KSCE Journal of Civil Engineering (2020) 24(8):2364-2371
DOI 10.1007/s12205-020-1812-5

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

An Improved Thermal Conductivity Model for Unsaturated Clay

Xinye Song[a], **Henghui Fan**[a], **Jiawei Liu**[a], **and Xiujuan Yang**[a]

[a]*College of Water Resources and Architectural Engineering, Northwest Agriculture and Forestry University, Yangling 712100, China*

ARTICLE HISTORY

Received 12 November 2019
Revised 7 February 2020
Accepted 16 April 2020
Published Online 22 June 2020

KEYWORDS

Thermal conductivity
Water content
Dry density
Unsaturated clay
Prediction model

ABSTRACT

The thermal properties of soils vary because of the different textures of soils; thus, it is valuable to conduct research on the development of thermal conductivity models for soils with different textures. Clay samples with different dry densities and increasing incremental water contents were prepared, their thermal conductivities were measured by the transient plane source (TPS) method. The experimental results show that the thermal conductivity of clay increases with increasing water content and dry density. The water content has a stronger influence than the dry density on the thermal conductivity. This paper presents an improved model to predict the thermal conductivity of unsaturated clay. The model considers the different contributions of minerals in the soil and the distribution of water and air in pores. The accuracy of the model is verified by soil thermal conductivity data that was previously measured and collected from ten regions. Compared with the three similar models proposed in the literature, the new model proposed in this paper has a higher degree of correlation to describe the thermal conductivity of clay.

1. Introduction

Houses built using soil are still widely distributed around the world, such as temples in Japan, the cave-dwelling and Fujian earth buildings in China, the fortified city in Morocco, Kapelle der Versöhnung in Berlin, and the handmade school in Bangladesh. The thermal parameters of soil are needed in these projects to assist in the calculation and simulation of the indoor environment. The thermal conductivity value also shows great importance in evaluating the heat transfer capacity of raw soil materials, which involves many heat-related engineering projects, such as buried underground thermal pipelines, pavement performance due to the heat generated from driving, heat preservation and heat storage of the earth wall.

There are many causes that affect the thermal properties of soil; these are closely related to the soil temperature, pores in the soil, soil density, mineral composition, water content, and freeze-thaw state of soil (Xu et al., 2011; Wang et al., 2012; Barry-Macaulay et al., 2015). For many years, researchers have performed much research on the test and theoretical analysis of the soil thermal conduction. According to the law of conservation of energy for heat transfer, Smith (1940) carried out experiments and measured the watered soil thermal conductivity using the steady-state method, and has proved the inaccuracy of using the steady-state method to determine the thermal conductivity of wet soil without sealing. Heating the test specimen for a period of time is often necessary when using the steady-state method to carry out the measurement of the wet soil's thermal conductivity. During this process, the moisture migration and changes of the soil moisture content will greatly affect the test, which leads to inaccurate test results. The thermal conductivity test of soil includes indoor tests and field tests. Laboratory tests often undergo the nonsteady state method to save testing time and improve measurement accuracy (Horai, 1969; Tarnawski et al., 2009; Ochsner et al., 2001; Côté and Konrad, 2005; Zhang, 2015). Many testing methods have been developed based on the nonsteady state method, such as the thermal probe test (Nakshabandi and Kohnke, 1965; Verhoef et al., 1996), transient plane source method, hot-wire method, transient hot-strip method and pulse method (Ross and Bridge, 1987; Bristow, 1998). Based on different measurements and theories, empirical models, theoretical models and semitheoretical semiempirical models have been derived (Woodside and Messmer, 1961; de Vries, 1963; Balland and Arp et al., 2005; Lu et al., 2007; Johansen, 1975). The existing models are devoted to describing the thermal conductivity of soils with one system; however, soils exist in different textures.

CORRESPONDENCE Henghui Fan ✉ yt07@nwsuaf.edu.cn College of Water Resources and Architectural Engineering, Northwest Agriculture and Forestry University, Yangling 712100, China

Because of the soil heterogeneity and the environment complexity, other properties of soil can have significant effects on its thermal properties, such as particle composition, mineral composition and soil structure. These models provide a good prediction for some soils but are not as accurate for other soils. Johansen's model (1975) has a low accuracy in predicting the coarse granular soil's thermal conductivity when the soil is in a low saturation state; however, the Côté and Konrad model (2005) has good agreement with coarse granular soils while providing a low fit to the fine grain soil than the model of Lu et al. (2007). Because the solid-liquid-gas three-phase contact characteristics are different in different soils, such as clay, sandy soil and silty soil, the path and method of heat transfer between solid-liquid-gas in soil produces different degrees of influence on the thermal properties of soil. Thus, it can be seen that the establishment of different models for the thermal conductivity of various soil types might be an advantage of model research. Models mentioned above have high adaptability to some soils, but show limited adaptability to other soils, while these models are applied to multiple types of soils. So we recommend to use different models for different soils to describe their thermal conductivity. Then, we proposed a model for clay soil and verified this model with tested data and data from the literature.

In this paper, the clay samples with different water content and different density were made into disc-shaped samples, and the thermal conductivity of the samples was measured by the TPS method. The relationship among the thermal conductivity, the water content and the dry density is discussed and analyzed. An improved model for the calculation of the thermal conductivity of clay is proposed, it considers the different proportion of mineral compositions and the pore-water-air ratios. The data of 10 kinds of clays were collected by means of laboratory test and literature collection, then were used for model evaluation. The performance of the new model is evaluated along with three commonly used thermal conductivity prediction models. Section 2 and Section 3 of this paper are the conduction and discussion of the thermal conductivity test of clay, from which the measured values here is obtained.

2. Materials and Methods

The tested soil was selected from Xianyang, China. The liquid limit (LL) of the tested soil is 37.7%, and the plastic limit (PI) is 23.8%, which indicates that the soil is a low liquid limit clay. Table 1 provides some physical properties of the tested clay.

The thermal conductivity measurement was conducted by a rapid thermal conductivity tester produced by Hunan Xiangtan Xiangyi Instrument Co. Ltd. In China (Fig. 1). Measurements were based on the TPS method (Gustafsson, 1991), which is derived from the transient temperature response generated by a disc-shaped heat source that has been heated in a stepwise manner under an infinite medium. The probe was placed in the middle of two identical specimens, and the standard deviation of each set of test results was less than 0.05. Considering the influence of testing temperature on thermal conductivity (Tarnawski and Leong, 2000), prior to measuring the specimens, the tester was calibrated with the thermal conductivity of polymethyl methacrylate and quartz glass at 20ºC.

Table 1. Physical Properties of Tested Soil

Specific gravity	LL (%)	PL (%)	PI	Maximum dry density (g/cm^3)
2.74	37.7	23.8	13.9	1.73

(a) (b)

Fig. 1. Thermal Conductivity Tester: (a) Signal Receiving Processor, (b) Probe and Testing Samples

A 2-mm screen was used to sieve the air-dried clay, and then the clay was saturated to produce different water contents of 3%, 6%, 9%, 12%, 15%, 18%, 21%, and 24%. The saturated soil was sealed and transferred to a thermostat to stand for 24 hours to cause the water in the soil to migrate evenly throughout. After 24 hours of curing, a jack was used to maintain the static pressure during the preparation of round disc-shaped specimens into diameters of 6.18 cm and heights of 2 cm.

3. Results and Discussions

Figure 2 reveals that the thermal conductivity of clay under certain water content conditions increases with dry density, and this phenomenon can be observed under different water content

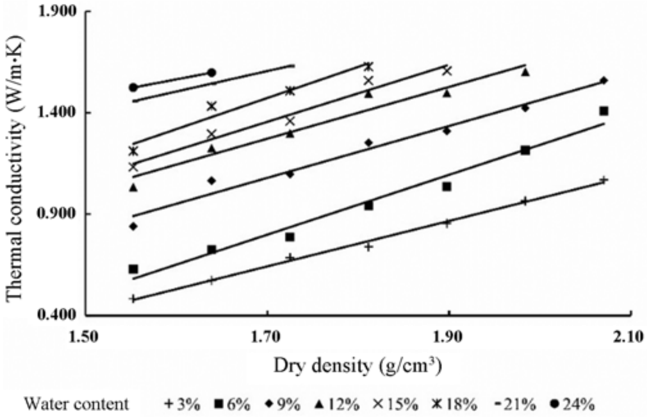

Fig. 2. Thermal Conductivity and Dry Density

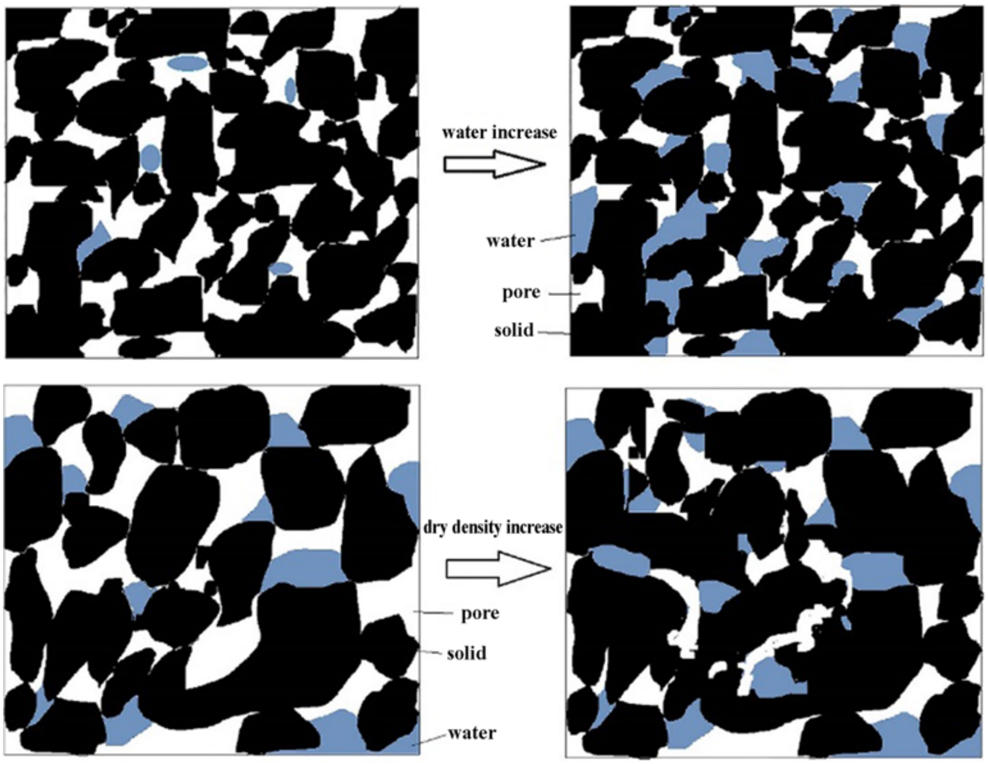

Fig. 3. Schematic Diagram of Contact Form

conditions. When the moisture content of clay increases, its thermal conductivity also increases.

Soil is a complex system composed of three phases: solid, liquid, and gas. Because of the difference of the three phases, the thermal conductivity of soil is affected by many factors. The thermal conductivity of water at room temperature is 0.599 $W{\cdot}m^{-1}{\cdot}K^{-1}$, more than ten times that of air, 0.024 $W{\cdot}m^{-1}{\cdot}K^{-1}$, while the solid particle has a higher value of approximately 1.3-6.0 $W{\cdot}m^{-1}{\cdot}K^{-1}$. Due to the higher thermal conductivity of soil particles and water, the soil thermal conductivity is mainly determined by the characteristics of the solid and the distribution of water in soil. When the soil moisture content is at a low level, the solid phase and pore in soil play a main role in the process of heat conduction. Since the thermal conductivity of minerals in soil is hundreds of times that of air (Côté et al., 2011), the composition of the soil particles and the type of contact occurring between the soil particles plays a major role in the heat conduction of the soil. In the theory of thermal conductivity prediction of Campbell (1994), the increase of moisture content will promote the increase of thermal conductivity. Based on this theory, Bao et al.'s (2019) temperature simulation at the same depth of soil with different moisture content shows that the soil with higher moisture content transfers heat faster. When the soil is gradually saturated by water, the pores are gradually filled with water. The water film formed between the soil particles increases the contact between the soil particles, which is beneficial to the transfer of heat, therefore, leading to the climb of the soil thermal conductivity. When the dry density of soil increases, the soil is compressed, the porosity of soil decreases, and the surface-surface contact between solid phase and solid phase, solid phase and liquid phase increases (Fig. 3). As the heat transfer capacity between the particles is greater than that of the soil particles and the air, the heat conductivity between the soil particles and the liquid is better than the conductivity between the solid and the air; moreover, the expanded contact area of the soil particle and the liquid phase improves the thermal conductivity as the dry density of the soil increases.

The calculation results of Pearson correlation coefficient from the linear regression analysis of the data in Fig. 2 are shown in Table 2. The Pearson correlation coefficient of water content and thermal conductivity is 0.759, which indicates that there is a stronger correlation between the two variables. Therefore, it can be deduced that the effect of water on the soil thermal property is stronger, which illustrates that the form of pores in soil could affect the thermal conductivity. Although in this study, the conclusion is deduced from clay, its adaptability to other types of soil is worth discussing in the future research.

Table 2. Pearson Correlation Coefficient

Person correlation coefficient	Thermal conductivity	Water content	Dry density
Thermal conductivity	1.000	0.759	0.263
Water content	0.759	1.000	-0.393
Dry density	0.263	-0.393	1.000

4. Thermal Conductivity Prediction Models

4.1 Johansen Model

The thermal conductivity model of unsaturated clay proposed by Johansen (1975) can be expressed as Eq. (1).

$$k = (k_{sat} - k_{dry})k_e + k_{dry} \tag{1}$$

where k_{sat} and k_{dry} represent the thermal conductivity of saturated soil and dry soil respectively, they can be expressed as Eqs. (2) and (3), respectively, in which ks and kw express the solid and liquid thermal conductivity, respectively, and n represents the porosity. ke is the Kersten number; for coarse grained soil, ke can be expressed as Eq. (4). For fine grained soil, ke can be expressed as Eq. (5).

$$k_{sat} = k_s^{(1-n)} k_w^n \tag{2}$$

$$k_{dry} = \frac{0.137\rho_d + 64.7}{2700 - 0.947\rho_d} \pm 20\% \tag{3}$$

$$k_e = 0.7\log S_r + 1 (S_r > 0.05) \tag{4}$$

$$k_e = \log S_r + 1 (S_r > 0.1) \tag{5}$$

Johansen suggested Eq. (6) for the solid particle thermal conductivity, in which k_q and k_o represent the thermal conductivity of quartz and other minerals, respectively, q is the ratio of quartz content to the full mineral content of the soil.

$$k_s = k_q^q k_o^{(1-q)} \tag{6}$$

4.2 Côté and Konrad Model

Johansen's (1975) model was improved by changing Eqs. (2) – (5) to calculate k_{sat}, k_{dry} and k_e (Eqs. (7) – (9)) (Côté and Konrad, 2005).

$$k_{sat} = k_s^{\theta_s} k_w^{\theta_w} k_i^{\theta_i} \tag{7}$$

$$k_{dry} = \chi \times 10^{-\eta n} \tag{8}$$

$$k_e = \frac{\kappa S_r}{1 + (\kappa - 1)S_r} \tag{9}$$

where χ, η and κ are parameters considering the particle size. The thermal conductivity of soil particles is represented by Eqs. (10) and (11).

$$k_s = \prod_j k_{m_j}^{x_j} \tag{10}$$

$$\sum_j x_j = 1 \tag{11}$$

where K_m represents different minerals' thermal conductivity, and x represents the proportion of different minerals to the total mineral content of the soil.

4.3 Lu et al. Model

A new expression of k_e and k_{dry} was proposed trying to improve the Johansen's model (Lu et al., 2007). Here, k_e is given as Eq. (12), and k_{dry} can be obtained by Eq. (13).

$$k_e = \exp\left\{\alpha[1 - S_r^{(\alpha - 1.33)}]\right\} \tag{12}$$

$$k_{dry} = -an + b \tag{13}$$

where a, b and α are parameters determined by soil characteristics.

4.4 The New Model

4.4.1 Theory

Compared with other minerals commonly found in soil, quartz has a higher thermal conductivity (Horai, 1969; Ramazan, 2007; Suekuni et al., 2012), some studies have shown that the content of quartz in soil is outstanding in regard to the soil thermal conductivity (Lu et al., 2007; Tarnawski et al., 2009). Given that different soils have different mineral compositions, it is nonrigorous to fit one thermal conductivity model to different soils.

In this model, it is assumed that the solid particles, water, and air in the soil are evenly distributed, the solid, liquid and gas phases of soil play a simultaneous role in the process of heat transfer. Here, a sphere is used to represent a basic unit of soil, and each unit contains solid, water and gas phases. The heat transfer between one unit and another unit in contact with it is shown in Fig. 4. If we let the volume and radius of the soil microunit be V and R, then R can be represented by Eq. (14).

$$R = \sqrt[3]{\frac{3V}{4\pi}} \tag{14}$$

The equivalent radius of solid and pore in the soil microunit is represented by Eqs. (15) and (16).

$$R_s = \sqrt[3]{\frac{3(1-n)V}{4\pi}} \tag{15}$$

$$R_p = \sqrt[3]{\frac{3nV}{4\pi}} \tag{16}$$

The tortuosity τ is considered to reflect the microstructural characteristics of soil as porous media and can be represented by Eq. (17). Here, C represents the length of the route, and L is the distance between the two ends.

$$\tau = \frac{C}{L} \tag{17}$$

When considering the soil pore, the heat transfer path between

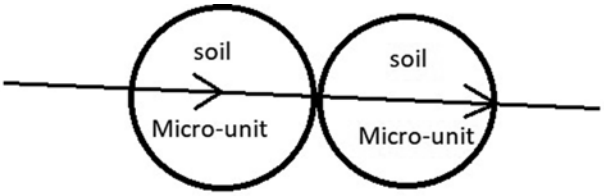

Fig. 4. Geometric Models of Heat Transfer Routines

Table 3. Mineral Composition of Loess

Minerals	Clay minerals				Other minerals				Others
	Illite	Montmorillonite	Kaolinite	Chlolite	Quartz	Potash feldspar	Plagioclase	Calcite	
Content/%	15.5	9.4	1.7	2.3	39.6	3.6	8.7	18.1	1.1

Table 4. Thermal Conductivity of Some Minerals ($W \cdot m^{-1} \cdot K^{-1}$)

Anorthosite	Basalt	Diabase	Dolostone	Gabbro	Gneiss	Granite
1.8	1.7	2.3	3.8	2.2	2.6	2.5
Feldspar	Limestone	Marble	Quartzite	Sandstone	Schist	Shale
2.3	2.5	3.2	7.7	3	1.5	2
Syenite	Trap rock	Kaolinite	Calcite	Salt rock	Dolomite	
2	2	2.6	3.57	5.6	4.7	

two soil microunits is $L = 2R$, while the heat transfer path between two soil microunits considering the pore can be represented by Eq. (18).

$$C = 2R_s + 2R_p \tag{18}$$

By substituting Eqs. (14) – (16) and (18) into Eq. (17), the tortuosity can be represented by Eq. (19).

$$\tau = \frac{C}{L} = \sqrt[3]{1-n} + \sqrt[3]{n} \tag{19}$$

The thermal conductivity is expressed as Eq. (20).

$$k_0 = \frac{\Phi L}{A \Delta T} \tag{20}$$

where Φ represents the heat transferred, L is the length of heat transferred, A indicates the heat transfer area, and ΔT is the difference in temperature between the two sides. Considering the soil tortuosity, the formula of the thermal conductivity can be expressed as Eq. (21).

$$k = \tau k_0 = (\sqrt[3]{1-n} + \sqrt[3]{n}) k_0 \tag{21}$$

It is assumed that the three phases of solid-liquid-gas in clay are evenly distributed. The solids and pores in each soil microelement in the soil are involved in heat transfer. For unsaturated soil, its thermal conductivity is estimated by Eq. (22) considering the different contributions of particles, liquid and air in soil to the thermal conductivity.

$$k_0 = k_s^{1-n} k_w^{nS_r} k_a^{n(1-S_r)} \tag{22}$$

According to Eqs. (21) and (22), Eq. (23) is derived to calculate the thermal conductivity of unsaturated clay.

$$k = (\sqrt[3]{1-n} + \sqrt[3]{n}) k_s^{1-n} k_w^{nS_r} k_a^{n(1-S_r)} \tag{23}$$

4.4.2 Verification of the New Model

The thermal conductivity of different minerals differs greatly, the difference in mineral composition in soil has different effects on the soil thermal conductivity. Therefore, the proportions of the contents of different minerals in the soil is a key factor in obtaining an accurate thermal conductivity model of soil. To determine the proportion of various mineral components in the tested soil, the percentages of different mineral components were obtained by X-ray diffraction, and the results are listed in Table 3.

According to the thermal conductivity of minerals given in the literature (Sass et al., 1971; Andersland, 1978; Johnston, 1981; Côté and Konrad, 2005; Côté et al., 2011; Gao, 2015), Table 4 presents the thermal conductivity of some minerals commonly found in the soil.

By substituting these values into Eq. (10), the solid phase thermal conductivity is obtained.

$$k_s = \prod_j k_{m_j}^{x_j} = 3.669 W \cdot m^{-1} \cdot K^{-1} \tag{24}$$

The liquid thermal conductivity is recorded as k_w = 0.599 $W \cdot m^{-1} \cdot K^{-1}$, while that of air is k_a = 0.024 $W \cdot m^{-1} \cdot K^{-1}$. Substituting these values into Eq. (23) can obtain the thermal conductivity of clay with various porosities and saturation levels. Fig. 5 shows the comparison between the tested data and the calculated model values. The model proposed in this paper has good agreement

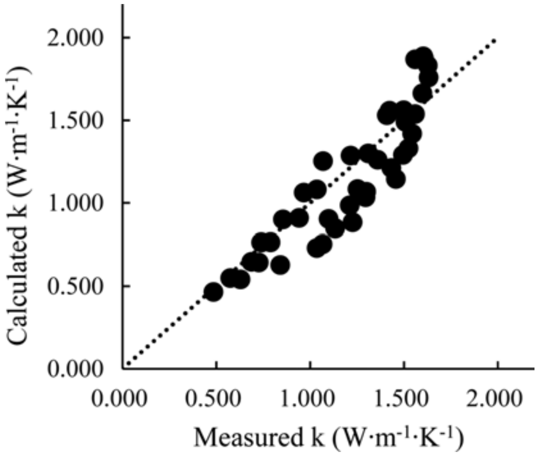

Fig. 5. Calculated Values and Measured Values

with the actual data, which shows that this model has a good accuracy for predicting the thermal conductivity of clay. Because the soil temperature is considered to be strongly related to the thermal properties of soil (Campbell, 1995; Bao et al., 2019; Massman, 2012), the experimental data in this study are obtained based on the ambient condition of 20ºC. It should be noted that the model has not been verified to be applicable for frozen soil in low-temperature areas and high-temperature underground soil involved in thermal energy pipelines or surface fire.

5. Model Evaluation

Thermal conductivity data and the mineral data of soil from nine regions in the literature (Campbell et al., 1994; Tarnawski et al., 2002; Barry-Macaulay et al., 2013; Zhang et al., 2014; Luo et al., 2015) were collected and substituted into the four models to investigate the applicability of the prediction models. Table 5 presents the LL, PI, specific gravity and k_s of these soils. Table 6 presents the mineral components of these soils. The thermal conductivity values of solid fraction of the three soils, Salkum Soil, Royal Soil and Volkmar Soil (Campbell et al., 1994), are given in Table 5, so the mineral components of the three soils are not shown here.

The Johansen model (Johansen, 1975), the Côté and Konrad model (Côté and Konrad, 2005), the Lu et al. model (Lu et al., 2007) and the new model were evaluated with the thermal conductivity test data of soils listed in Table 5, the relationship between the calculated values of the models and the actual data is shown in Fig. 6.

Table 7. RMSE of Four Models

Johansen model (Johansen, 1975)	0.89
Côté and Konrad model (Côté and Konrad, 2005)	0.41
Lu et al. model (Lu et al., 2007)	0.93
The new model	0.33

Table 7 shows the RMSE of the four models. The new model` RMSE is at a minimum among the four models. The new model assumes that the three phases of solid, water and gas in clay are uniformly distributed, which is a balance more difficult to achieve in sand and silt. The new model takes into account the parameters in the process of heat transfer - tortuosity, the content of different minerals in clay and the distribution of water in clay pores. Combined with the comparison shown in Fig. 6, it can be concluded that the new model is doing well in predicting the clay thermal conductivity within a reasonable error range.

6. Conclusions

The water content and dry density of the soil have a significant influence on the thermal conductivity of the soil. The thermal conductivity of the soil increases as the water content and the dry density of the soil increase. Compared with dry density, the effect of water content on clay is more significant.

The thermal conductivity prediction model proposed in this paper takes into account the effects of different mineral compositions and tortuosity and the proportion of moisture in the pores. The accuracy of this model is verified by soil thermal conductivity

Table 5. Basic Properties of Soils

	LL	PI	Specific gravity	k_s (W·m^{-1}·K^{-1})
Silty Clay (Henan) (Luo et al., 2015)	—	8.1	2.70	—
Loess (Lanzhou) (Zhang et al., 2014)	28.8	10.8	2.71	—
Clay (The Brazil City) (Zhang et al., 2014)	27.5	13.0	2.70	—
Clay (Liangzhu) (Zhang et al., 2014)	40.7	18.5	2.70	—
Brighton Group Clayey Sand (Barry-Macaulay et al., 2013)	28.8	10.8	2.59	—
Basaltic Clay (Barry-Macaulay et al., 2013)	70.0	50.0	2.67	
Salkum Soil (Campbell et al., 1994)	—	—	—	2.21
Royal Soil (Campbell et al., 1994)	—	—	—	2.57
Volkmar Soil (Campbell et al., 1994)	—	—	—	4.71

Table 6. Mineral Component of Soils (%)

	Quartz	Feldspar	Calcite	Dolomite	Illite	Montmorillonite	Others
Silty Clay (Henan) (Luo et al., 2015)	40	—	—	30.1	12	8	10
Loess (Lanzhou) (Zhang et al., 2014)	29.3	19.7	24.3		12.7	5.3	8.7
Clay (The Brazil City) (Zhang et al., 2014)	39.2	12	3	32	2.8	—	11
Clay (Liangzhu) (Zhang et al., 2014)	78.0	11	—	—	5	—	6
Brighton Group Clayey Sand (Barry-Macaulay et al., 2013)	63	—	—	—	—	33	4
Basaltic Clay (Barry-Macaulay et al., 2013)	57	5	—	—	—	38	—

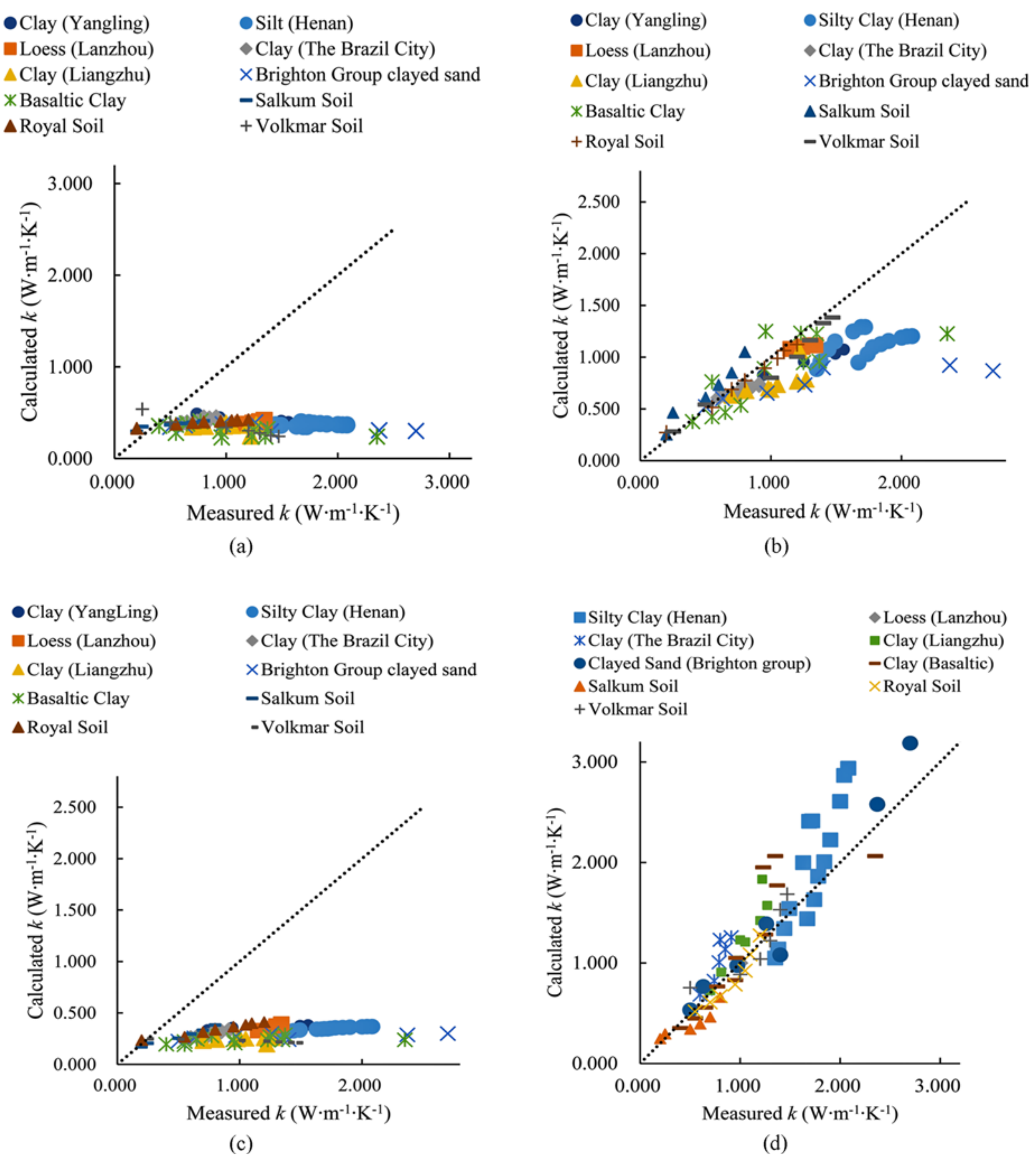

Fig. 6. Measured *k* Compared with Calculated *k*: (a) Johansen Model, (b) Côté and Konrad Model, (c) Lu et al. Model, (d) The New Model

data collected from ten regions. When compared to three similar soil thermal conductivity prediction models, the new model shows an improvement in the prediction of the thermal conductivity of unsaturated clay.

Acknowledgements

This presented work is supported by the National Key Research and Development Program "Eco-Safety Guarantee Technology and Demonstration of Gully and Slope Treatment Engineering in Loess Hilly and Gully Region" (No. 2017YFC0504703).

ORCID

Not Applicable

References

Andersland OB (1978) Geotechnical engineering for cold regions. McGraw-Hill, New York, NY, USA, 40-121

Balland V, Arp PA (2005) Modeling soil thermal conductivities over a wide range of conditions. *Journal of Environmental Engineering Science* 4:549-558, DOI: 10.1139/s05-007

Bao T, Liu S, Qin Y, Liu Z (2019) 3D modeling of coupled heat and transport beneath a surface fire. *International Journal of Heat and Mass Transfer* 149:119163-119175, DOI: 10.1016/j.ijheatmasstransfer.2019.119163

Barry-Macaulay D, Bouazza A, Singh RM (2013) Thermal conductivity of soils and rocks from the Melbourne (Australia) region. *Engineering Geology* 164:131-138, DOI: 10.1016/j.enggeo.2013.06.014

Barry-Macaulay D, Bouazza A, Wang B, Singh, RM (2015) Evaluation of soil thermal conductivity models. *Canadian Geotechnical Journal* 52(11):1-9, DOI: 10.1139/cgj-2014-0518

Bristow KL (1998) Measurement of thermal properties and water content of unsaturated sandy soil using dual-probe heat-pulse probes. *Agricultural and Forest Meteorology* 89:79-84, DOI: 10.1016/s0168-1923(97)00065-8

Campbell GS, Jungbauer JJ, Bidlake WR, Hungerford RD (1994) Prediction the effect of temperature on soil thermal conductivity. *Soil Science* 158(5):307-313, DOI: 10.1097/00010694-199411000-00001

Campbell GS, Jungbauer JJ, Bristow KL, Hungerford RD (1995) Soil temperature and water content beneath a surface fire. *Soil Science* 159(6):363-374, DOI: 10.1097/00010694-199506000-00001

Côté J, Fillion M, Konrad JM (2011) Estimating hydraulic and thermal conductivities of crushed granite using porosity and equivalent particle size. *Journal of Geotechnical & Geoenvironmental Engineering* 137(9):834-842, DOI: 10.1061/(asce)gt.1943-5606.0000503

Côté J, Konrad JM (2005) A generalized thermal conductivity model for soils and construction materials. *Canadian Geotechnical Journal* 42(2):443-458, DOI: 10.1139/t04-106

de Vries DA (1963) Thermal properties of soils. In: Physics of plant environment. North-Holland Publishing Company, Amsterdam, Netherlands, 210-235

Gao P (2015) Analysis of rock thermal physical parameters and research on multi-field thermal effect coupled model. PhD Thesis, Jilin University, Jilin, China

Gustafsson SE (1991) Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials. *Review of Scientific Instruments* 62(3):797-804, DOI: 10.1063/1.1142087

Horai K (1969) Thermal conductivity of rock-forming minerals. *Journal of Geophysical Research* 76(5):1278-1308, DOI: 10.1016/0012-821x(69)90076-4

Johansen O (1975) Thermal conductivity of soils. PhD Thesis, University of Trondheim, Trondheim, Norway

Johnston GH (1981) Permafrost engineering design and construction. John Wiley & Sons, New York, NY, USA, 59-61

Lu S, Ren T, Gong Y, Horton R (2007) An improved model for predicting soil thermal conductivity from water content at room temperature. *Soil Science Society of America Journal* 71(1):8-14, DOI: 10.2136/sssaj2006.0041

Luo H, Zhang H, Guo P (2015) Experimental research on thermal conductivity of loess and modified loess. *Journal of Highway and Transportation Research and Development* 5:109-112, DOI: 10.1061/9780784479292.088

Massman WJ (2012) Modeling soil heating and moisture transport under extreme conditions: Forest fires and slash pile burns. *Water Resources Research* 48(10):10548-10560, DOI: 10.1029/2011wr011710

Nakshabandi GA, Kohnke H (1965) Thermal conductivity and diffusivity of soils as related to moisture tension and other physical properties. *Agricultural Meteorology* 2(4):271-279, DOI: 10.1016/0002-1571(65)90013-0

Ochsner TE, Horton R, Ren T (2001) A new perspective on soil thermal properties. *Soil Science Society of America Journal* 65(6):1641-1647, DOI: 10.2136/sssaj2001.1641

Ramazan D (2007) Thermal conductivity and compressive strength of concrete incorporation with mineral admixtures. *Building and Environment* 42(7):2467-2471, DOI: 10.1016/j.buildenv.2006.06.010

Ross PJ, Bridge BJ (1987) Thermal properties of swelling clay soils. *Australian Journal of Soil Research* 25(1):29-41, DOI: 10.1071/sr9870029

Sass JH, Lachenbruch AH, Munroe RJ (1971) Thermal conductivity of rocks from measurements on fragments and its application to heat-flow determinations. *Journal of Geophysical Research* 76(14):3391-3401, DOI: 10.1029/jb076i014p03391

Smith WO (1940) Thermal conductivities in moist soils. *Soil Science Society of America Journal* 4:32-40, DOI: 10.2136/sssaj1940.036159950004000c0007x

Suekuni K, Tsuruta K, Ariga T, Koyano M (2012) Thermoelectric properties of mineral tetrahedrites $Cu_{10}Tr_2Sb_4S_{13}$ with low thermal conductivity. *Applied Physics Express* 5(5):1201-1211, DOI: 10.1143/apex.5.051201

Tarnawski VR, Leong WH (2000) Thermal conductivity of soils at very low moisture content and moderate temperatures. *Transport in Porous Media* 41(2):137-147, DOI: 10.1023/A:1006738727206

Tarnawski VR, Leong WH, Gori F, Buchan GD, Sundberg J (2002) Inter-particle contact heat transfer in soil systems at moderate temperatures. *International Journal of Energy Research* 26(15):1345-1358, DOI: 10.1002/er.853

Tarnawski VR, Momose T, Leong WH (2009) Assessing the impact of quartz content on the prediction of soil thermal conductivity. *Géotechnique* 59(4):331-338, DOI: 10.1680/geot.2009.59.4.331

Verhoef A, Bart JH, Jacobs AG, Heusinkveld BG (1996) Thermal soil properties for Vineyard (EFEDA-I) and Savanna (HAPEX-Sahel) sites. *Agricultural and Forest Meteorology* 78(2):1-18, DOI: 10.1016/0168-1923(95)02254-6

Wang H, Yang P, He Z (2012) Influence of porosity and saturation on thermal properties of silty soils. *Journal of Nanjing Forestry University* 32(2):42-46, DOI: 10.3969/j.issn.1000-2006.2012.02.009

Woodside W, Messmer JH (1961) Thermal conductivity of porous media. I. Unconsolidated sands. *Journal of Applied Physics* 32(9):1688-1699, DOI: 10.1063/1.1728419

Xu M, Wang D, Jiang W, Qi J (2011) Review on thermal conductivity coefficient of rock and soil mass. *Journal of Earth Sciences and Environment* 33(4):95-107, DOI: 10.3969/j.issn.1672-6561.2011.04.015 (in Chinese)

Zhang N, Yu X, Pradhan A, Anand JP (2015) Thermal conductivity of quartz sands by thermo-time domain reflectometry probe and model prediction. *Journal of Materials in Civil Engineering* 27(5):899-909, DOI: 10.1061/(asce)mt.1943-5533.0001332

Zhang HY, Zhang X, Chen X (2014) Research on thermal parameters of different earthen monument soils. *Rock and Soil Me*chanics 35(1):57-62, DOI: 10.16285/j.rsm.2014.s1.006