



Mediate relation between electrical and thermal conductivity of soil

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Abstract Thermal conductivity is a key parameter for many soil applications, especially for dimensioning shallow and very shallow geothermal systems based on the possible heat extraction rate and for modelling heat transfer processes around high voltage underground cables. Due to the limited purview of direct thermal conductivity measurements, for an investigation of extensive areas, usually other geophysical methods like electrical resistivity tomography measurements are applied. To derive thermal conductivity of soil from geoelectrical measurements a relation between electrical and thermal conductivity is needed. Until now only few approaches worked on a direct correlation between both conductivities. Due to the difficulties of a direct relation, within this study a modular approach of a mediate correlation between electrical and thermal conductivity was investigated. Therefore, a direct relationship between a corrected electrical conductivity and water content as well as the standard and simple thermal conductivity model of Kersten (Bull of the Univ Minnesota 28:1–227, 1949) was used. To develop this concept soil types of sand, silt loam and clay were investigated where different saturation steps and pressure loads were applied. For each configuration electrical and thermal conductivity

as well as water content and bulk density was determined. To refine the results of the calculated water content a corrective factor was applied. Furthermore, bulk density as an inlet parameter of the Kersten equation was also derived based on electrical conductivity. The suggested proceeding enables the determination of thermal conductivity solely based on electrical conductivity without prior soil property information.

Keywords ERT · Heat transfer · Kersten model · Water content · Bulk density

1 Introduction

Thermal conductivity (TC), which is a valuable soil parameter especially within the subjects of shallow and very shallow geothermal applications (Bertermann et al. 2014; Sáez Blázquez et al. 2017; Vieira et al. 2017; Di Sipio and Bertermann 2018) and high voltage underground cable surroundings (de Lieto et al. 2014; Salata et al. 2016; Chatzipanagiotou et al. 2017; Drefke et al. 2017; Rerak and Oclon 2017), is tricky to determine accurately in the field. Since, thermal conductivity itself can only be determined by sensors with direct contact at selective points of interest, indirect proceedings concerning other geophysical applications like electrical resistivity

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tomography (ERT) are needed to examine wide areas in a small timeframe, also enabling a deeper penetration. Concurrently, TC is a very sensitive parameter within further data processing such as calculations of heat extraction rates or heat transport modelling: a slight divergence within TC results can produce critical deviations. Therefore, a simple, experience based, and prone to failure estimation is insufficient. Hence, a proper processing of measured data is key to produce valid results and enables an adequate and not time-consuming assessment.

By performing geophysical investigations non-invasive and extensive measurements are possible and physical properties of the subsurface can be determined at low costs in a short time. However, expert knowledge and a proper assessment of geophysical measurements as well as good and practicable concepts and models to derive applicable soil parameters like TC are essential. Results based on examined derivations are just as meaningful as quality of the implemented concept allows. Tian et al. (2020a), for instance, made an investigation using S-wave velocity and the microtremor survey method for thermal conductivity correlation. The focus of this study is the determination of TC based on geoelectric measurements which is a standard application for underground hydraulic assessments (Dahlin and Loke 2018; Ghulamkari et al. 2019)

Due to the fact, that EC and TC are basically depending on the same soil parameters like water content, bulk density and grain size distribution (Abu-Hamdeh and Reeder 2000; Singh and Devid 2000; Tarnawski et al. 2000; Bristow et al. 2001; Ochsner et al. 2001; Abu-Hamdeh 2003; Cosenza et al. 2003; Friedman 2005; Samouelian et al. 2005; Logsdon et al. 2010; Bai et al. 2013; Barry-Macaulay et al. 2013; Usowicz et al. 2013, 2017; Bertermann and Schwarz 2017; Drefke et al. 2017) as well as temperature (Campbell et al. 1994; Tarnawski et al. 2000; Nouveau et al. 2016; Robert et al. 2019; Xu et al. 2020) a direct correlation between both conductivities seems feasible.

For developing a direct correlation between electrical conductivity (EC) and TC of soil few investigations and approaches, which are described in the following lines, were realised (Singh et al. 2001; Sreedeeep et al. 2005; Fragogiannis et al. 2008, 2010; Logsdon et al. 2010; Tokoro et al. 2016; Wang et al. 2017; Sun and Lü 2019). Singh et al. (2001)

established a general relationship between thermal and electrical resistivity, where the percentage sum of the gravel and sand fraction has to be predetermined. This approach was based on a laboratory analysis of a loam and a clay soil based on the USDA soil classification. Additionally, the resulting correlation was validated with soil samples which are CL or CH according to the USCS soil classification (ASTM D2487 2017). Thus, the validation includes samples with a sand fraction < 50% and a clay fraction < 65% which corresponds to their analysed soil probes. Hence, it is an approach for mainly fine-grained soil types.

Within the concept of Sreedeeep et al. (2005) a relation between electrical resistivity and saturation in dependence of the pooled gravel and sand fraction was developed, serving as basis for a renewed correlation between EC and TC. This approach is based on the same general relationship stated by Singh et al. (2001). In Addition, a dependence on saturation of soil was pointed out and additionally incorporated. To calculate the multiplier also three variables, depending on the gravel and sand fraction, must be ascertained. Thus, to deliver this multiplier for the relation between EC and TC, also a soil saturation and a grain size distribution must be known priorly.

Fragkogiannis et al. (2010) also proposed a stand-alone approach of a correlations between TC and EC, but with the need of consideration of specific soil type groups. Furthermore Fragkogiannis et al. (2010) described edge effects of the EC measurements, as stated also by Kowalczyk et al. (2014). When EC measurements are burdened with edge effects caused by a small sample case, trends and coherences can be showcased, but the results are hardly to compare to other approaches or to in situ measurements.

Within another survey, established by Logsdon et al. (2010), a derivation of EC (Ewing and Hunt 2006) and a derivation of thermal conductivity (Lu et al. 2007), both related to water content, were confronted. Both conductivities were investigated and discussed, but not directly correlated.

Tokoro et al. (2016) also compared EC and TC of soil. They investigated two sands and one volcanic soil. Inside this study, the measurements of EC were performed in a different container as the TC measurements, by applying the same soil conditions (dry density and water content). A general coherence between EC and TC was stated with the help of two

constant values and one variable value. However, this variable value is depending on each measured soil type, and with that a general application is actual impossible.

Wang et al. (2017) provided another laboratory approach, where the relation between EC and TC was examined with a similar idea of an inlet parameter restriction as within this study. There four grain size groups were used to define 8 soil types. The relation itself should be invented without considering saturation and soil type, while dry density is kept constant for all measurements. As a result, a direct correlation between electrical resistivity and TC was suggested. Wang et al. (2017) concluded, that there is no obvious relation to soil gradation, which is in contrary to other experiences.

Also, Sun and Lü (2019) investigated a semi-empirical correlation between TC and EC. Within this study the relation was evaluated merely for silt and silty clay, two very similar soils. Therefore, the correlation is hardly transferable to other soil types.

These mentioned investigations are all valuable within their own research focus. However, all these approaches are in the need of a priori soil information or are just valid for a distinct soil type. Hence, it is hard to transfer these correlations on a general application. This is not surprising, since the dependence between EC and TC and the physical soil parameters differs and thus a direct correlation between both conductivities without further known inlet parameters is intricate. Yet, the aim of this study was to provide the opportunity to perform non-invasive ERT measurements and a following deduction of the parameter thermal conductivity without any other expense. The introduced method should be practicable for extensive ERT field measurements with none or only few selective verification samplings. Such an approach is just possible by operating without any a priori information and purview for all soil types, as described within this study.

Therefore, the mentioned difficulties must be bypassed by the help of a method with a mediate relation between EC and TC, introduced within this study. This data analysis is referred to laboratory soil property measurements from 2016 (Bertermann and Schwarz 2017, 2018), which are comparable to measurements performed by Barry-Macaulay et al. (2013), Giordano et al. (2013) or Liu et al. (2013). Within the first step of correlation, EC values are

related to soil parameters, which are relevant for implementation in a TC determining model. In this case, the relevant parameters are water content and bulk density as well as a grading of grain size fractions. The dependence of water content, bulk density and the amount of different grain size fractions on soil TC is evidenced by many common thermal conductivity models (Kersten 1949; de Vries 1963; Johansen 1975; Côté and Konrad 2005; Lu et al. 2007, 2014; Tokoro et al. 2016; Markert et al. 2017), whereas EC is predominantly influenced by soil water content and only subordinately affected by the other mentioned physical soil parameters (Zhou et al. 2001; Friedmann 2005; Ewing and Hunt 2006). Regarding the significant relation between EC and water content some correlations had been established (Archie 1942; McCutcheon et al. 2006; Ozcep et al. 2010; Bertermann and Schwarz 2018). Thus, such correlation can be applied within the introduced operation without concerns. The derivation of bulk density on the other hand side has no high accuracy which is evidenced by mid-level correlation factors. In a second step the TC model is applied. Due to the few inlet parameter, within this study the TC model according to Kersten (1949) modified by Farouki (1981) was opted. Due to a great variety of TC models, in further approaches this method can also be adapted to other TC models. With these two steps, a holistic relation between EC and TC was processed, which is practicable without any ancillary information.

2 Methods

2.1 Data acquisition

To ensure proper framework conditions with known physical soil parameters, the investigations were performed in a laboratory environment. To avoid edge effects of the electrical field (Kowalczyk et al. 2014) by measuring the EC, a remarkable sample size of > 50 l was required (Bertermann and Schwarz 2017).

To cover a wide spectrum of soil types regarding the grain size distribution, samples of sand, silt loam and clay were investigated (Bertermann and Schwarz 2018). Following description was performed with all three soil types: First the complete sample material was dried to start the measurements with a water

content almost around 0%. Within a mixing machine water was added to the sample material and mingled, to adjust the next step of soil water content. To achieve a more homogeneous distribution of the added water after mixing, the material was left for 60 min covered by a clingfilm. After the material was blended the sample with an adjusted water content was filled in a box (≈ 63 l). In a further step, incremental pressure loads of 75, 1000, 3000, and 5000 kg inter alia 39.3 g cm^{-2} , 524 g cm^{-3} , 1572 g cm^{-2} , 2620 g cm^{-2} were applied on this material for each set water content. Thus, the physical soil properties of every sample material were measured within different saturation steps and for four bulk densities. Due to the insufficient compaction by the first pressure load, for further data processing only the pressure loads of 524 g cm^{-3} and higher were considered.

Within each water content and each incremental pressure load following physical soil parameters were determined: Water content and bulk density were measured subsequent according to DIN 18121 (2012) and DIN 18125-2 (2011), respectively. TC was measured with the TR-1 probe of the KD2 Pro application according to the ASTM D5334 (2014) and EC was determined by using a four-point electrode configuration performed with the 4point light application (<https://www.l-gm.de>) by applying the Wenner array and an electrode spacing of 5 cm. The electrode penetration was around 2 cm depending on how smooth the sample surface was. The used TC reference value is a mean of two repeat measurements. For further evaluation, the EC values (σ) were corrected to the temperature of 25 °C (1 + 2) according to Sheets and Hendrickx (1995) (Corwin and Lesch 2005).

$$\sigma_{25} = f_T * \sigma_T \quad (1)$$

$$f_T = 0.4470 + 1.4034 * e^{-T/26.815} \quad (2)$$

Within this study, the EC as well as the other soil parameters were measured at temperatures of 16–20 °C. For data analysis the measurement results given in Tables 1, 2 and 3 were used.

Due to the undisturbed measurements within this laboratory setup avoiding the edge effects a highly diagnostic comparison between TC and EC is possible, which enables a transfer to in situ field measurements.

2.2 Concept setup

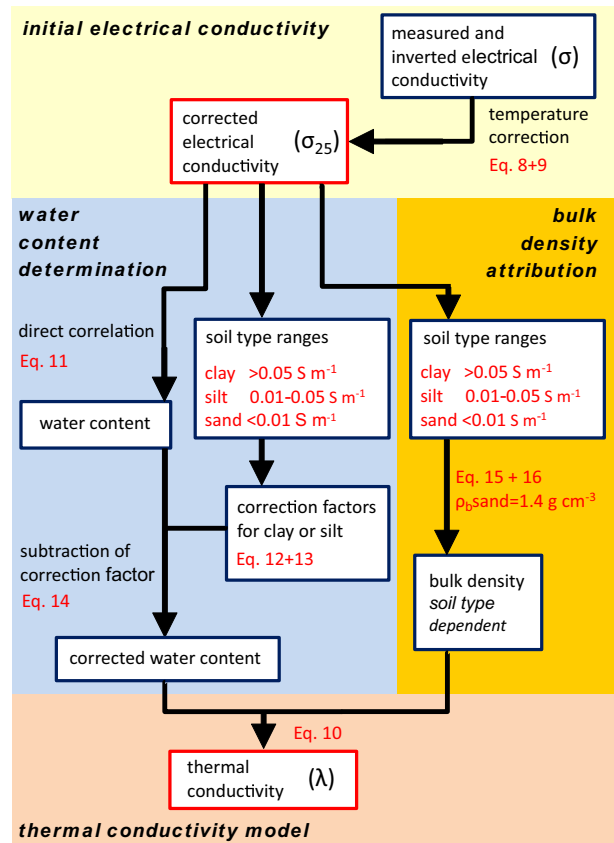
Within this study the principle intention was the determination of TC exclusively out of EC measurements. Due to the lack of a direct correlation between both conductivities a determination concept (Fig. 1) with the simple thermal conductivity model (3) according to Kersten (1949) modified by Farouki (1981) was applied. There it should be considered that only the equation intended for soils of a grain size distribution with > 50% sand content was used within this concept.

$$\lambda = 0.1442 \left(0.7 \log \left(\frac{\theta_w}{\rho_b} \right) + 0.4 \right) * 10^{0.6243 * \rho_b} \quad (3)$$

Thus, to use this model to determine TC (λ) only by applying EC, both soil properties, volumetric water content (θ_w) and bulk density (ρ_b), must be derived from EC. To do so a correlation between EC and water content was applied and an EC depending correction factor which manages soil type depending differences, was developed. A similar procedure was carried out regarding the relation between EC and bulk density. The evolved segmentation goes approximately in conformity with the supposed separation of the GGU (Gesellschaft für Geophysikalische Untersuchungen mbH 2011), which is 0–20 Ωm for clay; silt: 20–100 Ωm and sand: > 100 Ωm (Bertermann and Schwarz 2018). This separation relies on soil moisture ranges around field capacity, which is usually expectable below a soil depth of around 1,0 m within unsaturated conditions. Based on this EC separation also within this study the soil types were divided in a sand range (< 0.01 S m^{-1}), a silt loam range (0.01–0.05 S m^{-1}) and a clay range (> 0.05 S m^{-1}). Also, Fragkogiannis et al. (2010) separated their results into sand (fine, medium and coarse), loamy soil (loam, loamy sand and sandy loam) and fine-grained material (silty clay; silt loam, kaol). For each mentioned range inter alia grain size fraction, a separate determination of both input parameter for the TC model is proposed, which represents the soil type dependent aspect. The derivation of this input parameter definitions is described within the next sections and based on the laboratory measurement results.

The concept can be used as a stand-alone tool to derive TC from EC for soils with a water content

Fig. 1 Workflow of the introduced mediate determination of thermal conductivity of soil by solely using electrical conductivity



around field capacity. Organic matter, saltwater effects, effects of frozen soils or other EC and TC biasing boundary conditions cannot be considered. However, when further information concerning water content or bulk density is available, it can be implemented just by integrating the existing parameter into the thermal conductivity model (10), too.

2.3 Determination of water content

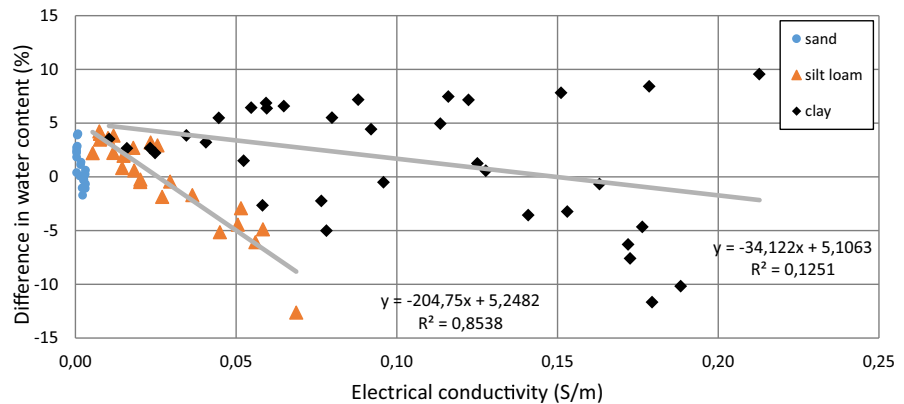
Within the performed laboratory experiments the sand sample was measured from a volumetric water content of 2% until wet conditions of 10%. The silt loam sample and the clay sample were measured accordingly from dry conditions until $> 30\%$ and nearly 50%, respectively (Tables 1, 2 and 3). The appropriate field capacity ranges for sand (4–11%), silt loam (14–36%) and clay (28–41%) were applied according to Bertermann et al. (2014). The correlation between the corrected EC (σ_{25}) and water content (11) stated by Bertermann and Schwarz (2018) has a correlation coefficient of $R^2 = 0.95$ and serves as base to

determine water content of soil. It is a linear relation between a natural logarithm of EC and volumetric water content (θ_w). The correlation coefficient underlines predications of similar approaches (McCutcheon et al. 2006) and indicates that this relation is basically soil type independent.

$$\theta_w = e^{0.3415 \cdot \ln(\sigma_{25}) + 4.228} \tag{4}$$

Nevertheless, within this study a correction factor implying grain size fractions was evolved. This factor is based on the comparison between the measured EC and the divergence from the measured water content to the water content, calculated by applying Eq. 4 (Fig. 2). Correlating the differences in water content with EC shows, that for the sand sample there are just minor deviations ($< 5\%$). Whereas, the silt loam (significant $R^2 = 0.85$) and the clay sample (not significant $R^2 = 0.13$) show differences in water content, which are in dependence of EC. Within ranges of lower EC, the calculated water content is higher than the measured one. Regarding increasing

Fig. 2 Relation between the electrical conductivity and the difference of the measured and calculated water content by using Eq. (4) regarding the three main soil types (sand, silt loam and clay)



EC values it swaps to lower calculated water contents in relation to the measured results. To compensate this effect these correction factors are applied.

With the outcome of this comparison (Fig. 2) the calculated water content can improve by applying the relation of the trend lines as correction factors (5–7). Due to the minor deviations for sand no further correction referring to the separation sand range ($< 0.01 \text{ S m}^{-1}$) is needed.

Separation clay range ($> 0.05 \text{ S m}^{-1}$):

$$X_{clay} = -34.122 * \sigma_{25} + 5.1063. \tag{5}$$

Separation silt loam range ($0.01\text{--}0.05 \text{ S m}^{-1}$):

$$X_{silt} = -204.75 * \sigma_{25} + 5.2482 \tag{6}$$

Thus, the calculation of volumetric water content is set up with an EC depending correction factor as follows:

$$\theta_w = e^{0.3415 * \ln(\sigma_{25}) + 4.228} - X_{(clayorsilt)}. \tag{7}$$

2.4 Attribution of bulk density

The second parameter, which must be implemented for TC calculation by only applying EC within this concept (Fig. 1; Eq. (3)), is bulk density. To do so, the measured bulk density was compared to the measured EC (Fig. 3). Regarding the clay and silt loam sample bulk density increases with increasing EC values. Roughly outlined, bulk density for clay is around $1.1\text{--}1.4 \text{ g cm}^{-3}$ and for silt loam from 1.3 g cm^{-3} up to 1.65 g cm^{-3} . Regarding the sand sample after the first appropriate pressure load all measured bulk densities are around 1.4 g cm^{-3} . Regarding the correlation coefficients the relation between EC and bulk

density ($R_{silt\ loam}^2 = 0.6$ and $R_{clay}^2 = 0.4$) is not as profound as between EC and water content.

In this case, it is not possible to establish a soil type independent, direct correlation between bulk density and EC. Thus, for determining bulk density also the separation between sand, silt and clay as described in the concept setup was applied. The attribution of bulk density was carried out in accordance with the derivation of the correction factor regarding the determination of water content before. Due to the inability to compact sand solely by pressure (DIN 18125-2 2011) the suggested and in this concept applied bulk density for sand is just 1.4 g cm^{-3} . Regarding the other separation ranges of clay and silt loam, following relations between EC (σ_{25}) and bulk density (ρ_b) were used as calculation models (8 + 9).

Bulk density for the separation clay range ($> 0.05 \text{ S m}^{-1}$):

$$\rho_{b_clay} = 0.9565 * \sigma_{25} + 1.1683 \tag{8}$$

Bulk density for the separation silt loam range ($0.01\text{--}0.05 \text{ S m}^{-1}$):

$$\rho_{b_silt} = 4.6015 * \sigma_{25} + 1.3362 \tag{9}$$

By applying these bulk density equations, the deviations of the calculated thermal conductivity within the displayed concept is around $0.05 \text{ W (m}^* \text{K)}^{-1}$ less than by using just a single value of 1.4 g cm^{-3} for every soil type. After determining the inlet parameter, volumetric water content and bulk density, by only applying EC the Kersten (1949) TC model (Eq. 3) can be carried out.

Within excel an operation, combining Eqs. 3–9, can be used as follows:

Fig. 3 Comparison of the measured bulk density and the measured EC (sand, silt loam and clay)

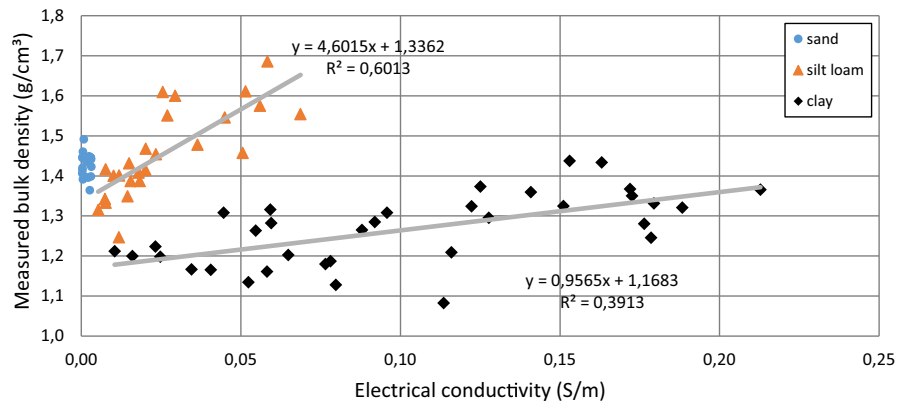
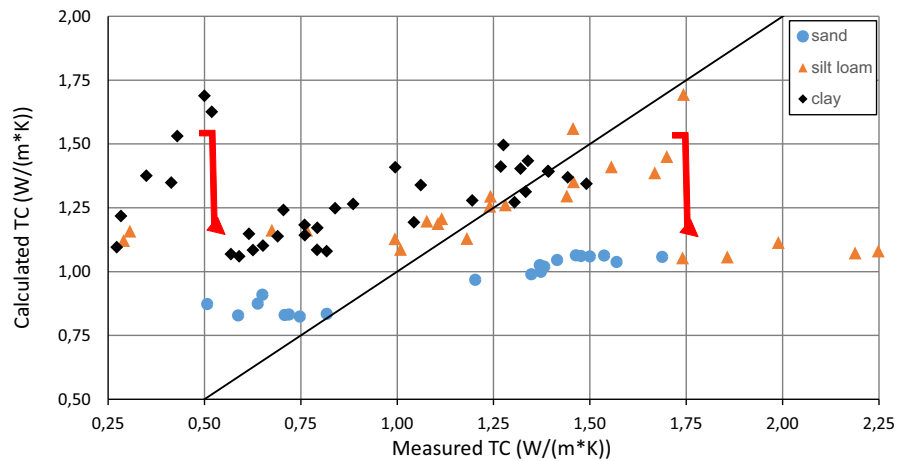


Fig. 4 Comparison between measured and calculated TC of sand, silt loam and clay samples [W (m*K)⁻¹]. TC values of appropriately compacted soil mixtures in a nearly dry until full saturated state. Red arrows display bounds at the soil type depending EC segmentation boundaries



Row 1: = 0.1442*(0.7*LOG((EXP(0.3415*LN(σ_{25}) + 4.228))

Row 2: -(IF($\sigma_{25} < 0.01$;0;IF($\sigma_{25} < 0.05$; - 204.75 * σ_{25} + 5.2482; - 34.122* σ_{25} + 5.1063))

Row 3: /(IF($\sigma_{25} < 0.01$;1.4;IF($\sigma_{25} < 0.05$;4.6015* σ_{25} + 1.3362;0.9565* σ_{25} + 1.1683)))) + 0.4)

Row 4: *POWER(10;(0.6243*(IF($\sigma_{25} < 0.01$;1.4; IF($\sigma_{25} < 0.05$;4.6015* σ_{25} + 1.3362;0.9565* σ_{25} + 1.1683))))))

There, within the framework of the thermal conductivity model, it starts with the direct correlation between EC and water content (Row 1) and the deduction of the corrective value for sand, silt and clay (Row 2). The hereby determined volumetric water content has to be divided by the bulk density for sand,

silt and clay, to get the gravimetric water content (Row 3). In Row 4 the last part of the thermal conductivity model is listed with the input of the bulk density.

3 Results and discussion

Although, EC as well as TC are depending on the same soil properties, a direct correlation between both conductivities is not possible. For one soil type or a group of similar soil types there are valuable approaches (Singh et al. 2001; Tokoro et al. 2016; Sun and Lü, 2019), but a single correlation for the whole spectrum of soil types seems impossible. To face this challenge, within this study a mediate relation between EC and TC was introduced, without a need of any further information.

Fig. 5 Comparison between measured and calculated TC of sand, silt loam and clay samples of soil mixtures within their characteristic field capacity range $[W (m^*K)^{-1}]$. Red arrows display the left bound at the soil type depending EC segmentation boundary between silt and clay

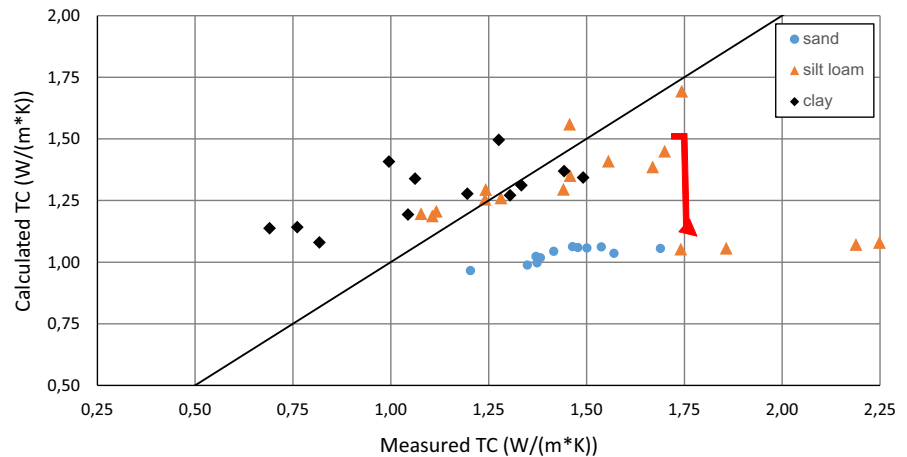
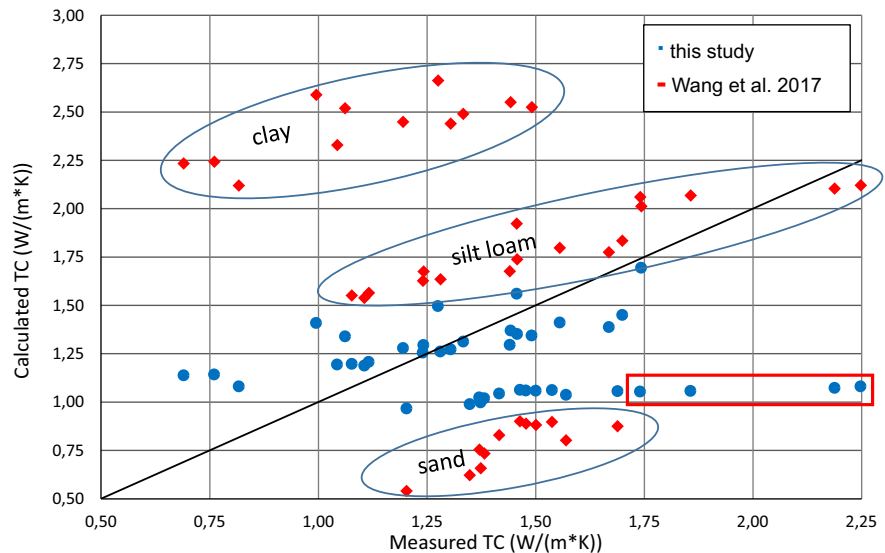


Fig. 6 Comparison between TC $[W (m^*K)^{-1}]$ results based on the concept of this study and calculated according to Wang et al. (2017) in relation to the measured TC values of sand, silt loam and clay. At this point just the investigations of the soil type characteristic field capacity range were considered



Due to the significant correlation between EC and soil water content ($R^2 = 0.95$), it is straightforward to determine water content for implementation in the TC model. Nevertheless, a soil type depending correction factor was added for improving this correlation. However, it must be considered that the correction factor for clay is not significant. Although, the correlation coefficient is not definite, it improves the already significant correlation between EC and soil water content slightly. Hence, the correction factor for silt loam should be applied but the factor for clay is not imperatively required.

The relation between EC and bulk density is only obvious for a single soil type ($R^2 = 0.5$) and even then,

it is not as significant as the correlation with water content (Bertermann and Schwarz 2018). Due to overlapping bulk density ranges it is not characteristic for each soil type. Under certain conditions like full saturation and considering single values bulk density might be more soil type characteristic (Bertermann et al. 2018) but by declaration of bulk density ranges from a loose to a more compacted state this is not true anymore. Hence, a direct correlation regarding bulk density is unpromising and must be bypassed for instance by applying different separation ranges. The segmentation, as applied within this study includes electrical resistivity ranges that are continuous (clay 0–20; silt 20–100; sand > 100 Ohm·m) and they are

corresponding to a medium soil moisture around field capacity. A continuous cover of electrical resistivity or rather EC is mandatory for a general EC based calculation.

For verifying the introduced approach, the calculated TC was compared to the measured values (Figs. 4+ 5). In Fig. 4 all in the laboratory determined values, besides the very low-density measurements of the first pressure load, are used (Tables 1, 2, and 3). It displays, that there are some distinct differences (average difference = $0.31 \text{ W (m}^*\text{K)}^{-1}$) between the calculated and the measured values. TC of clay with low water content is overpredicted and TC for pure sand is too conservative. However, for soils with a fine grain fraction and a medium water content range, TC is fitting well.

Since, values of investigated soil sample mixtures with very high and very low water contents were considered, EC of one soil type is not limited to the related EC separation range causing bounds within the data of one soil type itself. This issue is obvious regarding the silt and clay data (red arrows in Fig. 4). For this reason, the delineation of 'natural conditions' according to Bertermann and Schwarz (2018) was applied. This implies that only soil mixtures with a saturation appropriate to their characteristic field capacity range were concerned (Fig. 5). This is in accordance with the soil type depending separation ranges since these segmentations are also suggested for soil with a moisture around field capacity. With this field capacity constraint the result is improved evidently. Nevertheless, this bound at a relatively high level of water content ($\approx 28\%$) within the range of the silty soil remains and depicts the segmentation boundary between silt and clay (red arrow, Fig. 5). This offset is caused by the mismatch between the soil type depending separation ranges defined by EC and the applied field capacity extent defined by water content ranges.

Apparently, also these three separation ranges must be applied cautiously. The correction used for the computed water content and the determination of bulk density are both based on the three main soil type segmentations for sand, silt, and clay. These three soil types are defining rigid boundaries in the range of gradual increasing or decreasing grain sizes. On the one hand side the used segmentation implements an easy to handle and reasonable soil type differentiation, but on the other hand there are always soil types

traversing these boundaries. For softening those boundaries investigations with focus on a broader data pool concerning different soil types could enable more precise corrections. But within this concept also the application of more soil types might be difficult due to an indistinct soil type depending EC attribution. It should be noted, that the effect of the mentioned boundary issue mainly arises from the rough derivation of bulk density, since the relation between EC and water content is a profound direct correlation (Friedman 2005; McCutcheon et al. 2006; Bertermann and Schwarz 2018) where just the correction factors are in dependence of this segmentation.

To display the difficulties regarding a soil type independent relation between EC and TC the results of this study were compared with the approach of Wang et al. (2017) (Fig. 6). There, a similar idea of an inlet parameter restriction was introduced but a conclusion was, that there is no obvious relation to soil gradation. By applying the calculation by Wang et al. (2017) the results for all three investigated soil types are divided in three domains. The results for silt loam are matching most with the measured TC values. The clay and sand domain are deviating significantly more than the TC values determined by the mediate relation introduced within this study. Thus, an approach taking a soil type depending differentiation into consideration is worthwhile.

In this case, volumetric water content and bulk density are provided to calculate thermal conductivity by applying the Kersten (1949) model. These basic parameters can be used similarly for applying one of many other thermal conductivity models (Johansen 1975; Campbell et al. 1994; Tarnawski et al. 2000; Côté and Konrad 2005; Lu et al. 2014; Markert et al. 2017; Yan et al. 2019). However, for most other methods a precise grain size distribution is necessary, which cannot be determined by solely using the measured electrical conductivity. Besides the two mentioned inlet parameter also other relevant parameter could be considered. Regarding the TC of soil there are other relevant parameters like the amount of quartz (Usowicz et al. 2017), organic matter or the quality of grain contact. But while focusing the relation between EC and TC it needs to be considered how each particular parameter can be derived from EC. Moreover, bulk density covers the aspect of the grain contact quality already to some extent.

Due to the lack of accuracy regarding the determination of bulk density a TC model with a low emphasis on bulk density should be preferred. Furthermore, it should be considered, that TC models also might have a focus on special soil types and with that they are not generally applicable (Dong et al. 2015, Wang et al. 2020). For instance, the calculation model introduced by Bi et al. (2018) has a selective scope on fine-grained soils and the study of Xu et al. (2020) was focused on silty clay. But within future investigations, regarding such a mediate relation between EC and TC, other thermal conductivity models should be kept in mind, although the Kersten (1949) model is still common (Tokoro et al. 2016).

The application of data measured with similar laboratory setups (Barry-Macaulay et al. 2013; Giordano et al. 2013; Liu et al. 2013) could enable more insights. For an intended data comparison, a sufficient amount of elaborated soil material to avoid edge effects as experienced by Kaufhold et al. (2014) or Kowalczyk et al. (2014) should be considered. Both used inlet parameters, water content and bulk density, are soil depth-dependent (Bertermann et al. 2014). Thus, on this concept an additional application of different soil depth ranges may be imprinted prospectively.

It must be concerned, that these outcomes are only true for common soil or unconsolidated sediments. The influence of soil organic matter is not included. And it is not tested for other porous materials like construction materials or artificial modified soils. Furthermore, the results are not transferable to frozen soil conditions. For frozen soil also Kersten (1949) or another TC model (e.g. Tian et al. 2020b) could be utilized. By applying EC within such a concept, it has also to be considered, that these findings were developed for normal unsaturated freshwater conditions. For studies within salt water or brackish water, the results of ERT measurements have to be adapted (Ronczka et al. 2017; Dahlin and Loke 2018). With the influence of groundwater, soil thermal properties would differ, accordingly (Jiang et al. 2016).

By applying the presented concept, ERT measurements bring also worthwhile results to the table, with regard to investigations of shallow geothermal systems or high voltage underground cable surroundings. Deploying this non-invasive method for TC determination, a validation of assumptions for modelling heat transfer processes or heat extraction rates is possible. As tested by Fraggogiannis et al. (2010), an approach

as described within this study may prospectively be an alternative to thermal response tests (TRT) for shallow geothermal systems.

However, further investigations of a wide variety of soil types should help to improve the in this study treated mediate relation between EC and TC, for example in terms of an upgraded determination of the inlet parameters.

4 Conclusion

Within this study an empirical mediate correlation concept between a measured EC and a derived TC was investigated by the help of laboratory soil sample measurements. This suggested approach may be one way to bypass the complication of a direct correlation between EC and TC. In this case, bulk density, water content, EC and TC was analysed upon a huge sample volume (≈ 63 l) to avoid edge effects of the EC measurement. To consider a wide spectrum of grain size distributions, three different soil types (sand, silt loam and clay) were examined.

The concept declares no direct correlation between EC and TC, but a relation with a detour through a TC model. The Kersten (1949) TC model is applied due to the few inlet parameters, which must be defined in advance. Thus, water content and bulk density must firstly be derived from EC and secondly inserted in the TC model. The correlation between EC and water content is significant and generally accepted, but the relation between EC and the bulk density is rough. Thereby, it is easy to optionally integrate existing water content or bulk density information within the second step.

This mediate correlation between EC and TC can help to deploy ERT measurements within soil thermal conductivity issues. It could allow the verification of a pre-defined heat extraction rate for shallow geothermal systems or of thermal conductivity arrangements around high voltage underground cables.

Within future investigations also other TC models can be evaluated. The divergences of the calculated TC to the measured ones are good enough for an initial assessment. But the results also reflect the difficulties of the correlation between EC and TC and the need of soil type depending input, mainly regarding the bulk density. Within the introduced concept the soil type depending input is implemented in form of three

different EC segmentation ranges, which causes some boundary issues. But on the other hand, it is an approach for a wide spectrum of soil types.

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Compliance with ethical standards

Conflicts of interests The authors declare that they have no conflict of interest.

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Appendix

See Tables 1–3.

Table 1 Measured and calculated values regarding water content, bulk density and thermal conductivity as well as the temperature, EC²⁵ and field capacity range of the investigated sand sample (measured values from Bertermann and Schwarz 2018)

EC ₂₅	Field capacity range ^a	Measured water content (Vol. %)	Calculated and corrected water content (Vol.%)	Measured bulk density (g cm ⁻³)	Calculated bulk density (g cm ⁻³)	Measured thermal conductivity (W (m*K) ⁻¹)	Calculated thermal conductivity (W (m*K) ⁻¹)	Temperature (°C)
0.00037	Sand	4.22	4.62	1.41	1.40	0.75	0.82	19.34
0.00039	4-11	2.88	4.71	1.45	1.40	0.71	0.83	19.23
0.00039	Vol.%	2.24	4.68	1.42	1.40	0.59	0.83	19.12
0.00040		2.48	4.73	1.41	1.40	0.72	0.83	19.23
0.00041		2.04	4.78	1.44	1.40	0.82	0.83	19.24
0.00057		2.51	5.36	1.39	1.40	0.51	0.87	18.87
0.00058		1.51	5.39	1.46	1.40	0.64	0.87	19.00
0.00080		1.98	6.00	1.49	1.40	0.65	0.91	18.94
0.00134		7.09	7.16	1.40	1.40	1.20	0.97	18.93
0.00163		6.52	7.66	1.43	1.40	1.35	0.99	18.95
0.00177		6.52	7.88	1.45	1.40	1.37	1.00	18.92
0.00223		10.25	8.53	1.40	1.40	1.37	1.02	18.90
0.00213		9.42	8.39	1.44	1.40	1.38	1.02	18.85
0.00250		9.18	8.87	1.45	1.40	1.57	1.04	18.86
0.00307		10.58	9.51	1.40	1.40	1.48	1.06	19.44
0.00314		8.96	9.58	1.44	1.40	1.54	1.06	19.38
0.00303		9.17	9.46	1.45	1.40	1.50	1.06	19.37
0.00267		9.34	9.07	1.36	1.40	1.42	1.04	19.45
0.00317		10.27	9.61	1.42	1.40	1.46	1.06	19.42
0.00298		9.21	9.41	1.45	1.40	1.69	1.06	19.36

^aField capacity ranges are according to Bertermann et al. (2014)

Table 2 Measured and calculated values regarding water content, bulk density and thermal conductivity as well as the temperature, EC₂₅ and field capacity range of the investigated silt loam sample. (measured values from Bertermann and Schwarz 2017)

EC ₂₅	Field capacity range ^a	Measured water content (Vol. %)	Calculated and corrected water content (Vol. %)	Measured bulk density (g cm ⁻³)	Calculated bulk density (g cm ⁻³)	Measured thermal conductivity (W (m*K) ⁻¹)	Calculated thermal conductivity (W (m*K) ⁻¹)	Temperature (°C)
0.00533	Silt loam	9.26	11.48	1.32	1.40	0.29	1.12	18.64
0.00739	14–36	8.60	12.84	1.34	1.40	0.31	1.16	18.59
0.00765	Vol.%	8.99	12.99	1.42	1.40	0.77	1.16	18.56
0.00765		9.52	12.99	1.33	1.40	0.68	1.16	18.35
0.01010		10.66	11.10	1.40	1.38	1.01	1.09	18.33
0.01183		11.23	12.24	1.40	1.39	1.18	1.13	18.34
0.01180		12.83	12.23	1.25	1.39	0.99	1.13	19.15
0.01495		14.36	14.14	1.43	1.40	1.08	1.20	19.03
0.01797		14.68	15.81	1.41	1.42	1.24	1.26	18.94
0.01452		15.33	13.89	1.35	1.40	1.11	1.19	18.60
0.01827		16.89	15.98	1.39	1.42	1.28	1.26	18.45
0.02019		18.34	16.97	1.47	1.43	1.44	1.30	18.59
0.01546		14.41	14.43	1.39	1.41	1.12	1.21	18.61
0.02339		15.83	18.56	1.45	1.44	1.46	1.35	18.62
0.02553		16.66	19.58	1.61	1.45	1.67	1.39	18.50
0.02012		18.55	16.94	1.41	1.43	1.24	1.30	18.05
0.02695		21.82	20.23	1.55	1.46	1.56	1.41	17.92
0.02943		21.01	21.35	1.60	1.47	1.70	1.45	17.81
0.03639		23.82	24.32	1.48	1.50	1.46	1.56	16.82
0.04496		28.93	27.73	1.55	1.54	1.74	1.69	16.88
0.05148		27.82	21.55	1.61	1.22	1.86	1.06	16.70
0.05054		29.20	21.36	1.46	1.22	1.74	1.05	16.74
0.05599		31.70	22.43	1.58	1.22	2.19	1.07	16.65
0.05830		30.86	22.86	1.69	1.22	2.25	1.08	16.60
0.06868		40.10	24.71	1.55	1.23	1.99	1.11	17.69

^aField capacity ranges are according to Bertermann et al. (2014)

Table 3 Measured and calculated values regarding water content, bulk density and thermal conductivity as well as the temperature, EC²⁵ and field capacity range of the investigated clay sample (measured values from Bertermann and Schwarz 2018)

EC ₂₅	Field capacity range ^a	Measured water content (Vol. %)	Calculated and corrected water content (Vol. %)	Measured bulk density (g cm ⁻³)	Calculated bulk density (g cm ⁻³)	Measured thermal conductivity (W (m*K) ⁻¹)	Calculated thermal conductivity (W (m*K) ⁻¹)	Temperature (°C)
0.01044	Clay	10.91	11.33	1.21	1.38	0.27	1.10	20.17
0.01599	28-41	14.04	14.73	1.20	1.41	0.28	1.22	20.11
0.02322	Vol.%	16.28	18.48	1.22	1.44	0.41	1.35	20.08
0.02479		17.18	19.23	1.20	1.45	0.35	1.38	19.72
0.04461		18.22	27.60	1.31	1.54	0.50	1.69	19.71
0.05926		19.24	23.04	1.32	1.22	0.63	1.08	19.65
0.03451		17.85	23.54	1.17	1.49	0.43	1.53	19.37
0.05465		18.97	22.17	1.26	1.22	0.57	1.07	19.35
0.05953		19.79	23.09	1.28	1.23	0.79	1.08	19.43
0.04058		19.74	26.02	1.17	1.52	0.52	1.63	20.07
0.06483		20.36	24.05	1.20	1.23	0.65	1.10	20.14
0.08794		22.71	27.79	1.26	1.25	0.79	1.17	19.99
0.05235		23.54	21.72	1.13	1.22	0.59	1.06	19.64
0.09194		25.91	28.39	1.28	1.26	0.76	1.18	19.59
0.12230		26.29	32.53	1.32	1.29	0.89	1.26	19.58
0.07977		23.41	26.53	1.13	1.24	0.62	1.15	19.58
0.11596		25.38	31.71	1.21	1.28	0.84	1.25	19.45
0.15106		28.14	36.01	1.32	1.31	1.06	1.34	19.36
0.11351		27.66	31.39	1.08	1.28	0.71	1.24	18.79
0.17850		29.64	39.06	1.25	1.34	1.00	1.41	18.80
0.21277		30.85	42.58	1.37	1.37	1.28	1.50	19.00
0.05821		28.61	22.85	1.16	1.22	0.82	1.08	19.64
0.09582		31.28	28.95	1.31	1.26	1.04	1.19	19.63
0.12507		32.46	32.88	1.37	1.29	1.30	1.27	19.65
0.07652		30.74	26.02	1.18	1.24	0.69	1.14	19.63
0.12766		33.38	33.21	1.30	1.29	1.20	1.28	19.58
0.16304		37.57	37.37	1.43	1.32	1.44	1.37	19.52
0.07810		33.72	26.27	1.19	1.24	0.76	1.14	18.63
0.14087		38.66	34.82	1.36	1.30	1.33	1.31	18.52
0.15298		39.35	36.23	1.44	1.31	1.49	1.34	18.48
0.17638		42.58	38.83	1.28	1.34	1.32	1.40	19.21
0.17254		45.22	38.42	1.35	1.33	1.39	1.39	19.19
0.17196		43.88	38.35	1.37	1.33	1.39	1.39	19.01
0.17942		49.80	39.16	1.33	1.34	1.27	1.41	19.41
0.18830		48.95	40.09	1.32	1.35	1.34	1.43	19.32

^aField capacity ranges are according to Bertermann et al. (2014)

References

- Abu-Hamdeh NH, Reeder RC (2000) Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. *Soil Sci Soc Am J* 64(4):1285–1290
- Archie GE (1942) The electrical resistivity log as an aid in determining some reservoir characteristics. *Trans Am Inst Min Metall Pet Eng* 146:54–62. <https://doi.org/10.2118/942054-G>
- ASTM D5334 (2014) Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe Procedure. ASTM International, West Conshohocken. <https://doi.org/10.1520/D5334-14>
- ASTM D2487 (2017) Standard practice for classification of soils for Engineering purposes (Unified Soil Classification System). ASTM International, West Conshohocken. <https://doi.org/10.1520/D2487-17>
- Bai W, Kong L, Guo A (2013) Effects of physical properties on electrical conductivity of compacted lateritic soil. *J Rock Mech Geotech Eng* 5:406–411. <https://doi.org/10.1016/j.jrmge.2013.07.003>
- Barry-Macaulay D, Bouazza A, Singh RM, Wang B, Ranjith PG (2013) Thermal conductivity of soils and rocks from the Melbourne (Australia) region. *Eng Geol* 164:131–138. <https://doi.org/10.1016/j.enggeo.2013.06.014>
- Bertermann D, Schwarz H (2017) Laboratory device to analyse the impact of soil properties on electrical and thermal conductivity. *Int Agrophys* 31(2):157–166. <https://doi.org/10.1515/intag-2016-0048>
- Bertermann D, Schwarz H (2018) Bulk density and water content-dependent electrical resistivity analyses of different soil classes on a laboratory scale. *Environ Earth Sci* 77(16):570. <https://doi.org/10.1007/s12665-018-7745-3>
- Bertermann D, Klug H, Morper-Busch L, Bialas C (2014) Modelling vSGPs (very shallow geothermal potentials) in selected CSAs (case study areas). *Energy* 71:226–244. <https://doi.org/10.1016/j.energy.2014.04.054>
- Bertermann D, Müller J, Freitag S, Schwarz H (2018) Comparison between measured and calculated thermal conductivities within different grain size classes and their related depth ranges. *Soil Syst* 2(3):50. <https://doi.org/10.3390/soilsystems2030050>
- Bi J, Zhang M, Chen W, Lu J, Lai Y (2018) A new model to determine the thermal conductivity of fine-grained soils. *Int J Heat Mass Tran* 123:407–417. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.035>
- Bristow KL, Kluitenberg GJ, Goding CJ, Fitzgerald TS (2001) A small multi-needle probe for measuring soil thermal properties, water content and electrical conductivity. *Comput Electron Agr* 31(3):265–280. [https://doi.org/10.1016/S0168-1699\(00\)00186-1](https://doi.org/10.1016/S0168-1699(00)00186-1)
- Campbell GS, Jungbauer JD Jr, Bidlake WR, Hungerford RD (1994) Predicting the effect of temperature on soil thermal conductivity. *Soil Sci* 158(5):307–313
- Chatzipanagiotou P, Chatziathanasiou V, De Mey G, Więcek B (2017) Influence of soil humidity on the thermal impedance, time constant and structure function of underground cables: A laboratory experiment. *Appl Therm Eng* 113:1444–1451. <https://doi.org/10.1016/j.applthermaleng.2016.11.117>
- Corwin DL, Lesch SM (2005) Apparent soil electrical conductivity measurements in agriculture. *Comput Electron Agr* 46:11–43. <https://doi.org/10.1016/j.compag.2004.10.005>
- Cosenza P, Guerin R, Tabbagh A (2003) Relationship between thermal conductivity and water content of soils using numerical modelling. *Eur J Soil Sci* 54(3):581–588. <https://doi.org/10.1046/j.1365-2389.2003.00539.x>
- Côté J, Konrad JM (2005) Thermal conductivity of base-course materials. *Can Geotech J* 42(1):61–78. <https://doi.org/10.1139/T04-081>
- Dahlin T, Loke MH (2018) Underwater ERT surveying in water with resistivity layering with example of application to site investigation for a rock tunnel in central Stockholm. *Near Surf Geophys* 16(3):230–237. <https://doi.org/10.3997/1873-0604.2018007>
- de Lieto Vollaro R, Fontana L, Vallati A (2014) Experimental study of thermal field deriving from an underground electrical power cable buried in non-homogeneous soils. *Appl Therm Eng* 62(2):390–397. <https://doi.org/10.1016/j.applthermaleng.2013.09.002>
- De Vries DA (1963) Thermal properties of soils. *Physics of plant environment* 210–235. North-Holland, Amsterdam
- Di Sipio E, Bertermann D (2018) Soil thermal behavior in different moisture condition: an overview of ITER project from laboratory to field test monitoring. *Environ Earth Sci* 77(7):283. <https://doi.org/10.1007/s12665-018-7454-y>
- DIN 18121 (2012) Soil investigation and testing—water content—Part 2: determination by rapid methods. Beuth press, Berlin (in German)
- DIN 18125-2 (2011) Soil investigation and testing—determination of density of soil—Part 2: field tests. Beuth press, Berlin (in German)
- Dong Y, McCartney JS, Lu N (2015) Critical review of thermal conductivity models for unsaturated soils. *Geotech Geol Eng* 33(2):207–221. <https://doi.org/10.1007/s10706-015-9843-2>
- Drefke C, Schedel M, Stegner J, Balzer C, Hinrichsen V, Sass I (2017) Measurement method of thermal properties of cementitious bedding materials and unsaturated soils: hydraulic influence on thermal parameters. *Geotech Test J* 40(1):160–170. <https://doi.org/10.1520/GTJ20160027>
- Ewing RP, Hunt AG (2006) Dependence of the electrical conductivity on saturation in real porous media. *Vadose Zone J* 5:731–741. <https://doi.org/10.2136/vzj2005.0107>
- Farouki OT (1981) Thermal properties of soils (No. CRREL-MONO-81-1). Cold regions research and engineering lab, Hanover NH
- Fragogiannis G, Papatheodorou N, Stamatakis S (2008) Evaluation of thermal performance of ground-source energy systems. A geophysics supported approach. In *World Renewable Energy Congress X and Exhibition (WRECX)*, Glasgow, Scotland, July 19th_25th
- Fragogiannis G, Apostolopoulos G, Stamatakis S (2010) Correlation of thermal conductivity and electrical resistivity of soil—for near surface geothermal applications. In: *72nd EAGE conference and exhibition incorporating SPE EUROPEC 2010*
- Friedman SP (2005) Soil properties influencing apparent electrical conductivity: a review. *Comput Electron Agr* 46:45–70. <https://doi.org/10.1016/j.compag.2004.11.001>

- GGU—Gesellschaft für Geophysikalische Untersuchungen mbH (2011) Die Widerstandsgeoelektrik. Karlsruhe. URL: <http://www.ggukarlsruhe.de/> Accessed 1st April 2020 (in German)
- Ghalamkari S, Asadi A, Pourkermani M, Mazdarani A (2019) Geoelectric assessment of groundwater aquifers at RONIZ area, Southeastern SHIRAZ, IRAN. *Geomech Geophys Geo-Energy Geo-Resour* 5(4):425–436. <https://doi.org/10.1007/s40948-019-00121-4>
- Giordano N, Firmbach L, Comina C, Dietrich P, Mandrone G, Vienken T (2013) Laboratory scale electrical resistivity measurements to monitor the heat propagation within porous media for low enthalpy geothermal applications. In: *Proc. Conf. GNGTS*, November 19–21, Trieste, Italy
- Jiang J, Zhao L, Zeng Y, Zhai Z (2016) Experimental study of the effect of shallow groundwater table on soil thermal properties. *Front Earth Sci-prc* 10(1):29–37. <https://doi.org/10.1007/s11707-015-0502-y>
- Johansen O (1975) Thermal conductivity of soils. Dissertation, University of Trondheim, Trondheim, Norway, CRREL Draft English Translation 637, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H
- Kaufhold S, Grisseman C, Dohrmann R, Klinkenberg M, Decher A (2014) Comparison of three small-scale devices for the investigation of the electrical conductivity/resistivity of swelling and other clays. *Clay Clay Miner* 62(1):1–12. <https://doi.org/10.1346/CCMN.2014.0620101>
- Kersten MS (1949) Thermal properties of soils. *Bull Univ Minnesota* 28:1–227
- Kowalczyk S, Maślakowski M, Tucholka P (2014) Determination of the correlation between the electrical resistivity of non-cohesive soils and the degree of compaction. *J Appl Geophys* 110:43–50. <https://doi.org/10.1016/j.jappgeo.2014.08.016>
- Liu X, Jia Y, Zheng J, Shan H, Li H (2013) Field and laboratory resistivity monitoring of sediment consolidation in China's yellow river estuary. *Eng Geol* 164:77–85. <https://doi.org/10.1016/j.enggeo.2013.06.009>
- Logsdon SD, Green TR, Bonta JV, Seyfried MS, Evett SR (2010) Comparison of electrical and thermal conductivities for soils from five states. *Soil Sci* 175:573–578. <https://doi.org/10.1097/SS.0b013e3181fce006>
- Lu S, Ren T, Gong Y, Horton R (2007) An improved model for predicting soil thermal conductivity from water content at room temperature. *Soil Sci Soc Am J* 71(1):8–14. <https://doi.org/10.2136/sssaj2006.0041>
- Lu Y, Lu S, Horton R, Ren T (2014) An empirical model for estimating soil thermal conductivity from texture, water content, and bulk density. *Soil Sci Soc Am J* 78(6):1859–1868. <https://doi.org/10.2136/sssaj2014.05.0218>
- Markert A, Bohne K, Facklam M, Wessolek G (2017) Pedo-transfer functions of soil thermal conductivity for the textural classes sand, silt, and loam. *Soil Sci Soc Am J* 81(6):1315–1327. <https://doi.org/10.2136/sssaj2017.02.0062>
- McCutcheon MC, Farahani HJ, Stednick JD, Buchleiter GW, Green TR (2006) Effect of soil water on apparent soil electrical conductivity and texture relationships in a dryland field. *Biosyst Eng* 94(1):19–32. <https://doi.org/10.1016/j.biosystemseng.2006.01.002>
- Nouveau M, Grandjean G, Leroy P, Philippe M, Hedri E, Boukcim H (2016) Electrical and thermal behavior of unsaturated soils: experimental results. *J Appl Geophys* 128:115–122. <https://doi.org/10.1016/j.jappgeo.2016.03.019>
- Ochsner TE, Horton R, Ren T (2001) A new perspective on soil thermal properties. *Soil Sci Soc Am J* 65(6):1641–1647
- Ozcep F, Yıldırım E, Tezel O, Asci M, Karabulut S (2010) Correlation between electrical resistivity and soil-water content based artificial intelligent techniques. *Int J Phys Sci* 5(1):47–56
- Rerak M, Ocloń P (2017) Thermal analysis of underground power cable system. *J Therm Sci* 26(5):465–471. <https://doi.org/10.1007/s11630-017-0963-2>
- Robert T, Paulus C, Bolly PY, Koo Seen Lin E, Hermans T (2019) Heat as a proxy to image dynamic processes with 4D electrical resistivity tomography. *Geosci J* 9(10):414. <https://doi.org/10.3390/geosciences9100414>
- Roncza M, Hellman K, Günther T, Wisén R, Dahlin T (2017) Electric resistivity and seismic refraction tomography: a challenging joint underwater survey at Äspö hard rock laboratory. *Solid Earth* 8(3):671–682. <https://doi.org/10.5194/se-8-671-2017>
- Sáez Blázquez C, Farfán Martín A, Martín Nieto I, Gonzalez-Aguilera D (2017) Measuring of thermal conductivities of soils and rocks to be used in the calculation of a geothermal installation. *Energies* 10(6):795. <https://doi.org/10.3390/en10060795>
- Salata F, Nardecchia F, Gugliermetti F, de Lieto Vollaro A (2016) How thermal conductivity of excavation materials affects the behavior of underground power cables. *Appl Therm Eng* 100:528–537. <https://doi.org/10.1016/j.applthermaleng.2016.01.168>
- Samouelian A, Cousin I, Tabbagh A, Bruand A, Richard G (2005) Electrical resistivity survey in soil science: a review. *Soil Till Res* 83(2):173–193. <https://doi.org/10.1016/j.still.2004.10.004>
- Sheets KR, Hendrickx JMH (1995) Noninvasive soil water content measurement using electromagnetic induction. *Water Resour Res* 31(10):2401–2409. <https://doi.org/10.1029/95WR01949>
- Singh DN, Devid K (2000) Generalized relationships for estimating soil thermal resistivity. *Exp Thermal Fluid Sci* 22(3–4):133–143
- Singh DN, Kuriyan SJ, Manthena KC (2001) A generalized relationship between soil electrical and thermal resistivities. *Exp Thermal Fluid Sci* 25:175–181. [https://doi.org/10.1016/S0894-1777\(01\)00082-6](https://doi.org/10.1016/S0894-1777(01)00082-6)
- Sreedeeep S, Reshma AC, Singh DN (2005) Generalized relationship for determining soil electrical resistivity from its thermal resistivity. *Exp Therm Fluid Sci* 29:217–226. <https://doi.org/10.1016/j.expthermflusci.2004.04.001>
- Sun Q, Lü C (2019) Semiempirical correlation between thermal conductivity and electrical resistivity for silt and silty clay soils. *Geophysics* 84(3):MR99–MR105. <https://doi.org/10.1190/geo2018-0549.1>
- Tarnawski VR, Leong WH, Bristow KL (2000) Developing a temperature-dependent Kersten function for soil thermal conductivity. *Int J Energy Res* 24(15):1335–1350. <https://doi.org/10.1080/01449190010001651000>

- [doi.org/10.1002/1099-114X\(200012\)24:15%3c1335:AID-ER652%3e3.0.CO;2-X](https://doi.org/10.1002/1099-114X(200012)24:15%3c1335:AID-ER652%3e3.0.CO;2-X)
- Tian B, Kong Y, Gong Y, Ye C, Pang Z, Wang J, Qin P (2020a) Thermal conductivity characterisation of shallow ground via correlations with geophysical parameters. *Eng Geol*. <https://doi.org/10.1016/j.enggeo.2020.105633>
- Tian Z, Ren T, Heitman JL, Horton R (2020b) Estimating thermal conductivity of frozen soils from air-filled porosity. *Soil Sci Soc Am J*. <https://doi.org/10.1002/saj2.20102>
- Tokoro T, Ishikawa T, Shirai S, Nakamura T (2016) Estimation methods for thermal conductivity of sandy soil with electrical characteristics. *Soils Found* 56(5):927–936. <https://doi.org/10.1016/j.sandf.2016.08.016>
- Usoiwicz B, Lipiec J, Usoiwicz JB, Marczewski W (2013) Effects of aggregate size on soil thermal conductivity: comparison of measured and model-predicted data. *Int J Heat Mass Tran* 57(2):536–541. <https://doi.org/10.1016/j.ijheatmasstransfer.2012.10.067>
- Usoiwicz B, Łukowski MI, Rüdiger C, Walker JP, Marczewski W (2017) Thermal properties of soil in the Murrumbidgee river catchment (Australia). *Int J Heat Mass Tran* 115:604–614. <https://doi.org/10.1016/j.ijheatmasstransfer.2017.08.021>
- Vieira A, Alberdi-Pagola M, Christodoulides P, Javed S, Loveridge F, Nguyen F, Cecinato F, Maranhã J, Florides G, Prodan I, Van Lysebetten G, Ramalho E, Salciarini D, Georgiev A, Rosin-Paumier S, Popov R, Lenart S, Erbs Poulsen S, Radioti G (2017) Characterisation of ground thermal and thermo-mechanical behaviour for shallow geothermal energy applications. *Energies* 10(12):2044. <https://doi.org/10.3390/en10122044>
- Wang J, Zhang X, Du L (2017) A laboratory study of the correlation between the thermal conductivity and electrical resistivity of soil. *J Appl Geophys* 145:12–16. <https://doi.org/10.1016/j.jappgeo.2017.07.009>
- Wang J, He H, Dyck M, Lv J (2020) A review and evaluation of predictive models for thermal conductivity of sands at full water content range. *Energies* 13(5):1083. <https://doi.org/10.3390/en13051083>
- Xu X, Zhang W, Fan C, Li G (2020) Effects of temperature, dry density and water content on the thermal conductivity of Genhe silty clay. *Results Phys* 16:102830. <https://doi.org/10.1016/j.rinp.2019.102830>
- Yan H, He H, Dyck M, Jin H, Li M, Si B, Lv J (2019) A generalized model for estimating effective soil thermal conductivity based on the Kasubuchi algorithm. *Geoderma* 353:227–242. <https://doi.org/10.1016/j.geoderma.2019.06.031>
- Zhou QY, Shimada J, Sato A (2001) Three-dimensional spatial and temporal monitoring of soil water content using electrical resistivity tomography. *Water Resour Res* 37(2):273–285. <https://doi.org/10.1029/2000WR900284>

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