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Research and analysis on influence factors of accuracy of geotechnical thermal response test

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Abstract

In this paper, simulation model of thermophysical properties test have been established and the accuracy of which have been verified by actual test data. Using linear heat source model to process simulation data for the analysis of different factors influences on simulation results. It shows that when using linear heat source model as the regression model for rock-soil thermophysical properties, in order to improve the thermophysical property accuracy identification, test duration should be 72 hours with elimination of the first 12 hours data and ensure a strong turbulent state for the flow velocity in pipes.

Keywords: Borehole heat exchanger；thermophysical properties test；linear heat source model

1. Background

Technology of thermophysical properties of rock-soil test is the premise and foundation of the highly efficient and energy-saving operation of the ground source heat pump (GSHP) system. By simulating the heat transfer characteristics of the borehole heat exchanger under the actual working conditions and with the help of theoretical analysis model or professional simulation software, an effective bridge is built between obtaining thermophysical properties of rock-soil and guiding the design of the actual GSHP system which effectively promote the scientific nature and rationality of GSHP system design.

The common test methods of under-ground rock-soil thermophysical properties include geotechnical types identification method, steady-state plate test, probe test and thermal response test, etc. [1,2], among which the most widely used type is the thermal response test. And currently, the most commonly used ones are the constant heat flow method and constant temperature method. The constant heat flow method was first proposed by C.eklof in 1996 [3-6], which has been recommended by the IGSHPA and ASHRAE standards as the international practice. This method only test the exothermic condition which uses the electric heater to provide stable heating quantity, records the water temperature at the inlet and outlet of the buried tube at each time, and uses the mathematical model to obtain the thermophysical properties of the rock and rock-soil, that is easy to operate and widely used and is also applied by the national standard of GB50366 *Technical code for ground source heat pump system* for thermophysical properties measurement of soil and rock [7].

The main calculation method of rock-soil thermophysical property test is to deduce the thermophysical parameters by inverse algorithm which requires input of the test results in the computer and compare them with the simulation results. By repeatedly adjusting the thermophysical parameters of the rock-soil in the heat transfer model until the variance of the average temperature value and the minimum value are obtained, it is considered that the thermophysical parameters in the heat transfer model are exactly those of the rock and soil in the location.

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2. Model establishment and verification

In this paper, simulation model of the soil and rock thermophysical properties test has been established through TRNSYS as is shown in Fig.1. Duct Ground Heat Storage Model (DST) has been applied for borehole heat exchanger which is a typical mixed solution of both analytical and numerical methods. Verified by the actual test results, reliability of the model has been confirmed, and input conditions are changed to obtain the operation results under different boundary conditions. Taking simulation results as the true value, influence of different test factors on the accuracy of identification results is analyzed by using linear heat source model to process the data.

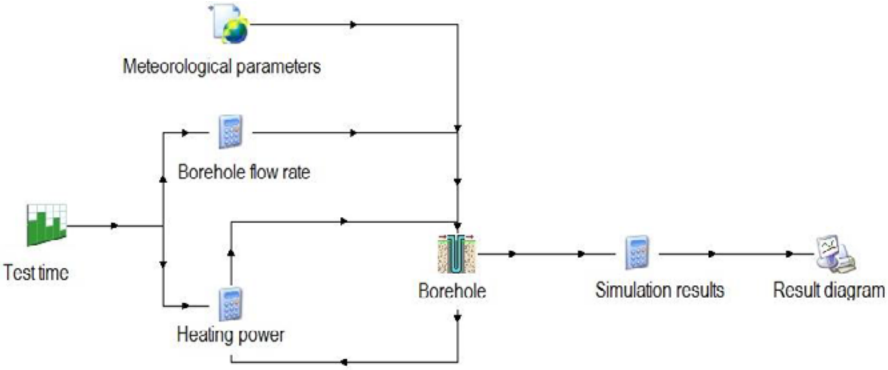

Fig. 1. TRNSYS Simulation model

In order to verify the simulation model of rock-soil thermophysical test, simulation study on an actual GSHP test was conducted for comparison between simulation and test results. In the thermal response test, the constant heating power is 5.938kw, the fluid carrying capacity is 0.854m3/h, and the structural parameters of DN32 single U-type borehole heat exchanger are shown in Table 1. In order to measure the temperature of rock-soil, 10 temperature sensors are arranged along the depth, with an interval of 10 meters between each two temperature sensors. After 48 hours, the values of the 10 temperature sensors are added and averaged. The initial temperature of rock-soil is 20.05℃, and its physical parameters are shown in Table 2.

Table 1 Structural parameters of buried tube heat exchanger

Drilling depth/m	**Hole radius/mm**	**Tube internal diameter/mm**	**Tube wall thinkness/mm**	**Center distance/mm**
100	65	26	3	64

Table 2 Physical parameters of borehole heat exchanger

Substance	**Density/kg/m³**	**Specific heat capacity /J/(kg·K)**	**Thermal conductivity /W/(m·K)**
Soil and rock	1600.0	1645	2.71
Backfill	1860.0	840	2.00
Buried tube	950.0	2300	0.44
Fluid carrying	998.2	4182	0.60

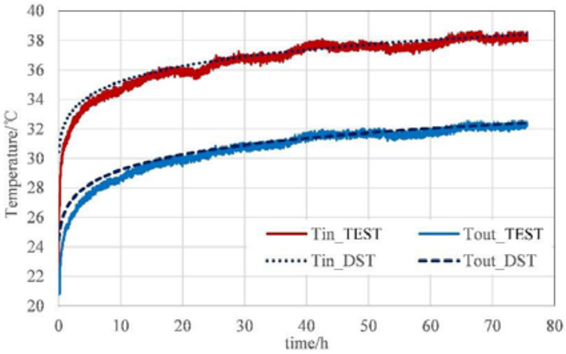

Fig. 2. Comparison between simulation and test values of inlet and outlet temperature

Fig.2 shows that during the 75 hours of simulation calculation, Simulation values of the model (based on DST) have a good agreement with the heat response test data which verifies the accuracy of simulation model.

3. Influence factors of thermophysical properties identification

Using the simulation model to calculate thermophysical properties of the borehole heat exchanger, simulation results are taken as the true values. Comprehensive thermal conductivity of rock-soil based on the simulation results is obtained by using the linear heat source theory to process the data for the analysis of the pattern of various influence factors on thermal response test results.

According to the characteristics of large length to diameter ratio of borehole heat exchanger, the model assumes that heat transfer process is between an underground linear source and the surrounding semi-infinite rock and soil. Therefore, the linear heat source model not only ignores the vertical heat transfer, but also omits the heat capacity inside the hole, namely, the linear heat source model cannot reflect the transient heat transfer process inside the hole, so that when data processing is carried out for the thermophysical property test of rock and soil, linear heat source model fails to process the data before a to-be-steady state inside the hole. In this paper, factors such as test duration, abandoning the early data period, heating power, flow velocity of the fluid inside the tubes are have been respectively analyzed, and the influence of these factors on thermophysical parameters identification of rock-soil are studied.

According to the linear source model, after taking the natural logarithm of the test duration (T), the average temperature T of the carrying fluid corresponding to each time point has a linear relationship with the logarithm value ln (T) of time.

Linear heat source model formula is shown as follows：

$$T = k \cdot \ln(t) + b \tag{1}$$

$$k = \frac{Q}{4\pi\lambda H} \tag{2}$$

$$b = \frac{Q}{4\pi\lambda H}\left[\ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma\right] - \frac{Q}{H} \cdot R_b + T_0 \tag{3}$$

Where T is the average value of the temperature at the inlet and outlet of the fluid in the ground heat exchanger, ℃；

Q is the total heating power under the test condition, W;

H is the buried pipe depth, m;

λ is the thermal conductivity of soil and rock, w / (m.k);

α is the thermal diffusivity of soil and rock and, m²/s;

t is the test duration, s;

r_b is the drilling radius, m;

R_b is the thermal conductivity, (m.K)/W;

T_0 is the incipient soil and rock temperature, ℃;

γ is the Euler constant, （γ=0.5572）。

The T-ln (T) curve of the average water temperature at the inlet and outlet of the buried pipe and the test time can be obtained according to the simulation data of the thermophysical properties test of the rock-soil. Least square method is used to estimate the parameters of the simulation data, which minimized the variance between the average temperature and the simulation value of the regression model of the carrier fluid to obtain the slope of the T-ln (T) curve, and thus, acquiring the K value in the formula. Finally, the K value can be calculated. Finally, comprehensive thermal conductivity of rock-soil is obtained. For the convenience of data analysis, the relative error of comprehensive thermal conductivity of rock-soil is defined as follow:

$$EER = \frac{\lambda - \lambda_0}{\lambda_0} \times 100\% \tag{4}$$

Where λ represents the comprehensive thermal conductivity obtained through simulation calculation of linear heat source model; λ_0 represents thermal conductivity of rock and soil set in simulation model W/(m-K).

3.1. Test duration influence

The stable value of comprehensive thermal conductivity of rock-soil needs certain calculation time interval, and the guarantee of such calculation time interval needs a certain test duration first which is related to the test conditions of specific project. In this paper, based on the simulation model, the linear heat source model is used for data regression, and the curve of comprehensive thermal conductivity of rock-soil with the test duration is shown in Fig.3.

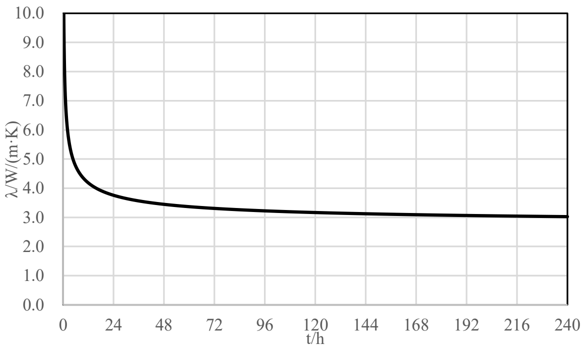

Fig. 3. Curve of comprehensive thermal conductivity of rock and soil with test duration

Fig.3 shows that with the extension of test duration, comprehensive thermal conductivity of rock-soil became closer to the true value. The relative error in early stage of the test decreases rapidly with the increase of time (the early time slope is larger) which indicates that in order to ensure the accuracy of the test results, it is necessary to extend the test duration as much as possible. When test duration is longer than 48h, the comprehensive thermal conductivity of rock-soil has become stable, and the error is within the acceptable range of the project. If the duration is 72h, the error will be further reduced. According to the regression calculation results and the relevant research results at home and abroad, it can be seen that 48h is the necessary test duration, and the optimal one is 72h [8,9].

3.2. Elimination length of transient data influence

From the above calculation, it can be seen that the linear heat source model cannot reflect the transient heat transfer process inside the hole, and the comprehensive heat transfer coefficient obtained from the data regression in this stage changes dramatically which has great deviation from the true value. If part of the transient heat transfer process data is removed, and data under steady state heat transfer process is used for regression simulation, the obtained thermophysical parameters will be more reliable. In this paper, influence of different elimination length of transient data on thermophysical parameters of soil is analyzed as is shown in Figure 4, the comprehensive thermal conductivity curve of rock-soil varies with the length of elimination time, and the accuracy is positively related with this elimination length.

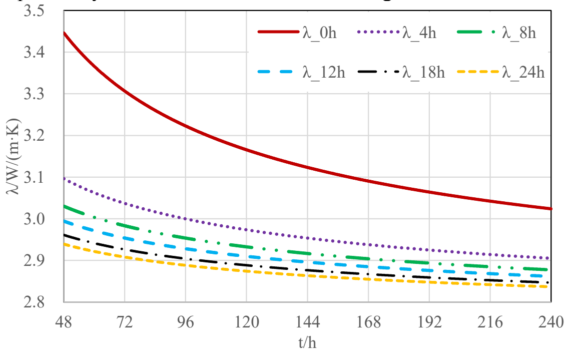

Fig. 4. Curve of rock-soil thermal conductivity under different elimination length of transient data

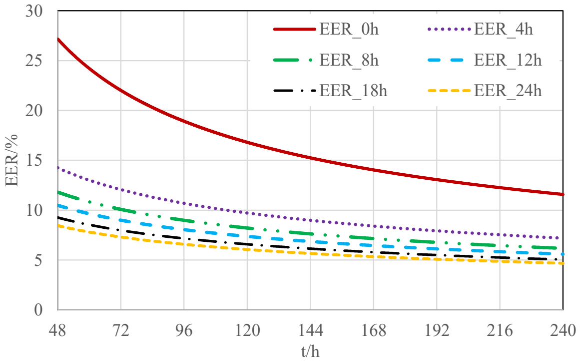

Fig. 5. Curve of rock-soil thermal conductivity relative error under different elimination length of transient data

Error change between rock-soil comprehensive thermal conductivity and the true value caused by the elimination length of transient time is shown in Figure 5. It can be seen for that when eliminating length is 12h, error rate is within 10%, and then with the increase of eliminating time, the error rate is significantly reduced. When the rock-soil comprehensive thermal conductivity is obtained by the inverse calculation of linear heat source model with the elimination of the first 12 hours of unsteady test data, more scientific and reasonable results can be obtained.

3.3. Influence of different heating power

Influence of different heating power on the identification results of rock-soil thermophysical properties test are analyzed. Under the same flow rate, heating power difference is realized through different inlet and outlet temperature ΔT, as shown in Figure 6, the following conditions are set as: 2 ℃, 4 ℃, 6 ℃, 8 ℃, 10 ℃. When different heating power is used, comprehensive thermal conductivity of rock-soil changes as shown in Figure 7.

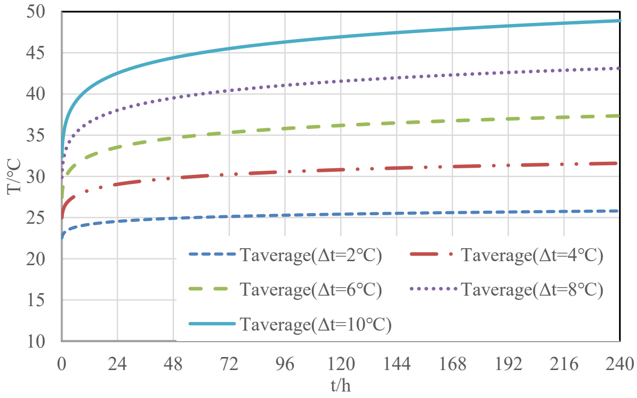

Fig. 6. Curve of average temperature under different heating power by different inlet and outlet temperature ΔT

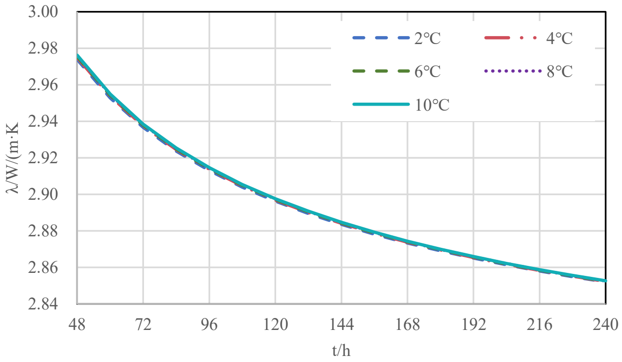

Fig. 7. Curve of rock-soil comprehensive thermal conductivity under different heating power by different inlet and outlet temperature ΔT

It can be seen from Figure 7 that under different heating power conditions, linear heat source model is used to regress the thermophysical parameters of rock-soil, and the results obtained by analyzing and comparing the comprehensive thermal conductivity are basically the same which indicates that the identification results of soil and rock thermophysical properties are not affected by heating power.

However, in the actual thermal response test, with the increase of the power of the heater, the thermal conductivity of the rock and soil tend to increase, which is caused by the leakage of groundwater. Because the buried depth of the underground tube is generally 50-200m where groundwater exists, heat transfer process inside and outside the hole will both be affected, thus the test results of rock-soil thermophysical properties are influenced. When using linear heat source regression calculation, the influence of groundwater is not considered, so the calculation results are not significantly different because of heating power. Therefore, the influence of groundwater leakage must be considered in the thermal response test. When there is no or little ground water leakage, the influence of the power of the heater can be ignored.

3.4. Flow velocity influence

Under the same condition of temperature difference between the inlet and outlet of the buried tube heat exchanger, influence of different velocity in the tube on the back calculation results of the thermophysical properties test is analyzed. The flow velocity in the pipe is set as follows: 0.1m/s, 0.15m/s, 0.2m/s, 0.3m/s, 0.4m/s, 0.6m/s, and the corresponding Reynolds number is shown in Table 3. Obtained comprehensive thermal conductivity curve of rock and soil is shown in Figure 8.

Table 3 Working condition group of simulation

No.	Velocity m/s	Flow rate kg/h	Re
1	0.1	190.79	3238.1
2	0.15	286.19	4857.1
3	0.2	381.58	6476.2
4	0.3	572.37	9714.2
5	0.4	763.16	12952.3
6	0.6	1144.74	19428.5

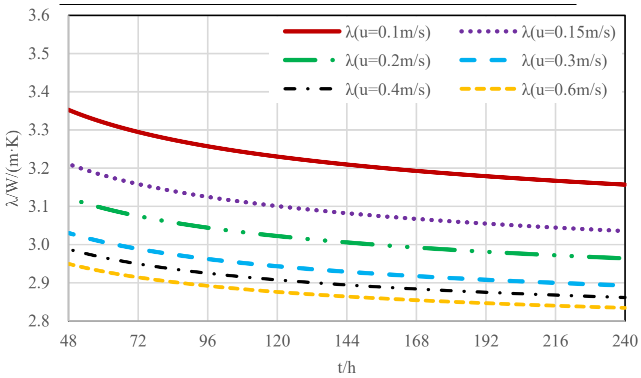

Fig. 8. Variation of rock-soil comprehensive thermal conductivity with test duration under different velocity

It can be seen from the above figure that when the velocity in the tube is in the laminar flow and transition area, error between the simulation and testing value of rock-soil comprehensive thermal conductivity is large with slow change. After turning into turbulence area, the deviation from the true value is rapidly reduced. Therefore, in order to get the most accurate parameters of thermal properties of rock-soil in limited testing duration, it is necessary to increase the flow velocity in the buried tube to maintain a strong turbulent flow.

4. Conclusions

In this paper, the simulation model of rock-soil thermophysical properties has been established, the linear heat source model is used to process the data. Influence of four factors on the accuracy of the identification results of thermophysical properties of rock-soil is analyzed including test duration, eliminating length of transient data, heating power and flow velocity. Results show that test duration is positively related to the accuracy of identification results of soil and rock thermophysical parameters. In order to ensure the accuracy of identification of these parameters, it is necessary to ensure a no-less-than 48hours test duration. Eliminating length of transient data is also positively related to the accuracy of identification results of soil thermophysical parameters, but considering the operability and accuracy of the test, the transient data in the first 12 hours is eliminated which can effectively improve the accuracy of parameter identification and have better operability. Under the linear heat source model with no or little groundwater leakage, heating power has no effect on the identification results of rock-soil thermophysical properties. By increasing flow velocity in the tubes and maintaining a strong turbulent flow state, the accuracy of identification results can be effectively improved and with less test duration.

Through the analysis of the four factors above, it can be seen that in order to achieve the accurate identification of rock-soil thermophysical parameters, it is necessary to emphasize the setting of several key influencing factors in the test link, and provide more scientific and reasonable basic data of thermophysical parameters for the design of ground source heat pump.

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