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Evaluation of calculation models for the thermal conductivity of soils

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ABSTRACT

In the study, a matrix model, based on the combinations of 1 thermal conductivity model for saturated soils (λ_{sat}), 4 thermal conductivity models for dried soils (λ_{dry}) and 4 Kersten number models for soils (K_e), was proposed to calculate the thermal conductivity of soils. 16 calculation models were included in the matrix. The matrix could be used to investigate the effects of the λ_{dry} models and K_e models on the calculational results of the 16 calculation models for the thermal conductivity of soils. The matrix was evaluated by 40 Canadian soils, and it is found that the He et al. model for λ_{dry} performs best among the 4 λ_{dry} models, the Côté and Konrad model for K_e performs best among the 4 K_e models. It also shows that the results of the calculation models in the matrix are different significantly, but the JCM (combination of the geometric mean model for λ_{sat}, the Johansen model for λ_{dry}, and the Côté and Konrad model for K_e) performs best among the calculation models for the thermal conductivity of soils. The effects of the λ_{dry} models and K_e models on the calculational results of calculation models for the thermal conductivity were evaluated by the modified difference index (MDI), showing that the K_e models have much larger effect on the calculational results than the λ_{dry} models. Besides, the calculation models containing the Côté and Konrad model for K_e were recommended to calculate the thermal conductivity of soils for its high accuracy.

1. Introduction

Thermal conductivity is an important thermal parameter for heat transfer analysis of soils [1–5]. Steady state method and transient state method are usually used to measure it [6,7]. However, it is not easy to determine the thermal conductivity of soils (λ) because some factors, e.g. high cost, hard work, are the main hindrances to experimentally obtain the thermal conductivity of soils [2]. Therefore, many calculation models were proposed to determine it [8–16]. Johansen [8] proposed a model to determine the thermal conductivities of unsaturated soils in both frozen and unfrozen states by the relationship between the normalized thermal conductivity (Kersten number, K_e) and degree of saturation (S_r). He also proposed two empirical models for the thermal conductivities of saturated and dried soils. Nevertheless, Ewen and Thomas [9] found that the Johansen model underestimated the thermal conductivities at low water contents. To improve it, a new K_e model was put forward to determine the thermal conductivity of unsaturated sands. The result suggested that the new K_e model performed better than the previous K_e model, but the new K_e model was only available to unfrozen sands. Later, Côté and Konrad [11] modified the relationship between K_e and S_r with a soil-type factor for covering the full range of S_r. They also developed a new model to calculate the thermal conductivity of dried soils (λ_{dry}) from porosity. However, Lu et al. [12] suggested that the Côté and Konrad model gave unexpected thermal conductivity, especially for fine-grained soils at low water contents. Then he proposed a new model to reduce the errors at low water contents, and introduced a simple linear model to calculate λ_{dry} from porosity (n). Besides, other researchers also improved the calculation models for the thermal conductivity of soils by considering different soil parameters [10,17].

From the above studies, λ can be calculated by 3 types of models, i.e. λ_{sat} models, λ_{dry} models, and K_e models. λ_{sat} was usually determined by the geometric mean model [1,14,18]. To obtain λ_{dry}, many empirical models were proposed to calculate it, such as the Johansen model [8], Balland and Arp model [10], Côté and Konrad model [11], Lu et al. model [12], He et al. model [2]. A lot of models were also used to calculate K_e, i.e. Johansen model [8], Ewen and Thomas model [9], Balland and Arp model [10], Côté and Konrad model [11], Lu et al. model [12], Lu and Dong model [13], Go et al. model [14]. Researches of calculation models for the thermal conductivity can be classified into

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two groups: (1) evaluation of the previous calculation models for the thermal conductivity (e.g. the Johansen model, the Côté and Konrad model, the Lu et al. model.) by different soils [19,20] and (2) development of a new calculation model for the thermal conductivity and comparison between the new calculation model and previous calculation models or measured data [12,13,21–25]. However, there are seldom researches on the evaluation of the calculation models with different combinations of λ_{sat} models, λ_{dry} models and K_e models. Different combinations of the 3 types of models will form significant different calculation models for the thermal conductivity, yielding the difference of the calculated thermal conductivity. Therefore, a matrix consisting of 1 λ_{sat} model, 4 λ_{dry} models and 4 K_e models was proposed to calculate the thermal conductivity of soils, and to investigate the effects of the K_e models and λ_{dry} models on the calculational results of the thermal conductivity. The 4 λ_{dry} models, the 4 K_e models, and the 16 calculation models in the matrix were also evaluated by 40 Canadian soils from references [26,31].

2. Theory and method

Johansen [8] developed a model to determine the thermal conductivity of soils. The model is given as,

$$\lambda = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry} \tag{1}$$

where λ, λ_{dry}, λ_{sat} are the thermal conductivities of soils, dried soils, saturated soils, respectively; K_e is the dimensionless thermal conductivity [8], and can be expressed as,

$$K_e = \frac{\lambda - \lambda_{dry}}{\lambda_{sat} - \lambda_{dry}} \tag{2}$$

Eq. (1) shows that λ can be calculated by 3 parameters (i.e. λ_{sat}, λ_{dry}, and K_e). Actually, K_e is not an independent parameter and relies on the 3 measured parameters (i.e. λ_{sat}, λ_{dry}, and λ) in Eq. (2). However, K_e can be regarded as an independent parameter in the calculation model for the thermal conductivity. Many models have been proposed to describe the relationship between K_e and S_r with various mathematical functions. Moreover, λ_{sat} and λ_{dry} can be also calculated by empirical models [8,11,12]. Here, 1 λ_{sat} model, 4 λ_{dry} models (i.e. the Johansen model, the Côté and Konrad model, the Lu et al. model, and the He et al. model) and 4 K_e models (i.e. the Johansen model, the Ewen and Thomas model, the Côté and Konrad model, and the Lu et al. model) were selected to calculate the thermal conductivity of soils. The geometric mean model was used to determine λ_{sat} for the high accuracy and simplest form [27]; the Johansen model, the Côté and Konrad model, and the Lu et al. model are the classic models for λ_{dry} while the He et al. model is a newly developed model [2]; the Johansen model, the Ewen and Thomas model, the Côté and Konrad model, and the Lu et al. model are the classic models for K_e, and are widely used to calculate K_e. Therefore, a matrix is formed, as shown in Table 1. It shows that a total number of 16 calculation models for the thermal conductivity were included in the matrix. The name of each calculation model for the thermal conductivity can be represented by 3 capitals; namely, the first capital is the λ_{dry} model, the second capital is the K_e model, and the third capital M stands for model. No capital stands for the λ_{sat} model because the λ_{sat} model is the same for all the 16 calculation models. For example, JJM suggests the calculation model was obtained by the combination of the geometric mean model for λ_{sat}, the Johansen model for λ_{dry}, and the Johansen model for K_e while LEM suggests the calculation model was obtained by the combination of the geometric mean model for λ_{sat}, the Lu et al. model for λ_{dry}, and the Ewen and Thomas model for K_e.

The 3 types of models (i.e. λ_{sat} models, λ_{dry} models, and K_e models) can be expressed as follows:

2.1. λ_{sat} model

Although many models have been proposed to calculate the thermal conductivity of saturated soils, of which geometric mean model (Eq. (3)) is widely used [27]. For Eq. (3), it contains two parameters, i.e. λ_s, λ_w. Lu et al. [12] indicated that λ_w is 0.594 $\mathrm{W m^{-1} K^{-1}}$. For λ_s, if mineral composition is completely known, λ_s can be calculated by Eq. (4) [27], otherwise, Eq. (5) is used to calculate λ_s [8].

$$\lambda_{sat} = {\lambda_s}^{1-n}{\lambda_w}^{n} \tag{3}$$

where λ_s, λ_w are the thermal conductivities of soil grains and water, respectively; n is the porosity.

$$\left.\begin{array}{l} \lambda_s = \prod_j \lambda_{m_j}^{x_j} \\ \sum_j x_j = 1 \end{array}\right\} \tag{4}$$

where λ_{m_j} is the thermal conductivity of mineral j; x_j is the volumetric fraction of mineral j.

$$\lambda_s = \begin{cases} 2.0^{1-q} \times 7.7^q & q > 0.2 \\ 3.0^{1-q} \times 7.7^q & q \le 0.2 \end{cases} \tag{5}$$

where q is the quartz content.

In this paper, Eq. (4) was used to calculate the thermal conductivity of soil grains because all minerals are available [28]. Tarnawski et al. [28] measured the mass fractions of all minerals of the 40 soils, and assumed the densities of all minerals are the same. Therefore, the values of volumetric fraction and mass fraction are the same. The mass fractions of all minerals can be found in reference [28]. The thermal conductivity of soil minerals is shown in Table 2 [29,30]. Tarnawski and Leong [31] also calculated the thermal conductivities of soil grains (λ_s) for 40 Canadian soils, but their results are slightly different from the calculated λ_s in this study. It is because the mean thermal conductivity of quartz and minimum thermal conductivities of other soil minerals were selected to calculate λ_s by Tarnawski and Leong [31], whereas the mean thermal conductivities of all soil minerals were selected to calculate λ_s in this study.

Table 1
Matrix for calculation models of the thermal conductivity.

			K_e category			
			Johansen (J)	Ewen and Thomas (E)	Côté and Konrad (C)	Lu et al. (L)
			Johansen model group	Ewen and Thomas model group	Côté and Konrad model group	Lu et al. model group
λ_{dry} category	Johansen (J)	Johansen model group	**JJM**	**JEM**	**JCM**	**JLM**
	Côté and Konrad (C)	Côté and Konrad model group	**CJM**	**CEM**	**CCM**	**CLM**
	Lu et al. (L)	Lu et al. model group	**LJM**	**LEM**	**LCM**	**LLM**
	He et al. (H)	He et al. model group	**HJM**	**HEM**	**HCM**	**HLM**

Note: The first capital is the λ_{dry} model, the second capital is the K_e model, and the third capital M stands for model.

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