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Method of Forecasting Undisturbed Ground Temperature under Warm Temperate Climates in China

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ABSTRACT

Undisturbed ground temperature is an important parameter for geothermal field and ground source heat pump systems. Lots of previous research focus on the characteristics of the geothermal field of basin area which rely on long-term ground temperature monitoring, however, little research has done to warm temperate regions in China. By using measured data obtained from long-term monitoring in seven cities with typical warm temperate climate, two different calculation methods have been developed, each registering a satisfactory degree of 0.98 and 0.96. Results show that undisturbed ground temperature can be forecasted accurately with data on air ambient temperature, sky temperature, wind velocity and solar radiation density on a horizontal surface. What's more, air ambient temperature is the dominant parameter weighing more than 76%. The simplified correlation which is only a function of the air ambient temperature has a broader application.

1. INTRODUCTION

Undisturbed ground temperature is an important parameter for geothermal field and ground source heat pump systems, which indicates stable energy can be recharged /discharged from/into the ground. This data can derived from thermal response test or long-term temperature monitoring data. Many previous studies in China focused on the basin area and relied on ground temperature monitoring. For example, the undisturbed temperature is calculated as 20 °C in Xinjiang by Feng Changge et al. (2010) and 16.8 °C in Huaibei coalfield by Peng Tao et al. (2015). For the warm temperate areas of North and Northwest China, little research was carried out. In order to obtain the relatively accurate undisturbed ground temperature, a numerical analysis model method is needed.

The earliest numerical analysis model was proposed by Van Wijk (1963) based on the Fourier analysis and energy balance models of multi-year data, followed by many improved models. Sun Zhanxue et al. (2006) considered that the temperature of a typical constant temperature zone is roughly equivalent to the local average annual temperature. Zhao Xiaoyan et al. (2007), based on the energy conservation law, used the temperature measurement data of four cities to prove that undisturbed ground temperature is equal to the ambient temperature. However, the amount of data is insufficient, and the accuracy of the conclusion is yet to be verified. Tsilingiridis and Papakostas (2014) and Ozgener et al. (2013) respectively establish the relationship between the ground temperature and the temperature within 1.5m and 3m, but the accuracy depends on that of meteorological data and other input parameters. Ouzzane et al. (2015) managed to establish correlations between the initial formation temperature and annual mean temperature, as well as meteorological data (dew point temperature, wind speed, solar radiation) based on Canadian meteorological and thermal response test data. It is considered that the temperature is the most important parameter, and a simplified model is proposed in which only the influence of the ambient temperature on the initial geotemperature is considered. Badache et al. (2016) proposed a new method for calculating soil temperature profiles based on the research of Ouzzane et al.

All the above mentioned models based on certain assumptions and the input parameters will be costly and time-consuming aquired. At present, the service area with ground source heat pumps in the warm temperate zone in Beijing, Tianjin, Hebei, Shandong, Henan, Shanxi, Shaanxi and other cities are much more than 188 million m2. The objective of this paper is to analyze the impaction of meteorological data on undisturbed ground temperature in this region and establish the relationship between these factors.

2. METHOD

2.1 Ground Temperature Observation Data

Beijing, Tianjin, Shijiazhuang, Jinan, Zhengzhou, Xi'an and Taiyuan are chosen as the representative cities of warm temperate zone. Pt1000 platinium resistance thermometer with an accuracy of 0.01 ℃ were arranged on the wall of the buried heat exchangers at different depths for ground temperature monitoring. All sensors were calibrated with a high-precision Electro-thermostatic Water Cabinet. Data collection was performed by a temperature inspection instrument. Combined with previous studies (Ran Weiyan et al., 2014; Wei Wanshun et al., 2010; Liu Caibo et al., 2010; Zhao Yunzhang et al., 2010), the undisturbed ground temperatures (Tg) in Beijing, Tianjin, Xi'an and Zhengzhou were 14.00℃, 13.50 ℃, 15.10 ℃ and 16.50℃. For other cities, the monitoring data were used for calculation. Table 1 shows the location, the monitoring frequency and other main information of the monitoring boreholes. According to the temperature measurement data of the three monitoring boreholes, the ground temperature with times was plotted as shown in Figure 1. For data with a monthly monitoring frequency of 3 times, the average of the three times' data is calculated as the monthly data. Based on the geological conditions and other monitoring data, it is determined that the temperatures of the undisturbed ground temperature in Shijiazhuang, Jinan and Taiyuan are 15.00 °C, 15.70 °C and 12.27 °C, respectively.

Table1: Location and parameters for different ground temperature monitoring sites

City	Longitude	Latitude	Depth/m	Distance/m	Duration	Times(every month)
Shijiazhuang	114°22′E	38°08′N	100	5	2012.1~2012.12	1
Jinan	116°43′E	36°31′N	100	2 （ >50m) 5(50~70m)	2011.5~2012.4	3
Taiyuan	112°30′E	37°46′N	125	10(70~100m)	2012.7~2013.6	3

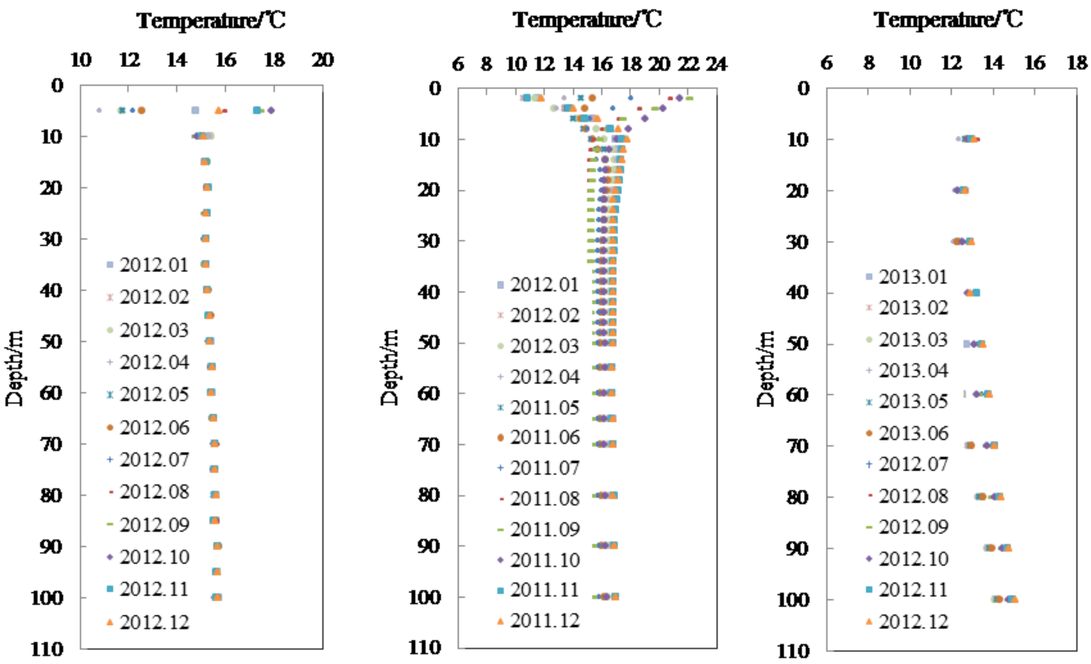

Figure 1: Typical ground temperature distribution profiles

Left：Shijiazhuang Middle:Jinan Right:Taiyuan

2.2 Meteorological Data

The meteorological data of the seven cities was derived from the "China Meteorological Data Service Center", which includes the annual mean ambient temperature Tamb, the dew point temperature Tdp, the wind speed Vw, and the horizontal direct radiation intensity Qsol. In order to get a better correlation with the ground temperature monitoring data, except that the dew point temperature Tdp is derived from the annual average, the others are calculated through the annual average of year from 2011 to 2013. The specific parameters are shown in Table 2.

Table2: Annual average meteorological data and undisturbed ground temperature for typical cities in warm areas

Location	T_{amb}/℃	T_{dp}/℃	V_w/m.s^{-1}	Q_{sol}/W.m^{-2}	T_g/℃
Beijing	13.03	2.10	2.17	299.27	14.00
Tianjin	12.73	2.05	2.90	316.41	13.50
Shijiazhuang	14.00	2.26	1.57	349.13	15.00
Jinan	14.37	3.90	2.63	342.90	15.70
Zhengzhou	15.57	6.90	2.03	264.30	16.50
Taiyuan	10.90	0.50	1.80	300.88	12.27
Xi'an	13.60	9.8	1.30	348.29	15.10

2.3 Data Analysis Method

Multiple linear regression is a method to study the relationship between a random variable and multiple variables. Its mathematical model is shown below.

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_m x_m \tag{1}$$

where b_0, b_1, b_2, ⋯, b_m are regression coefficients. According to the measured data sequence of y and x, after determining b_0, b_1, b_2, ⋯, b_m, the equation becomes clear. The regression coefficients of multiple linear regression equations are generally determined by least squares method (Zhou Wenbin and Che Qian, 2009).

The least squares method is a mathematical optimization technique which finds the best function match for the data by minimizing the squares of the errors. The regression coefficient in Equation 1 can be easily obtained by the least squares method, and the sum of the squares of the errors between the calculated data and the actual data is minimized. According to the study by Ouzzane et al. (2015), there is a linear regression relationship between initial temperature and ambient temperature, as well as the meteorological data (e.g. dew point temperature, wind speed, solar radiation) in Canada. This paper deploys the least squares method to calculate the linear regression coefficient of the parameter affecting the undisturbed ground temperature.

3 CONCLUSION AND ANALYSIS

3.1 Globe Correlation

The main source of soil heat comes from solar radiation. When the Earth's surface is heated by solar radiation, heat is scattered into the sky through long-wave radiation, and there is also thermal convection between the ground and the atmosphere. The net heat flux of the surface is determined by the interaction of the three, as shown in formula (2). Below the surface, the temperature changes with depth and gradually reaches an equilibrium with the thermal energy inside the Earth. It comes to the constant temperature zone once the equilibrium is reached.

$$\phi_{net} = \phi_{sol} a + \phi_c + \phi_r \tag{2}$$

where Φ_{net} is surface net heat flux density, W / m^2; Φ_{sol} is heat flux density of solar radiation, W / m^2; Φ_c is heat flux density generated by convection, W / m^2; Φ_r is heat flux density due to radiation, W/m^2; a is absorption coefficient.

According to formula (3), the surface net heat flux determined by meteorological factors is a key factor which exerts influence on the geothermal profile. Through the multiple linear regression method, the relationship between the temperature of the constant temperature zone, temperature, sky temperature, wind speed and direct radiation intensity of the horizontal plane was established. The sky temperature can be calculated from the dew point temperature, and except for the sky temperature, all use conventional meteorological observation data. The method is shown in formula (4) (Duffie and Beckman, 2006).

$$\phi_{net} = \lambda_g \cdot \frac{\partial T}{\partial Z}\Big|_{Z=0} = h_c (T_{amb} - T_{gs}) + \phi_{sol} a - h_r (T_{gs} - T_{sky}) \tag{3}$$

where λ_g is underground heat transfer coefficient, W/(m.℃); T is temperature, ℃; Z is depth, m; h_c is heat convection conductivity, W / (m^2.℃) ; h_r is thermal radiation conductivity, W / (m^2.℃); T_{amb} is atmospheric temperature, ℃; T_{gs} is surface temperature, ℃; T_{sky} is sky temperature, ℃.

$$T_{sky} = (T_{amb} - 273.15)[0.711 + 0.0056(T_{dp} - 273.15) + 0.000073(T_{dp} - 273.15)^2 + 0.013\cos(15t)]^{0.25} + 273.15 \tag{4}$$

where T_{dp} is dew point temperature, ° C; t is time, which is 0, s.

After multiple regression calculation, the relationship between the undisturbed ground temperature and the average ambient temperature, sky temperature, wind speed, and direct radiation intensity of the horizontal plane is as shown in equation (5). The undisturbed ground temperature is linearly related to these four factors, and the complex correlation coefficient R is 0.99, the coefficient of determination R^2 is 0.98, and the residual standard deviation is 0.29. The regression model works well.

$$T_g = 0.850 T_{amb} + 0.066 T_{sky} - 0.209 V_w + 0.002 Q_{sol} + 3.499 \tag{5}$$

where T_g is temperature of constant temperature zone, ℃； V_w is wind speed, m/s.

Through Equation 4, the influence of each parameter on the undisturbed ground temperature can be calculated (the influence of the constant term is not considered), and the ratio of the parameter multiplied by the parameter corresponding coefficient to the undisturbed ground temperature is used as a measurement value. The results are shown in Table 3. As the effects of sky temperature T_{sky} and wind speed V_w are both negative, the effect of average temperature turns out higher than the sum of the four values. As shown in the results, temperature is the most important parameter affecting the undisturbed ground temperature, accounting for 76.25%~80.31%, whereas the other three parameters combined are less than 10%, most of which are less than 5%. Taking into account the important role of temperature on the constant temperature zone, the correlation between temperature and temperature of the zone is established below.

Table3 The percentage contribution of the different parameters of Eq. (5).

Location	Percentage of contribution/%				T_g/%
	T_{amb}	T_{sky}	V_w	Q_{sol}	
Beijing	78.65	-5.19	-3.22	4.25	74.49
Tianjin	78.80	-5.20	-4.41	4.61	73.80
Shijiazhuang	78.84	-5.20	-2.17	4.63	76.09
Jinan	79.19	-3.45	-3.56	4.45	76.62
Zhengzhou	80.31	-2.66	-2.57	3.21	78.28
Taiyuan	76.58	-8.15	-3.11	4.97	70.29
Xi'an	76.25	-2.85	-1.79	4.59	76.20

3.2 Simplified Correlation

According to the constant temperature zone temperature in Table 2 and the average temperature in the past three years, the temperature change trends prove to be very similar. The relation between the undisturbed ground temperature and the ambient temperature can be expressed by a linear relationship (Fig. 3, Equation 5), of which the correlation coefficient is 0.96, with a good correlation. The constant term is 1.68, which represents the influence of other parameters including the sky temperature. The average undisturbed ground temperature in the warm temperate zone region is 1.12 ℃ higher than the local average annual temperature.

$$T_g=0.96T_{amb}+1.68 \quad (6)$$

In areas in the warm temperate zone in China and where there is no long-term monitoring data, the approximate local temperature and the formula (6) can be utilized to calculate the approximate undisturbed ground temperature.

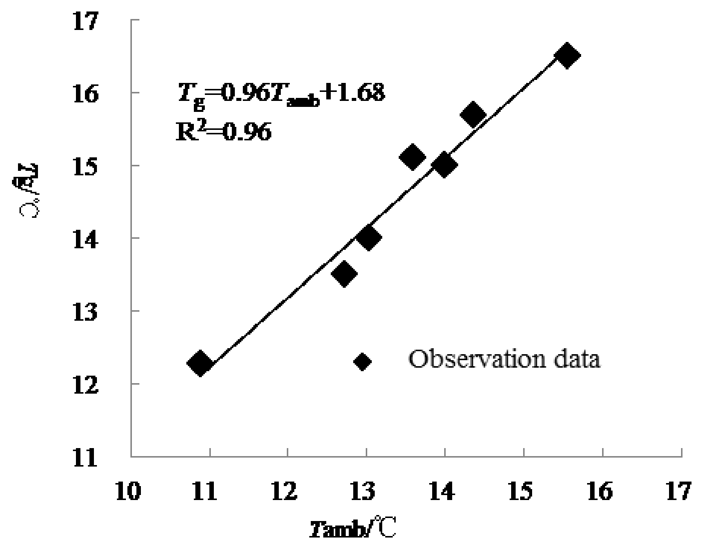

Figure 3: Linear correlation for undisturbed ground temperature versus ambient temperature.

3.3 Comparison with Measured Data

Table 4 presents a comparison between the two methods and the measured data. The error obtained in the table is the absolute error. The calculated value of Equation 4 has a high degree of fit with the measured one, the absolute error maximum is 0.28 ° C, and the minimum value is only 0.02 ° C. Comparing with Equation 5, Equation 6 has a larger error, yet not exceeding 1.2 °C, which satisfies the needs of everyday applications for prediction. Compared with Equation 5, one only needs to input in Equation 6 a conventional meteorological data to calculate the undisturbed ground temperature, and the error is within a reasonable range. Therefore, it enjoys wider application prospects.

Table4 Comparison between measured and predicted of the ground temperature

Location	Measurements /℃	Eq.(4) /℃	Error Eq.(4)/℃	Eq.(5) /℃	Error Eq.(5)/℃
Beijing	14.00	14.08	0.08	15.12	1.12
Tianjin	13.50	13.73	0.23	14.64	1.14
Shijiazhuang	15.00	15.09	0.09	16.08	1.08
Jinan	15.70	15.42	0.28	16.75	1.05
Zhengzhou	16.50	16.48	0.02	17.52	1.02
Taiyuan	12.27	12.10	0.17	13.46	1.19
Xi'an	15.10	15.16	0.06	16.18	1.08

4 CONCLUSION

The undisturbed ground temperature is a crucial indicator of the geothermal field and has a guiding role in developing and utilizing shallow geothermal energy. The study used meteorological data and measured ground temperature data to establish two formulas to calculate the undisturbed ground temperature in the warm temperate zone.

(1) The first formula aims to establish a linear correlation with the ambient temperature, sky temperature, wind speed, and direct radiation intensity of the horizontal plane, with a fitting degree of 0.98. It is found that the temperature is the most important parameter affecting the undisturbed ground temperature, and the proportion is somewhere between 76.25% and 80.31%, while the influence of the other three parameters is mostly less than 5%.

(2) The second formula aims at establishing a linear correlation with the mean ambient temperature with a fit of 0.96. The ambient temperature is the only parameter needed in the formula to calculate the undisturbed ground temperature, and its error is within a reasonable range. In China, it has a wider application prospect in areas in warm temperate zones which are in a lack of long-term monitoring data.

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