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A new method to model the thermal conductivity of soil–rock media in cold regions: An example from permafrost regions tunnel

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ABSTRACT

Thermal conductivity of soil–rock media is an important index for analyzing the temperature field of cold region engineering. As a kind of mixed media, the thermal conductivity is determined by many factors, e.g. porosity, dry density, saturation degree, temperature, water content and so on. In this study, the thermal conductivity model of soil-rock media is established by multiple linear regression method based on the basic parameters of soil–rock samples. The significant testing (correlation coefficient R^2, F-test and probability-of-F-to-enter) shows that the regression effect is well. To validate the multiple linear regression model, a comparison of the calculated values from the model with the tested data not used in the construction of the model shows that this model can effectively calculate thermal conductivity of soil–rock media. Additionally, compared with the other three general models, i.e. BP neural model, physical model and CK model, the multiple linear regression model is more reasonable and effective. Finally, based on the apparent heat capacity theory, a general regression model for soil–rock media in cold regions is obtained. It is hoped that a parameter basis can be provided for the temperature field simulation of cold region engineering from the study.

1. Introduction

The engineering construction will change the thermal balance of ground surface in cold regions, however, the thermal conductivity of soil–rock media influences significantly the temperature field of cold region engineering, which is related to engineering diseases caused by frost heave. Thermal conductivity is a key parameter to determine the heat transfer rate and the freeze–thaw depth in the thermal stability prediction of cold region engineering. It is impractical to test the soil–rock thermal conductivity for the whole engineering due to the complicated engineering geology and requirements of project schedule. Currently, the research methods of thermal conductivity of media are mainly divided into two kinds: one is the numerical back analysis method, namely, based on the given boundary conditions and distribution of temperature field, using Fourier law to calculate the equivalent thermal conductivity with the consideration of heat and mass transfer; The other is the theoretical prediction model measure, that is, establishing theoretical prediction model including the thermal performance of each component in the media based on the test results and theory analysis.

For theoretical prediction model, Kersten (1952) studied the effect of dry density and water content on thermal conductivity, and established the semi-theoretical and semi-experimental model. Devries (1963) introduced the shape coefficient to reflect the influence of soil grain structure on thermal conductivity. Omar (1981) calculated the thermal conductivity of frozen soils considering the influence of the saturation degree. Chen et al. (1992) proposed a general method of calculating the effective thermal conductivity of complex material based on the minimum heat resistance rule and the effective thermal conductivity rule. Vlodek and Bernhard (1993) proposed a model which could be employed for the quick estimation of thermal conductivity of any soil with lognormal grain size distribution based on the Devries model. Liu et al. (2002) established a simple suitable prediction model of thermal conductivity of frozen soils by indoor test, which includes two basic variables, i.e. porosity and saturation. Côté and Konrad (2005) thought that these models proposed by Kersten (1952) and Devries (1963) were not appropriate to frozen soils. Based on the experimental data of dry soil and saturated soil, he developed the prediction model proposed by Johansen (Johansen, 1975), which considered the freeze–thaw phase change. Rock–soil materials are generally considered to be porous media, thermal conductivity of which are related to porosity, dry density, saturation degree, temperature, etc. Parameters of rock-soil media are of great variable. All the above models may apply to certain kind of media, however large errors may occur for other media.

For the numerical back analysis method, based on the measured temperature field of the surrounding rocks in a cold region tunnel, Lu et al. (2000) analyzed the thermal conductivity by means of one-dimension steady heat conduction equation. Hu et al. (2001) calculated the temperature and heat flux by using finite element method and analyzed the influence of different saturation to thermal conductivity based on the moisture migration. Li et al. (2007, 2009) simulated the

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relationship between thermal conductivity of geotechnical material and its porosity and fractal dimension as well based on three-dimension steady heat conduction equation. Combined with random mixed media theory and steady heat conduction equation, Tan et al. (2010) studied application cases and special features of several methods by calculating the thermal conductivity during freeze–thaw cycle, which provided reference for the calculation of thermal conductivity under low temperature considering phase change. The numerical back analysis method is usually used to evaluate the thermal conductivity of rock–soil media. However, accurate temperature field and related heat conduction model are key to the numerical back analysis method. Additionally, other parameters of rock–soil media will also influence the result of back analysis, such as porosity, particle shape and saturation degree. More importantly, the temperature field usually cannot be obtained during constructions. So the theoretical prediction model, especially, a simple and useful model is still a common implementation technique.

In this paper, based on rock–soil parameters such as porosity, dry density, water content and saturation degree, the multiple linear regression model is established to predict thermal conductivity of rock–soil media. To validate the multiple linear regression model, a comparison of the calculated values from the model with the tested data not used in the construction of the model is carried out. Additionally, compared with the other three general models, i.e. BP neural model, Physical model and CK model, a better model is suggested. Finally, based on the apparent heat capacity theory, a general regression model is obtained.

2. Study sites and sample test

The E Lashan and Jiang Luling tunnels are located at Qinghai, China, which belongs to a periglacial region with tectonic erosion submountains. The two tunnels are bi-directional with an altitude above 4280 m under a typical continental arid and semi-arid climate. The winters are bitterly cold and long while the summers are cool. The mean annual air temperature is −4.2 °C. The extremely high temperature is 26.6 °C, and the extremely low temperature is −48.1 °C. Rainfall in this area increases with the gradually rising terrain, with the mean annual rainfall at 369.2 mm and the mean annual evaporation at 1372 mm. The maximum snow depth reaches 16 cm and the permafrost table is about 277 cm.

The E Lashan tunnel has a total length of 4695 m. The mileage at the left entrance of the tunnel is K300 + 940, with the mileage of K305 + 635 at the exit. According to the drilling data, the emergence strata of the tunnel zone are mainly Triassic clastic rock, volcanic rock and pyroclastic rock of neritic facies. The Tertiary is a set of deposited conglomerate mingled with mudstone of inland lake facies.

The Jiang Luling tunnel has a total length of 2925 m. The mileage at the left entrance of the tunnel is K329 + 710, with a mileage of K332 + 635 at the exit. Bedrock is mainly a set of clastic sedimentary rocks with geosynclinal facies of Lower Permian system. The covering layer is Holocene series of alluvial deposits and slope deposits in Quaternary.

During the excavation process of the two tunnels, 21 undisturbed rock samples at the tunnel surrounding rocks were obtained, of which 11 samples were from the E Lashan tunnel and 10 samples were from the Jiang Luling tunnel.

3. Establishment of the model

As a kind of mixed media, soil–rock media's thermal conductivity is determined by many factors, e.g. porosity, dry density, saturation degree, temperature, water content and so on. We propose a multiple linear regression model to derive a best-fit equation to predict thermal conductivity of soil–rock media. Variables can be entered or removed from the model depending on the significance testing.

3.1. Parameter selection of the model

1) Saturation S_r and porosity n
   Usually soil–rock media can be regarded as comprising four components, i.e. solid particle, unfrozen water, ice and air. The thermal conductivities of the four components are listed in Table 1.
   Table 1 shows that the thermal conductivities of the four components are significantly different, and the thermal conductivities of solid particle and ice are relatively larger among the four components. In order to perfectly demonstrate the effect of each component on the thermal conductivity of the media, the saturation degree Sr and porosity n are selected as the two basic parameters to describe the thermal conductivity of soils.
2) Temperature T
   The influence of temperature on the thermal conductivity of soil–rock media mainly includes two aspects: on a macro level, phase change of water occurs in the pore around the freezing point. Thus, the thermal conductivity difference between frozen and unfrozen water will affect thermal conductivity of the soil–rock media. On a micro level, heating makes the molecules of a material move faster, which may increase the thermal conductivity. Generally, the micro-effect could be disregarded for geo materials. Consequently, the thermal conductivity of geo materials increases with the decrease of negative temperature (Xu et al., 2009).
3) Particle dispersion
   The degree of dispersion affects the shape of porosity in soil–rock media and results in the change of contact between unfrozen water, ice, air and soil–rock particles. The shape factor is introduced to reflect the influence of particle dispersion on thermal conductivity.
   Studies propose that shape factor χ can describe the shape of soil–rock media (Côté and Konrad, 2005). The shape factor is related to the saturation degree of soil–rock media which could be defined as $\chi = \sqrt{Sr}$ (Liu et al., 2002). So the saturation degree S_r is taken as one parameter in the multiple linear regression model.

3.2. Multiple linear regression model

From the above analyses, the parameters selected in the thermal conductivity model are porosity, dry density, saturation degree, temperature and water content. The thermal conductivity model can uniformly be written as:

$$\lambda = (\lambda_m, n, \rho_d, S_r, T, w) \quad (1)$$

Where λ_m is the thermal conductivity of each component, n is porosity, ρ_d is dry density, S_r is saturation degree w is water content and T is temperature.

In this study, porosity n, dry density ρ_d ($/m^3$), saturation degree S_r, water content w(%),and thermal conductivity λ (W/(m·°C)) of 21 samples (two tunnels) were tested. Based on the data from the E Lashan tunnel (in Table 2), the multiple linear regression model was established. Then, the tested data from the Jiang Luling tunnel (in Table 3) were employed to validate the multiple linear regression model.

To consider the effect of temperature T on thermal conductivity, multiple linear regression models of thermal conductivity for frozen

Table 1
Thermal conductivity of each component of soil–rock media [$W/(m\cdot°C)$].

Component	Thermal conductivity ($W/(m\cdot°C)$)
Solid particle/λs	1.2–7.5
Unfrozen water/λw	0.4–0.6
Ice/λi	2.2–2.3
Air/λg	0.02