results, Ortenzi S, Mangoni M, Di Matteo L; writing-original draft preparation, Ortenzi S, Di Matteo L; writing-review and editing, Ortenzi S, Di Matteo L; visualization, Di Matteo L; supervision, Di Matteo L; project administration, Di Matteo L. All authors have read and agreed to the published version of the manuscript.

Additional information

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