An Assessment Methodology of Shallow Geothermal Energy Projects

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Abstract: Combination of theoretical and numerical analysis, an assessment approach of shallow geothermal energy project is proposed. A case study on Chongqing is carried out to verify the methods. According to the theoretical calculation, the heat transfer power per meter of typical boreholes in Chongqing is 40 W/m for cooling and 50 W/m for heating. The numerical model of 100m borehole heat exchanger (BHE) of ground sourced heat pump (GSHP) system is built, two sets of heating and cooling loads are input to calculate the ground thermal response, the results show that the thermal unbalance ratio equals to 1.5 would ensure the safe and reliable long time operation of GSHP system. By comparing the single and group borehole model, the heat transfer efficiency of BHE is not influenced by adjacent boreholes with 6m drilling spacing, the temperature distribution among boreholes almost uniform after a year running, however, the increase of cumulative temperature of the ground reaches 2.2°C after five years running.

Keywords: Assessment methodology, borehole heat exchanger, shallow geothermal energy, thermal unbalance.

1. INTRODUCTION

In order to guarantee the sustained utilization of shallow geothermal energy, reduce the development risk, and obtain the maximization of socioeconomic performance and environmental benefit, the exploration and evaluation of shallow geothermal energy is of great significance. The U.S. ASHRAE Association stipulates relevant clauses on on-site exploration of ground source heat pump engineering, and has two parts in work contents, including hydrologic condition and geological condition [1-2], China Specifications on Exploration and Evaluation of Shallow Geothermal Energy [3] also makes similar regulations, and divides the evaluation on shallow thermal energy into urban area and engineering project, the former evaluates the shallow geothermal energy at the regional scale, and the work content is mainly collecting regional geology and hydrogeological data; the latter is targeted at the site where the ground source heat pump(GSHP) project is located, which provides basis for engineering design, and the work content is mainly calculation for single-borehole geothermal energy, underground thermal equilibrium evaluation, forecast evaluation of change in underground temperature field and variation of heat storage.

The paper combines the theoretical equation and numerical model, and proposes an engineering project evaluation methodology of shallow geothermal energy. A case study of GSHP system on Chongqing is carried out, theoretical calculation of a single-borehole geothermal energy at 100m, and established three-dimensional numerical model for drilling. Simulated the heat exchange process of single-borehole and group-borehole buried pipe system under the dynamic load of two different accumulative cooling and heating load ratio, compared the average water temperature of buried pipe and temperature of rock-soil mass, and obtained some results feasible for engineering design and application.

2. SINGLE-BOREHOLE GEOTHERMAL ENERGY

Single borehole geothermal energy refers to the power of heat exchange provided by each borehole in the GSHP system, can be directly used for calculating the number of buried pipes in the engineering, and is the most important parameter in design and also the direct reflection of storage of shallow geothermal energy in the engineering. The equation for the geothermal energy in the U-shape buried pipe suggested in Specification on Exploration and Evaluation of Shallow Geothermal Energy [3] as

$$D = \frac{\Delta T}{R} = \frac{2\pi L\left|T_1 - T_4\right|}{\frac{1}{\lambda_1}\ln\frac{r_2}{r_1} + \frac{1}{\lambda_2}\ln\frac{r_3}{r_2} + \frac{1}{\lambda_3}\ln\frac{r_4}{r_3}} \tag{1}$$

where λ_1, λ_2 and λ_3 refer to the heat conductivity (W/m·°C) of pipe, backfill materials of borehole and rock-soil mass surrounding the borehole respectively; L is the length of heat exchanger of buried pipe (m); r_1, r_2, r_3 and r_4 are equivalent radius of buried pipe (m), equivalent external diameter of buried pipe (m), radius of borehole (m), and radius of temperature influence of heat exchange (m) respectively; T_1 and T_4 are the average temperature of fluid within the buried pipe and the initial temperature of rock-soil mass.

Bureau of Geology and Mineral Exploration drilled boreholes and samples in some region of Chongqing, collected 237 groups of rock-soil thermos-physical parameters [4]. The results show that in the region, the rock

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constitution is mainly mudstone, shale, sandstone and limestone, and the heat conductivity measured at the laboratory is 2.0~3.2 W/(m·K). Besides the laboratory measurement, Thermal response test is carried out in ten places, including Shuangfengqiao and Lijia Town in the main urban area, the rock-soil comprehensive heat conductivity λ3 was calculated by using infinite line source model, the result is 1.93~3.1 W/(m·K), and the average is 2.62 W/(m·K).

Borehole and pipe adopts vertical drilling of borehole in the stratum, and usually the HDPE pipe is positioned in the borehole, and then backfilled. The drilling depth is often 50-150m, and the diameter of borehole is 120-150mm [4]. In the following calculation, the radius of the borehole r_3 is 75mm, the length of the borehole L is 100m, the spacing between boreholes is 6m, which means the radius of temperature influence of heat exchange r_4=3 m, the pipe style is double U in series, the equivalent radius r_1 of buried pipe is the internal diameter of pipe 21mm, and the equivalent external diameter r_2 of buried pipe is the external diameter of pipe 25mm.

Given the data from geological exploration, the rock-soil initial temperature T_4 is measured through non-power circulation, and different boreholes are 17.79°C~21.27 °C, with the average of 19.83 °C. For the average temperature T_1 of fluid within the buried pipe, the current specification states that the temperature scope for the normal running of heat pump unit is 10~40 °C (cooling) and -5~25 °C (heating) [5]. In design, the average water temperature of buried pipe in cooling season and heating season applied is 35 °C and 0°Crespectively. λ_1 and λ_2 are adopted based on the specification, and the Table **1** shows the summary of calculation parameters of single-borehole geothermal energy.

Table 1. Calculation parameters of single-borehole geothermal energy.

λ_1	λ_2	λ_3	r_1	r_2	r_3	r_4	L	T_1	T_4
$W \cdot m^{-1} \cdot K^{-1}$			m					°C	
0.42	1.5	2.62	0.021	0.025	0.075	3	100	35/0	19.83

The single-borehole geothermal energy of the typical 100m borehole could be computed by Equ.1, are 4kW (cooling) and 5kW (heating) in Chongqing, and the heat transfer rate per meter of the corresponding borehole in the cooling season is 40 W/m, and that in the heating season is 50 W/m.

3. THERMAL UNBALANCE OF GSHP SYSTEMS

GSHP borehole extracts energy from underground rock-soil mass through borehole heat exchangers, its heat inject and heat release in the two seasons of winter and summer tend to be different, leading to thermal unbalance. The long-term unbalance between heat inject and heat release will induce in the constant deviation of rock-soil temperature from initial temperature, and gradual decline in system operation efficiency of ground source heat pump, which has become an important issue for GSHP system design [6-8].

The rock-soil thermal unbalance arises from various elements, which usually present in three aspects [7], (i) it is rock-soil thermal parameters. GSHP adopts shallow geothermal energy, and mainly relies on the heat storage capacity of rock-soil mass. By contrast, the heat capacity of rock and soil is less, cannot extract or store more energy, so heat exchange rate is lower; (ii) the difference of cooling and heating loads in each buildings. The climates in different areas of China vary greatly, so the all-year cooling and heating loads of buildings are non-equal, and the all-year ground heat exchanger shows inconsistent heat inject and heat release for underground soil and rock, thus forming “heat stack”. According to Thermal Design Code for Civil Building [9], Chongqing has hot summer and cold winter, and the climate is characterized by extremely hot summer and wet and cold winter, so the cooling load of buildings is more than the heating load; (iii) the design of GSHP system. rock-soil mass is a heat accumulation body with huge volume, so the reduction in spacing between boreholes and single-borehole load both can alleviate effectively heat unbalance.

This section builds the numerical model of borehole heat exchanger (BHE), selects the typical parameters of rock-soil thermal properties and heating and cooling loads from Chongqing to calculate the temperature response under different single-borehole loads, studies the thermal equilibrium, and analyzes the mutual effect between adjacent boreholes.

3.1. Numerical Model

The section selects three-dimensional finite element model to simulate the heat exchange process of underground heat exchanger. FLUID116 linear elements in ANSYS can simulate the flow of fluid in buried pipe, without the increase of additional mesh in rock-soil unit, which is a simplified and efficient method [10]. Simulation of the finite element mesh of buried pipe of two U series connection with linear elements is shown in Fig. (**1**), after the fluid in buried pipe drains out of the outlet, it circularly flows into the buried pipe through a linear element.

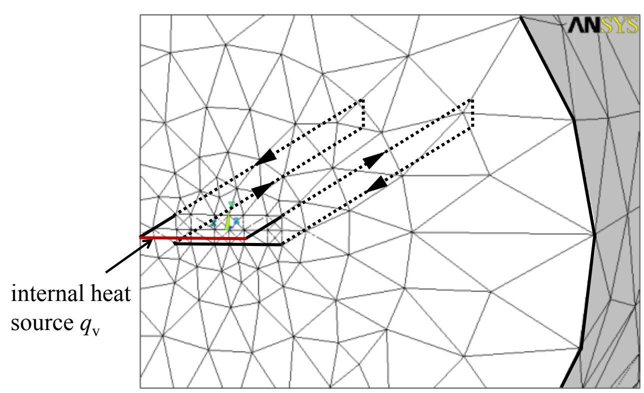

Fig. (1). Sketch map of finite element mesh of BHE.

Based on internal heat source qv in FLUID116 element through linear element and fluid convective heat transfer coefficient h, the process of circulating fluid heating can be simulated (Fig. **2**).

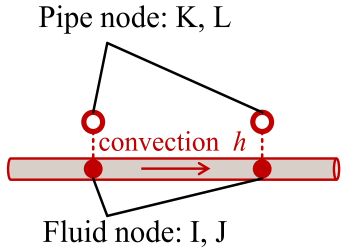

Fig. (2). Skeleton of FLUID116 element.

where internal heat source q_v is the source item of heat conduction differential equation, and can be directly set in element parameters as

$$\rho c\left(\frac{\partial T}{\partial t}+u_i T_{,i}\right)=\lambda T_{,jj}+q_v \quad (2)$$

Convective heat transfer coefficient h can be determined by setting four parameters of N_1~N_4 in Nu element fitting equation as

$$Nu=N_1+N_2 \mathrm{Re}^{N_3}\mathrm{Pr}^{N_4} \quad (3)$$

$$\mathrm{Pr}=\frac{v}{\alpha}=\frac{v\rho c}{\lambda};\ \mathrm{Re}=\frac{ud}{v};\ h=Nu\frac{\lambda}{d} \quad (4)$$

3.2. Calculation of Cooling and Heating Load

In GSHP system, the cooling and heating loads of buildings directly relates to the heat extraction and heat inject volume of buried pipe (heat exchanger), hence, the design of ground source heat pump system shall be based on the all-year hourly dynamic load as well as all-year accumulative load, namely, all-year heat inject volume and heat extraction volume, as well as reasonable selection of unit capacity and number of buried pipes and numerical simulation under dynamic load.

Based on the typical meteorological year of Chongqing, the heating season is from Dec. 5 to Mar. 7 (93 days), the cooling season is from May 3 to Sep. 27 (148 days). Air conditioning system opens 12h under simulated condition, and the rest time is temperature recovery period, without GSHP. Table **2** shows the several time nodes used for analysis of calculation results.

Table 2. Time nodes for heating/cooling process.

	Date	Days (d)	Process Details
t_0	Dec. 5	1	Start of heating
t_1	Mar. 7	93	End of heating
t_2	May 2	149	End of recovery
t_3	Sep. 27	297	End of cooling

The section has acquired the heat transfer rate per meter in cooling season and heating season is respectively 40 and 50 W/m, while Chongqing has hot summer and cold winter, where the cooling load of buildings is more than heating load. Therefore, the number of boreholes required in cooling season will be remarkably greater than that in heating season. With a view to improving the utilization efficiency of boreholes, in terms of engineering, the working condition in heating season is adopted for design of the number of boreholes, and cooling tower is selected as auxiliary cold source or the heating recovery technology is adopted so as to reduce the heat extraction volume of buried pipe in cooling season, which is called Ground Source Heat Pumps (GSHP) system [11]. On one hand, the GSHP system can reduce or eliminate underground thermal unbalance; on the other hand, it can also reduce the number of boreholes, and has good economic benefit.

When dynamic load is calculated, designed cooling and heating load is usually selected based on building type and meteorological parameter and then converted into the dynamic load of buried pipe through the COP value of heat pump unit [12]. This section calculates dynamic loads a and b according to the meteorological data of Chongqing in typical meteorological year. The heat transfer rate per meter for the corresponding borehole of dynamic load a is 50 W/m during heating season, while the heat transfer rate per meter is 110 W/m during cooling season (Fig. **3**), with accumulated cooling and heating load ratio of 2.0; the heat transfer rate per meter for the corresponding borehole of dynamic load b is 50W/m during heating season, while the heat transfer rate per meter is 80W/m during cooling season (Fig. **4**), with accumulated cooling and heating load ratio of 1.5. The starting point for the calculation cycle of dynamic load is t_0 (Dec. 5).

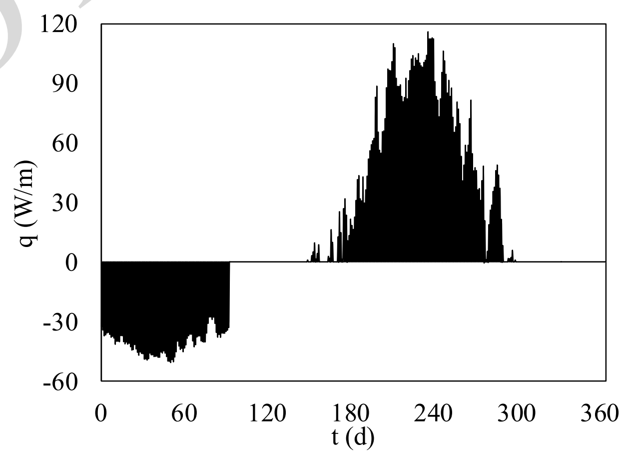

Fig. (3). Annual dynamic load (a) in Chongqing.

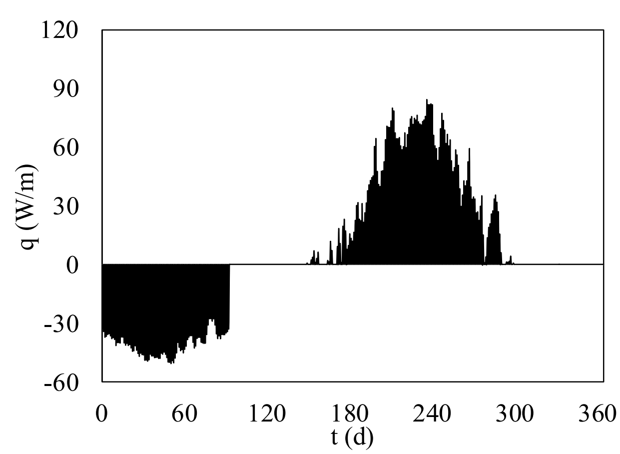

Fig. (4). Annual dynamic load (b) in Chongqing.

3.3. Calculation Simulation for Single-Borehole Model

According to the parameters in Table **1**, build numerical model for 100m buried pipe, input the two dynamic loads in Figs. (**3**, **4**) for calculation, and analyse the average water and rock-soil temperature of buried pipe.

3.3.1. Dynamic Load a

The designed heat transfer rate per meter for the buried pipe of dynamic load a is 50 W/m, accumulated cooling and heating load ratio is 2.0, and calculation period lasts for one year. The average water temperature variation is showed as in Fig. (**5**) and the average water temperature at time nodes of Table **1** are listed in Table **3**.

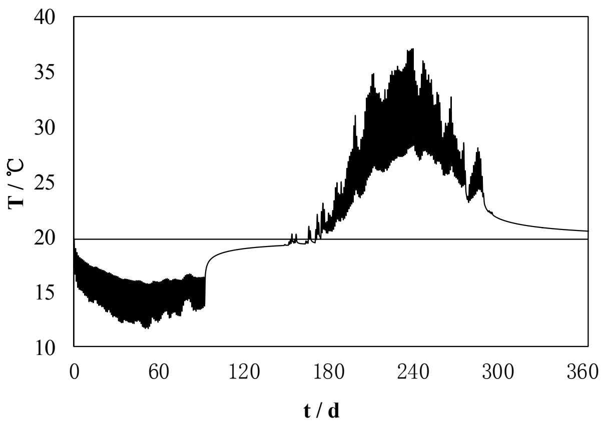

Fig. (5). Average water temperature of buried pipe under dynamic load a (one year).

Table 3. Average water temperature of buried pipe at time nodes under dynamic load a.

Time (d)	t_0	t_1	t_2	t_3	t_4
Average water T. (°C)	19.8	13.7	19.2	22.2	20.5

According to the results of Table **3** and Fig. (**5**), the lowest water temperature is 11.6 °C during heating season and the highest water temperature is 37.2 °C during cooling season. After one-year cooling and heating, the average water temperature increases by 0.7 °C and the heat exchange efficiency falls.

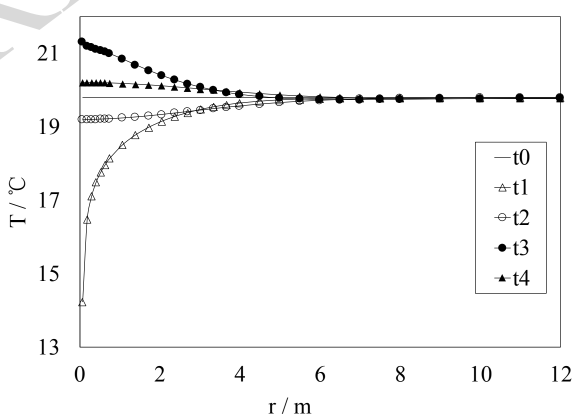

Fig. (6). Ground temperature diffusion curve for dynamic load a.

After one operation cycle (Fig. **6**), the temperature diffusion distance of the single-borehole model is about 5m and the temperature variation amplitude for the place 2m away from the borehole is about 1.5 °C, with significant heat accumulation. And the rock-soil temperature fails to be recovered during recovery period.

For further consider the accumulative effect of cooling and heating loads, the calculation duration is determined to be five years, with other model parameters constant. the average water temperature variations of buried pipe can be seen in Fig. (**7**). The highest average water temperature of buried pipe is 40.0 °C during the cooling season within the fifth periodic year, which does not comply with relevant provisions on GSHP. The system cannot function correctly. It needs to be indicated that as a matter a fact, the water pump has stopped working during the recovery period and fluid in the pipe stops flowing. Theoretically, the flow velocity of numerical model should decrease to zero. However, relative to the surrounding rock and soil, the volume of fluid in pipe is so small that its temperature after long-term recovery period will be equal to the surrounding rock-soil temperature although the fluid is static. Therefore, the error can be ignored.

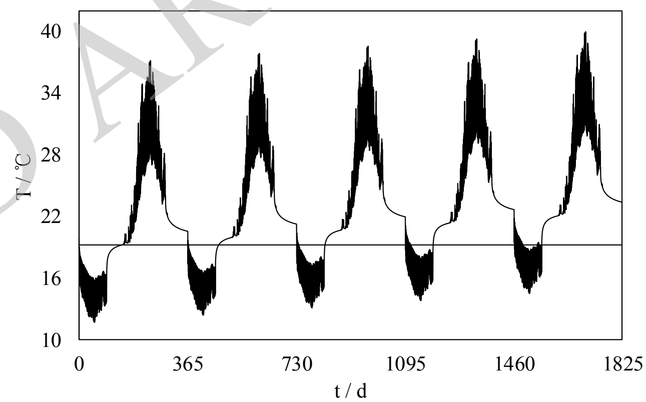

Fig. (7). Average water temperature of buried pipe under dynamic load a (five years).

3.3.2. Dynamic Load b

The designed heat exchange amount per liner meter for the buried pipe of dynamic load b is 50 W/m, with accumulated cooling and heating load ratio of 1.5. Fig. (**8**) describe for the average water temperature variations after ten-year operation.

The average water temperature range is almost the same every year during 10 periodic years, namely, 12~30 °C (Fig. **8**). When the time reaches 3650 days, the average water temperature of buried pipe is 19.87 °C. Relative to the starting ground temperature, it increases by 0.07 °C only, there is no "hot stack", and the heat exchange efficiency of buried pipe has not decreased. The variations of rock-soil temperature with time at the place 3m away the buried pipe is showed in Fig. (**9**).

After the system has worked for 1, 5 and 10 years, the rock-soil temperature at the place 3m away from the buried pipe is 20.0, 20.2 and 20.3 °C respectively, which reflects the heat storage and exchange capability of rock-soil mass.

The temperature can be recovered within certain period and heat is not accumulated in rock-soil mass.

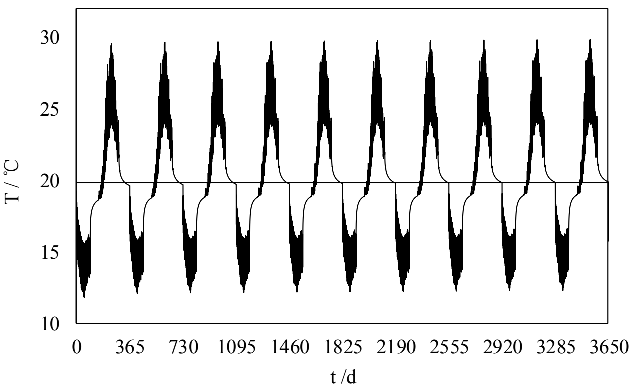

Fig. (8). Average water temperature of buried pipe under dynamic load b (ten years).

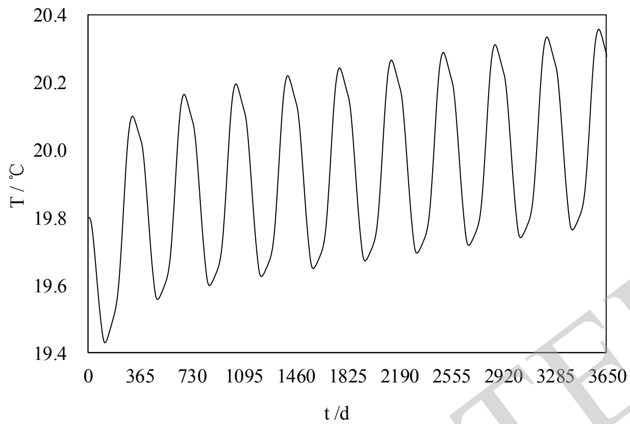

Fig. (9). Rock-soil temperature variations under dynamic load b (ten years).

The calculation comparison for two dynamic loads indicates that when the designed heat transfer rate per meter of buried pipe is 50 W/m, and it is reasonable when the accumulated cooling and heating load ratio is 1.5, because it can ensure the system keeps working in a long time; by contrast, when the accumulated cooling and heating load ratio is 2.0, the cooling and heating unbalance is beyond the heat storage and exchange capability of rock and soil, thus resulting in the heat unbalance of rock and soil and failure of the ground source heat pump system.

3.4. Computational Simulation of Group Borehole Model

It is not typical to analyse rock-soil temperature change with single-borehole model when the underground thermal equilibrium analysis is conducted. In order to save floor space, the layout of buried pipe is usually concentrated in engineering, which not only generates thermal disturbance and results in superposition of temperature field, but shortens thermal diffusion radius of borehole, thus accelerating the change of rock-soil temperature.

Group borehole model for 9 boreholes are built in this section, with spacing of 6m (Fig. **10**), other model parameters are the same as the last section- heat exchange process of buried pipe is simulated after input of dynamic load b.

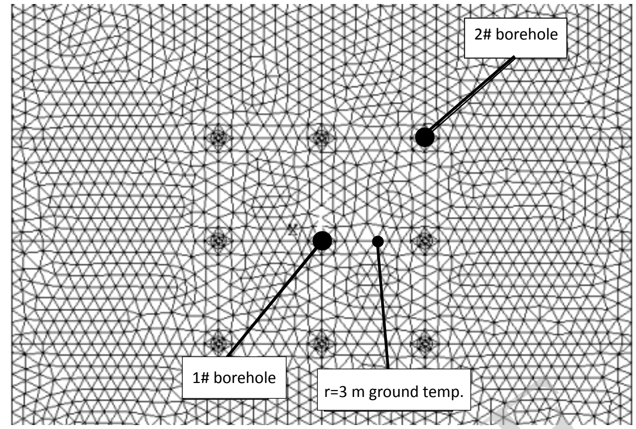

Fig. (10). Skeleton for finite element grid of group borehole model.

In group boreholes model, borehole 1# is located at the center, and its heat exchange process is greatly influenced by nearby boreholes; borehole 2# is seated at corner, relatively speaking, its heat exchange process is closer to single-borehole model. The average water temperature of 1# borehole and 2# borehole after five years operation is respectively shown as Figs. (**11**) and (**12**). The results show that the average water temperature of buried pipe for boreholes 1# and 2# borehole is basically consistent with the result of single-borehole model in Fig. (**8**), with both of deviations less than 0.1°C，thus it can be considered that 6m spacing of borehole is enough to ensure the heat exchange efficiency of buried pipe free from the influence of nearby boreholes under parameter of the dynamic load and rock-soil thermal performance.

Similarly, extract the rock-soil temperature at the place 3m away from borehole 1#, and the temperature change along with time is shown as Fig. (**13**). The rock-soil temperature at the place 3m away from the buried pipe is respectively 20.2 °C and 20.2°C after the system has operated for one and five years, which indicates that rock-soil temperature in group borehole model has certain range of accumulative temperature rise compared with the starting ground temperature due to influence of nearby borehole and realizes 2.2 °C after five periodic years, however, it fails to exert remarkable influence on heat exchange efficiency of underground heat exchanger.

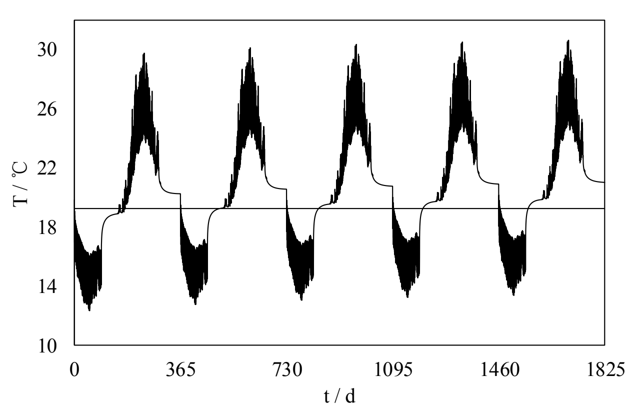

Fig. (11). Average water temperature of buried pipe of group borehole model 1# borehole (five years).

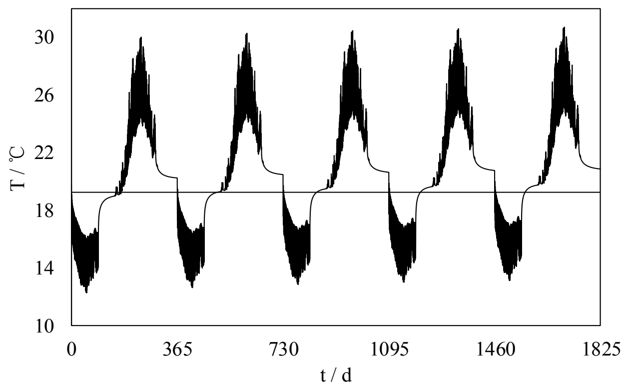

Fig. (12). Average water temperature of buried pipe of group borehole model 2# borehole (five years).

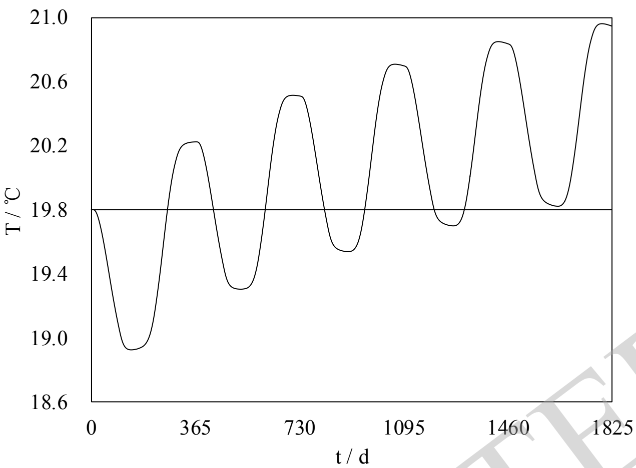

Fig. (13). Change of rock-soil temperature of group borehole model under dynamic load b with time.

For further analysis on rock-soil temperature field, obtain a profile at the center of group borehole model, and extract rock-soil temperature at depth of H=50m, and the temperature of profile increases along with time. The curves in Fig. (**14**) are respectively named as the rock-soil profile temperature at the end of 1st, 2nd, 3rd, 4th and 5th year. In the central (r=0 m), it is borehole1#, at the distance to central (r=±6 m), there are two boreholes nearby 1#. It is known from the Fig. (**10**). The temperature distribution of rock-soil among boreholes has become average after a year operation, and the temperature declines rapidly in the rock-soil mass outside the borehole.

CONCLUSION

In combination with computational equation and numerical model of single-borehole geothermal energy, the paper proposes an evaluation methodology for shallow geothermal energy resources. Taking GSHP system in Chongqing as an example, the paper calculates the single-borehole geothermal energy for 100m boreholes, and builds three-dimensional numerical model for borehole, calculate the dynamic load of two different accumulative cooling and heating load ratios and compare heat exchange process of buried pipe system between single borehole and group boreholes, and conduct analysis on underground thermal equilibrium.

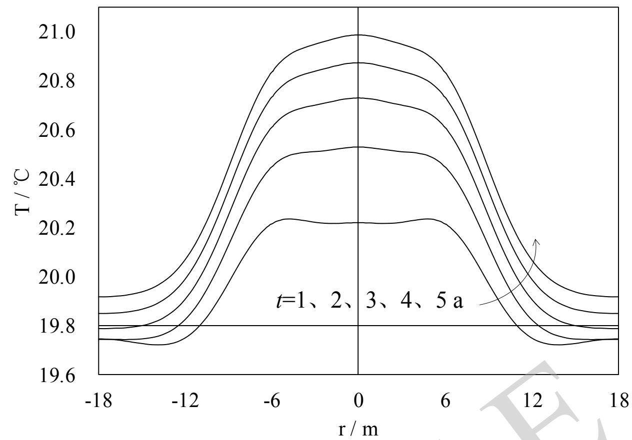

Fig. (14). Change of rock-soil profile temperature of group borehole model under dynamic load b.

(1) According to the proposed equation in regulations, heat transfer rate of the typical borehole in Chongqing in cooling season is 40 W/m, and that in heating season is 50 W/m.

(2) Through the calculation of two dynamic loads, when accumulative cooling and heating load ratio is 1.5, which is reasonable when the heat transfer rate of buried pipe is designed as 50 W/m, it can ensure long-term operation of the system. When the accumulative cooling and heating load ratio is 2.0, cooling and heating load unbalance will exceed the heat storage and heat exchange capacity of rock-soil itself, resulting in thermal unbalance of rock-soil and quick invalidation of ground source heat pump system.

(3) Comparison between single borehole and group borehole models, the distance between boreholes is 6m which can ignore the heat exchange influence from nearby boreholes. The temperature distribution of rock-soil among boreholes is uniform after a year, and rock-soil temperature has a certain accumulative compared with the starting ground temperature, it can almost rise 2.2 °C after five years.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

This work is supported by the Fundamental Research Funds for the Central Universities (FRF-TP-14-033A1).

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Received: January 6, 2015 Revised: May 20, 2015 Accepted: June 19, 2015