Analysis on variation characteristics of geothermal response in Liaoning Province

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Abstract: Due to energy shortage and increasing environmental awareness, resources in shallow underground space have been rapidly exploited and utilized. So that studying variation characteristics of geothermal response in gneiss is necessary for effective and rational use of underground heat. Based on field test of thermal response in gneiss under hydrogeological survey project carried out in shallow geothermal energy development zone in Liaoning Province, this thesis analyzes mathematical statistics of geothermal response characteristics in main gneiss of Laoning Province. The initial formation temperature ranges from 10.80 ℃ to 15.80 ℃ according to field test. The statistical results show that in the condition of natural water content, the average thermal conductivity of Quaternary loose rocks comes as clay< silty< silty fine sand< medium sand< coarse sand< gravelly sand. This order is consistent with thermal conductivity characteristics of gneiss obtained in the laboratory. Formation temperature recovery in different strata follows as granite> medium sand> clay. This order is opposite to the absolute value of temperature recovery curve slope of corresponding lithology, which shows that the stratum with higher temperature recovery rate has lower temperature recovery curve slope.

Keywords: Average initial formation temperature; Average thermal conductivity; Formation temperature recovery; Thermal response; Liaoning Province

Introduction

With economic and social development together with technology advances, the demand of underground resources is only limited to projects such as underground traffic, urban utilities networks or tunnels, *etc*. Exploitation and utilization of limited heat resources in shallow underground space have gradually received wide attention and rapid development. At present, building area of architectures utilizing shallow geothermal energy has reached 360 million m^2 in China. It will play an important role in optimizing energy mix, conserving resources and protecting atmospheric environment (ZHENG Gui-sen *et al*. 2011). Although China has made remarkable achievements in exploiting and utilizing shallow geothermal resources, problems in this aspect also exist (TAO Qing-fa and HU Jie, 2007; GAO Xin-yu *et al*. 2009). Thermophysical properties such as distribution characteristics of geothermal field, thermal conductivity of gneiss and thermal diffusivity are key factors that affect engineering design of geothermal heat pump. Therefore in order to be energy-saving, efficient and safe, it is necessary to conduct a study on variation characteristics of geothermal response in gneiss.

Some scholars have made achievements in factors which affect change rules of geothermal response characteristics in gneiss. Relevant departments have also set corresponding rules on it (XU Wei, 2001; China Academy of Building Research, 2005; ZHAO Jun *et al*. 2007). All these lay a solid foundation on this study. Through comparing and analyzing data from field test of thermal response and indoor test, this thesis proposes change rules of factors related to geothermal response, including average initial formation temperature, average thermal

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conductivity of gneiss and properties of formation temperature recovery in Liaoning Province.

1 General situation of Quaternary geology in Liaoning Province

The Quaternary stratum in Liaoning Province is composed of alluvial-proluvial, alluvial, marine -alluvial and talus-pluvial deposits. The distribution features of these deposits are totally subject to geomorphology and mainly distributed in lower Liaohe Plain and river valley plain in hilly area. The Quaternary alluvial-proluvial deposits are distributed in sloping piedmont plains in the eastern and western part of lower Liaohe Plain. Above water-bearing formation are mainly Pleistocene and Holocene alluvial-proluvial deposits. Above the deposits are 5-15 cm of sandy loam and clayey soil, below are 10-60 m of medium coarse sand gravel and pea gravel. The maximum depth of Taizi River fan can reach 80 m. Alluvial deposits are distributed in Xinmin, Liaozhong and Tai'an regions in central plain, which are alluvial plains formed by Liaohe River, Hunhe River and Taizi River. The depth of alluvial deposits increases from east and west to middle as well as from northeast to southwest. Marine-alluvial deposits are distributed in Panshan, Dawa and Yingkou regions in coastal delta plain. Due to transgressions during Quaternary geological period, marine deposits are 20-60 m of gray and hoary silty fine sand mixed with several strata of sandy loam and clayey soil. Below them are 200-300 m of mixture of fine sand, medium fine sand and clayey soil. Talus-pluvial deposits are mainly composed of clay soil and mixed with thin strata of sand, gravel detritus or lenticle. They are distributed in regions between alluvial-proluvial fans in sloping piedmont plains of lower Liaohe Plain and side slope are in hilly area of northern Liaoning Province. The depth of talus-pluvial deposits vary greatly with the maximum depth of 70 m.

2 Field test of thermal response (constant calorimetry)

Thermophysical parameters of gneiss directly demonstrate characteristics of geothermal response. Field test of thermal response, which is an important means to obtain thermophysical parameters, can be divided into three stages: Reactive cycle test, heating test and formation temperature recovery. Heating test can be divided into high-power test and low-power test. The drilling depth is 100 m. The test adopts double U pipe, and the backfill material is mainly medium coarse sand. Comprehensive thermal conductivity of different geomorphic units and different strata in main cities of Liaoning Province can be concluded from test data. According to data analysis, characteristics of geothermal response are closely related to formation lithology and bore diameter.

3 Mathematical statistics and analysis of test data

In order to minimize the abnormal values caused by test errors, this study uses the least squares fitting to eliminate the abnormal values of natural water content, and the formula is as follows:

$$y=a+bx \tag{1}$$

$$\begin{cases} ma+(\sum_{i=1}^{m} x_i)b=\sum_{i=1}^{m} y_i \\ (\sum_{i=1}^{m} x_i)a+(\sum_{i=1}^{m} x_i^2)b=\sum_{i=1}^{m} x_i y_i \end{cases} \tag{2}$$

$$H=\max_{1<<i<<m}|(a+bx_i)-y_i|\cdot 0.618 \tag{3}$$

The data in the formula $|(a+bx_i)-y_i|>h$ are outliers. Matlab software transforms this algorithm to operating program. By inputting corresponding data, ouliers can be removed.

3.1 Average initia formation temperature

Through temperature balance method by using buried pipe heat exchanger (hereinafter referred to as "buried pipe"), which is a reactive cycle method, water is filled in PE pipes after installing test holes. Temperature of water in PE pipes and gneiss temperature will balance after a period of time. Then water in buried pipes will be pumped out through water pump, and water temperature will be monitored to analyze gneiss temperature. Reactive cycle forms a circulation in buried pipes without heating or cooling them. When temperature of circulating becomes stable, circulating water and gneiss will also reach thermal equilibrium (HU Ping-fang, 2010; LV Peng *et al.* 2012). That temperature is initial average temperature of gneiss (Fig. 1- Fig. 2).

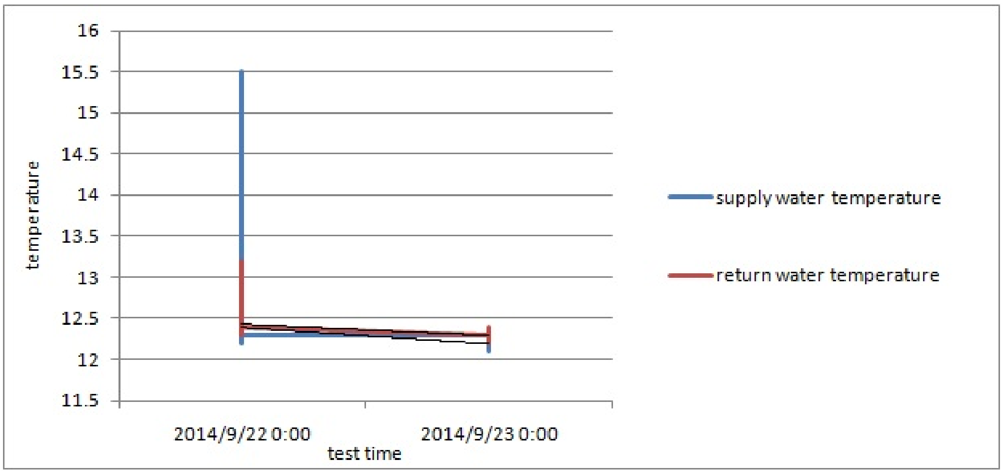

Fig. 1 Temperature change curve of entrance and exit of borehole ZK01

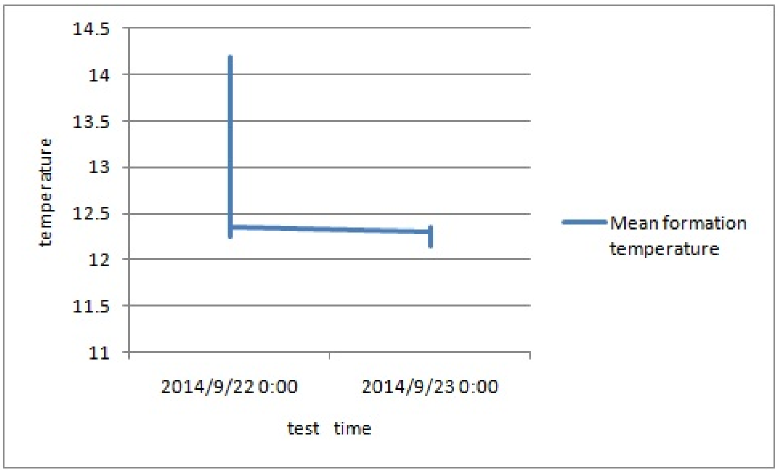

Fig. 2 The curve of average formation temperature test of borehole ZK01

The data of initial formation temperature in different sections of work area is obtained by the method described above (Table 1). The initial formation temperature shows the following characteristics according to analysis of test data: Temperature ranges from 10.80 ℃ to 15.80 ℃; high temperature areas are in bedrock and piedmont zones of eastern and western work area. These areas have thin Quaternary system which mostly contains granite and mainly granite in some areas. The thermal conductivity of granite is higher than that of other gneiss. So that initial formation temperature of these areas is higher than that of loose rocks; and among loose rock areas, temperature of areas mainly containing medium coarse sand is higher than that of clay soil areas. Thermophysical properties of gneiss shows that thermal conductivity of clay soil is lower than that of sandy soil, and thermal conductivity of mudstone and sandstone is lower than that of granite. So average formation temperature is higher in areas mainly containing gneiss of higher thermal conductivity.

Table 1 The initial formation temperature test of drilling formation in different cities in Liaoning Province

City	Geomorphic feature	Main lithology	Borehole diameter (mm)	Backfill material	Initial temperature (℃)
Fushun	Hilly and mountainous area in eastern Liaoning Province	Mudstone, granite	130	Medium coarse sand	11.5
Benxi		Sandstone			11.3
Dandong		Granite			13.2
Dandong					15.8
Dalian		Slate			13.3
Dalian					14
Tieling	Lower Liaohe Plain	Gravelly sand			12.9
Yingkou		Clay			12.3
Anshan		Coarse sand, silt			12.7
Liaoyang		Coarse sand, cobble			12.4
Jinzhou	Low mountains and hills in western Liaoning Province	Sandstone			10.8
Chaoyang		Shale			12.2
Huludao		Granite			13.9
Fuxin		Shale, breccia			11.8

3.2 Average thermal conductivity of gneiss

Average thermal conductivity of gneiss is obtained through simulation test of steady heat flow. That is to say, the test-bed will provide steady flow of heat to buried pipes. By monitoring and analyzing temperature change and flow of inlet and outlet water, average thermal conductivity of gneiss can be concluded. Simulation test of steady heat flow includes high-power test and low-power test (GAO Ping *et al.* 2014; LI Xin-guo, 2004). Data analysis of this test adopts IGSHPA line-source model (LSM).

3.2.1 IGSHPA line-source model (LSM)

The IGSHPA LSM is a widely used model for the calculation of underground heat exchangers. Its expression is as follows:

$$T_f = \frac{Q}{4\pi\lambda H}\ln(t) + \left\{ \frac{Q}{H}\left[\frac{1}{4\pi\lambda}\left(\ln\frac{4\alpha}{r_b^2} - \gamma\right) - R_b \right] + T_0 \right\}$$

In this expression:

T_f - Average temperature of inlet and outlet water of buried pipes, ℃;

t - Test time;

Q - Heat exchange of buried pipe holes per linear meter unit, W/m;

a - Thermal diffusivity of gneiss, m^2/s;

l - Thermal conductivity of gneiss, W/m·K;

H - Effective well depth, m;

r_b - Borehole radius, m;

g - Euler coefficient, 0.5772;

R_b - Internal thermal resistance of boreholes, m·K / W;

T_0 - Initial formation temperature, ℃.

LSM can be simplified as: $T_f = k \cdot \ln(t) + b$.

In this expression: $k = \frac{Q}{4plH}$

The calculated mode of gneiss' thermal conductivity can be derived from above formula:

$$l = \frac{Q}{4pkH}$$

In this formula: k refers to fitting curve slope of the logarithm of inlet and outlet water temperature and time.

Thermal diffusivity $a = l/c$ (4)

c refers to volumetric specific heat capacity of soil; thermal resistance of boreholes R_b

$$R_b = \frac{(m - T_0) * H}{Q_{heat}} - \frac{1}{4pl}\left(\ln\frac{4a}{r^2} - g\right) \quad (5)$$

m refers to the intercept of T_f changing with LNT; r refers to borehole radius.

By using Excel to simulate the IGSHPA LSM, the slope k of logarithmic fitting curve is obtained, and then thermal conductivity of gneiss can be calculated out (Fig. 3-Fig. 4). Through the above method, test results, including average initial formation temperature in different sections of work area, thermal conductivity of different power level and borehole thermal resistance (Table 2).

3.2.2 Characteristics of thermal conductivity

The average thermal conductivity of formations whose depth are within 100 m in Liaoning Province is 1.68-3.44 W/m·K. Bedrock areas in eastern and western Liaoning Province have higher thermal conductivity, which indicates formations in these areas have strong heat transfer capability. Piedmont regions with relatively high thermal conductivity also indicate relatively strong heat transfer capability. With same borehole diameter, the order of thermal conductivity comes as granite> medium sand> clay, which is consistent with indoor test results.

3.3 Characteristics of formation temperature recovery

When buried pipe heat pump system works, continuous injection or extraction of heat will change geothermal field. When this system stops running, geothermal field will have a recovery period. But recovery capability varies under different geological conditions. Geothermal recovery capability can be measured by no-load data after high-power and low-power thermal response tests. Recovery data under different geological conditions in this study are selected to reflect geothermal recovery capability. Data obtained in recovery periods between high-power and low-power tests are shown in Table 3.

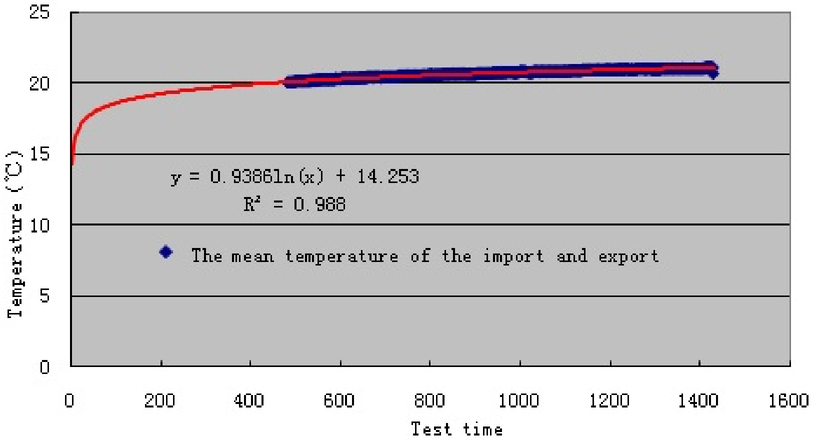

Fig. 3 Average temperature of inlet and outlet water and logarithmic fitting curve of borehole ZK03 in buried pipes with stable heat flow (3 KW)

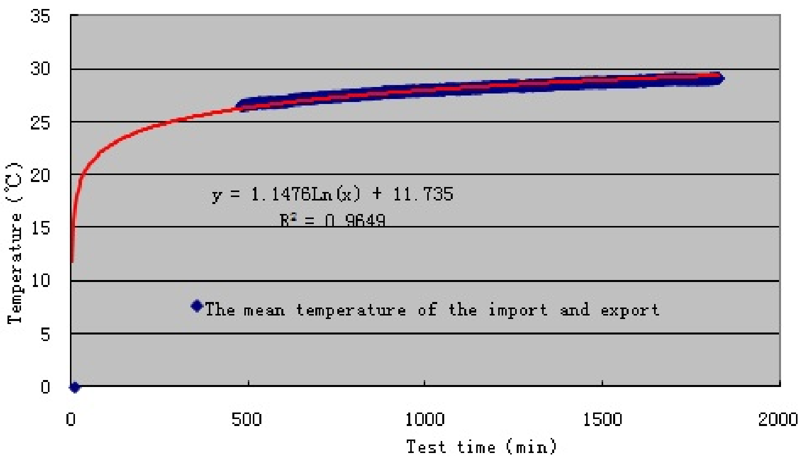

Fig. 4 Average temperature of inlet and outlet water and logarithmic fitting curve of borehole ZK03 in buried pipes with stable heat flow (6 KW)

Table 2 Calculation results of heat response test

City	Geomorphic feature	Main lithology	Borehole diameter (mm)	Backfill material	Results (W/m·K)				
					Initial temperature (℃)	3 KW	4 KW	6 KW	Average
Dalian	Hilly and mountainous area in eastern Liaoning Province	Slate	130	Medium coarse sand	13.3		2.96	3.92	3.44
Dalian		Slate			14	2.17		2.29	2.23
Dandong		Granite			15.8		2.60	2.80	2.70
Dandong		Granite			13.2	2.73		3.32	3.03
Benxi		Sandstone			11.3		1.99	2.78	2.39
Fushun		Mudstone			11.5	3.40		3.49	3.44
Tieling	Lower Liaohe Plain	Gravelly sand			12.9	2.51		2.50	2.51
Liaoyang		Coarse sand			12.4	2.35		2.63	2.49
Anshan		Medium sand			12.7	1.72		2.03	1.87
Yingkou		Clay			12.3		1.63	1.72	1.68
Chaoyang	Low mountains and hills in western Liaoning Province	Shale			12.2	2.08		2.26	2.17
Huludao		Granite			13.9	2.01		2.00	2.00
Jinzhou		Sandstone			10.8	2.46		2.61	2.54
Fuxin		Shale			11.8	2.29		2.31	2.30

Combining data statistics, comparative analysis, linear regression analysis of recovery data and analysis results of Table 3, conclusions can be drawn as follows: Recovery ability of geothermal field is directly related to thermophysical parameters such as thermal conductivity and specific heat capacity. If taking minimum temperature difference of initial and final temperature as standard, the order of geothermal recovery capability comes as granite> medium sand> clay. It indicates that formations with strong recovery capability have lower curve slope. If taking the standard of 1 ℃ temperature difference, recovery period is 5 days (calculated by linear regression formula) for formations mainly containing clay and 3 days for formations mainly containing medium sand. If taking the standard of 0.5 ℃ temperature difference, recovery period is 15 days (calculated by linear regression formula) for formations mainly containing clay and 7 days for formations mainly containing medium sand.

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Table 3 Comparison of temperature recovery of different geological conditions

Borehole number (city)	Quaternary depth (m)	Lithology	Recovery time (h)	Average temperature of entrances and exits		Initial formation temperature (℃)	Temperature difference (℃)	Difference from initial formation temperature (℃)
				Initial temperature (℃)	Final temperature (℃)			
ZK02 (Tieling)	47.1	Sandy loam, gravelly sand, mudstone, gravelly sandstone	71.5	20.35	15.25	13.65	6.1	1.60
ZK04 (Chaoyang)	5.2	Sandy loam, shale, granite	70.5	21.65	13.32	12.85	7.8	0.47
ZK08 (Dandong)	2.5	Sandy loam, granite	69.5	20.60	13.95	13.20	5.65	0.75
ZK10 (Dalian)	0.8	Slate	72.5	21.35	15.08	13.80	5.87	1.28
ZK12 (Anshan)	102	Sandy loam, fine sand, coarse sand, gravelly sand	75.5	20.3	13.15	12.25	6.85	0.90

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