Development and Optimization of a Multifunctional Sensor for Measuring Soil Thermal Properties, Water Retention Characteristics and Electrical Conductivity

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Abstract

Soil water content, matric potential, thermal properties, and electrical conductivity are fundamental and interrelated properties required by a variety of applications in soil science, hydrology, agriculture, and engineering. However, the measurements of the properties are affected by the temporal and spatial variability of soil due to employment of a variety of sensors, which hinders the research and modeling of coupled water, heat and solute transport. In addition, the laborious, costly and time-consuming sensor optimization is always a challenge for traditional sensor development. The objective of this study was to develop a multifunctional sensor integrating heat pulse, time domain reflectometry and porous ceramic matrix and optimize the sensor with COMSOL based numerical simulations. COMSOL simulated ceramic properties (e.g., thermal conductivity, volumetric heat capacity, dielectric permittivity, electrical conductivity) and soil properties (e.g., thermal conductivity and volumetric heat capacity) with different scenarios of sensor dimensions (e.g., the radius and length of the ceramic and extended rod length) were systematically evaluated and verified with experimental data. Our results show that the optimal radius and length of the ceramic are 18 mm and 40 mm, respectively, and the optimal rod length extended out of the ceramic is 50 mm. The optimized results indicate low estimation errors for dielectric permittivity (±1%), electrical conductivity (±1%), thermal conductivity (±2%), and volumetric heat capacity (±1%) of the ceramic as well as thermal conductivity (±3%) and volumetric heat capacity (±1%) of soil. The new multifunctional sensor can provide accurate measurement and modeling of soil hydrothermal properties.

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Highlights

- By coupling porous ceramic matrix to heat pulse and time domain reflectometry, a multifunctional sensor which can simultaneously measure soil thermal properties, water retention characteristics and electrical conductivity was developed
- COMSOL simulations were used to optimize sensor dimension and verified with experimental measurements
- Considering the different combinations of porous ceramic matrix and soil water content, the measurement errors of soil thermal conductivity (288 treatments) and porous ceramic matrix thermal conductivity (including the

errors caused by radial heat conduction and axial heat conduction, 288 treatments respectively), dielectric permittivity (3960 treatments) and electrical conductivity (5940 treatments) were evaluated

- Porous ceramic matrix radius of 18 mm, ceramic length of 40 mm and extended rod length of 50 mm is the optimal sensor design

Abstract:

Soil water content, matric potential, thermal properties, and electrical conductivity are fundamental and interrelated properties required by a variety of applications in soil science, hydrology, agriculture, and engineering. However, the measurements of the properties are affected by the temporal and spatial variability of soil due to employment of a variety of sensors, which hinders the research and modeling of coupled water, heat and solute transport. In addition, the laborious, costly and time-consuming sensor optimization is always a challenge for traditional sensor development. The objective of this study was to develop a multifunctional sensor integrating heat pulse, time domain reflectometry and porous ceramic matrix and optimize the sensor with COMSOL based numerical simulations. COMSOL simulated ceramic properties (e.g., thermal conductivity, volumetric heat capacity, dielectric permittivity, electrical conductivity) and soil properties (e.g., thermal conductivity and volumetric heat capacity) with different scenarios of sensor dimensions (e.g., the radius and length of the ceramic and extended rod length) were systematically evaluated and verified with experimental data. Our results show that the optimal radius and length of the ceramic are 18 mm and 40 mm, respectively, and the optimal rod length extended out of the ceramic is 50 mm. The optimized results indicate low estimation errors for dielectric permittivity (±1%), electrical conductivity (±1%), thermal conductivity (±2%), and volumetric heat capacity (±1%) of the ceramic as well as thermal conductivity (±3%) and volumetric heat capacity (±1%) of soil. The new multifunctional sensor can provide accurate measurement and modeling of soil hydrothermal properties.

Keywords: Thermo-TDR, thermal/heat dissipation, matric potential, heterogeneity, measurement sensitivity, finite element simulation

Abbreviations: AC/DC, alternating current/direct current; DPHP, dual-probe heat pulse; Ho, homogeneous soil without ceramic; I, rods subjected to inward deflection; ILS, infinite line source; M, measured data; *MSC*, measurement sensitivity to the ceramic; *MSS*, measurement sensitivity to the soil; N, rods subjected to no deflection; O, rods subjected to outward deflection; RE_a, absolute value of relative error; *RMSE*, root means square error; S, simulated data; STP, soil thermal properties; SWRC, soil water retention characteristics; TDR, time domain reflectometry; Thermo-TDR, heat pulse-time domain reflectometry.

1 Introduction

Soil thermal properties (STP) and soil water retention characteristics (SWRC) determining the soil thermal dynamics, status and momentum of water (e.g., ice, liquid water or vapor), affecting a series of processes such as crop growth and development (Nagai and Makino 2009), soil structure change (Zhang et al. 2017), water and energy exchange between land and atmosphere (Brocca et al. 2013), and distribution of solute, gas, water and energy in soil (Mortensen et al. 2006). They are therefore closely related to hydrological, meteorological, agricultural, engineering, ecological environment and geophysical research (Saito et al. 2006). Among them, SWRC represents the relationship between water content (θ, cm^3 cm^{-3}) and matric potential (ψ_m, kpa), and STP are important parameters for evaluating surface energy and geothermal resources, which mainly include thermal conductivity (λ, W m^{-1} °C^{-1}), volumetric heat capacity (C, M J m^{-3} °C^{-1}), and thermal diffusivity (κ, m^2 s^{-1}). Accurate, non-destructive, continuous and simultaneous monitoring of these properties at both laboratory and field is therefore of great significance, especially with the development of smart agriculture and hydrology (Lekshmi et al. 2014; Bwambale et al. 2022; Datta and Taghvaeian 2023).

A variety of techniques for measuring SWRC and STP have been developed. For instance, the dual-probe heat pulse (DPHP) method (He et al. 2018), time domain reflectometry (TDR) method (Robinson et al. 2003; He et al. 2021; He et al. 2023), and ceramics or gypsum based matric potential sensors are currently the most widely used techniques to continuously, rapidly and accurately measure STP, θ and electrical conductivity (EC, σ), and ψ_m, respectively in both laboratory and field. These methods share similarities in measuring principles. For example, DPHP estimate STP based on transport of heat by solving the heat transport equation and TDR measure soil water content based on the dielectric permittivity of water that is much greater than other soil components (e.g., 80 for water vs 5–10 for other components at room temperature). Existing matric potential sensors estimate soil matric potential by indirectly measuring change of soil water content (Noborio et al. 1996; Or and Wraith 1999), thermal conductivity or heat capacity (Phene et al. 1971; Reece 1996; Kojima et al. 2017; Kojima et al. 2021), or electrical resistance or conductivity (Xin et al. 2007) of a porous ceramic or gypsum matrix in equilibrium with its surrounding soils. However, employment of the abovementioned DPHP, TDR and matric potential sensors is affected by unmatched measurement frequency, sensing volume and installation locations between the sensors due to the highly temporal and spatial variability of the soil. This is among the dominant challenges for coupled water and heat transport.

Previous studies have attempted to combine these methods for measuring multiple soil properties with satisfactory performance. For instance, coiled TDR (Noborio et al. 1999; Scanlon et al. 2002; Lungal and Si 2008) or time domain transmissometry (Kojima et al. 2023) was incorporated into ceramics or gypsum to simultaneously measure both water content and matric potential to obtain the SWRC, which describes the change of water content as a function of matric potential. Ren et al. (1999) combined DPHP and time domain reflectometry to develop the thermo-TDR or T-TDR technique for continuous and simultaneous measurement of θ, σ, temperature (T), C, λ and κ of the same soil sample. However, thermo-TDR cannot measure ψ_m that is needed to study soil water movement and the short TDR needs to be calibrated for accurate estimate of θ (He et al. 2015; He et al. 2018). Kojima et al. (2021) incorporated part of DPHP sensor into a ceramic block to simultaneously estimate θ, C, and λ (by DPHP) as well as ψ_m (by ceramics) of the same soil sample. However, it indirectly estimates soil water content with additional known information (e.g., bulk density, ρ_b) and would introduce extra uncertainties in measurement without calibrations and limits its application in the field to continuously monitor θ (Ren et al. 2005). Moreover, a soil multifunctional sensor coupling TDR can be used to measure EC (Dalton et al. 1984; Kargas and Soulis 2019; He et al. 2021). Currently there is an urgent need for a multifunctional sensor that enables the fully couple of DPHP, TDR and porous ceramic matrix for simultaneous measurement of STP and SWRC.

A good design is imperative to the high accuracy of the multifunctional sensor. According to the infinite line heat source (ILS) model, the heater size of DPHP is usually simplified, that is, the heat source of finite length is considered as the heat source of infinite length, and the cylindrical heat source is considered as the linear heat source (Campbell et al. 1991; Bristow et al. 1994). The rod of the DPHP should be slender to conform to the ILS model. However, the design results in a variable rod spacing (*r*, mm), which increases the measurement error of *C* (Noborio et al. 1996). A small *r* allows easier identification of the maximum temperature rise and the time corresponding to the maximum temperature rise at a lower heat strength (q', W m^{-1}), effectively avoiding convective heat transfer around the heater. However, a small *r* means a higher relative error in determining *r* and less representative measurements, because of the small sampling volume (Ren et al. 1999). Therefore, the DPHP was designed with a rod length (*L*) of 28 mm, a rod diameter (*d*) of 0.8 mm, and an *r* of 6 mm (Bristow et al. 1994). To reduce the TDR signal attenuation (which varies with soil texture, θ, and σ) and accurately estimate the travel time, the maximum and minimum rod lengths of the TDR rod can be estimated as (Dalton and Van Genuchten 1986; Ren et al. 1999):

$$L_{max} = \frac{\ln\left(\frac{V_T}{V_R}\right)\cdot\sqrt{\varepsilon}}{12\pi\sigma} \tag{1}$$

$$L_{min} = \frac{t_e v_0}{2\sqrt{\varepsilon}} \tag{2}$$

where L_{max} and L_{min} are the maximum and minimum rod lengths (m), respectively, V_T and V_R are excitation voltage and reflected voltage (V), respectively, ε is dielectric permittivity, σ is electrical conductivity (dS m^{-1}), t_e is the travel time of electromagnetic wave (s), and v_0 is the velocity of light in a vacuum (3×10^8 m s^{-1}).

To avoid the skin effect and excessive soil disturbance, the ratio of rod spacing to rod diameter (r/d) should be as large as possible but less than 10 (Knight 1992). Considering the accuracy of soil thermal properties and water content measurement, the thermo-TDR developed by Ren et al. (1999) was designed with a L of 40 mm, d of 1.3 mm, and r of 6 mm.

In addition, traditional sensor optimization requires numerous designs/types (e.g., sensor dimension: rod length and size, rod spacing, material, and heat strategies) for comparison and screening the best-performing sensor design (Or and Wraith 1999; Liu et al. 2008; Kamai et al. 2015; Menne et al. 2022). This approach is effective but costly, time consuming and laborious, the best optimized design may not be properly selected and the sampling volume and interferences among methods may still remain unknown. Therefore, there is a need to introduce numerical simulations to facilitate probe design in order to comprehensively evaluate numerous factors and their combinations affecting the sensor, and avoid the effects of uncontrollable sources of error in applications (Zhao et al. 2023). A few previous studies have analyzed various factors affecting the accuracy of TDR or DPHP based on numerical simulation software such as GeoStudio (Zhan et al. 2015), HYDRUS (Saito et al. 2007), and COMSOL (Rakesh et al. 2021; Meng et al. 2023). This approach has been approved effectively and cost effective and led to improvements in sensor design and construction under different measurement conditions, which in turn improved the measurement range, accuracy and precision of newly designed sensors. Numerical simulations have the potential to optimize multifunctional sensors combing the DPHP, TDR and ceramics.

Therefore, the objective of this study was to design a soil multifunctional sensor and optimize it using numerical simulation. DPHP, TDR and matric potential sensor were coupled to allow the simultaneous and continuous measurement of SWRC and STP of the same soil, that is, to obtain unified soil hydrothermal data in the same time and space. COMSOL that supports multi-physical field simulations was used to quantitatively analyze the measurement error and to optimize sensor design in terms of soil-ceramic equilibrium as well as heat (for heat pulse measurements) and electromagnetic transfer (for TDR measurements).

2 Materials and methods

2.1 Porotype sensor development

We developed a soil multifunctional sensor by coupling a porous ceramic matrix to extended thermo-TDR rods (**Figure 1**). The ceramic was prepared by a sintering technology, with raw materials of diatomite, kaolin, dextrin, activated carbon powder and silica sol at a mass ratio of 8: 3: 2: 7: 9. The raw materials were mixed, filled into a specific mold, and pressed at a pressure of 12 Mpa for 3 min. It was sintered in a muffle furnace at 1200 °C for 15 h after drying at room temperature for 24 h. The activated carbon powder was composed of equal weights of five different particle sizes (< 75 μm, 75–250 μm, 125–250 μm, 250–400 μm, and 400–1000 μm) of powder. The activated carbon power was used as a pore-forming agent, which sublimated during sintering, forming numerous pores of different sizes. A ceramic with wide pore size distribution can prevent hydraulic decoupling due to a mismatch between the pore size distribution of the sensor and that of the soil, thus providing maximum sensitivity in the range of matric potential studied (Phene et al. 1971; Malazian et al. 2011; Menne et al. 2022). The thermo-TDR in this study was a traditional three-rod sensor, with rod spacing r of 6 mm and rod diameter d of 1.3 mm. The heating wires were placed in the middle rod as a linear heat source. Two thermocouples were placed in each rod to sense the temperature rise of the ceramic and soil. High-thermal-conductivity epoxy glue was then drawn into hollow place next to heating wires and thermocouples in the rods to construct a water-resistant, electrically-insulated rod. The joints of the electrical leads and the heating wires or the thermocouples were soldered. For the TDR part of the sensor, the central rod and two external rods were connected to the positive central lead and metal shield of the coaxial cable, respectively. The joints of the rods and the electrical leads were then encased in epoxy as the sensor handle.

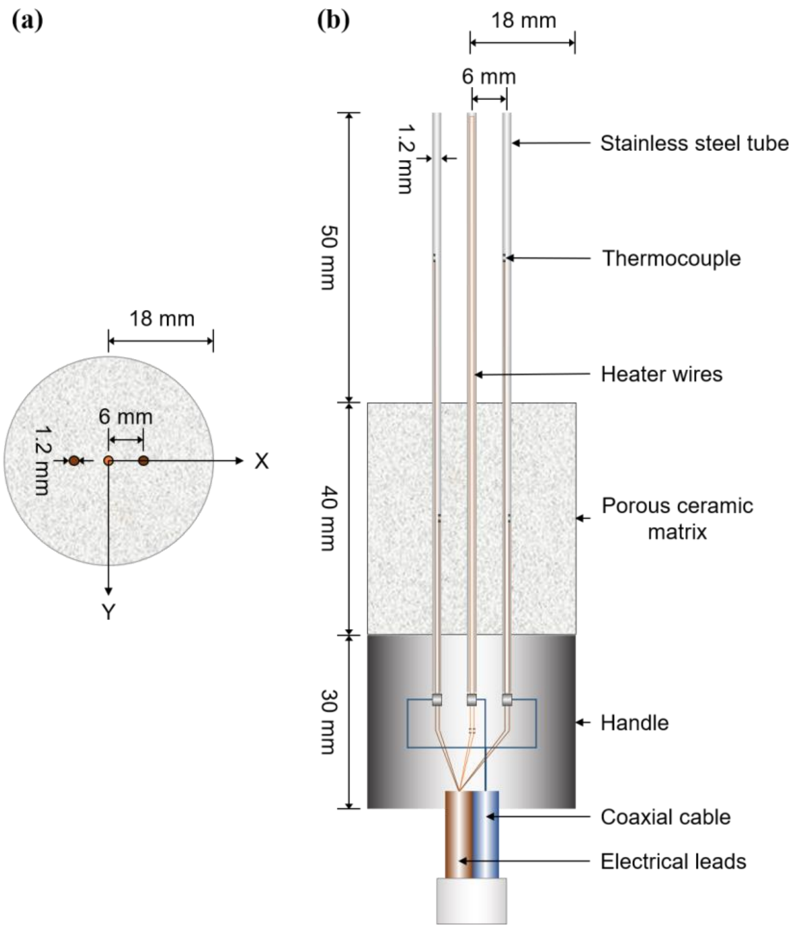

Figure 1. Front view (a) and cross section view (b) of the soil multifunctional sensor.

The rod base of the sensor was incorporated into a ceramic (**Figure 1**). The extended rods were in contact with the soil to directly measure soil water content and thermal properties when the sensor is placed in the soil. The base rods were in contact with the ceramic to measure ceramic thermal properties, water content and electrical conductivity. The ceramic matric potential was estimated using the pre-determined calibration curve (λ-ψ_m, C-ψ_m, θ-ψ_m or σ-ψ_m). Depending on different measurement environments, the various calibration curves proposed in this study can be selected to achieve the highest prediction accuracy of matric potential. The measured ceramic matric potential was equal to the soil matric potential when both of them are at equilibrium.

The following two sections focus on the sensor optimization in terms of soil-ceramic equilibrium and meanwhile considering the effects of heat transfer for DPHP measurements (**Section 2.2**) and electromagnetic transport for TDR measurements (**Section 2.3**) with COMSOL simulations. Different scenarios were tested and literature data were used for verification and validation.

2.2 COMSOL simulation of heat transport with heat pulse method

2.2.1. Numerical model setup and governing equations

An optimal ceramic should be small to ensure faster water equilibration and prevent excessive soil disturbance. However, a too small ceramic radius (R_C, mm) leads to heat loss from the ceramic in the radial direction, and a too short ceramic length (L_C, mm) leads to the measured temperature rise released by the heat pulse method being affected by the axial heat transfer at the interface between the two mediums. A 2D axisymmetric model of module of heat transfer in solids in COMSOL (Version 6.1, COMSOL, Inc., Burlington, MA, USA) was used to optimize the sensor size based on the module of heat transfer in solids. The governing equation used in the module is:

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + Q \quad t > 0 \tag{3}$$

where t is time (s), Q is rate per unit volume of heat generation for the numerical model (W m^{-3}). Assuming that the heat is uniformly distributed in the heater of heat pulse, then in the heater volume, Q can be represented by:

$$Q = \begin{cases} q'/S_H & 0 < t \le t_0 \\ 0 & t > t_0 \end{cases} \tag{4}$$

where S_H is the cross-sectional area of the heater (m^2), t_0 is the heat pulse duration (s). For a linear heat source, d is negligible, i.e., S_H approaches 0.

As shown in **Figure 2a**, soil, ceramic and handle were represented by rectangles with dimensions of 80 mm width × 200 mm height, 30 mm width × 65 mm height and

30 mm width × 65 mm height, respectively. Note that L_C and R_C could be modified in subsequent tests. To simplify the model, the heater and the temperature-sensing rods were not shown in the figure. A linear heat source was added on the axis of symmetry. The linear heat source was 140 mm in length, of which 10 mm was in the lower end of the handle, 65 mm was distributed throughout the ceramic and the remaining 65 mm was in the soil. The length of the heat source in the ceramic and the soil could be modified with the L_C and the length of the extended rod buried in soil (L_S, mm) in the subsequent simulation. The distance between the domain point probe and the linear heat source was 6 mm, corresponding to the rod spacing of 6 mm. The temperature rise curves of the ceramic and the soil were obtained using domain point probes. The outer boundary of the entire study region was set to thermal insulation. This boundary condition indicates that the heat flowing across the outer boundary is negligible. This setting is reasonable because a sufficiently large area is chosen for analysis to conform to the assumption of the infinite measured medium in the ILS model. The material properties of the handle were set to λ = 0.36 W m^{-1} °C^{-1}; density, ρ = 1410 kg m^{-3}; and specific heat, c = 1286 J kg^{-1} °C^{-1} (Kamai and Hopmans 2007). The setup of material properties for ceramic and soil are described in detail in **Section 2.2.3**. Since the mesh resolution affects simulation accuracy, we established a maximum mesh size of 0.92 mm in the ceramic region and the region between the heater and the temperature-sensing rod. The maximum mesh size for the other regions increased from 0.92 mm to 2.3 mm based on a maximum element growth rate of 1.1 (**Figure 2a**). To generate easier identification of the maximum temperature rise and avoid convective heat transfer around the heater, Kluitenberg (2002) suggested maximum temperature rise should fall in the range of 0.5–1.5 °C. Based on this, by testing the ceramic and soil with different water content, the optimal q' and t_0 were determined to be 58 W m^{-1} and 8 s, respectively.

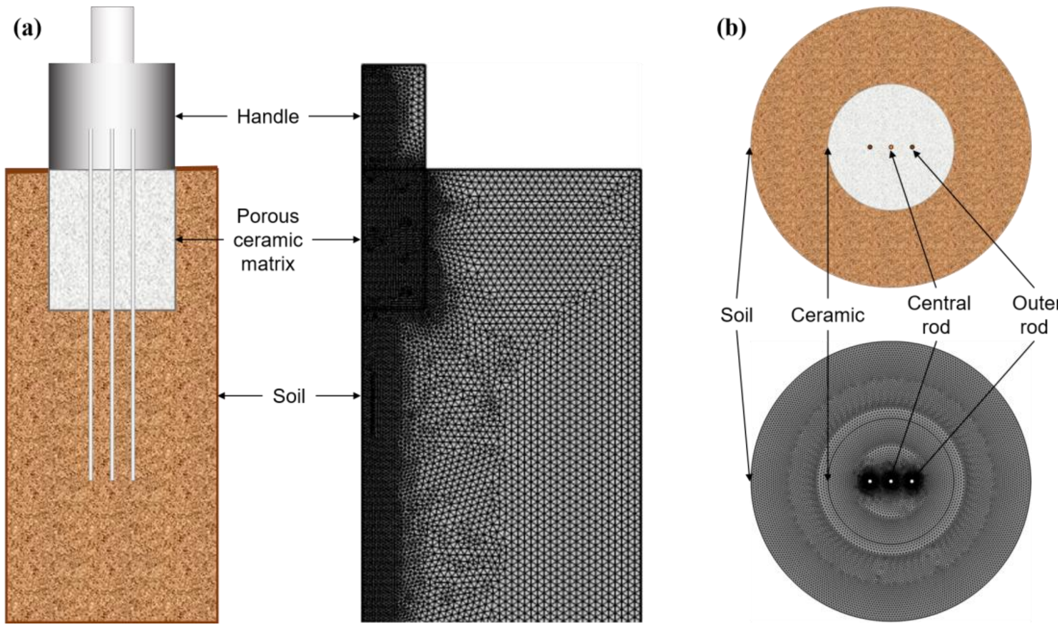

Figure 2. The scenario and the mesh for (a) heat pulse numerical simulation (the mesh area was not completely drawn) and (b) TDR sensitivity simulation.

2.2.2. Verification of heat pulse simulation

The validity of heat pulse simulation were verified based on the experimental setup and measured data of Mori et al. (2003) and Kluitenberg et al. (2010). The thermal properties of dry sand, water and saturated sand measured by heat pulse were simulated by adjusting the sensor setup and the material properties of the measured medium. In Kluitenberg et al. (2010), the L of the sensor was 27 mm, and the r was 4.99, 5.81 and 6.66 mm, corresponding to the rods subjected to inward deflection, no deflection, and outward deflection, respectively. Applied q' was 110 W m^{-1} for t_0 of 8 s. The λ, ρ and specific heat c of the measured medium are shown in **Table 1**.

Table 1. *Material properties for simulation verification. Note that the symbol λ represents thermal conductivity, ρ represents wet bulk density, and c represents specific heat.*

Medium	Deflection treatment	λ (W m^{-1} °C^{-1})	ρ (kg m^{-3})	c (J kg^{-1} °C^{-1})
	inward	0.26	1630	759
Dry sand	none	0.26	1630	759
	outward	0.29	1630	759
	inward	0.6	998	4182
Water	none	0.6	998	4182
	outward	0.59	998	4182

	inward	1.85	2000	1393
Saturated sand	none	1.85	2000	1393
	outward	1.89	2000	1393

2.2.3. Material properties for heat pulse simulations

Measurement using the multifunctional sensor requires that water in ceramic equilibrates with soil water, but this does not mean that the water contents of the two mediums are equal, and the water content gradient may change due to the surrounding soil. To broaden the applicability of the simulation, 36 water content combinations were considered, i.e., six degrees of saturation ranging from dry to saturation (the water content at saturation is equal to total porosity) were set to ceramic and soil, respectively. The degrees of saturation or water contents of the medium was numerically reflected by λ, c and ρ. The thermal conductivity and specific heat of ceramic corresponding to different water contents were measured by a thermo-TDR and the wet bulk density of ceramic was measured by weighing. The sandy soil provided by Kodešová et al. (2013), which had a wide range of thermal conductivity, was used as the simulated soil. The sandy soil comprised of 93.7% sand, 3% silt, and 3.3% clay, with ρ = 1710 kg m^{-3}, porosity (p) of 0.396 and volumetric heat capacity of solids ($\rho_{solids}c_{solids}$), of 2.164 M J m^{3} °C^{-1}.

The thermal conductivity corresponding to different soil water contents was predicted based on the Yan et al. (2019) model:

$$\lambda = \begin{cases} \lambda_{dry} & \theta \le 0.01 \\ \left(\lambda_{sat} - \lambda_{dry}\right) \dfrac{1 + \left(\dfrac{p}{\beta}\right)^{-\beta}}{1 + \left(\dfrac{\theta}{\beta}\right)^{-\beta}} + \lambda_{dry} & \theta > 0.01 \end{cases} \tag{5}$$

where λ_{dry} and λ_{sat} are dry and saturated thermal conductivity, respectively (W m^{-1} °C^{-1}); β is empirical parameter; λ_{dry} was calculated by the linear function proposed by He et al. (2017):

$$\lambda_{dry} = -0.5815p + 0.4999 \quad p \le 0.86 \tag{6}$$

λ_{sat} was calculated by the geometric mean model proposed by Woodside and

Messmer (1961):

$$\lambda_{sat} = \lambda_w^p \lambda_{solids}^{1-p} \quad (7)$$

where λ_w is the thermal conductivity of water, which is 0.594 W m^{-1} °C^{-1} at 20 °C (Bristow 2002), λ_{solids} is the thermal conductivity of solids, which can be determined by another geometric mean model based on the thermal conductivity and mass fractions of quartz and other minerals (Johansen 1975; He et al. 2020):

$$\lambda_{solids} = \lambda_q^{qc} \lambda_o^{1-qc} \quad (8)$$

where qc is quartz content, λ_q is thermal conductivity of quartz (7.7 W m^{-1} °C^{-1}), and λ_o is thermal conductivity of other minerals, which is assumed to be 2.0 W m^{-1} °C^{-1} and 3.0 W m^{-1} °C^{-1} for soils with qc > 20% and $qc \leq$ 20%, respectively. Similar to Peters-Lidard et al. (1998), Lu et al. (2007) and He et al. (2020), quartz content was assumed to be equal to the sand content. According to Yan et al. (2019), β was calculated based on the sand fraction for soil solids (f_{sa}, gravimetric %):

$$\beta = -0.303\lambda_{sat} - 0.201 f_{sa} + 1.532 \quad (9)$$

And the ρ of the soil was predicted based on ρ_b and θ, written as:

$$\rho = \rho_b + \theta\rho_w \quad (10)$$

where ρ_w is the density of water (1000 kg m^{-3}). The c of the soil was calculated as:

$$c = C / \rho \quad (11)$$

where the C of soil was predicted from the volumetric heat capacity of soil solids and water:

$$C = (1-p)\rho_{solids}c_{solids} + \theta\rho_w c_w \quad (12)$$

where c_w is the specific heat of water (4180 J kg^{-1} °C^{-1}). The soil physical properties corresponding to saturation degrees (i.e., ratio of water content to saturated water content) of 0, 0.2, 0.4, 0.6, 0.8, 1.0 were used. The material properties of ceramic and soil are shown in **Table 2**.

The effect of R_C, L_C and L_S on the measurements were studied by changing the basic sensor dimension in **Section 2.1**. Only one effect was assessed in each simulation to avoid complications from additional effects. The ceramic temperature rise with 8 R_C gradients (9, 12, 15, 18, 21, 24, 27 and 30 mm) and 36 water content combinations (288 treatments) was simulated. Ceramic thermal conductivity (λ_C) was estimated based on the pulsed infinite line source model, which was used to screen the optimal R_C. The optimal R_C was used to optimize L_C, with the L_C set to 30, 35, 40, 45, 50, 55, 60 and 65 mm. Similarly, the optimization results were used to optimize L_S, and the settings of L_S and L_C were consistent.

Table 2. *Material properties of the ceramic and soil for simulations. Note that the symbol λ represents thermal conductivity, ρ represents wet bulk density*, and *c represents specific heat.*

Medium	λ (W m^{-1} °C^{-1})	ρ (kg m^{-3})	c (J kg^{-1} °C^{-1})
Dry ceramic	0.35	951	1049
Unsaturation ceramic 1	0.53	1071	1472
Unsaturation ceramic 2	0.61	1192	1668
Unsaturation ceramic 3	0.74	1278	1802
Unsaturation ceramic 4	0.95	1311	2037
Saturation ceramic	1.37	1427	2093
Dry soil	0.27	1710	764
Unsaturation soil l	1.63	1789	916
Unsaturation soil 2	2.04	1868	1054
Unsaturation soil 3	2.30	1948	1181
Unsaturation soil 4	2.50	2027	1298
Saturation soil	2.65	2106	1407

2.3 COMSOL simulations of TDR-measured dielectric permittivity and electrical conductivity

2.3.1. Theory for measurement sensitivity of TDR

Ignoring the effect on the measurements of the heterogeneity of dielectric permittivity in the plane parallel to the rods, the effective dielectric permittivity (ε_{eff}) and effective electrical conductivity (σ_{eff}) can be predicted by the sensitivity of TDR rods to lateral variations in dielectric permittivity (Knight 1992; Ferré et al. 2003; Nissen et al. 2003). The spatial weighting factor $w(x, y)$ is the energy proportion of a specific point in the heterogeneous medium field with the same boundary conditions.

The $w(x, y)$ at each point for the spatial sensitivity of the TDR rod is defined as:

$$w(x,y)=\frac{\left|\nabla\Phi(x,y)\right|^{2}}{\iint_{\Omega}\left|\nabla\Phi_{0}(x,y)\right|^{2}dxdy} \tag{13}$$

where $\nabla\Phi(x, y)$ and $\nabla\Phi_0(x, y)$ are potential gradients in homogeneous and heterogeneous fields (V m^{-1}), respectively. The $\nabla\Phi(x, y)$ satisfies:

$$\nabla\Phi(x,y)=\text{-}E(x,y) \tag{14}$$

where $E(x, y)$ is the electric field intensity (V m^{-1}) and could be computed using COMSOL. The weighting function is defined as:

$$\iint_{\Omega}w(x,y)dxdy=1 \tag{15}$$

ε_{eff} and σ_{eff} are calculated as:

$$\varepsilon_{eff}=\iint_{\Omega}\varepsilon(x,y)w(x,y)dxdy \tag{16}$$

$$\sigma_{eff}=\iint_{\Omega}\sigma(x,y)w(x,y)dxdy \tag{17}$$

The contribution level of the measured medium (ceramic) to ε_{eff} is expressed as the measurement sensitivity to the ceramic of the TDR (*MSC*):

$$MSC=\iint_{C}w_{C}(x,y)dxdy \tag{18}$$

where $w_C(x, y)$ is the weighting factor that is distributed in the ceramic region. Similarly, the measurement sensitivity to the soil surrounding the ceramic of the TDR (*MSS*) is:

$$MSS=\iint_{S}w_{S}(x,y)dxdy \tag{19}$$

where $w_S(x, y)$ is the weighting factor that is distributed in the soil region. In a plane perpendicular to the TDR rods, *MST* and *MMS* satisfy:

$$MSC+MSS=1 \tag{20}$$

The effective ceramic dielectric permittivity ($\varepsilon_{eff\text{-}C}$) and effective ceramic electrical conductivity ($\sigma_{eff\text{-}C}$) measured by TDR can be expressed as:

$$\varepsilon_{eff\text{-}C}=MSC\times\varepsilon_{C}+MSS\times\varepsilon_{S} \tag{21}$$

$$\sigma_{eff\text{-}C}=MSC\times\sigma_{C}+MSS\times\sigma_{S} \tag{22}$$

where ε_C and ε_S are the apparent dielectric permittivity of ceramic and soil, respectively, and σ_C, σ_S, are the apparent electrical conductivity of ceramic and soil, respectively. Therefore, a greater value of the *MSC* for TDR indicates a larger sensitivity to the ceramic and a higher accuracy.

2.3.2. Simulation setup in the module of alternating current/direct current

The ceramic radius in terms of electromagnetic propagation was optimized by using the alternating current/direct current (AC/DC) module of COMSOL. A 2D model was established to simulate the electrostatic field perpendicular to the plane of the TDR rods. As shown in **Figure 2b**, the central rod of the TDR, ceramic and soil surrounding ceramic were represented by circles with radii of 0.6, 7 (adjustable) and 40 mm, respectively. At 6 mm to the left and to the right of the central rod, two circles with a radius of 0.6 mm were added to represent the outer rods. The entities of the three smallest circles are subtracted to simplify the model. The initial value of the entire study region was set to 0. Similar to Bruvik et al. (2012) and Zhan et al. (2015), the outer boundary of the soil and the two outer rods was set as zero charge and ground boundary conditions, respectively, and the central rod was set as terminal boundary condition, with the type voltage and the value of 1. Different combinations of ceramic radius and dielectric permittivity were set by parametric sweep to yield different electrostatic fields. The ceramic dielectric permittivity was set to 3, 6, 9, 12, 15, and 19, as measured by a TDR. The ceramic dielectric permittivity was set to 2, 5, 10, 15, 20, and 25, corresponding to the soil water content from drying to saturation (Nissen et al. 2003; Lekshmi et al. 2014). The ceramic radius increased from 7 to 18 mm in steps of 0.1 mm. Therefore, 3960 (6 × 6 × 110) treatments were set. The mesh used was the smallest mesh by default (0.0016–0.8 mm).

The matric potential sensor based on the relationship between the ressistance and matric potential fails when the electrical conductivity is higher than 0.5 dS m^{-1} (Campbell and Gee 1986; Xin et al. 2007). Therefore, the electrical conductivity set in this study ranged from 0.01 to 0.50 dS m^{-1}. In addition, the electrical conductivity is related to the water content, that is, there is a certain correlation between the electrical conductivity and the dielectric permittivity (Hamed et al. 2003; Kargas and Soulis 2019). Consequently, 54 electrical conductivity combinations based on low, medium and high water contents were considered (**Table 3**). The ceramic radius increased from 7 to 18 mm in steps of 0.1 mm. Therefore, 5940 (54 × 110) treatments were set. Based on the computed electric field intensity and the given dielectric permittivity and electrical conductivity, $\varepsilon_{eff\text{-}C}$ and $\sigma_{eff\text{-}C}$ were determined using **Equation (21)** and **(22)**, respectively.

Table 3. *Ceramic-soil electrical conductivity combinations based on low, medium and high water contents. Note that the symbol ε_C represents apparent dielectric permittivity of ceramic, σ_C represents apparent electrical conductivity of ceramic, ε_S represents apparent dielectric permittivity of soil, σ_S represents apparent electrical conductivity of soil.*

Water content treatment	ε_C	σ_C (dS m^{-1})			ε_S		σ_S (dS m^{-1})		
low water content	3	0.01	0.02	0.03	2	5	0.01	0.02	0.03
medium water content	2	0.04	0.12	0.20	10	15	0.04	0.12	0.20
high water content	9	0.10	0.30	0.50	20	25	0.10	0.30	0.50

2.3.3. Verification for TDR sensitivity simulation

The validity of TDR sensitivity simulation was verified based on the experimental setup and measured data of Nissen et al. (2003). The effect of fluid level height on the ε_{eff} measurements were simulated and analyzed with a horizontally placed TDR. The study region was expanded to a square with a side length of 300 mm, and the medium boundary was adjusted to a horizontal line to represent the liquid-air interface. The bottom material was set as ethanol or water, corresponding to the dielectric permittivity of 25 and 80 respectively. The top boundary material was set as air, corresponding to the dielectric permittivity of 1. The rod radius and spacing were adjusted to 2.3 mm and 35 mm respectively. The simulation results were compared with the measurements.

2.4 Statistical analysis

The estimated physical properties based on COMSOL simulation (x_{eff}) were normalized:

$$x_n = \frac{x_{eff}}{x} \tag{23}$$

where x_n and x represent the normalized physical properties and the known reference values as preset for the medium in the simulation, respectively. Likewise, the absolute value of relative error (RE_a) was calculated to evaluate the influence of different sensor sizes on the accuracy:

$$RE_a = \left| \frac{x_{eff} - x}{x} \times 100\% \right| \tag{24}$$

Root means square error ($RMSE$) was used to compare the simulated temperature rise data with the measured data in the literatures:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(x_s - x_m \right)^2}{n}} \tag{25}$$

where x_s and x_m represent the simulated data based on COMSOL and measured data in the literatures, respectively, and n is the number of data points. To match the simulated data, the measure data were modified by using an interpolation function in Matlab.

3 Results and discussion

3.1 Simulation verification

3.1.1. Verification for heat pulse simulation

The temperature rise curves of DHPP heated water, dry sand and saturated sand were simulated and compared with the measurements of Kluitenberg et al. (2010). As shown in **Figure 3**, the simulated temperature rise curves were in good agreement with the measurements. However, the interference of many uncontrollable factors in the measurement leaded to error, including the thermal resistance of the contact between the rods and the dry sand for the dry sand cases. In the case of outward deflected rods for measuring saturated sand, the $RMSE$ was 7.29×10^{-3} °C, which was the lowest, while in the case of outward deflected rods for measuring dry sand, the $RMSE$ was 1.60×10^{-1} °C, which was the greatest. Even though, the $RMSE$ were within an acceptable range, which indicated that our COMSOL models were accurate and can be applied to the sensor optimization.

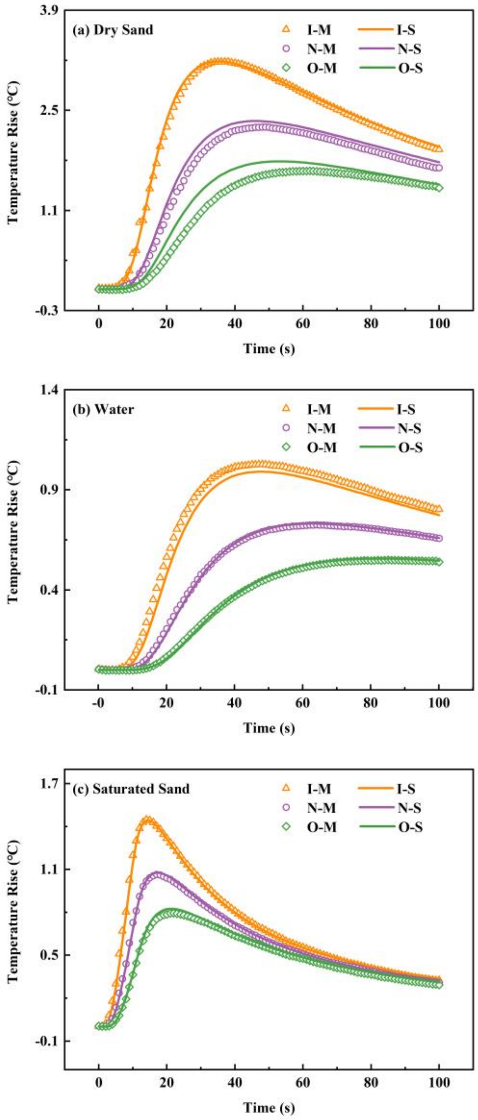

Figure 3. Measured (M) and simulated (S) temperature rise curves of dry sand, water, and saturated sand. All results were for the same DPHP sensor, with rods subjected to inward deflection (I), no deflection (N), and outward deflection (O). Measurements were retrieved from Mori et al. (2003) and Kluitenberg et al. (2010).

3.1.2. Verification of TDR sensitivity simulation

By comparing the dielectric permittivity measured by Nissen et al. (2003) at different liquid levels with our COMSOL simulation results, the feasibility of using COMSOL simulation to study TDR sensitivity was examined. The results of measurement and simulation are shown in **Figure 4**. The simulations deviated from the measurements when the air-liquid boundary was at close proximity to the rod midpoint, although their trends were similar. The *RMSE* values were as low as 2.43×10^{-3} and 3.99×10^{-3} for water and ethanol, respectively. Therefore, our simulation can accurately and reliably predict TDR sensitivity and evaluate sensor accuracy.

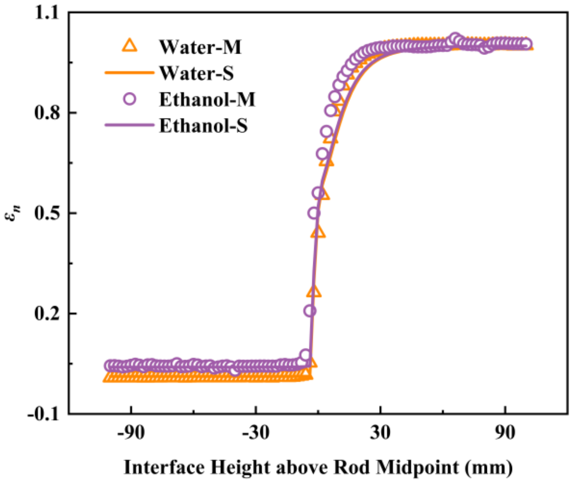

Figure 4. Measured (M) and simulated (S) normalized dielectric permittivity (ε_n) of water and ethanol for the air-liquid interface at difference distances related to the rod midpoint (0 indicates the air-liquid interface is located at the rod midpoint, positive and negative values indicate interface is above and below the rod midpoint, respectively). Data were retrieved from Nissen et al. (2003).

3.2 Simulation for thermal property estimations

3.2.1 Ceramic radius optimization for simulating thermal conductivity

The widely used ILS model is based on the assumption that the heat pulse sensors are embedded in an infinite and homogenous medium (Campbell et al. 1991; Philip and Kluitenberg 1999). The medium heterogeneity affects the heat transfer process, and therefore changes the temperature field, heat flux and temperature rise curve (Ren et al. 2005). The simulation results of temperature field and heat flux corresponding to different ceramic radii are shown in **Figure 5**. The porous ceramic matrix with a larger radius can retain more energy released by the heat pulse. Therefore, less of the heat propagates to the surrounding soil through radial heat transfer, which leads to lower estimation error. **Figure 6** shows the simulated ceramic temperature rise curves (i.e., temperature as a function of time) based on different combinations of thermal properties of ceramic and soil. The ceramic temperature rises shown in **Figure 6d** and **6g** were higher due to the higher C caused by the higher ceramic water content, while in other cases the result was opposite due to the lower ceramic water content. When the ceramic radius was 9 mm, the temperature rise curves deviated noticeably. With the increase in ceramic radius, the deviation of the temperature rise curves decreased until they tended to be constant. In addition, the deviation degree of the temperature rise curves was affected by the difference in thermal properties between the two mediums. As shown in **Figure 6a** and **6h**, the temperature rise curves deviated slightly due to the similarity of the thermal properties of soil and ceramic. On the contrary, the considerable difference in thermal properties between the soil and ceramic increased the difficulty of obtaining accurate temperature rise curves, such as **Figure 6c** and **6g**. For these cases, the ceramic radius must be increased to improve the estimation accuracy.

Figure 7 shows the normalized ceramic thermal conductivity ($\lambda_{n\text{-}C}$) corresponding to 36 combinations of thermal properties. The $\lambda_{n\text{-}C}$ is inaccurate because it is based on both the ceramic and the soil when the ceramic cross section is smaller than the sampling area of the heat pulse. The positive or negative relative error dependeds on the difference in thermal properties between the ceramic and the soil, which is in agreement with **Figure 6**. Estimation accuracy improved with increasing ceramic radius. The $\lambda_{n\text{-}C}$ was between 0.99 and 1.01 when the ceramic radius ≥ 18 mm (**Figure 7**), which indicates that the RE_a caused by radial heat transfer can be controlled within 1% when the ceramic radius is 18 mm. The theoretical analysis of Campbell et al. (1991) showed that at the time corresponding to the maximum temperature rise, the outer boundary with a temperature rise of 1% of the maximum temperature rise was a circle with a radius of 2.37 r. The results of Ren et al. (2005) indicated that the sampling area of the heat pulse was a circle with a radius of 14 mm, i.e., 2.3 r. Thus, the optimal ceramic radius is larger than the theoretical analysis and experimental results. This may be attributed to that considerable difference in thermal properties between the soil and the ceramic are considered in our study. It should be noted that, in practice, the water contents of the ceramic and the soil are similar due to water equilibration, i.e., there are few cases where the thermal properties of the two mediums are noticeably different. Therefore, the ceramic radius of 18 mm can ensure high accuracy of the sensor (RE_a < 1%).

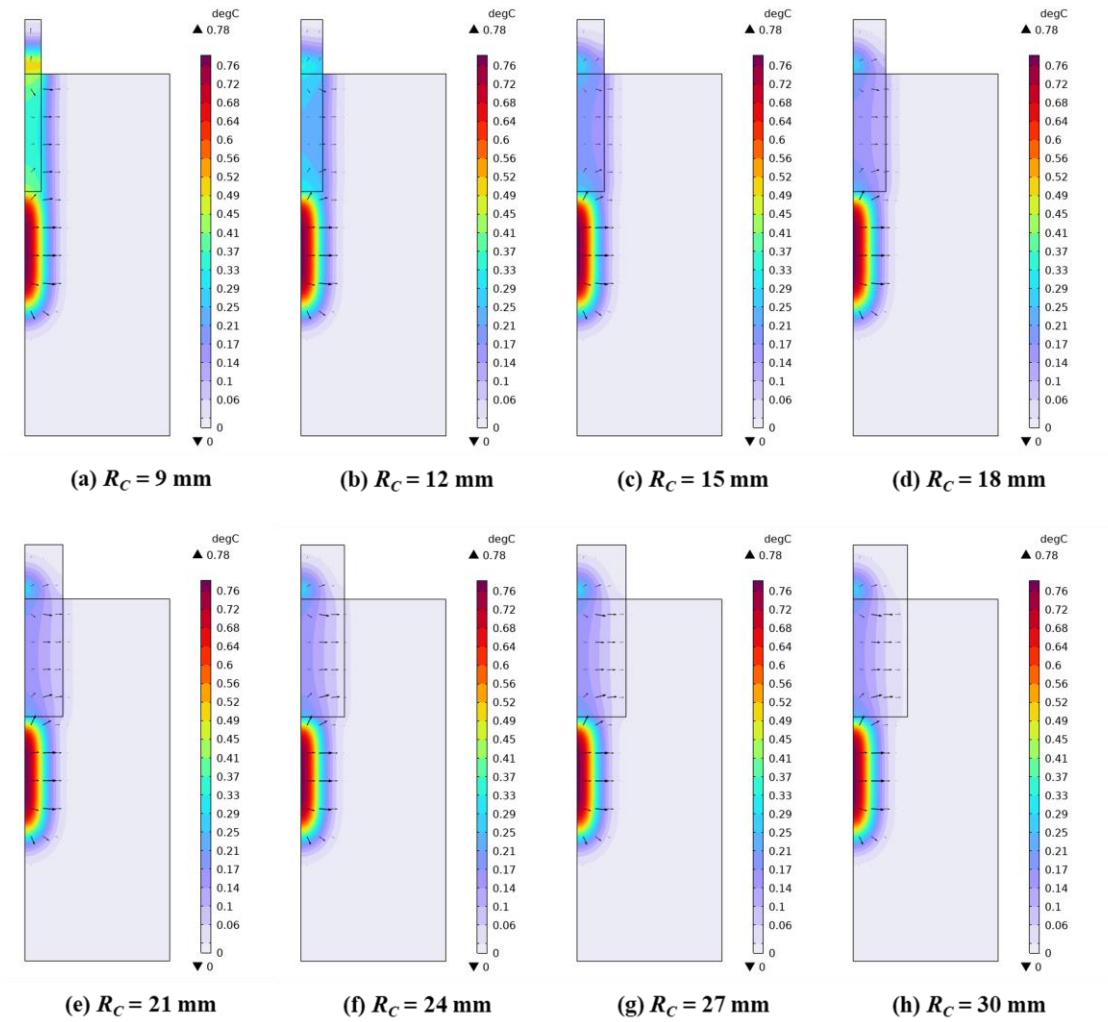

Figure 5. COMSOL simulated temperature distribution and heat flux at ceramic radius, R_C = 9, 12, 15, 18, 21, 24, 27 and 30 mm at 180 s after the 8-s heat input when ceramic thermal conductivity, λ_C = 0.35 W m^{-1} °C^{-1} and soil thermal conductivity, λ_s = 2.65 W m^{-1} °C^{-1}. Arrow direction represents direction of heat transfer, arrow size is proportional to magnitude of heat flux.

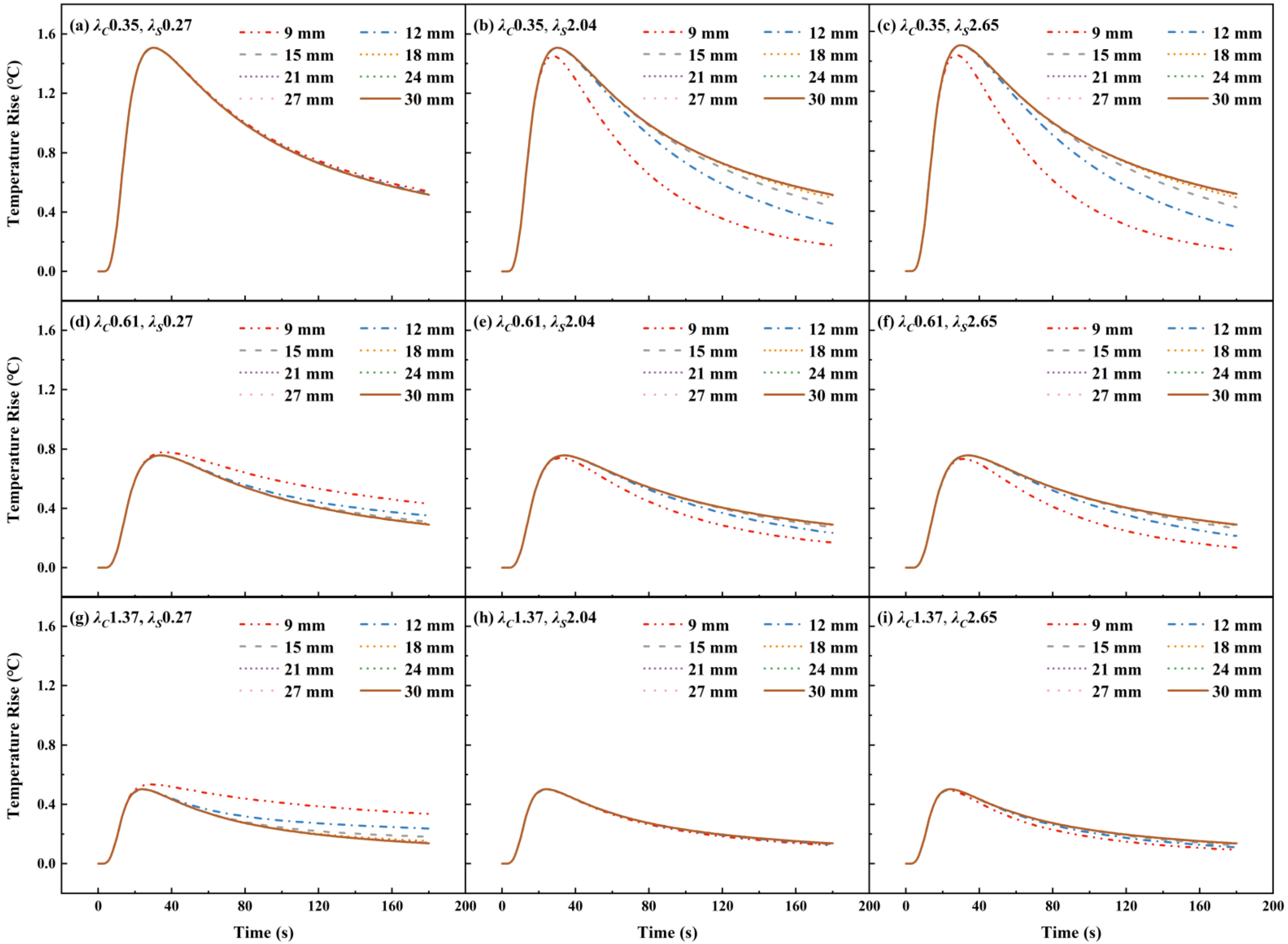

Figure 6. COMSOL simulated ceramic temperature rise as a function of time for different combinations of thermal conductivity of ceramic and soil. Ceramic thermal conductivity, λ_C that is set to be 0.35, 0.61 and 1.37 W m^{-1} °C^{-1} and soil thermal conductivity, λ_S that is set to be 0.27, 2.04, and 2.65 W m^{-1} °C^{-1}; ceramic radius ranged from 9 to 30 mm. The data following λ_C or λ_S is the value of thermal conductivity (W m^{-1} °C^{-1}).

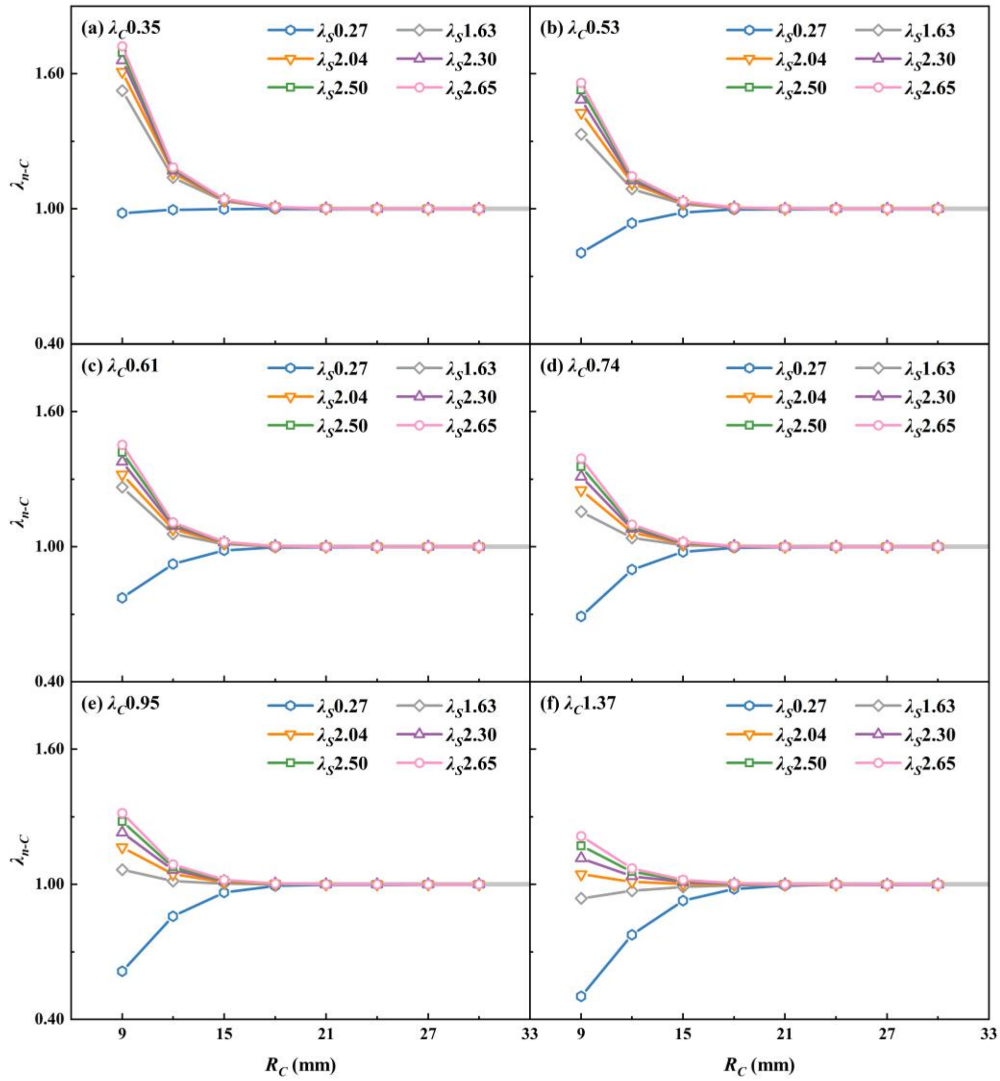

Figure 7. Normalized ceramic thermal conductivity ($\lambda_{n\text{-}C}$) as related to different ceramic radius (R_C, with the settings of 9, 12, 15, 18, 21, 24, 27 and 30 mm) for different combinations of thermal conductivity of ceramic (λ_C, ranging from 0.35 to 1.37 W m^{-1} °C^{-1}) and soil (λ_S, ranging from 0.27 to 2.65 W m^{-1} °C^{-1}), the unoptimized ceramic length and extended rod length is set to be 65 mm. The data following λ_C or λ_S is the value of thermal conductivity (W m^{-1} °C^{-1}), and the regions with the absolute value of relative error (RE_a) < 1% are marked with gray rectangle.

3.2.2 Ceramic length optimization for simulating thermal conductivity

Figure 8 shows the results of the $\lambda_{n\text{-}C}$ corresponding to the 36 thermal property combinations, with all results based on the ceramic radius of 18 mm. The error caused by axial heat transfer decreased and the accuracy of thermal conductivity estimation improved with increasing ceramic length. Some extreme cases were excluded, such as soil thermal conductivity (λ_S) higher than 2.04 W m^{-1} in **Figure 8a** and λ_S of 0.27 W m^{-1} in **Figure 8f**, because they represent the assumption that one medium is dry and the other medium is at a higher water content. Based on this, we found that the $\lambda_{n\text{-}C}$ was between 0.98 and 1.02 when the ceramic length ≥ 40 mm (as shown in the area marked by the gray rectangle in **Figure 8**), i.e., the RE_a caused by axial heat transfer can be controlled within 2%. Axial heat conduction occurred not only between the ceramic and the soil, but also between the handle and the soil. Meng et al. (2023) indicated that accurate measurement of thermal properties became more challenging as thermal properties of handle material increase relative to those of the measured medium. Therefore, the overestimation or underestimation of the λ_C did not completely correspond to the higher or lower λ_S, and the effect from the handle needs to be additionally considered. For example, in the case of **Figure 8f** where λ_S was higher than that of the ceramic, the λ_C may be underestimated, because of the large difference in thermal conductivity between the ceramic and the handle (the handle thermal conductivity was only 0.36 W m^{-1}). For the case in **Figure 8a** where the λ_S was 0.27 W m^{-1}, the temperature rise of the handle was less than that of the ceramic due to the high heat capacity of the handle and the short (10 mm) heat source in the handle. Due to the temperature gradient, more heat in the ceramic was transferred to the handle, which led to an overestimation of the λ_C.

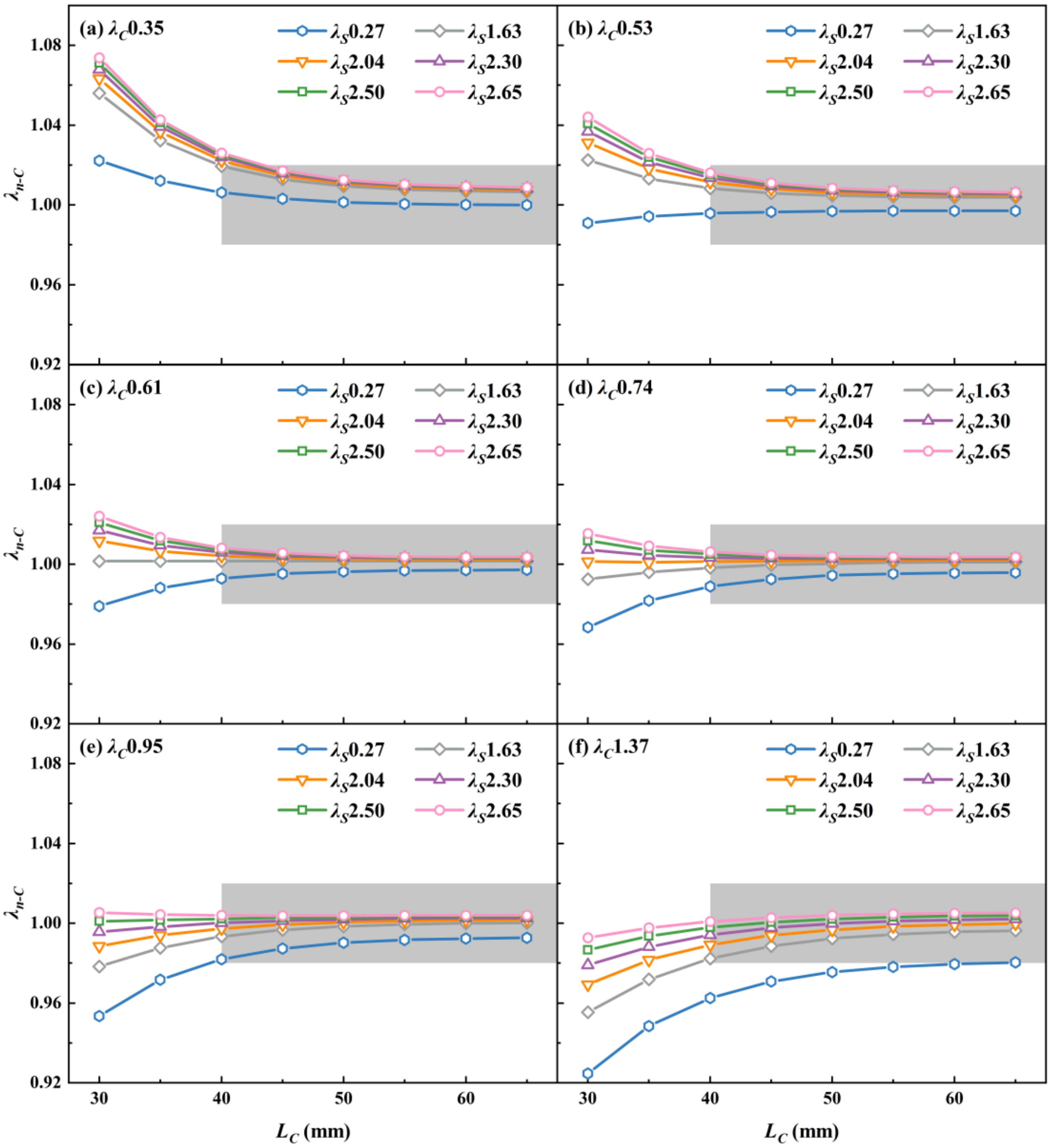

Figure 8. Normalized ceramic thermal conductivity ($\lambda_{n\text{-}C}$) as related to different ceramic lengths (L_C, with the settings of 30, 35, 40, 45, 50, 55, 60 and 65 mm) for different combinations of thermal conductivity of ceramic (λ_C, ranging from 0.35 to 1.37 W m^{-1} °C^{-1}) and soil (λ_S, ranging from 0.27 to 2.65 W m^{-1} °C^{-1}), the optimized ceramic radius and unoptimized extended rod length were set to 18 mm and 65 mm, respectively. The data following λ_C or λ_S is the value of thermal conductivity (W m^{-1} °C^{-1}), and the regions with the absolute value of relative error (RE_a) < 2% are marked with gray rectangle.

3.2.3 Optimization of the extended rod length for simulating thermal conductivity

The extended rod length was optimized based on the optimal ceramic radius and length. The relationship between normalized soil thermal conductivity ($\lambda_{n\text{-}S}$) and the extended rod length is shown in **Figure 9**. The accuracy of λ_S estimation improved with increasing extended rod length due to a decrease in the error caused by axial heat transfer. However, considering the deflection problem caused by the long rods, the extended rod length of 50 mm was finally adopted. At the 50-mm extended rod length, the RE_a of λ_S estimation was less than 3% as shown in the regions marked by the gray rectangles in **Figure 9**, which was 3% lower than that of a traditional thermo-TDR with rod length of 40 mm (He et al. 2018). Therefore, our optimization considerably improved the sensor accuracy.

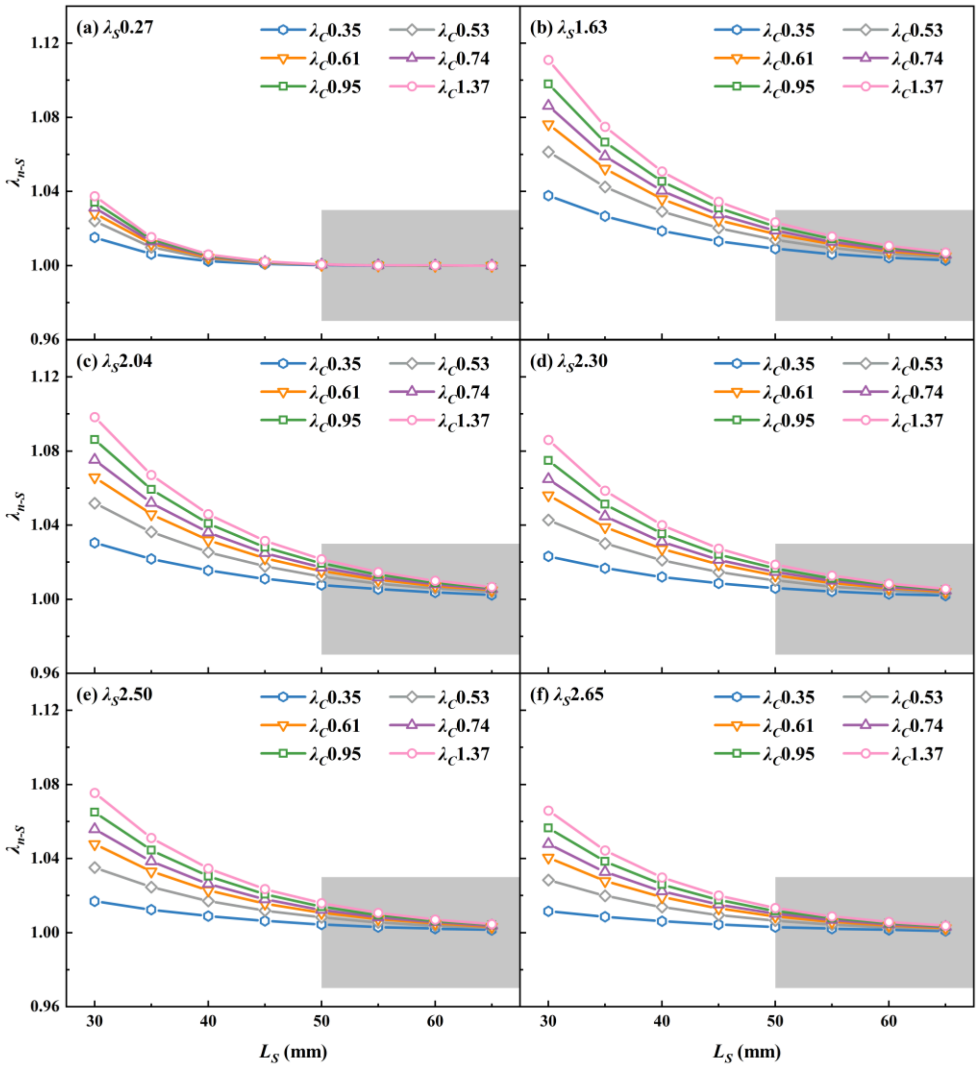

Figure 9. Normalized soil thermal conductivity ($\lambda_{n\text{-}S}$) as related to different extended rod length (L_S, with the settings of 30, 35, 40, 45, 50, 55, 60 and 65 mm) for different combinations of thermal conductivity of ceramic (λ_C, ranging from 0.35 to 1.37 W m^{-1} °C^{-1}) and soil (λ_S, ranging from 0.27 to 2.65 W m^{-1} °C^{-1}), the optimized ceramic radius and length were set to 18 mm and 40 mm, respectively. The data following λ_C or λ_S is the value of thermal conductivity (W m^{-1} °C^{-1}), and the regions with the absolute value of relative error (RE_a) < 3% are marked with gray rectangle.

For the cases of $\lambda_S = 0.27$ W m^{-1} °C^{-1}, the RE_as are lower than others as shown in **Figure 9a**. The explanation may be that less heat was lost from the soil with low λ_S to the surrounding medium during the temperature measurement, which resulted in a smaller area of the soil affected by heat pulse. Unlike the ceramic optimization results, the estimated errors were all positive, even if the λ_S was much lower than λ_C. This is because the λ_S estimation is not only affected by the difference in thermal conductivity between the two mediums, but also by the finite length of the heat source, and the latter always contributes a positive error (Kluitenberg et al. 1993). Therefore, longer extended rods will not only reduce the influence of medium heterogeneity on the temperature measuring point, but also avoid deviation from the assumption of the heat source of finite length. However, it is also noteworthy that long rods would be affected by deflection when inserting into soils and significantly affect measurement accuracy (Kluitenberg et al. 1993; Bristow et al. 1994; Kluitenberg et al. 1995).

The relative location of the temperature measuring point was defined as the ratio of the distance from the temperature measuring point to the ceramic-soil boundary (*D,* mm) to the extended rod length. The effect of the evaluated rod length and the relative location of the temperature measuring point on the estimation of λs was evaluated, and the results were shown in **Figure 10**. In the simulations, ceramic was represented as soils (corresponding to the cases represented by dotted lines in **Figure 10**) to exclude the effect of heterogeneity and evaluate the effect of the heat source of finite length on the estimations. The results indicated that the positive error caused by heat source of finite length increased with increasing value of D/L_S. The λ_n-s showed a stable trend because the positive error caused by heterogeneity decreased with increasing value of D/L_S (**Figure 10a)**. While the λ_n-s showed an increasing trend because the negative error caused by heterogeneity decreased with increasing value of D/L_S (**Figure 10b**). For The RE_a of the λs estimation was the lowest when D/L_S =0.50, that is, the midpoint of the extended rode was the optimal temperature measuring point (**Figure 10a**). While the RE_a of the λs estimation was the lowest when D/L_S =

0.49 (**Figure 10b**), that is, the location closer to the ceramic was the optimal temperature measuring point. The RE_a of the λs estimation can be controlled within 1.5% and 0.2% by extended rod length of 50 mm and 80 mm, respectively, that is, the RE_a can be effectively reduced by increasing extended rod length, which is consistent with the result in **Figure 9**.

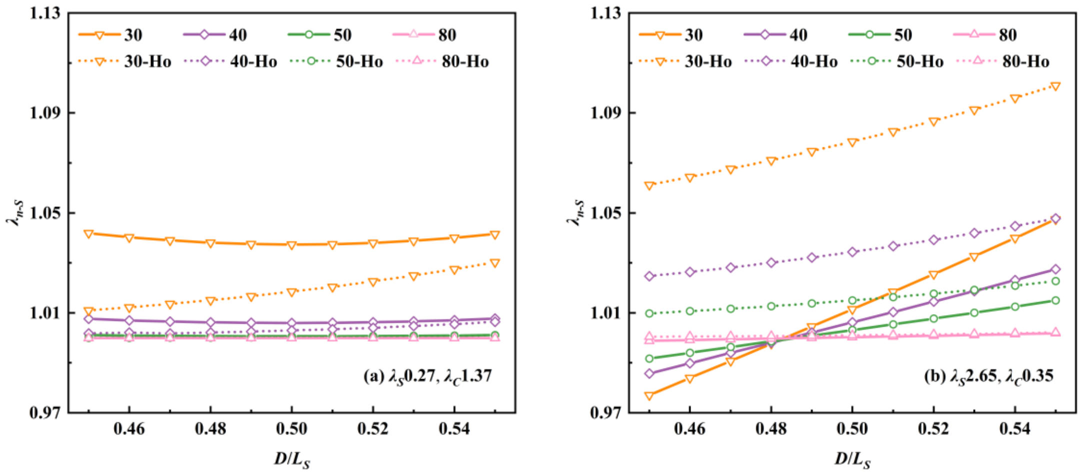

Figure 10. Normalized soil thermal conductivity ($\lambda_{n\text{-}S}$) related to the ratio of the distance from the temperature measuring point to the ceramic-soil boundary (D, mm) to the extended rod length (L_S, with the settings at 30, 40, 50 and 80 mm) for different combinations of thermal conductivity of ceramic (λ_C, with the settings of 0.35 and 1.37 W m^{-1} °C^{-1}) and soil (λ_S, with the settings of 0.27 and 2.65 W m^{-1} °C^{-1}), the optimized ceramic radius and length are set to 18 mm and 40 mm, respectively. The data following λ_C or λ_S is the value of thermal conductivity (W m^{-1} °C^{-1}), and the dotted lines represented cases in which the measured medium was homogeneous soil without ceramic (Ho).

3.2.4 Estimation accuracy of volumetric heat capacity

Figure 11 shows the normalized ceramic volumetric heat capacity ($C_{n\text{-}C}$) and normalized soil volumetric heat capacity ($C_{n\text{-}S}$) corresponding to the extreme thermal property combinations. Compared with thermal conductivity, volumetric heat capacity was more accurately estimated, even though the thermal properties of the ceramic and soil differ greatly. This is consistent with numerical analysis of Philip and Kluitenberg (1999) and the experimental results of Zhang et al. (2014), which indicated that the sensitivity of volumetric heat capacity data to heterogeneity is less than that of thermal conductivity data to heterogeneity when near-surface STP were measured by heat pulse method.

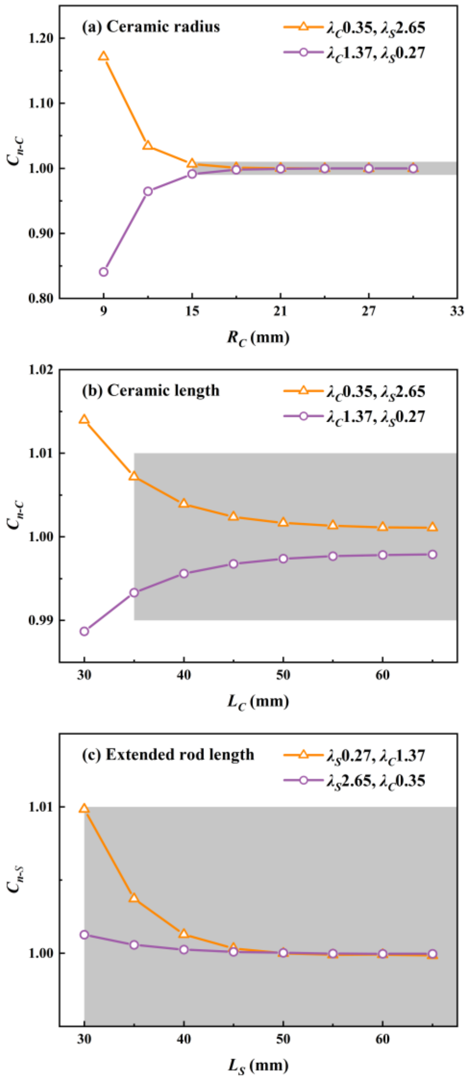

Figure 11. (a) normalized ceramic volumetric heat capacity ($C_{n\text{-}C}$) as related to ceramic radius (R_C), the unoptimized ceramic length (L_C) and extended rod length (L_S) are set to be 65 mm; (b) $C_{n\text{-}C}$ as related to L_C, the optimized R_C and unoptimized L_S are set to 18 mm and 65 mm, respectively; and (c) normalized soil volumetric heat capacity ($C_{n\text{-}S}$) as related to L_S, the optimized R_C and L_C are set to 18 mm and 40 mm, respectively, when different combinations of thermal conductivity of ceramic (λ_C, 0.35 and 1.37 W m^{-1} °C^{-1}) and soil (λ_S, 0.27 and 2.65 W m^{-1} °C^{-1}) for. The data following λ_C or λ_S is the value of thermal conductivity (W m^{-1} °C^{-1}), and the regions with the absolute value of relative error (RE_a) < 1% are marked with gray rectangle.

The RE_a of estimated ceramic volumetric heat capacity caused by radial and axial heat transfer can be controlled within 1 % when the $R_C \geq 15$ mm and $L_C \geq 35$ mm, respectively. The RE_a of estimation of soil volumetric heat capacity caused by axial heat transfer and finite length of the heat source can be controlled within 1%

when $L_S \geq 30$ mm. Similar to the soil thermal conductivity, the soil volumetric heat capacity was always overestimated, which was also due to the limited length of the heat source (Kluitenberg et al. 1993). Therefore, the optimized sensor sizes (ceramic radius of 18 mm, ceramic length of 40 mm and extended rod length of 50 mm) based on ceramic and soil thermal conductivity estimations can ensure a low RE_a (< 1%) of ceramic and soil volumetric heat capacity estimation.

3.3 Simulations for the estimations of ceramic dielectric permittivity and electrical conductivity

3.3.1 Ceramic radius optimization for dielectric permittivity estimations

Similar to thermal property estimation, the medium heterogeneity affects the electric field, and therefore leads to errors in estimating dielectric permittivity and electrical conductivity. The simulation results of electric field corresponding to different ceramic radii are shown in **Figure 12**. The porous ceramic matrix with a large radius can contain more energy released by the central rod. Therefore, less of the energy prorogates to the surrounding soil and leads to lower estimation error. **Figure 13** shows the results of ceramic radius optimization based on ε_C estimations. As ceramic radius increased, normalized ceramic dielectric permittivity ($\varepsilon_{n\text{-}C}$) gradually approached 1. The $\varepsilon_{n\text{-}C}$ was between 0.99 and 1.01 when the ceramic radius ≥ 13 mm, as shown in regions marked by the gray rectangles in **Figure 13**.The RE_a caused by the difference in dielectric permittivity between the ceramic and the soil can be controlled within 1% when the ceramic radius is 13 mm. The sampling radius of the TDR with a rod diameter of 1.3 mm and a spacing of 6 mm is 11 mm, the associated RE_a of ε_C was 2%, which is in good agreement with Ren et al. (2005).

A soil differing considerably in dielectric permittivity from the ceramic results in a higher ε_C estimations error. For example, the RE_as of ε_C estimation at ε_S of 2 (blue hexagons), 5 (gray diamonds), 20 (green squares), and 25 (pink circles) at R_C = 7 mm, were 11 %, 6 %, 2 %, and 3 %, respectively, which were higher than those of 1% at ε_S = 10 (orange triangles) and 15 (purple triangles) as indicated by **Figure 13d**. In addition to the considerable dielectric permittivity difference between the two mediums, a high RE_a may also be caused by a soil with a low dielectric permittivity. The RE_a of ε_C estimation at $\varepsilon_S = 2$ (blue hexagons) was 7 % at $R_C = 7$ mm, which was higher than that of 3 % at ε_S =25 (pink circles), even though the dielectric permittivity of the two mediums were more similar in the former case as shown in **Figure 13b**. Similarly, the RE_a of ε_C estimation at $\varepsilon_S = 10$ (orange triangles) was 3 % at $R_C = 7$ mm, which was higher than that of 2% at $\varepsilon_S = 25$ (pink circles) as shown in **Figure 13a**. This is because the measurement sensitivity is biased toward the lower permittivity region, as the soil with lower dielectric permittivity shows a higher contribution to $\varepsilon_{eff\text{-}C}$. This bias arises because the potential gradient of the energy through the region with low dielectric permittivity is much higher than that through the region with high dielectric permittivity. This is also shown by the simulation results in **Figure 12a**, **12b**, and **12c**, where some soil regions have higher electric field intensity than the ceramic on the edge due to its their lower dielectric permittivity although the soil is further away from the central rod than the ceramic. According to **Eq. (13)**, a high potential gradient means that the energy and the sensitivity is concentrated within the region with low dielectric permittivity (Nissen et al. 2003). Numerical analysis indicates that the interference medium with low dielectric permittivity has a greater impact on the measured dielectric permittivity than the interference medium with high dielectric permittivity (Knight et al. 1997). Therefore, the soil with low dielectric permittivity and a considerable difference from ε_C result in a high RE_a of ε_C estimation. For example, the RE_a of ε_C estimation (12%) was the highest of all cases for $\varepsilon_S = 2$ and $R_C = 7$ mm (**Figure 13f)**.

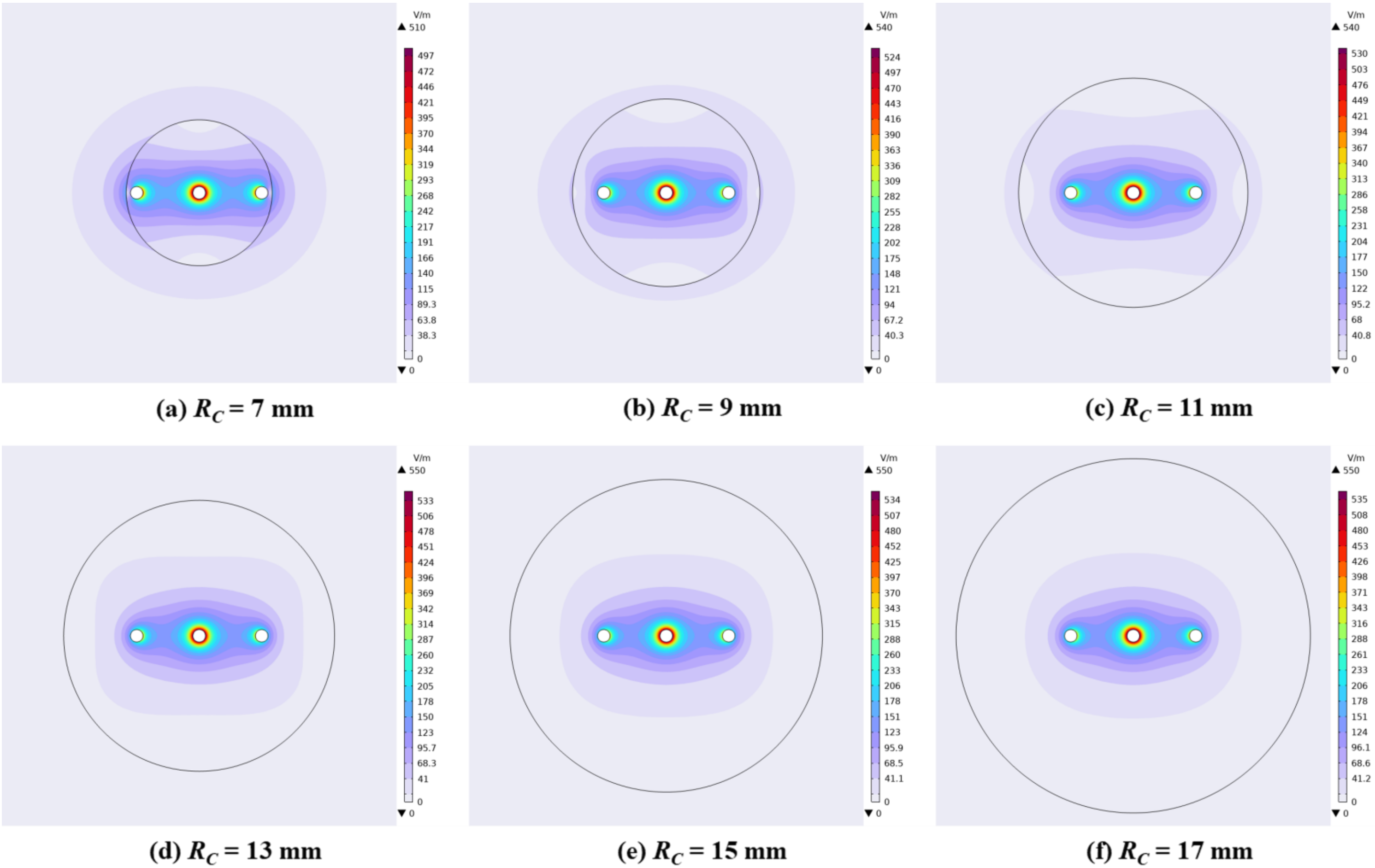

Figure 12. The simulated electric field intensity at ceramic radius, R_C = 7, 9, 11, 13, 15 and 17 mm for the case of ceramic dielectric permittivity of 19 and soil dielectric permittivity of 2. Circles represent the ceramic-soil boundary.

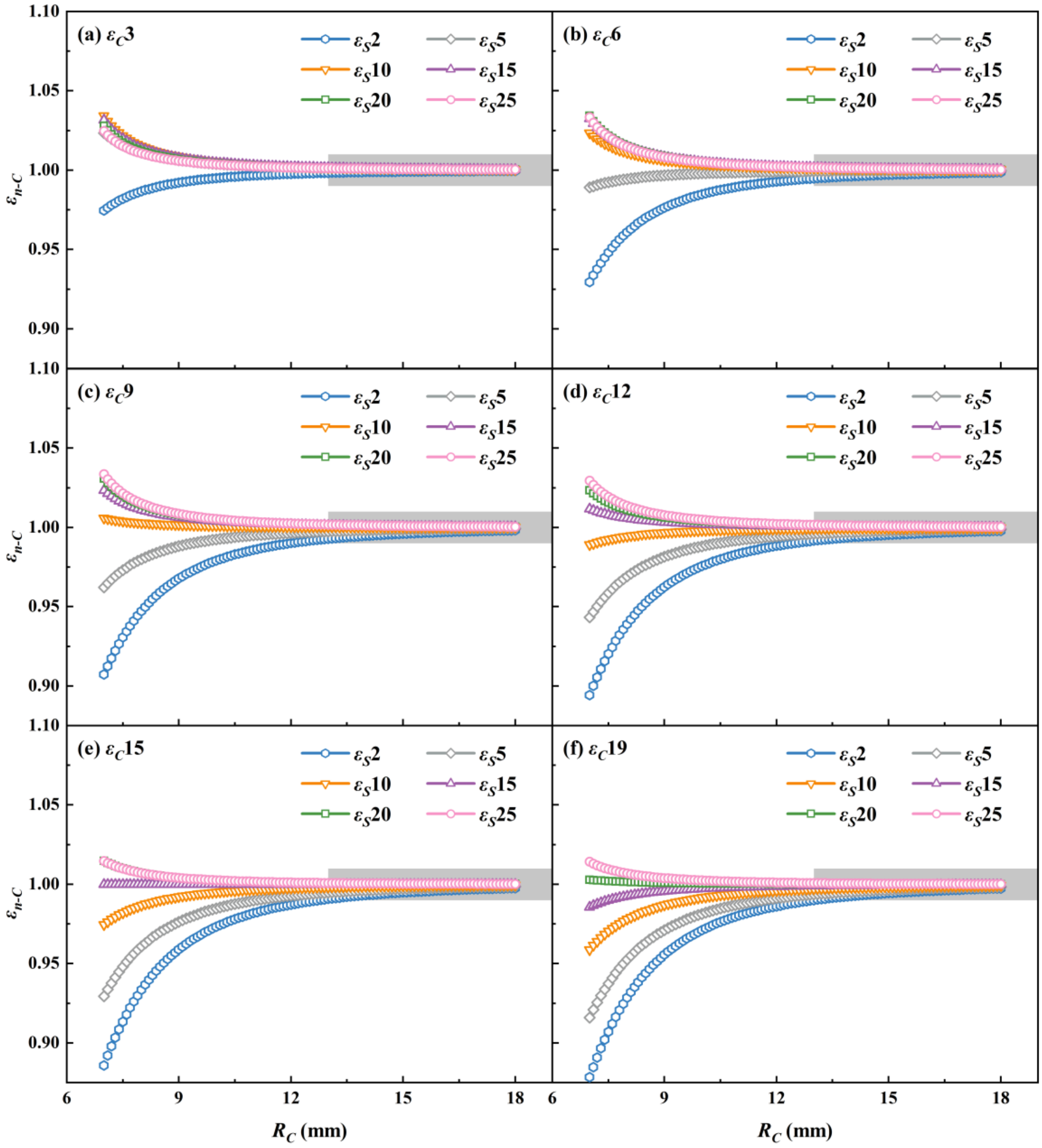

Figure 13. Normalized ceramic dielectric permittivity ($\varepsilon_{n\text{-}C}$) as related to ceramic radius (R_C, ranging from 7 to 18 mm) for different combinations of ceramic dielectric permittivity (ε_C, ranging from 3 to 19) and soil dielectric permittivity (ε_S, ranging from 2 to 25). The data following ε_C or ε_S is the value of dielectric permittivity, and the regions with the absolute value of relative error (RE_a) < 1% are marked with gray rectangle.

3.3.2 Ceramic radius optimization for electrical conductivity estimations

Figure 14 shows the relationship between normalized ceramic electrical conductivity ($\sigma_{n\text{-}C}$) and ceramic radius. When the ceramic radius was small, the RE_a of σ_C estimation was high; conversely, the error decreased with increasing ceramic radius. The RE_a was controlled within 1% for a radius up to 14.8 mm, as shown in the and regions marked by the gray rectangles (**Figure 14**).

According to **Eq.** (22), the error source of σ_C estimation was similar to that for ε_C, including the difference in values between ε_C and ε_S and the contribution of soil to $\varepsilon_{eff\text{-}C}$. Since the contribution level of the soil to $\sigma_{eff\text{-}C}$ was calculated based on the dielectric permittivity of the two mediums, $\sigma_{eff\text{-}C}$ was affected by the dielectric permittivity of the two mediums as well as their electrical conductivity. In **Figure 14g**, due to the greater difference in electrical conductivity between the soil and the ceramic, the RE_a of σ_C estimation at R_C = 7 mm was 22% for ε_S = 20 and σ_S = 0.50 (orange triangles), which was higher than 11% for ε_S =20 and σ_S = 0.30 (gray diamonds). Due to the lower ε_S, in the case of ε_S = 20 and σ_S = 0.50 (orange triangles) in **Figure 14**, at R_C = 7 mm, the RE_a of σ_C estimation of 22% is greater than that of 18% corresponding to the case of ε_S = 25 and σ_S = 0.50 (pink circles). Nissen et al. (2001) and Ferré et al. (2003) indicated that the sensitivity of TDR to electrical conductivity measurement was independent of the conductivity distribution of the medium. This conclusion differs from ours is that the interfering medium was not soil in their study, but air with electrical conductivity of 0. In this case, the part of "$\sigma_S \times$ *MSS*" in **Eq. (22)** is equal to 0, and $\varepsilon_{eff\text{-}C}$ is only affected by the dielectric permittivity distribution, independent of the electrical conductivity distribution. The $\sigma_{n\text{-}C}$ is therefore equal to the contribution level of the measured medium to $\varepsilon_{eff\text{-}C}$, i.e., *MSC* in **Eq. (18)**.

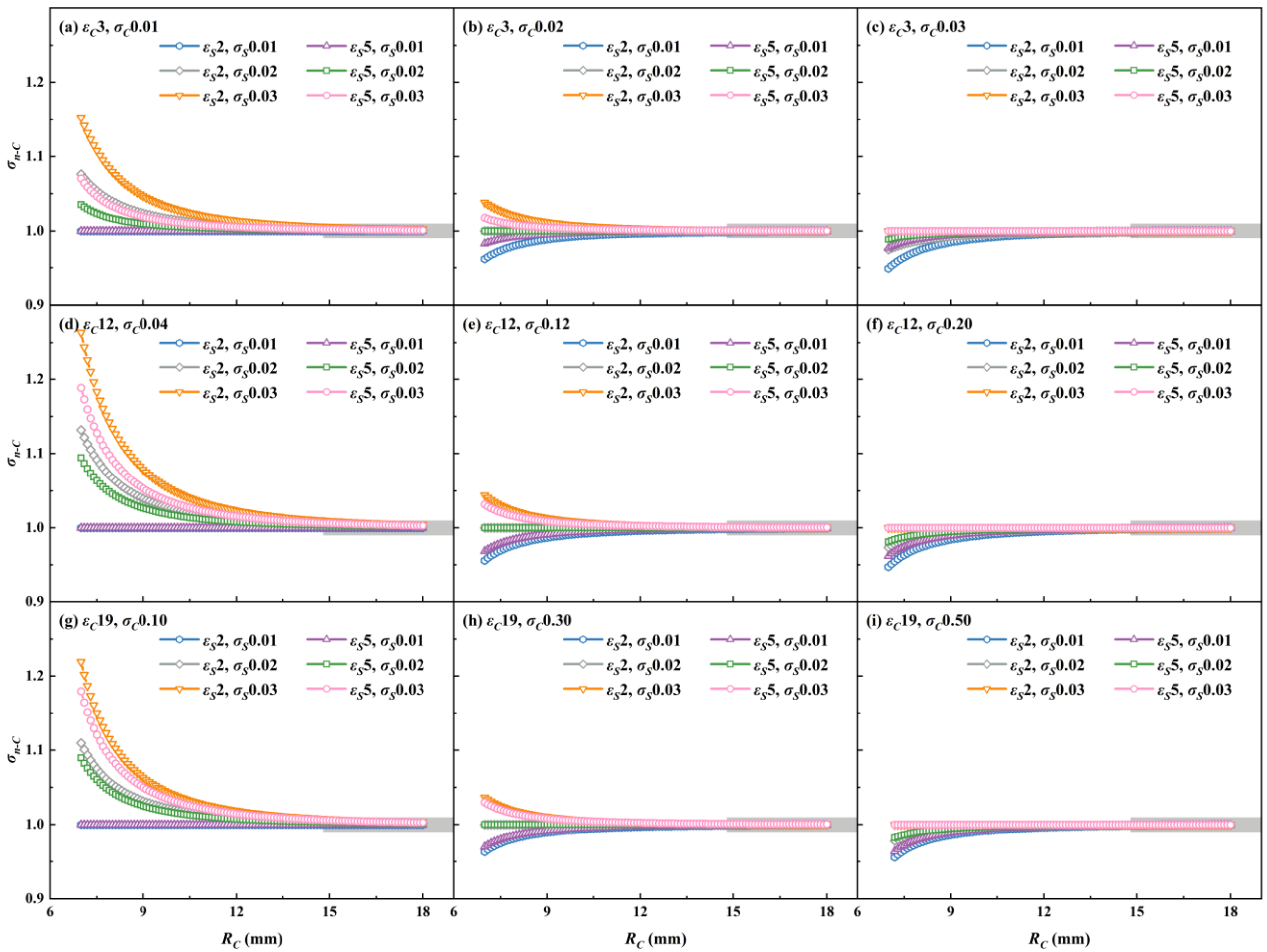

Figure 14. Normalized ceramic electrical conductivity ($\sigma_{n\text{-}C}$) as related to ceramic radius (R_C, ranging from 7 to 18 mm) for different combinations of ceramic dielectric permittivity (ε_C = 3, 12, and 19), soil dielectric permittivity (ε_S =2 and 5), ceramic electrical conductivity (σ_C = 0.1, 0.3 and 0.5 dS m^{-1}) and soil electrical conductivity (σ_S = 0.01, 0.02 and 0.03 dS m^{-1}). The data following ε_C or ε_S is the value of dielectric permittivity, the data following σ_C or σ_S is the value of electrical conductivity (dS m^{-1}), and the regions with the absolute value of relative error (RE_a) < 1% are marked with gray rectangle.

4 Conclusion

A multifunctional sensor was developed by coupling heat pulse, TDR and matric potential sensors to simultaneously measure soil water content, matric potential and thermal properties of the same soil sample. The soil water content and thermal properties are measured directly by the rods extended out of the ceramics, while the soil matric potential can be predicted indirectly based on the thermal conductivity, volumetric heat capacity, water content or electrical conductivity of the porous ceramic matrix. Compared with the measured data in the literatures, our COMSOL models were verified to be able to accurately and reliably evaluate the sensor error and optimize the sensor. The simulation results indicated that a high estimation accuracy can be attained by increasing the size of the porous ceramic matrix, even in the presence of considerable differences in physical properties between the soil and the ceramic matrix. Our optimization results indicate that the optimal design for the porous ceramic matrix was a cylinder with a radius of 18 mm and a height of 40 mm and the heat pulse sensor extended a rod length of 50 mm out of the ceramics. This design ensures that the estimation errors for dielectric permittivity, electrical conductivity, thermal conductivity and volumetric heat capacity of the porous ceramic matrix are within acceptable ranges. The optimized multifunctional sensor was high in accuracy, low in cost and non-destructive. More importantly, the sensor can simultaneously measure soil hydrothermal properties accounting for temporal and spatial variability of soil, which is of great significance for the better understating and modeling of coupled water, heat and solute transport.

List of symbols

C	volumetric heat capacity	$\mathrm{M\ J\ m^{-3}\ °C^{-1}}$
$C_{n\text{-}C}$	normalized ceramic volumetric heat capacity	unitless
$C_{n\text{-}S}$	normalized soil volumetric heat capacity	unitless
D	distance from the temperature measuring point to	mm

	the ceramic-soil boundary	
$E(x, y)$	electric field intensity	V/m
L	rod length	mm
L_C	ceramic length	mm
L_{max}	the maximum rod length	m
L_{min}	the maximum rod length	m
L_S	length of the extended rod buried in soil	mm
p	porosity	unitless
Q	rate per unit volume of heat generation for the numerical model	W m^{-3}
S_H	cross-sectional area of the heater	m^2
T	temperature	°C
V_T	excitation voltage	V
V_R	reflected voltage	V
c	specific heat	J kg^{-1} $°C^{-1}$
c_w	specific heat of water	4180 J kg^{-1} $°C^{-1}$
d	rod diameter	mm
f_{sa}	sand fraction for soil solids	%
n	number of data points	unitless
q'	heat strength	W m^{-1}
qc	quartz content of the total solids content	unitless
r	rod spacing	mm
t	time	s
t_0	duration	s
t_e	travel time of electromagnetic wave	s
v_0	velocity of light in a vacuum	3×10^8 m s^{-1}
$w(x, y)$	spatial weighting factor	m^{-2}
$w_C(x, y)$	weighting factors that are distributed in the ceramic region	m^{-2}
$w_S(x, y)$	weighting factors that are distributed in the soil region	m^{-2}
x	reference physical properties as preset for the medium in the simulation,	/

x_{eff}	estimated physical properties based on COMSOL simulation	/
x_m	measured data in the literatures	/
x_n	normalized physical properties	/
x_s	simulated data based on COMSOL	/
β	empirical parameter	unitless
ε	dielectric permittivity	unitless
ε_C	apparent dielectric permittivity of ceramic	unitless
ε_S	apparent dielectric permittivity of soil	unitless
ε_{eff}	effective dielectric permittivity	unitless
ε_n	normalized dielectric permittivity	unitless
$\varepsilon_{n\text{-}C}$	normalized ceramic dielectric permittivity	unitless
θ	water content	$cm^3\ cm^{-3}$
κ	thermal diffusivity	$m^2\ s^{-1}$
λ	thermal conductivity	$W\ m^{-1}\ °C^{-1}$
λ_C	ceramic thermal conductivity	$W·m^{-1}·°C^{-1}$
λ_{dry}	dry thermal conductivity	$W·m^{-1}·°C^{-1}$
$\lambda_{n\text{-}C}$	normalized ceramic thermal conductivity	unitless
$\lambda_{n\text{-}S}$	normalized soil thermal conductivity	unitless
λ_o	thermal conductivity of other minerals	$W·m^{-1}·°C^{-1}$
λ_S	soil thermal conductivity	$W·m^{-1}·°C^{-1}$
λ_q	thermal conductivity of quartz	$7.7\ W\ m^{-1}\ °C^{-1}$
λ_{sat}	saturated thermal conductivity	$W·m^{-1}·°C^{-1}$
λ_{solids}	thermal conductivity of solids	$W·m^{-1}·°C^{-1}$
λ_w	thermal conductivity of water	$0.594\ W\ m^{-1}\ °C^{-1}$ at 20 °C
ρ	wet bulk density	$kg\ m^{-3}$
ρ_b	bulk density	$kg\ m^{-3}$
$\rho_{solids}c_{solids}$	volumetric heat capacity of solids	$M\ J\ m^{-3}\ °C^{-1}$
ρ_w	density of water	$1000\ kg\ m^{-3}$
σ	electrical conductivity	$dS\ m^{-1}$
σ_C	apparent electrical conductivity of ceramic	$dS\ m^{-1}$
σ_S	apparent electrical conductivity of soil	$dS\ m^{-1}$

σ_{eff}	effective electrical conductivity	unitless
$\sigma_{n\text{-}C}$	normalized ceramic electrical conductivity	unitless
ψ_m	matric potential	kpa
$\nabla\Phi(x, y)$	potential gradients in homogeneous fields	V/m
$\nabla\Phi_0(x, y)$	potential gradients in heterogeneous fields	V/m

Author contributions

HH conceptualized the study; JH and JC wrote the original paper; HH, YC, CZ ,LJ, ZC and FZ reviewed and revised the manuscript. All authors contributed to the discussions and provided feedback on the final version.

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Data availability statement

Data generated in this study is available at https://zenodo.org/records/10529525.

Conflicts of interest

The authors declare no conflict of interest.

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