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ORIGINAL RESEARCH ARTICLE

Sustainability study of medium-deep geothermal buried pipe for heat supply

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ABSTRACT

In order to study the temperature change trend of the surrounding geotechnical soil during the operation and thermal recovery of the medium-deep geothermal buried pipe and the influence of the geotechnical soil on the operational stability of the vertical buried pipe after thermal recovery. Based on the data of geological stratum in Guanzhong area and the actual engineering application of medium-deep geothermal buried pipe heating system in Xi'an New Area, the influence law of medium-deep geothermal buried pipe heat exchanger on surrounding geotechnical soil is simulated and analyzed by FLUENT software. The results show that: after four months of heating operation, in the upper layer of the geotechnical soil, the reverse heat exchange zone appears due to the higher fluid temperature; in the lower layer of the geotechnical soil, the temperature decreases more with the increase of depth and shows a linear increase in the depth direction; without considering the groundwater seepage, after eight months of thermal recovery of the geotechnical soil after heating, the maximum temperature difference after recovery is 3.02 ℃, and the average temperature difference after recovery is 1.30 ℃ The maximum temperature difference after recovery was 3.02 ℃ and the average temperature difference after recovery was 1.30 ℃. The geotechnical thermal recovery temperature difference has no significant effect on the long-term operation of the buried pipe, and it can be operated continuously and stably for a long time. Practice shows that due to the influence of various factors such as stratigraphic structure, stratigraphic pressure, radioactive decay and stratigraphic thermal conductivity, the actual stratigraphic temperature below 2,000 m recovers rapidly without significant temperature decay, fully reflecting the characteristics of the Earth's constant temperature body.

Keywords: Medium-Deep Ground Source Heat Pump; Heat Transfer Characteristics; Buried Tube Heat Exchanger; Full-Size Model; Heat Influence Radius

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1. Introduction

Conventional ground source heat pump technology is a technology that uses shallow geothermal energy to heat and cool surrounding buildings with clean and renewable, efficient[1]. However, the application of shallow geothermal energy has the disadvantages of large footprint, rapid changes in soil heat, and unstable operation.

In order to overcome the disadvantages of the shallow geothermal buried pipe, scholars designed to increase the depth of the borehole to about 2,000 ~ 3,000 m, the temperature in the high temperature rock soil of 70 ~ 90 ℃, the buried pipe can obtain a higher temperature and stable operation of the outlet water temperature for heating, which is suitable for application in the northern part of China. This technology was listed as a green promotion technology by the

National Development and Reform Commission in 2020 due to its huge energy reserves, clean and non-disturbing, wide distribution, and high safety factor[2]. This technology has also become one of the research hotspots for air conditioning technology in China. At the present stage, the research on medium-deep geothermal buried pipe heating system mainly focuses on the research of heat extraction capacity of buried pipe, heat transfer optimization of buried pipe[3-5].

The core of the heat transfer technology of medium and deep buried pipes lies in the heat transfer between the buried casing and the surrounding geotechnical soil. There are fewer studies on the heat transfer changes in the rocky soil around the casing during operation. In similar studies, related scholars used numerical programming or finite element simulation software to complete relevant calculations, such as Fang *et al.*[6,7] established the analytical and numerical solutions for the heat exchanger of the medium-deep buried pipe based on the original theory of shallow buried management; Jia *et al.*[8] assumed the surrounding geotechnical layer as a homogeneous medium and studied the single-hole and multi-hole medium-deep (2,000 m) by numerical methods under multiple operating conditions The thermal response of the geotechnical soil around the geotechnical buried pipe; Renaud *et al.*[9] used numerical programming to calculate and analyze the thermal disturbance of the geotechnical rock during years of operation of a vertical buried pipe of high temperature geotechnical rock near the Icelandic subsurface magma. Lu *et al.*[10] used CFD software to construct a two-dimensional cluster well model and computationally analyzed the variation pattern of the geotechnical temperature field around the cluster well. Most of the existing studies are based on the homogeneous rock distribution model calculated by numerical programming, and the accuracy of which is unknown due to the lack of actual data comparison.

In this paper, using the subsurface rock layer distribution in the Guanzhong area, combined with the actual operation of the middle and deep geothermal buried pipe heating system in the Xi'an New Area, ICEM was used to establish geometric model and establish a 1:1:1 full-size 3D model of the heat transfer process between the vertical buried pipe and the surrounding geotechnical soil at a depth of 2,510.00 m; using FLUENT software was used to analyze and study the effect of single-hole heat extraction on the temperature law of the geotechnical region.

2. Medium-deep geothermal buried pipe and geotechnical model

The coaxial casing heat extraction model of medium-deep geothermal buried pipe is shown in **Figure 1**.

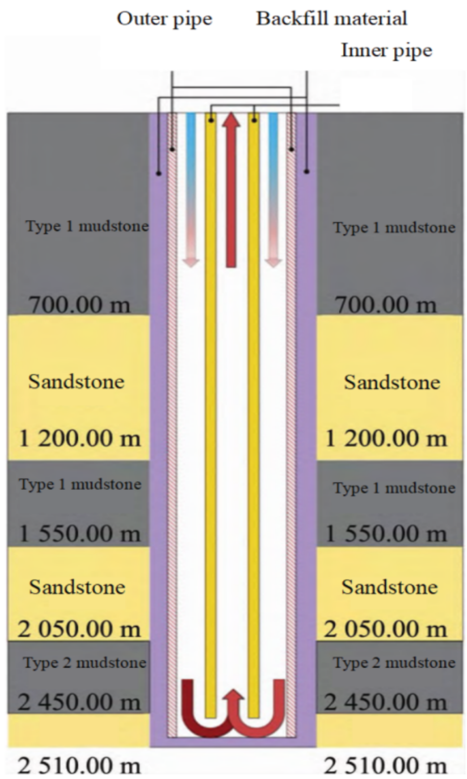


Figure 1. Schematic diagram of medium and deep buried pipe and geotechnical model**.**

The circulating mass in the casing is fed from the annular cavity area between the inner and outer tubes, and continuously absorbs heat from the subsurface geotechnical soil along the way, and the high temperature hot water flows back to the inner tube from the bottom of the casing and is output via the inner tube. The outer pipe of the buried pipe is a high thermal conductivity iron pipe, which facilitates the indirect heat transfer between the water and the rock in the annular cavity. The inner pipe is a plastic pipe with low thermal conductivity to reduce heat loss due to heat transfer between hot water in the inner pipe and cold water in the cavity pipe. In addition, the buried pipe is covered with cementing (backfill) material after drilling the well and the rest of the area is rocky soil.

2.1 Geotechnical parameters

According to the geological data of Xian area, the top-down distribution is type 1 mudstone, sandstone, type 1 mudstone, sandstone, type 2 mudstone, sandstone. The model soil depth distribution and soil physical parameters are shown in **Table 1**.

2.2 Geometric dimensions and material physical parameters of the medium-deep buried pipe and geotechnical model

The model is a cylinder with a total depth of 2,510.00 m and a radius of 50.00 m. The casing part: inner pipe outer diameter 110.00 mm, inner diameter 90.00 mm; outer pipe outer diameter 177.80 mm, inner diameter 159.42 mm.

Table 1. List of geotechnical physical parameters

Lithology	Physical parameters		
	Density/(kg·m^{-3})	Specific heat capacity/(J·kg^{-1}·K^{-1})	Thermal conductivity/(W·m^{-1}·K^{-1})
Type 1 mudstone	2,027	1,099.39	1.823
Type 2 mudstone	1,551	1,410.02	2.224
Sandstone	1,800	1,531.10	1.600

Table 2. List of casing pipe material and physical property parameter

Material	Density/(kg·m^{-3})	Specific heat capacity/(J·kg^{-1}·K^{-1})	Thermal conductivity/(W·m^{-1}·K^{-1})
Polyethylene pipe	950	2,300.00	0.420
Steel pipe	7,850	498.00	40.000
Cement mortar	1,800	1,050.00	0.930

The cementing material is wrapped around the outer pipe with a thickness of 40.00 mm, and the cementing material is rocky soil outside of it.

The outer pipe is made of special steel pipe, the inner pipe is made of high-density polyethylene plastic pipe, and the cement mortar is used for the cementing material. The physical parameters of each material are shown in **Table 2**.

2.3 Model assumptions

Due to the large computational load for establishing the full-size model of buried pipe and ground rock, the following assumptions are made for the calculation of the model.

(1) The geotechnical soil in the model is uniformly distributed in the depth region, ignoring the phenomenon of groundwater seepage and fragmentation distribution.

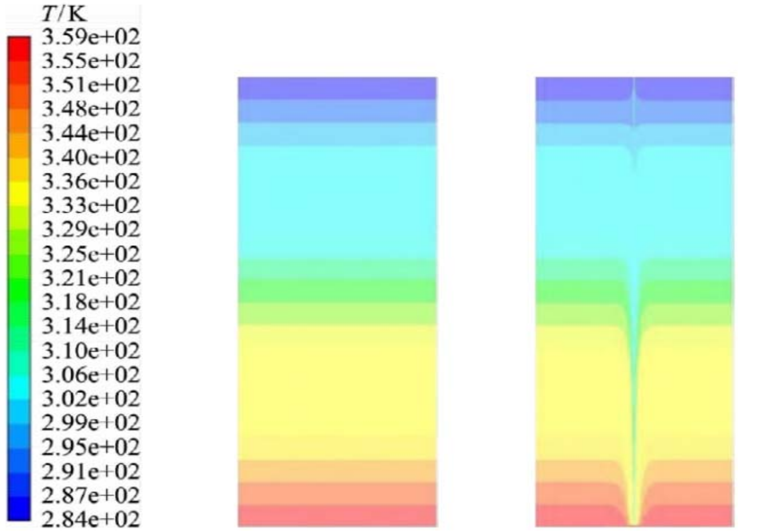
(2) Ignoring convective heat exchange between the geotechnical surface and air.

(3) Since the temperature difference from the geotechnical soil at infinity to the internal geotechnical soil is simulated during operation to maintain heat transfer, the geotechnical soil at the edge of the model (50.00 m radius) is constant temperature and the temperature of the outer wall surface of the model does not change with time.

2.4 Model calculation settings

The soil surface temperature is 10.41 °C and the temperature increases with depth at a temperature gradient of 0.0300 °C/m. The bottom surface is set as a constant temperature wall surface and the temperature is set to 85.71 °C. The initial temperature distribution of the model is shown in **Figure 2(a)**. The inlet water temperature was set to 16.00 °C and the flow rate was set to 25 t/h.

The model is imported into FLUENT software for numerical simulation, and the solution is solved using the split solver. The model was calculated using the Realizablek-ε model, the wall function method was chosen, the SIMPLEC algorithm was chosen for the pressure-velocity coupling, and the second-order windward format was chosen for the convective differential format in the model. In the boundary condition setting, the “turbulence specification method” is set to “intensity and hydraulicdiameter”, and the upper surface of the geometric model is set to "heatfluid". The upper surface of the geometric model is set to "heatflux" type wall; the inner wall surface of the inner pipe, the outer wall surface and the inner wall surface of the outer pipe are set to "couple" type wall; the outer wall surface of the geotechnical model is set to adiabatic interface.



(a) Before heat extraction **(b)** After heat extraction

Figure 2. Temperature distribution of rock and soil before and after heat extraction.

3. Heat extraction analysis of the geotechnical soil around the medium-deep buried pipe

Assuming a continuous heating season of 120 d, working 24 h per day, the temperature trend of the geotechnical soil around the buried pipe in the heating season can be calculated by the constructed physical model. **Figure 2** shows the temperature variation clouds before and after heat extraction in the rock around the medium-deep buried pipe at the end of one heating season.

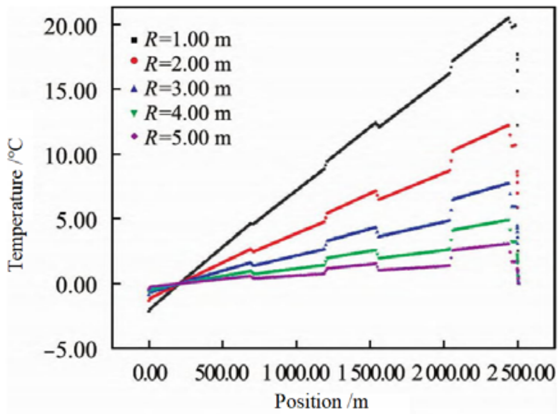
3.1 Temperature disturbance analysis

In order to accurately describe the thermal variation in the rock and soil area, the thermal disturbance radius $r_{\Delta t}$ is introduced and Δt is calculated as

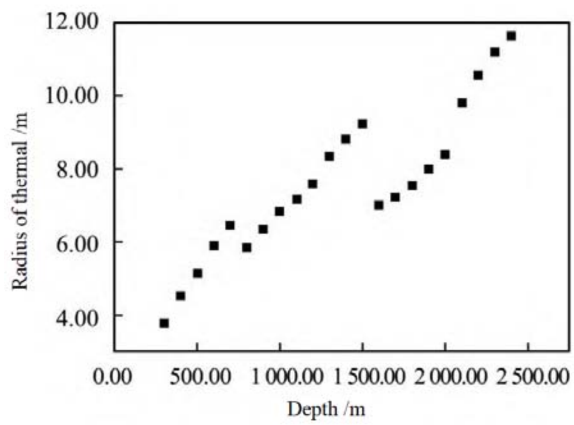
$$\Delta t_{r^*,\tau} = t_{r^*,\tau} - t_{r^*,0}$$

Where: $\Delta t_{r^*,\tau}$ is the temperature r, τ at τ time radius r* and the difference of temperature $t_{r^*,0}$. Select the appropriate Δt to find the interference radius.

Figure 3(a) shows the distribution of temperature difference between depth direction and initial temperature at different radii R = 1.00, 2.00, 3.00, 4.00, 5.00 m. In the depth region of 0.00 ~ 202.00 m, the temperature difference at different



(a) Geotechnical temperature difference at different radii



(b) Radius of geotechnical thermal disturbance at different depths

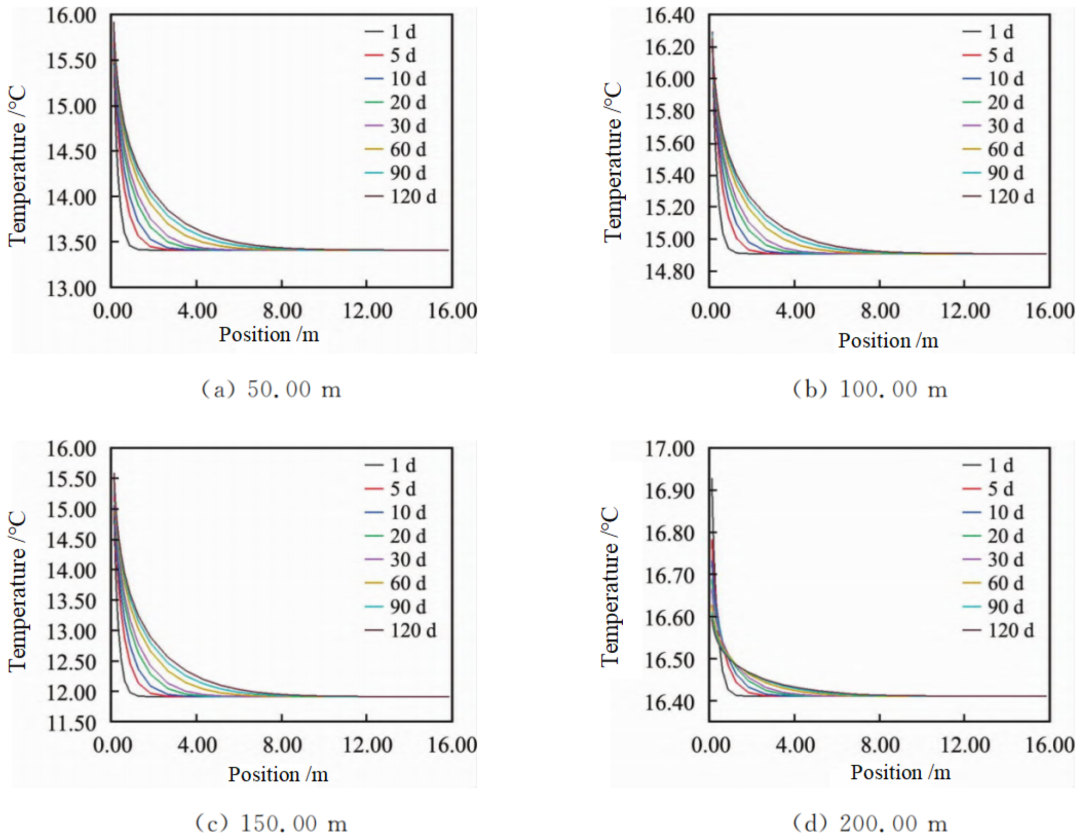
Figure 3. Distribution of temperature and radius direction heat interference radius in geotechnical area.

radii is negative, and in the whole depth range, the temperature difference distribution at different radii shows segmented linear distribution, and the temperature difference increases with depth The temperature difference increases with depth and reaches the maximum at 2,429.00 ~ 2,439.00 m; due to the uneven distribution of rock layers, the slope of the linear distribution of temperature difference in different geotechnical regions is approximately the same, and for the sandstone with small thermal conductivity, the slope of the temperature difference distribution is 0.0089 °C/m in the region of 700.00 ~ 1,200.00 m; for the type 2 mudstone with the largest thermal conductivity, the temperature difference slope is 0.0088 ℃/m. With moving away from the casing, the decrease of geotechnical temperature decreases, but still shows the segmental distribution trend of the same slope.

The variation of the thermal interference radius with depth determined by the temperature drop of 0.20 ℃ is shown in **Figure 3(b)**. It can be found that the thermal interference radius increases with depth, and basically also shows a linear increase, with the increase of the depth of the rock layer, the thermal interference radius keeps increasing, i.e., the deeper the rock layer is, the more the thermal interference can extend to the more distant rock layer under the same lithology. With the increase of depth, the heat transfer temperature difference between the bottom fluid and the rock layer is larger, and the heat transfer intensity at the bottom of the buried ground increases, so the temperature at the bottom of the rock soil decreases faster, and the temperature disturbance can extend to farther.

3.2 Reverse disturbance analysis

As shown in **Figure 3(a)**, the temperature difference in the rock and soil from 0.00 to 202.00 m depth is negative, which can be understood as the reverse interference zone. In this area, the depths of 50.00, 100.00, 150.00, 200.00 m are collected as monitoring lines in this paper, and the temperature change trend of each node is shown in **Figure 4**.



(a) 50.00 m (b) 100.00 m

(c) 150.00 m (d) 200.00 m

Figure 4. Variation of rock and soil temperature at different depths in reverse interference area.

From **Figure 4**, it can be seen that the reverse heat transfer trend occurs at 50.00, 100.00, 150.00 and 200.00 m depths, and the rock and soil around the buried pipe absorbs the heat from the buried pipe and the temperature increases continuously. This is because the inlet water temperature of the buried pipe is set to 16.00 °C, which is greater than the upper layer temperature of the rock, and the water temperature in the annular cavity pipe is higher than the surrounding rock layer temperature, therefore, the heat transfer in the upper part of the rock layer appears with the reverse heat transfer, that is, the buried pipe outputs heat to the rock layer. At the same time, according to the temperature gradient calculation, 16.00 °C rocky soil appears at 186.30 m, and the depth in the reverse interference area is up to 202.00 m, which is due to the heating of water in the annular cavity pipe by the inner pipe water and rocky soil along the way, and the upper water temperature is higher compared with the single pipe flow temperature, so the reverse interference area is wider.

3.3 Forward interference analysis

The collection depth is 500.00, 1,000.00, 1,500.00, 2,000.00, 2,250.00 m as the monitoring line, the temperature change trend of each node is shown in **Figure 5**.

From **Figure 5**, it can be seen that the temperature of the geotechnical soil near the buried pipe part decreases significantly, and the temperature change along the radius direction is flat and tends to the initial temperature. At the depths of 500.00, 1,000.00, 1,500.00, 1,750.00, 2,000.00, 2,250.00 m, after four months of operation, the temperature disturbances spread to 4.29, 5.77, 6.73, 7.95, 10.07 m of the rock radius respectively, calculated with a temperature drop of 1.00 °C.

4. Analysis of the thermal recovery of the rock and soil around the medium-deep buried pipe

After 4 months of continuous operation, the system is shut down and the fluid inside the casing

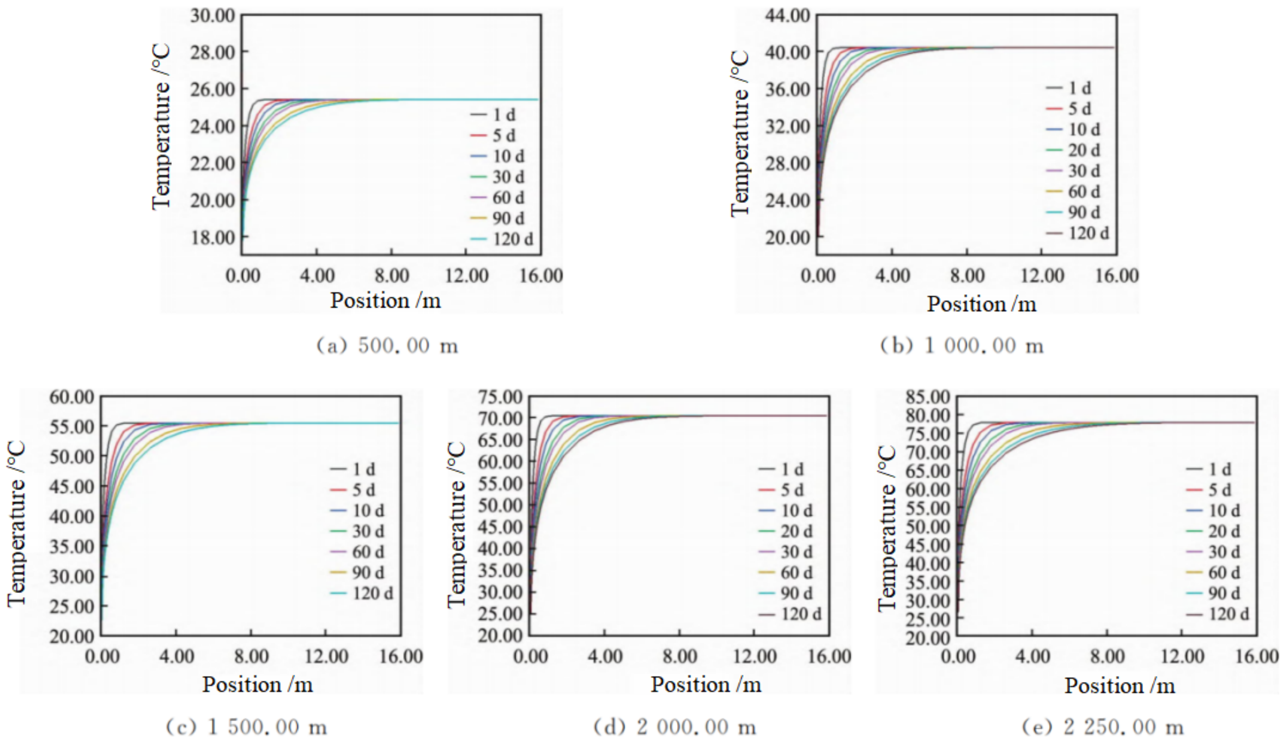


Figure 5. Variation of soil temperature at different depths in positive interference area.

is stationary and no longer draws heat from the rock layer, the model will continue the thermal recovery process for 8 months due to the continuous heating of the surrounding geothermal source. From the surface down the rocky soil can be divided into variable temperature zone, constant temperature zone and increasing temperature zone according to the temperature, and the relevant literature indicates that the rocky soil in the Guanzhong basin of Shaanxi Province is in the variable temperature zone from 0.00 to 11.00 m and in the constant temperature zone from 11.00 to 17.40 m[11]. In this simulation, we ignore the seasonal variation of geotechnical temperature and use the temperature distribution after 4 months of continuous heat extraction (**Figure 3(b)**) as the initial condition, and the upper surface of the geotechnical soil is set as the adiabatic wall surface, and the outer surface is set as the thermostatic wall surface with the original linear temperature distribution. The temperature cloud after thermal recovery is shown in **Figure 6**.

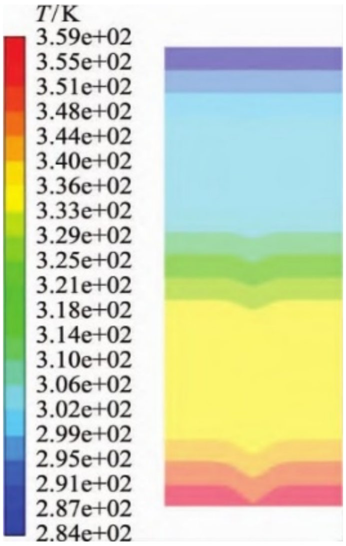


Figure 6. Temperature distribution of rock and soil after thermal recovery.

In this paper, the points at different depths of 500.00, 1,000.00, 1,500.00, 2,000.00, 2,250.00 m at the radius of 1.00 m of the medium-deep geothermal buried pipe heat extraction model were monitored, and the temperature changes during the 8 months of thermal recovery as shown in **Figure 7**.

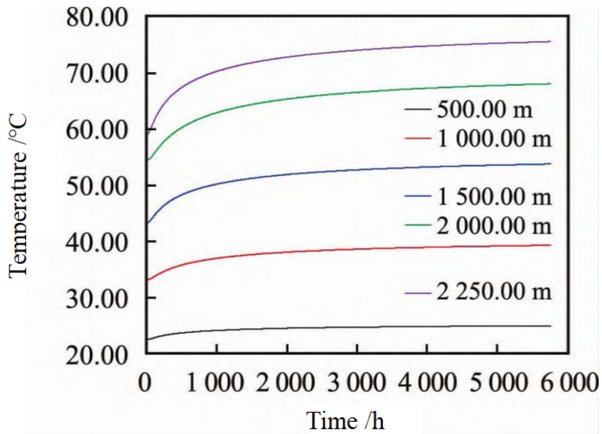


Figure 7. Temperature rise change of each point at R = 1.00 m of heating mode.

From **Figure 7**, it can be seen that the geotechnical temperature gradually increased at different depths of 1.00 m radius, and the temperature recovery slowed down and stabilized with time. At 500.00, 1,000.00, 1,500.00, 2,000.00, 2,250.00 m deep, the initial temperatures before heat extraction were 25.41, 40.41, 55.41, 70.41, 77.91 °C, respectively; after months of thermal recovery, the temperatures recovered to 25.03, 39.32, 51.78, 68.00, 75.50 °C respectively. The temperature differences from the original temperature were 0.38, 1.09, 1.64, 2.41, and 2.41 °C respectively. Due to the assumption of uniform distribution of rock and soil and neglect of groundwater seepage in this study, the effect of rock and soil thermal recovery is slow compared with the actual recovery process.

After 8 months of thermal recovery, the recovered temperature in the geotechnical area near the buried pipe differed from the original temperature, as shown in **Figure 8**, at 500.00, 1,000.00, 1,500.00, 2,000.00, 2,250.00 m depth radius direction, at 1.00°C, temperature disturbance residuals at radii 1.82, 5.14, 7.12, 6.81, 7.59 m. It can be found that the thermal recovery is less effective with increasing depth and the recovery is also related to the geotechnical parameters, for the type 2 mudstone near 2,000.00 m, the thermal recovery is better compared to the type 1 mudstone near 1,500.00 m due to higher thermal diffusion coefficient. In order to evaluate the effect of temperature recovery of the geotechnical soil after thermal recovery, the average temperature difference of the run line, i.e., the average temperature difference between the run line temperature after thermal recovery and the original temperature at a radius of 1.00 m at the geotechnical soil, was used. The temperature difference between the geotechnical soil temperature before and after the thermal recovery of 1.00 m of the path line and the initial temperature is shown in **Figure 9**.

As shown in **Figure 9**, in the whole depth range, after 8 months of thermal recovery, the temperature difference from the original temperature level before and after recovery has decreased, the maximum temperature difference before recovery is 20.51 ℃, the maximum temperature difference after recovery is 3.02 ℃, the average temperature difference before thermal recovery is 9.38 ℃, the average temperature difference after thermal recovery is 1.30 ℃, it can be considered that the whole geotechnical area has roughly recovered to the average temperature difference before thermal recovery was 9.38 ℃, and the average temperature difference after thermal recovery was 1.30 ℃.

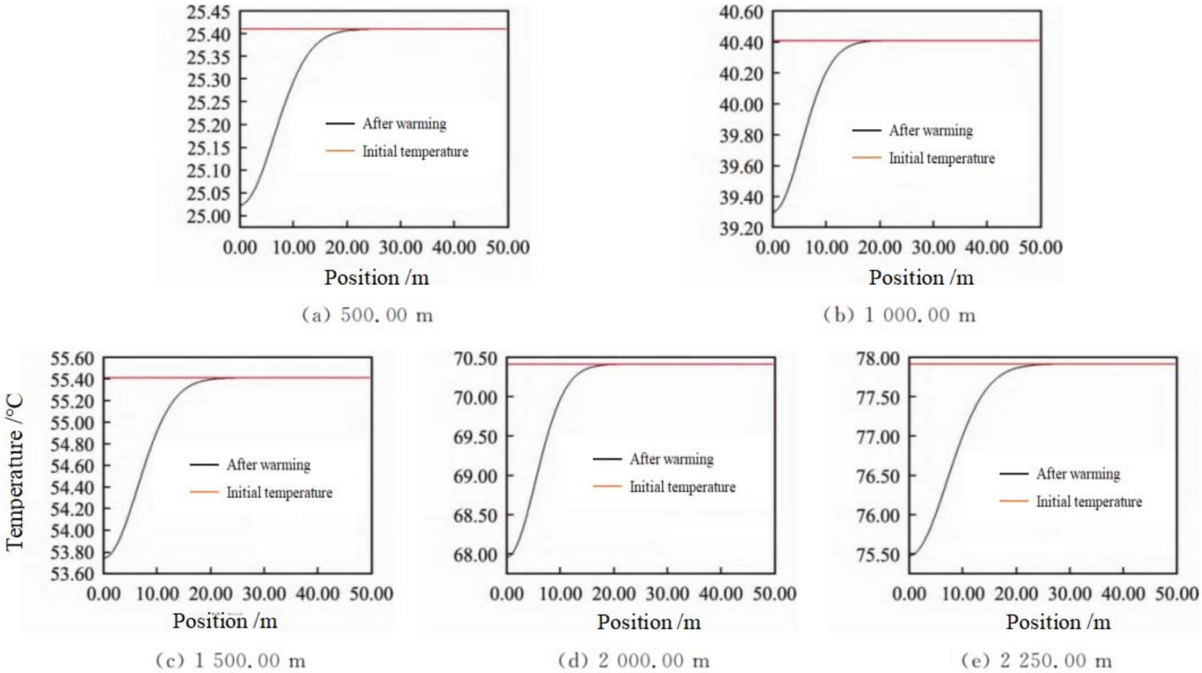


Figure 8. Comparison of temperature before and after thermal recovery in different depth and radius directions.

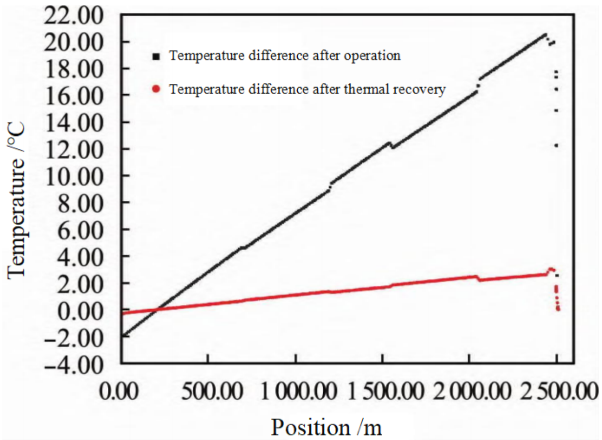


Figure 9. Comparison of temperature difference before and after thermal recovery at R = 1.00 m.

5. Analysis of the operational stability of the buried pipe

After analysis, the thermal recovery of the geotechnical area within 1a basically recovered to the initial temperature level, but there is still a small gap with the initial temperature, that is, each year the initial temperature of operation has decreased relative to the previous year, using this study conditions for 10a uninterrupted operation, that is, 4 months of operation in 1a heating, 8 months of shutdown to complete the thermal recovery, using the end of the heating season outlet water temperature as the buried pipe operating stability Judgment criteria, 10a inland buried pipe operation period at the end of the outlet water temperature as shown in **Figure 10**.

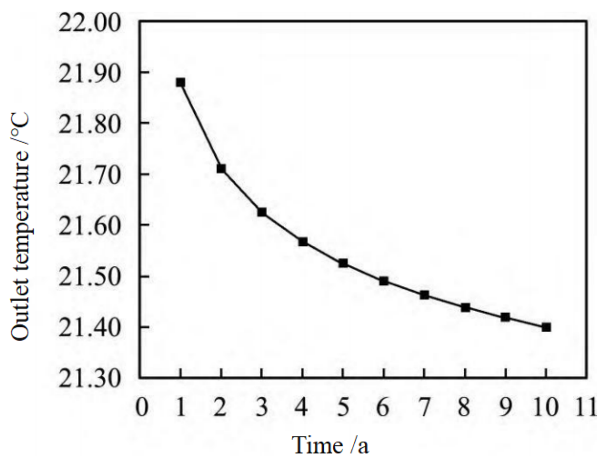


Figure 10. Change of outlet water temperature of casing pipe after years of operation.

From **Figure 10**, it can be seen that the outlet water temperature gradually decreases for each year, with the increase of time, the decrease decreases. The outlet water temperature was 21.88 ℃ at the end of the first heating season and 21.40 ℃ at the end of the 10th year, with a decrease of only 0.48℃ in 10a. Therefore, in the process of heat extraction and thermal recovery of the geotechnical soil around the buried pipe for many years, although the geotechnical soil temperature could not fully recover to the previous year's temperature after thermal recovery, the long-term operational stability of the medium-deep buried pipe could be ensured.

6. Practical comparison

The experimental verification uses a well in the 2,500.00 m medium-deep geothermal buried pipe heating system at the Innovation Port Energy Station in Xi'an New District, Shaanxi Province, with the same rock layer distribution as simulated in this paper, as shown in **Figure 1**. **Figure 11** shows the installation of fiber optic temperature measurement device at the position immediately outside the PE pipe, with measurement points 100.00 m apart, to monitor the water temperature change in the buried pipe dynamically for a long time, and to grasp the temperature change of the formation indirectly through the change of water temperature.

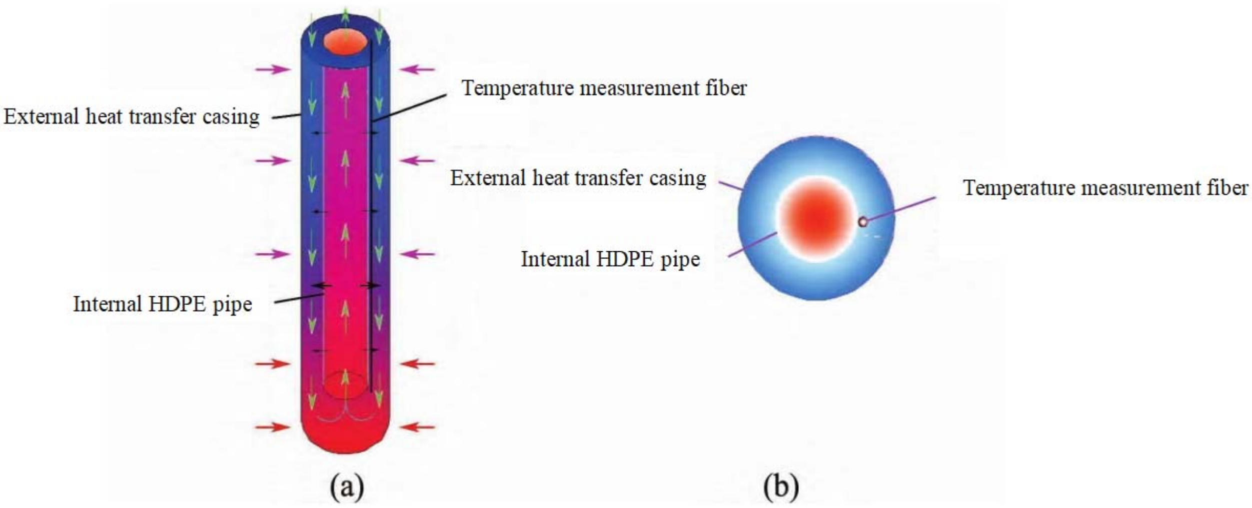


Figure 11. Schematic diagram of optical fiber installation position.

The comparison of dynamic monitoring data and simulation results is shown in **Figure 12**. The temperature of the surrounding stratum of the buried pipes of medium and deep geothermal energy is basically consistent with the temperature of the stratum at the beginning of the heating season, assuming that the liquid in the pipeline is stationary for a long time; however, at the end of the heating season, because the load is less than the heat output capacity of the stratum, the uninterrupted liquid circulation on the side of the heat source accelerates the temperature recovery of the surrounding stratum, while the relative temperature change of the heat source in the deep stratum is very small. And the thermal recovery effect of the simulated process is poor relative to the actual effect, and the reasons for this are analyzed as shown in **Figure 13**.

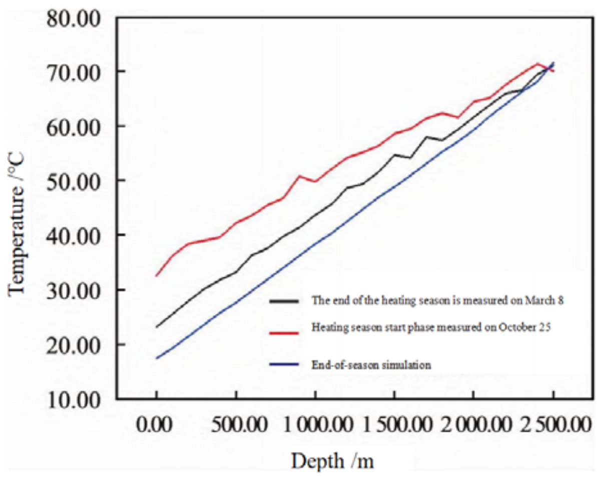


Figure 12. Comparison of water temperature in buried pipe.

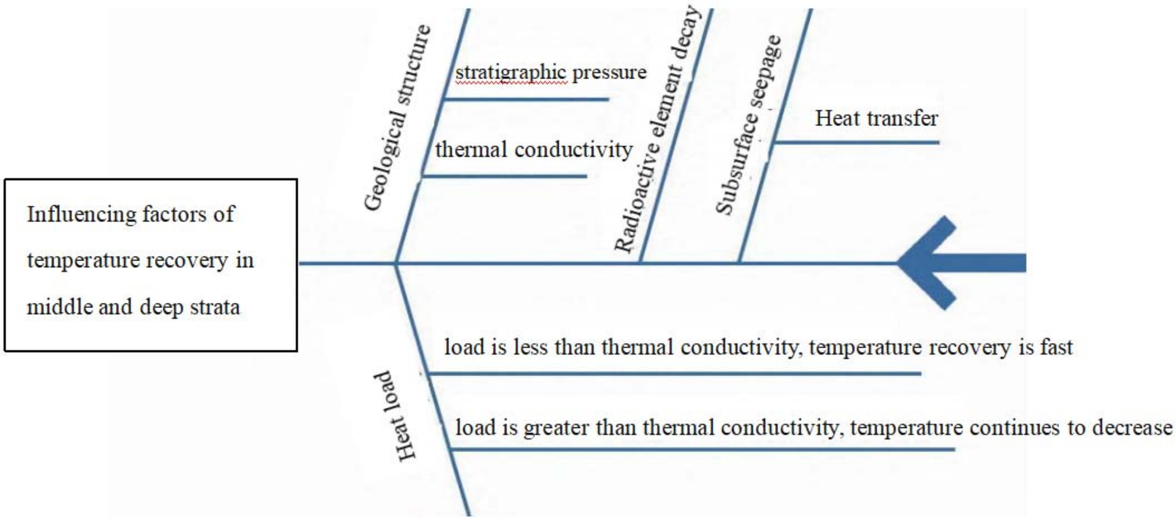


Figure 13. The main possible factors to accelerate the recovery of formation temperature.

Due to the influence of formation pressure, different thermal conductivity of formation structure, as well as the variation of subsurface seepage, ground thermal load, the actual recovery of formation temperature is better than the simulated process, because it is difficult to set the data boundaries such as subsurface seepage, formation structure and load variation in the simulated process.

7. Conclusion

In this paper, based on the geological data of Guanzhong area and combined with the operation of a medium-deep geothermal buried pipe heating system in Xi'an New Area of Shaanxi Province, a full-size model of the heat transfer process between the buried vertical buried pipe and the surrounding geotechnical soil at a depth of 2,510.00 m was established by numerical simulation, and the temperature influence law of the buried pipe on the surrounding geotechnical area was analyzed based on the assumption of a constant temperature of 85.71 °C at the bottom wall of the model. Conclusions are drawn.

1) The temperature difference and thermal disturbance radius of subsurface geotechnical soils show an increasing trend with depth; at the same depth, the geotechnical layers with larger thermal diffusion coefficients have larger disturbance radii. At the depths of 500.00, 1,000.00, 1,500.00, 2,000.00, 2,250.00 m, after four months of operation, the temperature interference spread to 4.29 m, 5.77 m, 6.73 m, 7.95 m, 10.07 m rock radius, at the temperature drop of 1.00 °C.

2) After 8 months of thermal recovery after heat extraction from the middle and deep geothermal buried pipe, the maximum temperature difference after thermal recovery is 3.02 °C, and the average temperature difference is 1.30 °C, the temperature recovery ability of the deep geotechnical soil is inferior to that of the shallow geotechnical soil. In addition, at 500.00, 1,000.00, 1,500.00, 2,000.00, 2,250.00 m, calculated at 1.00 °C, the temperature disturbance residuals at radii of 1.82, 5.14, 7.12, 6.81, 7.59 m.

3) There is no significant change in the outlet water temperature of the buried pipe after 10a of continuous operation, and the geotechnical temperature after thermal recovery can ensure the long-term operational stability of the buried pipe.

4) In practice, due to objective factors such as geological structure, subsurface seepage, and thermal load, the actual temperature recovery of the formation already starts when the load is small, and the recovery process is less than 8 months and rapid.

Conflict of interest

The authors declared no conflict of interest.

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