Distributed optical fiber monitoring test and numerical simulation analysis of water-heat coupling process

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Abstract: The distribution of shallow ground temperature field is controlled by the complex water-heat coupling effects of surface temperature, shallow groundwater temperature, and groundwater flow. An indoor medium-scale model box was established to explore the variation law of the shallow ground temperature field in the process of water-heat coupling between subsurface water and groundwater by using various temperature sensors. Based on this test, a two-dimensional numerical simulation was carried out with FEFLOW. The analysis combining the test and simulation results showed that distributed optical fiber monitoring can effectively monitor the temperature field. Additionally, the temperature data can be calibrated by FBG and PT100 sensors that are available to recognize the distribution of ground temperature field accurately. The groundwater flow plays an important role in the variation of temperature field; the evolutionary tendency of temperature field has roughly the same performance in soil layers as long as they share the same permeability and thermal properties. Thus, different characteristic layers will affect the distribution of seepage field, further controlling the temperature field. Finally, this work can be potentially used to quantitatively evaluate the storage potential of shallow geothermal energy at the city scale.

1. Introduction
Shallow geothermal energy refers to natural resources with low temperature (usually below 25 °C) and are stored below the ground surface from 0 m to 200 m (0–400 m) in several papers) [1]. In 1904, the first geothermal power plant was built in Lardero, Italy, marking the beginning of geothermal energy’s industrial exploitation [2]. Later, Swiss scholar H. Zoelly proposed the concept of shallow geothermal energy system. Since then, people have been paying more attention to shallow geothermal energy and considered it as a gold standard of clean, efficient, and renewable resource. As part of geothermal energy, shallow geothermal energy is mainly controlled by the shallow ground temperature field [3]; currently, our nation still mainly relies on wind energy, solar energy, hydraulic power, etc.; hence, we urgently need the supplement of this rising green power [4]. Herein, research on the shallow ground
temperature field is given attention.

Field investigation is a major means to explore the temporal and spatial distribution of the shallow ground temperature field. Susanne A Benz et al. analyzed the groundwater temperature and satellite surface temperature telemetry data and observed an up to 80% correlation between them [6-7]. Taniguchi M’s investigations in Osaka, Tokyo, Seoul, and Bangkok showed that groundwater extraction has crucial effect on changes in the shallow ground temperature field [8-9]. Shi Bin et al. established long-term observation stations and analyzed the monitoring temperature data to characterize the temporal and spatial distribution of the shallow ground temperature field in the urban and suburban areas of Nanjing [10]. Through analyzing the monitoring temperature data, Gao Xinyu discovered that the change in soil temperature is linearly related to depth, and the groundwater maintain in strata is beneficial to the recovery of soil temperature [11]. The research above shows that the distribution of and changes in shallow ground temperature field are affected by shallow groundwater and stratigraphic characteristics and related to the coupling effect of air temperature, surface ground temperature, and shallow groundwater temperature.

Numerical simulation is a common method for studying shallow ground temperature field given its low cost, high efficiency, and repeatability. Jaime A. Rivera et al. modeled the coupling effects of geothermal energy extraction, shallow surface heat conduction, underground horizontal flow, and land space utilization to analytically explain the vertically buried tube heat exchangers. The results suggest that the heat flux of surface asphalt or buildings combined with groundwater determines the distribution of ground temperature field [12]. Ke Zhu et al. established a two-dimensional water-heat conduction model in Cologne. The results indicate that the main heat conduction mechanisms in the gravel aquifer include long-term vertical heat flow input, horizontal convection, and lateral dispersion [13]. Hu Jihua et al. set up a coupled numerical model of groundwater flow and heat transportation. They developed the theory of hydraulic slope as a criterion for flow penetration through analyzing the interaction and influence of groundwater flow and temperature fields [14]. Zhang Yuandong et al. ran a three-dimensional thermal coupling numerical simulation model to simulate the changes in temperature field before and after aquifer energy extraction under different groundwater flow conditions; finally, they observed that the larger the natural groundwater flow rate is, the faster the temperature recovery [15].

The previous research on shallow ground temperature field based on field monitoring and numerical simulation involved the basic theory, key factors, etc., but studies on rising distributed fiber monitoring and quantitative analysis of the water-heat coupling process related to the ground temperature field are limited. Here, a medium-scale hydrothermal coupling model box was constructed using a high-precision distributed optical fiber temperature measurement system (DTS), fiber Bragg grating (FBG), and PT100 sensors to monitor the temporal and spatial distribution of the temperature field in the sand-soil interlayer under different groundwater flow conditions. Based on this test, a FEFLOW two-dimensional water-heat coupling numerical simulation and comparative analysis were carried out to elucidate the temperature field in this box. From the perspective of indoor simulation test and numerical simulation, the shallow ground temperature field was studied, and the monitoring scheme’s effectiveness was proven.
2. Process of Water-Heat Coupling Test and Equipment

An indoor water-heat coupling simulation platform, which can control the water supply temperature of the upper and lower aquifers, was built to simulate the actual water-heat coupling process of shallow surface water and groundwater under different boundary conditions. This platform can monitor the spatiotemporal distribution of temperature field supported by three kinds of sensors. The test equipment contains the model box, constant-temperature water supply tank, demodulator, and sensors.

![Model box and constant-temperature water-supply tanks.](image)

**Figure 1.** Model box and constant-temperature water-supply tanks.

2.1. Test equipment

The main body of the test platform has dimensions of $3 \times 1.5 \times 1.5$ m. The upper and lower sides of the box were respectively set up with 3 inlets and outlets and installed with equal-distance sprinklers for even watering. A pair of constant-temperature water supply tanks ($2.4 \times 2 \times 2$ m) were arranged on both sides of the box. The tanks can supply or pump water into the corresponding aquifer to form a pair of water circulation systems (Figure 1). Insulation boards were laid on the surface of the water tank, and heating rods with a power of 1.6 kw was fixed onto the tanks. An electric cabinet was used to control the constantly high temperature, whereas ice cubes or cold water were placed to maintain a low temperature. According to the monitoring data, the constant temperature error was within 0.5 °C.
Figure 2. On-site photo of temperature sensors.

The DTS sensor was used in this test to obtain accurate temperature field distribution data. At the same time, two types of point sensors, including FBG metal-protected fiber grating point thermometer and PT100, were used to calibrate the data collected by the DTS sensors (Figure 2).

DTS measurement accuracy can reach ±0.1 °C, the working temperature range was −40 °C–85 °C, and its winding fiber sensing rod improved the spatial resolution. The DTS shows strong resistance to destruction and exhibits high real-time performance, which are suitable for complex water-heat environment. The FBG’s accuracy reaches 0.1 °C, with the advantages of chemical resistance, high tensile strength, dense layout, and simultaneous monitoring of multiple points. The data collected can then be used as complement for DTS calibration. The working mechanics of PT100 determine its measurement relative reliability, with measurement range at ±200 °C. PT100 can retrieve and collect data in groups in real time, and its stability and high accuracy contribute to calibrating the temperature measurement data of other sensors.

The monitoring equipment included NZS-DTS-A03-type DTS demodulation instrument, PT100-32 channel inspection instrument, and NZS-FBG-A02 FBG demodulator. Table 1 shows the parameters. The coupling process is slow. Therefore, DTS and FBG sensors were set by 30 s interval to avoid collection of excessive data. Other parameters were set to their initial default value.

| Parameters             | Value          | Channels | 32   | Parameters             | Value          |
|------------------------|----------------|----------|------|------------------------|----------------|
| Distance (km)          | 1–16           | Wavelength range (nm) | 1527–1568 | Measuring range | 0.2FS%        |
| Measuring range (°C)   | −40–120        | Resolution (pm) | 1    | Temperature range      | −200–2400°C   |
| Fiber type             | Multimode (50/125) | Repeatability (pm) | ⩽3–3 | Humidity range        | 0–100%RH      |
| Accuracy (°C)          | 0.1            | Demodulation rate (Hz) | ⩽1   | Standard signal       | −20000(4–20mA) |
| Response time (s)      | 2s/channel      | Dynamic Range | 35dB | Sampling speed         | 1s            |
| Spatial resolution (m) | 0.5–3          | Maximum number | 30(per channel) | Channel isolation | 400v ( high voltage ) |
| Number of channels     | 4              | ——       | ——   | Control output        | 20 PID adjustment |
2.2. Test preparation

We designed the filling method and sensor layout scheme (Figure 3), which is divided into the following five steps:

1. Fill 10 cm gravel into the model box as the lower aquifer, compacting it. This layer, that is, the lower aquifer, was connected to a water tank and sprinklers that can control the water supply temperature.

2. Then, lay a thin metal filter above the lower aquifer to avoid the occurrence of sand or pipe surge. Arrange in parallel two rows of 10 sensors (Figure 3(a)). One of the two rows is the DTS temperature-measuring fiber, including five heating carbon-fiber rods and five high-performance distributed-temperature sensing rods. Two kinds of DTS sensors are staggered one by one. For comparison with DTS, equip the other row with 10 metal-protected FBGs (F1–F10); among these FBGs, attach F2, F5, and F8 sensors to the PT100 sensors.

3. Lay two layers of low- and high-permeability soil layers in the middle of the box at 25.5 and 101.5 cm thickness, respectively (Figure 3(b)). The soil layers are made from sand and kaolin, and the ratios are 8.5:1.5 and 9:1, respectively. The interface between should also contain a thin metal filter.

4. Then, place a thin metal filter on the shallow soil layer, continuing to fill 10 cm gravel as the upper aquifer. Check the demodulated signal and seal the box.

5. Install and check the two constant-temperature water tanks. Obtain a stable upper and lower aquifer water circulation system through pumping and supplying water into the box.

![Figure 3. Distribution of layers and planform of arrangement of sensors.](image-url)
2.3. Test processes
When the test platform preparation was completed, the water-heat coupling process test was operated by controlling the water supply temperature, switching the pump on or off, and performing the following steps:

1) The upper aquifer was supplied with water to saturate the whole soil body, whose temperature was roughly equal to air temperature. The process was continued until the temperature field in the box was stable. The temperature curve demodulated by DTS showing no change after 1 h was used as a standard to stop.

2) The upper aquifer was supplied with water whose temperature was roughly 7 °C. The water flow in the upper aquifer and the water tank circulated as a water cycle system, disturbing the initial temperature field for 3.5 h.

3) The lower aquifer started to be supplied with constant-temperature water (about 20 °C), and the water flow in the lower aquifer and the other constant-temperature water supply tank circulated as a cycle system until the end of the test.

4) The water supply temperature of the upper aquifer was changed from a low temperature (about 7 °C), gradually dropped to about 2 °C, and then slowly increased to about 30 °C, monitoring the distribution and change of the temperature field throughout the process for 48 h.

The boundary yielded several small channels, causing the nearby temperature field to change faster than the middle area of the box. We applied several measures to reduce the effects of the boundary: 1) keeping the sensors at a certain distance away from the boundary; 2) treating the corners where each layer interfaced the box with water-proof material; 3) prioritizing the data obtained by the sensors in the middle for the analysis and using other information as auxiliary calibration and reference; 4) maintaining the small-difference discharge of water supply and pump.

3. Result Analysis
Figure 4 shows the actual measured water supply temperature (monitoring location is the geometric center of water tank) of the upper and lower aquifers. The beginning at 35 min was marked as zone A, which shows the initial temperature field; 35–235 min, zone B: only the upper aquifer was supplied with low-temperature water; 235–526 min, zone C (3.5–9 h): the average temperature was 4.4 °C; 526–1011 min (9–17 h), zone D: the average water temperature was 2.1 °C; 1011–1320 min (17–22 h), zone E: water temperature was 2 °C–10 °C; 1320–1830 min (22–30.5 h), zone F: water temperature was 10 °C–20 °C; 1830–2160 min (30.5–36 h), zone G: water temperature was 20 °C–30 °C. After zone H, the average water supply temperature of the upper and lower aquifers were up to 31.4°C and 20.4°C, respectively, until the end of the test. The test lasted for 48 h. Here, the letters were set for subsequent analysis of the temperature fields in different time intervals to visually recognize the water supply temperature information during this period.
Figure 4. Water supply temperature of upper and lower aquifer layers.

Figure 5 shows the temperature cloud diagram on the left side of the box monitored by DTS2. The abscissa represents the operating time, and the ordinate denotes the depth of soil layers. The temperature in zone A, which shows the initial temperature field, was maintained at about 9.4 °C. The initial monitoring for 25 min showed that the temperature field was unchanged without water supply. Later, the upper aquifer was supplied with low-temperature water at 7 °C. At 35 min, the temperature of the shallow layer with low permeability was significantly reduced, and the influence reached a certain depth in zone B (45 cm). Additionally, at 211 min, the lower aquifer was supplied with water, whose temperature was roughly 20.4 °C. The temperature field changed at 235 min. Specifically, the bottom soil layer with high permeability started to heat up. The infiltration of the water flow seriously changed the initial temperature field.

After zone C, the upper and lower aquifers were all supply with water. A complex process of water-heat coupling occurred in the box. The water supply temperature of the lower aquifer was maintained at

Figure 5. The temperature field on the left side of the model box varies with time
20.4 °C, whereas that of the upper aquifer gradually increased from 2 °C to about 31.4 °C. Therefore, we can simulate the spatial and temporal distribution of the shallow ground temperature field under the action of shallow surface water in different water temperature conditions. In zone D, the two aquifers were only affected at a certain distance from the upper and lower interfaces, but the effect gradually extended toward into the middle. In zones E–H, the temperature fronts of the temperature fields influenced by the upper and lower aquifers made contact. They reached a comparable stable state in zones E–G. At this point, the temperature field remained unchanged at the adjacent zone of 56 cm, forming a normal-temperature layer of about 11 °C. In zone H, the water supply temperature of the upper aquifer reached the ridge, thus expanding its influence. This condition caused the soil layers to warm up to a large extent. Meanwhile, the normal-temperature layer was disturbed. At this point, the water supply temperature of the lower aquifer was still constant, and the influence range was unchanged. Therefore, the rate of temperature increase, which was notably lower than that of the upper soil layer, was also significantly reduced. The upper and lower aquifers at different temperatures seriously changed the temperature field in the box. With the considerable change in water supply temperature, the aquifers’ effect expanded, and the temperature increase rate also rose.

Figure 6 shows the PT100 monitoring results of the corresponding position versus DTS1, which indicated the same pattern. After supplying water, the initial temperature field immediately changed, demonstrating that groundwater flow strongly affected the initial temperature field. The slope of the curve can intuitively analyze the temperature variation at each zone. In zone B, only the upper part of this box was supplied with the low-temperature water. Then, the temperature of the shallow soil layer immediately dropped, affecting the shallow soil layer depth at 50.6 cm. With the increase in depth to 35 cm, the permeability of soil layer worsened, and the temperature change rate decreased. However, the rate in the soil with the same permeability was roughly the same, as shown in Figure 6(a). In zone C, the lower aquifer was supplied with water, and the temperature field of the lower soil layer increased. The lower soil layer with the same permeability thus had the same temperature increase rate, as shown in Figure 6(b). In addition, given the water inrush into the upper aquifer, the water supply was temporarily cut off. Hence, the temperature of the shallow soil layer in zone C rebounded, as shown in Figure 6(c), which reflects the important role of groundwater flow in temperature field distribution. As the supply water temperature of the upper aquifer increased, in zones D–H, the upper aquifer with high temperature limited the capability of the lower aquifer to disturb the temperature field, as shown by the extremely steady and slight rise of the temperature curve of the bottom soil layer. The scope of the upper aquifer influence expanded, as indicated by the significant rise in the temperature curve of the lower soil layer, which gradually changed the temperature field. Under the convection of aquifers with different temperatures conditions in zone F, a normal-temperature layer with a small thickness appeared at about 50 cm. The water supply temperature of the upper aquifer in zone G rose to 31.4 °C, whereas the temperature change rate in the shallow soil layer was notably greater than that in the bottom one. The normal-temperature layer moved downward to the right, but no new normal-temperature layer appeared. Zone H showed the dramatic temperature increase of shallow soil layers by 25.8, 38.2, and 50.6 cm. The temperature increase at 75.4, 87.8, and 100.2 cm was not evident, and the lowest temperature appeared at about 63 cm. Thus, under the coupling effect of the upper and lower aquifers, the relatively low-temperature area was forced to increase in
temperature and moved downward to the right. The initial temperature field disappeared finally at the lower right and changed the whole temperature field in the box.

![Temperature curves at different depths on the left side of the model box](image)

**Figure 6.** Temperature curves at different depths on the left side of the model box

In general, groundwater flow can significantly change the initial temperature field; the permeability of the soil layer affects the flow field distribution, and a high permeability is beneficial to seepage, which in turn drives thermal convection to change the temperature field distribution in soil layers with different properties; soil layers with the same permeability and thermal properties have the same performance with regard to temperature field change; groundwater flow is a medium for the transmission and storage of low-temperature resources, and its thermal properties and storage environment are very meaningful for the distribution, transportation, storage, development, and utilization of ground temperature energy [16].

The times of 3.5, 9, 26, 36, 41, and 48 h were further subdivided based on the stage of water supply temperature division (Figure 4) to reveal the spatial and temporal distribution of the temperature field in the box at 48 h. Then, the temperature field distribution in the box under different temperature boundaries was drawn (Figure 7). At 0 h, the temperature field in the box was stable at about 9.4 °C, as shown by the initial assignment of two-dimensional numerical simulation. At 0–3.5 h, only the upper aquifer was supplied with water with an average temperature of 5.8 °C, immediately affecting the position at about 45 cm. At 3.5–9 h, the lower aquifer was supplied with water at about 20 °C, the upper and lower aquifers started to interact with each other in the box, and the bottom soil layer temperature started to rise. At 9–26 h, the two aquifers with water supplies of different temperatures continually underwent water-heat coupling, the shallow low-temperature area moved downward, and the bottom high-temperature area extended upward to the shallow soil layer. A contact tendency was observed between the two aquifers' temperature influencing fronts, and the water temperature of the lower aquifer continually increased to warm up the soil layer until 26 h, when fronts contacted. A normal-temperature layer appeared at the depth of about 56 cm. At 26–36 h, the water supply temperature of the upper aquifer rose rapidly, and each image showed that the water supply temperature increased by 5 °C. The temperature water supply temperature in the box reached 30 °C in 36 h. The normal-temperature layer was pushed downward to the right, as shown by the temperature
field distribution at 41 and 48 h. During this period, the upper aquifer began to play a dominant role in the temperature field disturbance. The temperature field in the shallow soil layer changed drastically, and the temperature rapidly increased. Meanwhile,

![Figure 7. Distribution of the temperature field under different time intervals.](image)

In general, the temperature-changing upper aquifer and constant-temperature lower aquifer worked together to affect a certain range of temperature distributions, and a relatively stable area appeared. As the boundary temperature continually increased, the influence range expanded, and a new normal-temperature layer formed. Eventually, the entire initial temperature field was changed; soil layers with different thermal properties and permeability behaved differently in the process of water-heat coupling. The soil layer with large permeability is more conducive to the flow of water, which is beneficial to transportation and supplementary of geothermal energy.

4. Numerical Simulation and Comparative Analysis

Based on the indoor water-heat coupling simulation test, the temporal and spatial distribution of the temperature field in the medium-scale model box was obtained, and the FEFLOW two-dimensional numerical simulation of the water-heat coupling test was carried out. The boundary conditions and initial assignments were feasible according to the test data. Thus, they can be used to simulate the distribution and evolution of the temperature field of the soil body under different temperature conditions of the two aquifers. Then, combining the test with numerical simulation, a means can be applied to evaluate and study the distribution and evolution of the ground temperature field quickly.
and reasonably in a certain area. Furthermore, FEFLOW, a commercialized and mature groundwater numerical simulation software, can accumulate the experience of numerical simulation in this research for future discrete element numerical simulation.

Table 2. Parameters of the four aquifer layers.

| Soil layer | Component         | Porosity | Permeability coefficient k(cm/s) | Thermal Conductivity W/(m·K) | Specific heat capacity kJ/(kg·K) | Thermal diffusion coefficient ×10⁻³(m³/h) |
|------------|-------------------|----------|---------------------------------|-----------------------------|---------------------------------|----------------------------------------|
| 1          | gravel            | 0.27     | 0.1                             | 1.5                         | 1.15                            | 3.55                                   |
| 2          | sand:kaolin 8.5:1.5 | 0.4      | 6×10⁻⁴                         | 1.85                        | 1.85                            | 1.15                                   |
| 3          | sand:kaolin 9:1   | 0.45     | 2×10⁻³                         | 1.15                        | 1.45                            | 1.9                                    |
| 4          | gravel            | 0.27     | 0.1                             | 1.5                         | 1.15                            | 3.55                                   |

A two-dimensional water-heat coupling model (3 m × 1.5 m) was established by applying FEFLOW with triangle division method, and the number of elements was 1.0×10⁶. The soil body was divided into four layers (Figure 3), whose parameters are shown in Table 2. The model was set to an unstable boundary. The first layer belonged to a second type of boundary (discharge boundary) on the left side of the water (−32 m²/day) versus the right side pumping (32 m²/day). The left and right sides of the third layer were the same as those of the first layer. The initial temperature was set to 9.4 °C, the temperature boundary of the first layer adopted the time series in Figure 1, and the fourth layer was the heat source boundary (20.4 °C). The process involved the quantitative monitoring of the temperature field changes in the box. The layers were not strictly compounded based on the characteristics of soil in Nanjing. In addition, considering the cost, we mixed the existing kaolin and sand. Then, a test was performed to determine the graduation. The value was obtained in accordance with a reference. Among the parameters, the permeability coefficient and density were measured, and thermal conductivity was the calculated one.
Figure 8. Numerical simulation results of the temperature field with different temperature boundaries.

Figure 8 shows that the temperature field distribution in the box was strictly simulated in accordance with the test conditions. The temperature boundaries were as follows: average temperatures of 4.4 °C, 2.1 °C, 5.4 °C–10 °C, 10 °C–20 °C, 20 °C–30 °C, and 31.4 °C at 9, 17, 26, 30.5, 36, and 48 h, respectively. The results show that the simulation results at different times were consistent with those in Figure 7. The water with different temperatures entered the two aquifers, the temperature field was immediately disturbed, and the upper aquifer with low-temperature water significantly reduced the temperature of the shallow soil layer. The lower aquifer with 21.4 °C water supply temperature caused the temperature in the box to rise. The continuous water-heat coupling process severely deformed the temperature field in the box. In addition, the upper and lower aquifers had different ranges of influence. The fronts of both aquifers contacted first on the left side of the box and gradually formed a relatively stable-temperature layer. As the water supply temperature of the upper aquifer increased, its influence range increased, whereas the lower aquifer maintained a constant water supply temperature. The scope of effect was limited to the side of the bottom high-permeability soil layer extending slowly. With the simulation progress, aquifers with different temperatures continued to interact and underwent a complex water-heat coupling process. The lower aquifer gradually stabilized, finally forcing the fronts to move downward to the right of the box. The initial temperature field gradually changed completely. At 36 h, the initial temperature field was almost completely changed. Only the lower part of the right side still had an initial temperature field of about 9 °C. Afterward, the upper and lower aquifers were maintained at 31.4 °C and 20.4 °C water supply
temperature condition, respectively, continuing the process for 12 h. The temperature in the rightmost area in the box was higher than the initial temperature of 9.4 °C, completely changing the initial temperature field. Thus, the upper and lower aquifers eventually induced the temperature field in the model box to a stable state, forming a new stable normal-temperature layer at a certain depth in the lower right if the test was continued under this condition.

5. Conclusions
In this paper, a medium-scale indoor model box was built to establish a water-heat coupling indoor simulation test platform. DTS, FBG, and PT100 sensors were used to monitor the temperature field changes and to explore the perturbation effect of groundwater flow to the temperature field and the process of water-heat coupling in the sand and soil interlayer. The findings and conclusions are as follows:

(1) The medium-scale model box was closed, pressure-bearing, simple, and controllable and can be used as a means to study shallow ground temperature field indoors.

(2) The DTS sensor, with characteristics of continuous temperature measurement, can effectively monitor the changes in ground temperature; PT100 temperature measurement is relatively accurate and can be used as a calibration; FBG is a new type of optical fiber sensor, which can be used reasonably with DTS and PT100 to improve the efficiency and accuracy of temperature monitoring.

(3) Shallow groundwater temperature is affected by the atmosphere and other heat sources, and groundwater flow is an important factor for the temperature field change compared with the initial temperature field and saturated soil.

(4) Different permeability and thermo-physical properties of the soil layer have varied convection effects, affecting the distribution of the seepage field and further controlling the distribution of the temperature field.

Here, indoor test and numerical simulation were used to analyze the influence of the medium-scale temperature field on the disturbance of groundwater flow and water-heat coupling process. The model box test and numerical simulation provide a new perspective and a simple and low-cost method to study of regional shallow geothermal energy. Further combination with on-site work is available to establish a city-scale 3D geological map for the quantitative evaluation and analysis of the potentiality of urban shallow geothermal energy.

Acknowledgments
This work was funded by the National Natural Science Foundation of China (41761134089, 41977218) and the Jiangsu Natural Science Foundation Youth Project (BK20170393). Thanks a lot to the test site and monitoring equipment provided by Suzhou Nanzhi Technology Co., Ltd.

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