

Experimental Research and Grey Prediction on the Long-term Behavior of U-shaped Ground Coupled Heat Exchangers

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Abstract: Experiments on the long-term behavior of practical U-shaped ground coupled heat exchangers (GCHE) were carried out. Based on the grey theory, GM(1,1) model was established, and further topological prediction was given for key parameters including heat-exchange rate Q and the coefficient of heat transfer K . Simulated results showed that there is a better coincidence between the test and predicted data. During the long-term operation of the GCHE, due to the unbalance of the load heat transfer is likely to become worse and worse, especially in the summer. The summer mode can be divided into three working zones: transitional period, steady period and weakening period. A dimensionless runtime τ is presented to express the long-term behavior of K , where $K = a\tau^b$. The runtime τ of three working zones is determined as 0-25%, 25-80% and 80-100%, respectively. Grey prediction can provide us with a quantitative basis for stable operation and next optimization of the ground source heat pump system (GSHP).

Keywords: ground source heat pump, ground coupled heat exchanger, long-term behaviour, grey prediction

NOMENCLATURE

- a the coefficient of development
- b grey effect quantity
- B coefficient matrix
- Cp thermal capacity [$\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$]
- k elements of a sequence
- K average coefficient of heat transfer [$\text{Wm}^{-1} \text{ } ^\circ\text{C}^{-1}$]
- L buried depth [m]
- n the number of underground heat exchangers
- q_i quantity of heat transfer per the well's depth [Wm^{-1}]
- Q average quantity of heat transfer [W]
- t time [s]
- T temperature [$^\circ\text{C}$]
- V flow quantity [$\text{m}^3 \text{ s}^{-1}$]
- X object sequence
- Y object matrix
- Z proximate mean generating sequence
- Greek letters:
- ρ density [kgm^{-3}]
- ξ_i threshold value
- τ runtime, dimensionless
- Subscripts:
- 0 the ground
- 1 the outlet
- 2 the inlet
- m arithmetic mean
- A vector
- Superscripts:
- 0 initial sequence
- 1 1-AGO transformation

1. INTRODUCTION

In recent years, many researches and applications on ground source heat pump system (GSHP) have been carried out [1-3]. Being one of the key components, ground coupled heat exchanger (GCHE) plays an important role on the behavior of the whole GSHP system. Some heat transfer characteristics of the GCHE had been investigated previously in the laboratory scale [4-5]. A transient fully three-dimensional numerical model for the prediction of the thermal behavior of soil heat exchanger-storage systems (SHESS) aimed at reducing the energy consumption was developed by Carol Gauthier [6]. Professional finite element software was used by J.D. Spitler to numerically simulate the effect of groundwater flow on the heat transfer and the long-term behavior of the GCHE [7]. The code of AUTOUGH 2.0 was adopted to calculate the ground temperature field around the GCHE, based on the inner heat source model, and further validation with short-term test data was given by X.G. Li under the mode of intermittent operation [8].

To some extent, practical underground heat exchanger can be treated as a grey system [9], which is full of known and unknown information. So it is possible that the theory of grey system will be introduced into the research on the GSHP systems. However, such research was seldom found in the previous similar work. In the present paper, grey GM(1,1) model was established to describe the long-term behavior of some key parameters including the quantity of heat extraction and injection and the coefficient of heat transfer, based on the experiments

of some practical U-shaped ground coupled heat exchangers. And further topological prediction was given, too. The purpose was to provide us with a relatively quantitative basis for stable operation and next optimization of the GSHP system.

2. EXPERIMENTAL INVESTIGATIONS

2.1 Experimental System

The object of this research was a multifunctional office building located in the Meijiang District, Tianjin, China. Its total area is about 3715 m². One GSHP system is designed and installed to provide heating, cooling and daily hot water for the whole building. Schematic representation of this experimental system is shown in Fig. 1. Two kinds of GCHEs were chosen, namely pile-buried heat exchanger with the depth of 20m and well-buried heat exchanger with the depth of 90m. The material for the GCHEs is U-shaped polyethylene plastic pipe with high density. The diameter and the distance of boreholes are 0.4m and 5.0m, respectively. Refilled material is the mixture of sand and gravel with the proportion of 1:2.

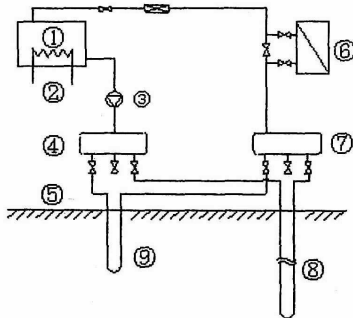


Figure1: Experimental diagram of U-shaped GCHE. Keys: ① water tank, ②Electric heating, ③circulating water pump, ④water-converged device, ⑤ground, ⑥ heat pump, ⑦water-allocated device, ⑧well-buried heat exchanger, ⑨pile-buried heat exchanger.

2.2 Data acquisition

In this experimental system (see Fig.2), the objects of data acquisition mainly included the temperature and the flow of the inlet and outlet of the GCHEs, the temperature of the soil at the different depths, the power of heat pump and circulating water pump, etc. Thermal resistance sensors with accuracy class of 0.2 were used to transmit the temperature signal, and LWGY-40 type turbine flow meters with accuracy class of 0.5 were used to send the flow signal. The whole data acquisition was automatically accomplished by the computer system.

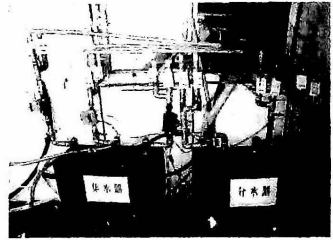


Figure 2: One corner of experimental system

In this experiment, the operation of the GCHE can be classified into two modes: the summer mode and the winter mode. The test was carried out continually in each operation mode. Acquisition period was as follows: 2003.11-2004.3 and 2004.11-2005.3 for the winter mode, and 2004.5-2004.9 for the summer mode. And detailed test data can be seen the later sections below.

3. GREY PREDICTION MODEL

3.1 GM(1,1) Model

According to the theory of grey prediction [9], we can construct the prototype of grey control GM(1,1) model for U-shaped GCHEs (see Fig.3). From the block diagram, we can see the GM(1,1) model has several advantages: (i) it is compatible with differential and exponential characteristics; (ii) its parameters are adjustable and not exclusive; (iii) the model's structure is elastic and changeable; (iv) the mechanism of constructing this model is grey; (v) it has a characteristics of constant coefficients and a grey distribution.

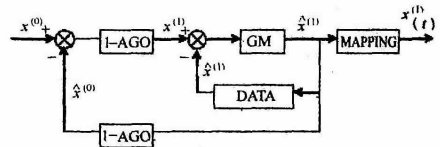


Figure 3: Block diagram of GM(1,1) control model

Further, the definition on the mathematical model or GM(1,1) model with the above characteristic parameters for underground heat exchangers can be given by Eq.(1). In order to be convenient for understanding and save the length of the context, some complicated mathematical reasoning was omitted.

$$X^{(0)}(k) + aZ^{(0)}(k) = b \quad (1)$$

It is clearly shown from Eq.(1) that GM(1,1) model is a grey differential equation with first-order connotation. Under the condition that quasi-smooth examination is satisfied, we can further obtain the white form of Eq.(2).

$$\frac{dX^{(1)}}{dt} + aX^{(1)} = b \quad (2)$$

where $X^{(0)}$ is initial sequence; $Z^{(0)}$ is proximate mean generating sequence; $X^{(1)}$ is generating sequence of $X^{(0)}$ through the transformation of one order Accumulated Generating Operation, or 1-AGO.

In order to get the coefficient of development a and grey effect quantity b , it is necessary to define a new parameter sequence, $\hat{a}$ (see Eq.(3) and Eq.(4)). And then by means of least square method, the coefficients of Eq.(2) can be determined.

$$\hat{a} = (a, b)^T = (B^T B)^{-1} B^T Y \quad (3)$$

and

$$Y = \begin{bmatrix} X^{(0)}(2) \\ X^{(0)}(3) \\ \vdots \\ X^{(0)}(n) \end{bmatrix} \quad B = \begin{bmatrix} -Z^{(0)}(2) & 1 \\ -Z^{(0)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(0)}(n) & 1 \end{bmatrix} \quad (4)$$

3.2 Time response function

Time response function can be obtained according to the solution of Eq.(2).

$$X^{(1)}(t) = \left(X^{(1)}(0) - \frac{b}{a} \right) e^{-at} + \frac{b}{a} \quad (5)$$

If the inversion is made for Eq.(5), we can obtain a recursion formula of initial sequence.

$$X^{(1)}(k+1) = X^{(1)}(k+1) - X^{(1)}(k) \quad (6)$$

$$k = 1, 2, 3, \dots, n$$

Based on the above basic analysis, a computer program on the grey topological prediction code was developed for U-shaped underground heat exchangers. Flow diagram for the complete topological prediction is shown in Fig.4.

4. RESULT ANALYSES

Fig.5 and Fig.6 show the test curve of the quantity of heat extraction or injection, and the coefficient of heat transfer in the winter of 2003 and in the summer of 2004, respectively. According to the above initial data, grey topological prediction is carried out for the winter mode of 2004 and the summer mode of 2005. And the comparison between prediction results and test data can be seen in Fig.7 and Fig.8. It is shown that there is a better coincidence. Further, this validates the applicability of grey topological

prediction method, which is used to analyze the long-term performance of underground heat exchangers. Different from other typical prediction methods such as multiple statistics, fuzzy mathematics and so on, essential characteristic of grey prediction is that the modelling based on a few data can be realized, and actual principle can be found by means of the overlaying of information and sequence generation. Thus, some uncertain problems with deficient information can be well settled in the engineering projects. In this research, it should be pointed out that the main reason that the curve of prediction seems smoother compared with real curve is the restriction by the range of threshold values and quasi-smooth examination condition.

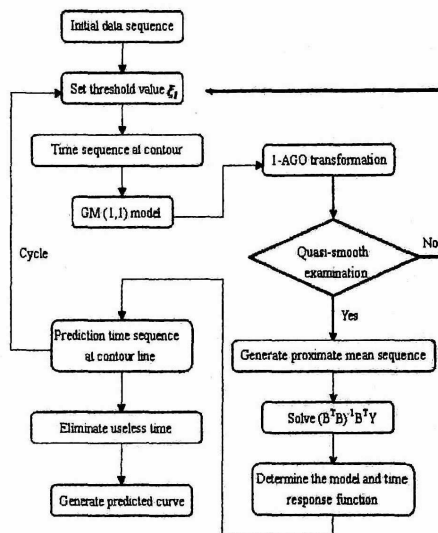


Figure 4: Test data of heat transfer in the winter of 2003 and in the summer of 2004

Fig.5-Fig.8 shows that there exists some difference on the behavior of heat transfer in the summer and winter, during the long-term operation of the GCHes. For the winter mode, heat transfer can quickly reach steady with the exception of a little fluctuation at initial stage. For the summer mode, it can be divided into three working zones, namely transition period, steady period and weakening period. During the transition period, underground heat exchangers have a higher performance of heat transfer, because the soil has experienced a recovery period in the former stage. With the increase of the load in the summer, the performance

of heat transfer gradually enters a steady period. When operation time is approaching the end of the whole summer mode, heat transfer begins to take on a weakening tendency. Take the prediction of summer mode of 2005 as an example. Within the transition period, average heat injection and average coefficient of heat transfer can reach 52.78W/m and 4.80 W/m²·°C, respectively; but within the weakening period, they will decrease to 43.32W/m and 3.56W/m²·°C, respectively. And decaying amplitude reaches 17.92 percent and 25.83 percent.

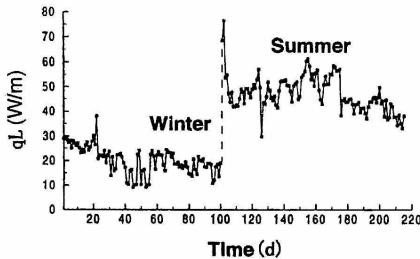


Figure 5: Test data of heat transfer in the winter of 2003 and in the summer of 2004

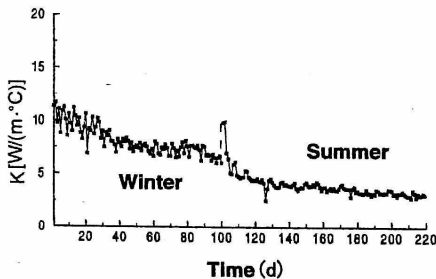


Figure 6: Test data of the coefficient of heat transfer in the winter of 2003 and in the summer of 2004

According to experimental and predicted results, the time ranges for different working periods can be determined preliminarily. Generally, transition period is 10-20 days after the summer mode starts, and weakening period is from 30-40 days before the end of the summer mode and the rest can be treated as steady period. However, in practical projects, there are many factors that affect the time domain of different zones. They include the underground heat exchangers behavior, working mode (intermission or continuousness), the soil's behavior including material properties as well as heat and moisture transfer, backfill materials, climate conditions and other random factors. Therefore, based on the above preliminary prediction, further research on accurate quantitative analysis should be continued in next work.

In this experiment, the influence of operation mode on the long-term performance of underground heat exchangers seems to be more obvious, compared with other factors. For the system is kept the status of halt at nights and transitional seasons, the performance of the soil and the whole underground system can be restored to some extents. And this positive effect is reflected directly in the transition period, where underground heat exchangers can keep a better performance of heat transfer.

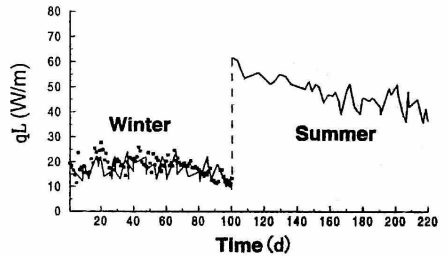


Figure 7: Comparison on test data and prediction data of heat transfer between the winter of 2004 and the summer of 2005

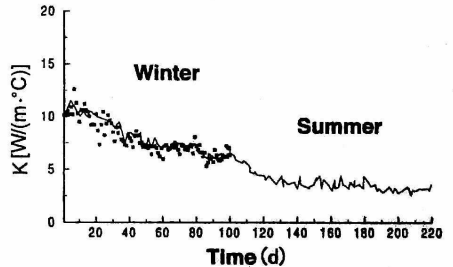


Figure 8: Comparison on test data and prediction data of the coefficient of heat transfer between the winter of 2004 and the summer of 2005

Though the above discussion is helpful in designing the GSHP systems, what's the most important problem faced by most designers is that how we can determine whether the system is under better working condition. Therefore, based on the above experimental data and qualitative analysis, we must further seek for some operable parameters so as to help us adjust or predict the long-term behavior of GCHes. Here one dimensionless runtime, τ , is introduced to represent the long-term behavior of average coefficient of heat transfer K of GCHes. Experimental results show that relationship between τ and K can be regressed as the form of exponential function, namely

$$K = a\tau^b \quad (7)$$

where a and b are the coefficient of regression equation, respectively. Detailed regression values in this experiment can be seen in Table.1.

Thus we can repeatedly define the time domains of the above working periods by means of the parameter τ . Dimensionless τ is 0-25%, 25-80% and 80-100% for transition period, steady period and weakening period, respectively. For the mode of intermission operation was adopted in this experiment, it is a limit situation when $\tau=100\%$. However, this assumptive situation is very useful in practical engineering. According to the value of K under this case, we can know the lowest limit of K of GCHEs, or rather the worst long-term behavior of GCHEs. And this is just what most GSHP designers care about, because general engineering projects are designed to guarantee normal operation under the worst working situation rather than the best working condition.

Table 1: Functional relation between K and τ under different operation modes

Mode	a	b	$\tau=20\%$	$\tau=50\%$	$\tau=100\%$
Summer	8.5321	-0.2138	4.50	3.70	3.19
Winter	13.4940	-0.1448	8.74	7.66	6.93

The next work is to find out the true reason that leads to the above different operation behaviors in the summer and winter. The answer is the unbalance of the load between the winter and the summer. That is to say, cooling load needed for air-conditioning in the summer is far higher than load needed for the heating in the winter. It is this unbalance that causes the heat injected to the soil by underground heat exchangers in the summer is higher than the heat absorbed from the soil in the winter. Thus, the temperature of the soil or cold resource will be kept increasing all the time. According to the basic analysis of the Second Law of thermodynamics, such a circumstance is better for the operation in the winter, but worse for the operation in the summer. Especially for those GSHP systems that work continuously, heat transfer is most likely to become worse and worse, as was shown in Fig.6 and Fig.8. Fortunately, through the grey prediction and Eq.(7), we will be able to understand its deteriorative degree, which can be an important basis for our decision-making.

In order to eliminate or weaken the above-mentioned weakening phenomenon of heat transfer, some active measures can be taken. They include intermission operation used in this experiment, hybrid system design^[10], inter-seasonal heat storage^[11], etc. Besides, the method of grey prediction presented in this paper can also provide us with a quantitative basis for stable operation and next optimization of the whole system.

5. CONCLUSIONS

In this present work, experiments on the long-term behavior of practical U-shaped ground coupled

heat exchangers (GCHE) were carried out. Based on the grey theory, GM(1,1) model was established and further topological prediction was given for key parameters including heat-exchange rate Q and the coefficient of heat transfer K . Simulated results showed that there is a better coincidence between the test and predicted data, which validates the applicability of grey topological prediction method in the design of GSHP system.

The summer mode can be divided into three working zones: transitional period, steady period and weakening period. Further, one dimensionless runtime τ is presented to express the long-term behavior of K , where $K = a\tau^b$. The runtime τ of three working zones is determined as 0-25%, 25-80% and 80-100%, respectively. During the long-term operation of the GCHE, heat transfer is likely to become worse and worse, especially in the summer, due to the unbalance of the load. The method of grey prediction presented in this paper can also provide us with a quantitative basis for stable operation and next optimization of the whole GSHP system, aiming at eliminating or weaken the above-mentioned weakening phenomenon of heat transfer.

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