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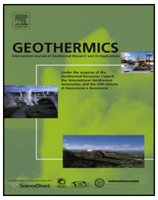

Correlation study of shallow layer rock and soil thermal physical tests in laboratory and field

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ABSTRACT

A new method was proposed in this study to determine the correlation between laboratory and thermal response tests that are usually applied to examine the thermal physical parameters of shallow-layer rock and soil. Layer depth, water content, density, and permeability were found to be the primary factors that affect the discrepancy between the two tests. Analytic hierarchy process was then used to compute the weighted values of each factor, and the testing results of the thermal physical parameters in the laboratory were modified based on the weighted values. Field and modified laboratory thermal physical parameters and practical heat transferring process were simulated using the numerical model, and the discrepancies in the heat conduction capacity were similar under three conditions. Finally, the product of pipe depth and thermal conductivity was suggested to represent heat transfer capacity, and the computed uniform thermal conductivity of the laboratory after modification was proposed to be basically equal to the comprehensive thermal conductivity of the thermal response test. This study provides new insights in determining the thermal physical parameters of rock and soil layers.

1. Introduction

The accurate measurement of the thermal physical parameters of rock and soil layers is a crucial step in the application of ground source heat pump (GSHP). The heat exchange capacity of the ground is determined by testing thermal physical parameters, such as thermal conductivity, specific heat capacity and thermal diffusivity. Thermal conductivity is a critical parameter that determines heat transfer capacity. Thermal physical parameters are determined by laboratory methods and thermal response tests (TRTs) (Wang et al., 2007; Chen, 2008; Abuel-Naga et al., 2009; Hao et al., 2011; Huang, 2012). The former consists of steady and transient states, which include need-probe (uncertainty, 2–3%), divided-bar (uncertainty, 4%), guarded hot plate (4%), and hot wire (uncertainty, 4–5%). The latter is an in situ technique that is widely adopted in GSHP application (Signorelli et al., 2007; Sharqawy, Said et al., 2009). However, laboratory tests are limited because they only provide every point value of samples within the borehole depth, in which several properties, such as structure and water content, have changed. Thus, the testing results do not fully reflect the on-site heat transfer capacity of rock and soil layers. The TRT measures the gross value of thermal physical parameters within the ground, which could simulate the actual GSHP operation (Hu et al., 2009a,b; Beier, 2011). Hence, the TRT is the best choice to test the thermal physical parameters for designing a ground heat exchanger. However, the TRT is also affected by many factors such as test cycle, power supply stability, groundwater seepage, and so on (Bandos, 2009; Song, 2009; Witte, 2013).

TRT has been paid increasing attention because of its importance in GSHP. Yavuzturk et al. (1999), Yavuzturk and Chiasson (2002), Zeng et al. (2002), Yu et al. (2006), and Guan et al. (2011) studied the theoretical models of TRTs. Field testing instruments are also improved and developed (Gehlin, 2002; Wang et al., 2007, 2009, 2010; Meng, 2012). Yu et al. (2003), Lim et al. (2007), Sharqawy, Mokheimer et al. (2009), Hu et al. (2009a,b), Guan et al. (2010), and Bandos et al. (2011) processed uncertain analysis for testing results. Wanger and Clauser (2005), and Wagner and Bayer (2012) analyzed and evaluated the TRT. However, only a few studies have focused on laboratory tests, and the differences between the two testing techniques are rarely reported (Yu and Fang, 2002; Fan et al., 2007; Wang et al., 2010; Huang, 2012; Barry-Macaulay et al., 2013). In addition, studies on the correlation of the two methods have not yet to be done.

Combined with the thermal physical tests of some projects in Shanghai and Jiagedaqi, the discrepancy between the experimental results from laboratory tests and TRTs was analyzed. The primary factors that affect the thermal physical parameters were selected,

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and the weighted vector of every influencing factor were determined using the analytic hierarchy process (AHP) (Saaty, 1980) as well as by comparing the two testing methods and analyzing the factors without considering in the laboratory tests. The thermal physical parameters of laboratory tests were modified based on the weighted values. The modified values could reflect the ground heat transfer capacity in the study area. Finally, the modified thermal physical parameters and the values of the TRTs were simulated with the simulation program developed by the authors to verify that the two conditions are basically similar in terms of heat transfer capacity and illustrate the applicability of the modified method. Two simulating results and the actual heat transfer process of the ground heat exchanger were also compared. The study indicates that use of laboratory thermal physical parameters can be more suitable, thereby providing a good supplement for in situ TRT and reference data for GSHP design.

2. Fundamental principle

Physical properties are generally always affected in the process of obtaining rock and soil samples. This process causes the differences in the thermal conductivity in actual situations. Thus, the results from TRT are adopted in designing a GSHP system. Based on these conditions, a new method is proposed in which AHP is used to modify the laboratory test data, and inversion thermal conductivity is performed by considering the primary influencing factors. This method enables the modified data to reflect the ground heat conduction capacity as close to that of the TRT.

Previous studies have shown that different factors had varying effects on the thermal physical parameters of rock and soil. The change in specific heat capacity slightly affects thermal conductivity (Hu, 2009; Li, 2009; Chang, 2011). When water content and density increase, their influence on thermal conductivity also increases. However, the influence of porosity presents contrasting results (Abu-Hamdeh, 2001, 2003; Li et al., 2009). The influence of ground water seepage on thermal conductivity is more obvious (Chiasson et al., 2000; Fujii et al., 2005; Fan et al., 2007; Bozdag and Paksoy, 2008; Hu, 2009; Lee and Lam, 2012). Thus, the following were considered in the present study:

1. Layer depth, water content, density, and permeability coefficient were selected as the main factors that affect the thermal physical parameter discrepancy between laboratory and field tests.
2. Detailed field exploration, in situ TRT, and laboratory tests were performed to obtain accurate geotechnical thermal physical parameters, physical parameters and lithology data.
3. The use of AHP could establish a hierarchical structure model of thermal conductivity, which could determine the weighted values of the influencing factors.
4. To verify the applicability of the modified method, three heat transfer conditions were simulated with the models of heat conduction and seepage. These conditions include the thermal physical parameters of laboratory tests before and after modification, the TRTs, and the practical ground heat exchange process of rock and soil layers.

2.1. AHP

Table 1
Fundamental scale of AHP (Saaty, 1980).

Value a_{ij}	Description
1	Elements *i* and *j* are equally important
3	Elements *i* is slightly more important than element *j*
5	Elements *i* is much more important than element *j*
7	Elements *i* is proved to be more important than element *j*
9	Elements *i* is absolutely more important than element *j*
2, 4, 6, 8	Middle values

Table 2
Average random consistency index (*RI*).

n	RI	*n*	RI
1	0	8	1.41
2	0	9	1.46
3	0.52	10	1.49
4	0.89	11	1.52
5	1.12	12	1.54
6	1.24	13	1.56
7	1.36	14	1.58

AHP can be divided into three stages in which the weights of the influencing factors in the thermal conductivity are analyzed (Deng et al., 2012; Kuzmana et al., 2013). Based on a scale from 1 to 9 (Table 1), which was suggested by Saaty (1980), the relative importance of pair-wise comparisons a_{ij}, $i, j = 1, \ldots, n$, of elements *i* and *j* was evaluated and collected in the pair-wise comparison matrix *A*. The inverse comparison was assigned a reciprocal value: $a_{ji} = 1/a_{ij}$.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad (1)$$

where a_{ij} is the important degree of element *i* relative to element *j*.

Then, the following values were calculated by Eqs. (2)–(5): vector of weights (ω), maximum eigenvalue ($\lambda_{\max}$), and consistency ratio (*CR*), respectively.

$$\omega_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}, \quad i = 1, 2, \ \ldots, \ n \qquad (2)$$

$$\lambda_{\max} = \frac{\sum_{i=1}^{n}((A\omega)_i/\omega_i)}{n} \qquad (3)$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \qquad (4)$$

$$CR = \frac{CI}{RI} \qquad (5)$$

where ω_i is the weight value, *n* is the matrix order, *CI* is the consistency index, and *RI* is the average random consistency index (Table 2).

Finally, Eqs. (6) and (7) were used to calculate the total hierarchy sorting and the corresponding consistency ratio, respectively.

$$\omega_j^L = \sum_{i=1}^{n_1}\omega_i^K \varphi_{ji}, \quad j = 1, 2, 3, \ \ldots, \ n_2 \qquad (6)$$

$$CR^L = \frac{\sum_{i=1}^{n_1}(\omega_i^K CI_{K_i}^L)}{\sum_{i=1}^{n_1}(\omega_i^K RI_{K_i}^L)} \qquad (7)$$

where ω_i^K is the total ordering weight vector of *i*th ($1 \le i \le n_1$) factor K_i in the upper layer (*K*), and φ_{ji} is the weighted value of *j*th ($1 \le j \le n_1$) factor L_j in the lower layer (*L*) corresponding to K_i (when L_j and K_i are unrelated, $\varphi_{ji} = 0$). ω_i^L is the total ordering weight vector of *j*th ($1 \le j \le n_1$) factor L_j in the lower layer (*L*). $CI_{K_i}^L$ and $RI_{K_i}^L$ are the consistency and average random consistency indexes of the judgment matrix in the *L* layer corresponding to K_i, respectively. CR^L is the total ordering random consistency ratio of the *L* layer.