Effect of material properties on the thermal performance of tubes in a layered subsurface

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SUMMARY
Thermal properties of the layered subsurface can affect the heat transfer performance of ground heat exchangers (GHEs) and consequently the system efficiency. Based on a laboratory apparatus considering double layers of sand and clay, a 3D numerical model was validated by experimental data, and further used to investigate the effect of thermal properties on water and ground temperature distributions. For GHEs with sufficient heat transfer, the sequence of layered structure has a negligible effect on the water temperatures while a significant effect on the ground temperature distributions. The ground temperature distributions in layered subsurface were different in operation and recovery periods, where the material with low thermal diffusivity had a smaller temperature variation and longer recovery time. Therefore, the layered subsurface, especially the materials with low thermal diffusivities, should be paid special attention to if insufficient heat transfers of GHEs occur.

INTRODUCTION
Ground source heat pump (GSHP) system applies shallow geothermal energy to heat or cool buildings, and it has been widely applied due to the high energy-efficiency and environmental friendliness in recent years (Mustafa Omer 2008). The system efficiency is largely determined by ground heat exchanger (GHE) system, which transfers the waste heat from buildings to the ground. As GHEs are buried underground, its efficiency of heat exchange is strongly affected by the thermo-physical properties of the soil and subsurface (Casasso and Sethi 2014). The underground thermal properties in the GHE field change drastically with geographic structure (Witte et al. 2002) and the moisture content (Leong et al. 1998). Therefore, for a typical vertical GHE system in practical engineering, whose depths range from 15 to 180 m (ASHRAE 2011), complex conditions such as layered structures should be carefully addressed.

Numerous studies have been conducted to investigate the effect of ground stratification on thermal performance. To simplify the calculation, some researchers proposed to use effective thermal properties for a multi-layer ground. Through several numerical simulations with various ground compositions, Lee (2011) found the adoption of effective thermal properties led to a very little error in water temperatures for long-term performance predictions. While other researchers found the homogeneous assumption can lead to excessive simplification of the observed strong heterogeneity (Perego et al. 2016) and overestimation or underestimation of the ground temperature change by 10% to 25% (Abdelaziz et al. 2014). Luo et al. (2014) investigated a practical GSHP system with GHEs buried in five bedded sedimentary layers experimentally and numerically, and found that both the homogeneous and layered models gave similar outlet water temperature, but different temperature distribution and heat transfer rate along GHEs. Additionally, the specific heat exchange rate along depths of GHEs was found to vary even within individual strata, and the redistributed heat between ground material layers could yield significant influence for long-term predictions (Oflman et al. 2014). Florides et al. (2013) also found that the underground thermal energy dispersed more easily in the top layers, thus, the outlet tube temperature was lower by about 2°C for the case of decreasing thermal conductivity with depth as opposed to the case of increasing thermal conductivity with depth.

Meanwhile, ground temperature recovery can improve the underground heat transfer (Shang et al. 2011), enhance heat pump system performance (Gao et al. 2010) and affect the borehole lengths (Baek et al. 2017). The soil properties have a great effect on the soil recovery, and the soil temperature recovers more quickly when heat conductivity increases and soil porosity decreases (Shang et al. 2011). Baek et al. (2017) found the recovery duration could be significantly influenced by the ground temperature recovery at low soil thermal conductivity. As the total amount of heat extraction rather than the duration of the production period determined the recovery period (Erol et al. 2015), special attention should be paid to the thermal properties of the underground subsurface.

Although numerous studies have analytically and numerically investigated the effect of layered subsurface on thermal performance of GHEs, the conclusions were different based on various cases and assumptions. Additionally, few researches have taken the thermal performance of GHEs in layered subsurface during the recovery period into consideration, which is considered to be common in practical GHE systems. Therefore, this study will numerically investigate the influence of thermal properties in a layered ground structure on the thermal performance of tubes during both the operation and recovery periods.

METHODS
Coupled heat transfer occurring in the GHE and surrounding layered subsurface is modelled in using a 3D CFD model, in which water flowing in the pipes and soil were included. All side walls of the soil domain were set with constant initial temperature. Thermal properties were assumed...
homogeneous for each material, and their initial temperature was identical and equal to the ground temperature. The thermal resistance of the tube material was calculated using the so-called thin-wall thermal resistance of FLUENT. The incompressible Navier-Stokes equations together with standard k-ε model were solved for the convective heat transfer of water in the pipes, while the thermal conduction through sand and clay were calculated by

\[ \frac{\partial T}{\partial t} = \frac{k}{\rho c} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \]

where \( k \), \( \rho \) and \( c \) represent the thermal conductivity, density and specific heat capacity of the sand and the clay, respectively.

The inlet temperature \( T_{in}(t) \) and outlet temperature \( T_{out}(t) \) can be joined by:

\[ T_{in}(t) = T_{out}(t) + \Delta T(t) \]

where \( \Delta T(t) = \frac{Q}{\rho w V w} \)

where \( Q \) is the heat extraction or injection; \( \rho w \), \( c_{pw} \) and \( V w \) represent the thermal conductivity, density and specific heat capacity of water, respectively.

The governing equations of the 3D GHE models were solved using the commercial CFD code ANSYS Fluent-16. Transient water temperature in each time step was calculated by integrating Eq. (2) and Eq. (3) through the FLUENT user-defined functions (UDFs). The unsteady simulation was performed with a time step of 180 s. Prior to performing CFD simulations, grid independent study was conducted. Mesh refinement was placed in the near wall regions of the HTF tube. Considering the computational efficiency and accuracy, mesh with elements numbers of 620,920 was used for further simulation in this study.

RESULTS

Experimental validation

Data from a 24h heat injection experiment from a laboratory apparatus in Chongqing University, in China was used to validate the numerical accuracy. As shown in Fig. 1, the 6.25 m×1.5 m×1 m model experimental apparatus consists of two copper U-tubes. Two typical used material, sand and clay, were filled in the box to investigate the influence of layered structure. Thermal properties of the clay were measured in laboratory, while those of the sand was obtained from the ASHRAE handbook (2011) due to the complication and difficulty of the laboratory measurement. A constant heat was designed to be inputted to the water in the tank by the electric heater, and the heat-carrier water was circulated to flow through U-tubes and later return back to the tank. The flow rate of circulating water was controlled by the flow adjust valve and measured by a flow meter. The relative uncertainty of the flow meter was calculated to be 8.7%, which was considered to be acceptable with a value less than 10%.

Copper-constantan thermocouples were used to monitor both the water and ground temperatures. Besides the thermocouples to monitor the inlets and outlets of U-tubes, detailed temperature distributions were also captured by thermocouples installed in the far field and interior ground. In this study, the temperature distribution along the depths between two U-tubes (\( x = 0.5 \text{ m} \) and \( y = 0.75 \text{ m} \) recorded by thermocouples 3# to 8# was selected as a representative ground temperature distribution at \( y \). The accuracy of the T-type thermocouples was 1 °C. A data logger system was connected to a computer to display and record the temperature data at a time-interval of 10 mins. Detailed experimental parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model</th>
</tr>
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<tbody>
<tr>
<td>Length of the U-tube</td>
<td>6.25 m</td>
</tr>
<tr>
<td>U-tube wall</td>
<td>0.0005 m</td>
</tr>
<tr>
<td>Inner diameter of the U-tube</td>
<td>0.005 m</td>
</tr>
<tr>
<td>Distance between centers of pipe</td>
<td>0.015 m</td>
</tr>
<tr>
<td>Thermal conductivity of sand (ASHRAE 2011)</td>
<td>1.5 W/mK</td>
</tr>
<tr>
<td>Thermal conductivity of clay</td>
<td>0.862 W/mK</td>
</tr>
<tr>
<td>Thermal conductivity of copper pipe</td>
<td>387.6 W/mK</td>
</tr>
<tr>
<td>Volumetric heat capacity of sand (ASHRAE 2011)</td>
<td>2.31×10^6 J/(K-m³)</td>
</tr>
<tr>
<td>Volumetric heat capacity of clay</td>
<td>2.06×10^6 J/(K-m³)</td>
</tr>
<tr>
<td>Volumetric heat capacity of copper pipe</td>
<td>3.42×10^6 J/(K-m³)</td>
</tr>
<tr>
<td>Thermal diffusivity of sand</td>
<td>6.49×10⁻² m²/s</td>
</tr>
<tr>
<td>Thermal diffusivity of clay</td>
<td>4.19×10⁻² m²/s</td>
</tr>
<tr>
<td>Specific heat capacity of fluid</td>
<td>4182 J/(kg·K)</td>
</tr>
<tr>
<td>Initial ground temperature</td>
<td>13.85 °C</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 m/s</td>
</tr>
</tbody>
</table>

To diminish the influence of the non-uniform initial temperature in experimental data, temperature increase (\( \theta \)) is defined as the difference between the testing soil temperature and its corresponding initial temperature, which is a positive value for the heat release process (Yang et al. 2016).

\[ \theta = T_g(t) - T_0 \] (4)

where \( T_g(t) \) and \( T_0 \) are the soil temperature at time \( t \) and initial soil temperature at \( t = 0 \), respectively.

The same inlet water temperature recorded in the experiments were used in the simulation. The numerical predictions of the outlet water temperature showed a good match with the
experimental data (Fig. 2), where the discrepancy decreased from 0.36 °C in the beginning to 0.10 °C at the late stage. Though a constant heat was inputted to the system, part of the heat was first used to heat the existing water in the water tank. Thus, the temperature difference increased and later constant around 3 °C.

Figure 2. The water temperature variations of the inlet and outlet of tubes with time.

Figure 3 compares the experimental and numerical temperature distributions of L. Both the sand and clay temperatures increased with time, and the increase rate slowed down with time. Along the depth of the tubes (from left to right), the temperature decreased with a sharp decline appeared at the interface of two materials, covering about 0.8 m in the middle, especially from 5# to 6#. The slope of the decline also increased with the time, the measurements showed a temperature decline of 0.16 °C at t = 12 h increased to 0.30 °C at t = 24 h. As more heat was transferred through the upper part of tubes, where the heat transfer process was also boosted by a higher thermal diffusivity, significant temperature increases could be found in sand (3#, 4# and 5#). With more heat absorbed in the upper layer, the thermal front in the sand travels faster and further away from the tubes, while the temperatures of clay increased slower due to a lower thermal diffusivity. Compared to the smooth temperature decreases along the tubes in individual materials, it seems that the thermal properties play a vital role in the temperature distribution. Both experimental and numerical temperatures agreed well, an obvious discrepancy in 3# may attribute to the constant temperature assumption for far-field boundaries. A relative significant discrepancy at the late stage was due to the uncertainty of thermal properties.

Figure 3. The ground temperature variation of L in the central sand or clay along the depth of tubes.

Table 2. Characteristics of three cases

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top (z=0 to 3m)</td>
<td>Sand</td>
<td>Clay</td>
<td>Sand</td>
</tr>
<tr>
<td>Bottom (z=3 to 6.25 m)</td>
<td>Clay</td>
<td>Sand</td>
<td>Sand</td>
</tr>
</tbody>
</table>

Figure 4 compares inlet and outlet water temperatures of three cases. The water temperatures increased during the operating time, and decreased sharply once stopping the operation, later decreased smoothly in the recovery period. Though the sequence and thickness of the materials are different in Case 1 and Case 2, they obtained similar inlet and outlet temperatures. The inlet and outlet water temperatures in Case 2 were 0.2 °C and 0.25 °C less than those of Case 1 at t = 48h, the slight decrease is mainly because a larger diffusivity of sand enables Case 2 to transfer more heat. Even if more heat is supposed to transfer through the top of tubes by a better heat transfer material in Case 1, the total thermal transfer ability seems to have a more significant effect on the thermal performance. Compared to Case 1 and Case 2 combining both sand and clay, the full filling of homogeneous sand in Case 3 led to average water temperature decreases of 2.45 °C during the 48 h operating time and 0.64 °C during the following 36 h recovery period. With no heat inputted in the recovery period, both the inlet and outlet water temperatures decreased with the same heat transfer rate.

Figure 4. Water temperature variations of the inlet and outlet of tubes in three cases.

Variations of ground temperature at L during the operation period were shown in Fig. 5. In Case 1 with sand filled in the top and clay in the bottom of the tubes, a larger thermal diffusivity boosted the heat transferred faster in sand and therefore a higher temperature than the clay by average 0.6 °C. While Case 2 witnessed an opposite trend with a temperature increase in the interface of two materials. Ground temperatures of sand and clay in Case 1 are similar to those
of Case 2, which can further account for their similar inlet and outlet water temperatures. Due to the homogeneous material, Case 3 had a slight variation of 0.1 °C along the tubes, indicating a negligible heat transfer difference. Due to a larger thermal diffusivity of sand, heat transferred faster in Case 3 and reduced to a relatively high temperature at \( t = 12 \) h. Later with more heat inputted and further dissipated, ground temperature at \( L \) increased in Case 3 was much lower than the other cases. Thus, the sand temperature was around 0.83 °C and 0.15 °C lower than the temperatures of sand and clay in the other cases at \( t = 48 \) h.

![Figure 5. Ground temperature variations of \( L \) in three cases during the operating period.](image)

During the recovery period, significant temperature reduction can be found in sand due to a relatively large thermal diffusivity (Fig. 6). Thus, the temperature distribution at \( L \) in recovery period was opposite to that in operation period. The sand temperature in case 1 was 0.6 °C higher than the clay temperature at \( t = 48h \), while the temperature discrepancy of sand and clay decreased in the first 12 h of the recovery period. The sand temperature decreased rapidly and became 0.4 °C lower than the clay temperature at \( t = 84h \). Case 2 witnessed an opposite trend of Case 1, while the ground temperatures were similar to those in Case 1. With less heat accumulated, ground temperatures in Case 3 were lower than those in the other cases. At the end of the recovery period, the sand temperature was around 0.33 °C and 0.76 °C lower than the temperatures of sand and clay in the other cases.

![Figure 6. Ground temperature variations of \( L \) in three cases during the recovery period.](image)

The ground temperature variations at points 4# (located at \( z=2.1 \) m) and 7# (located at \( z=3.9 \) m) in three cases were compared in Fig. 7. Both 4# in Case 1 and 7# in Case 2 were located in sand, thus they showed similar temperature variations with the time. Similar predictions were also achieved by 7# in Case 1 and 4# in Case 2, where both of them located in clay. Due to a smaller thermal diffusivity, the temperature of clay increased slower and reached a smaller value than that of sand. With homogeneous sand assumed, the discrepancy of the two points in Case 3 was negligible. The ground temperature in Case 3 increased faster and reached a relative low peak due to a better heat transfer performance.

![Figure 7. Ground temperature variations of at points 4# and 7# in three cases.](image)

**DISCUSSION**

By comparing Case 1 and Case 2, it seems that the sequence of layered subsurface has negligible influence on the outlet temperature or thermal performance, due to the similar effective thermal resistance. A similar conclusion was drawn from an experimental investigation, which obtained similar outlet water temperatures from numerical models with homogeneous or stratified assumptions (Luo et al. 2014).

However, it should be noticed that all the simulation results were based on the assumption of sufficient heat transfer, where all the heat carried by the water was transferred through tube wall and further absorbed by the surrounding ground. As more complicated conditions occurred in practical engineering, such as multiple GHEs or overload, the heat accumulation may cause insufficient heat transfers of GHEs. With less heat transferred and more heat accumulated, the materials with small thermal diffusivities have higher temperatures and longer recovery time, which later cannot meet the transferred load requirement and affected the water temperatures. Therefore, the insufficient heat transfers can amplify the influence of layered subsurface, especially material with a low thermal diffusivity.

**CONCLUSIONS**

Based on a laboratory apparatus consisting of sand and clay, a 3D numerical model was validated by the experimental data. Influence of layered subsurface on the thermal performance during operation and recovery periods was investigated by comparing three numerical cases with different geological structures. The conclusions arising from this study are summarized as follows:

1. For GHEs with sufficient heat transfer, the sequence of layered structure has negligible effect on the water temperatures while a significant effect on the ground temperature distributions. Thermal properties rather than heat transfer rate along the tubes play a more important role in the ground temperature distributions.
(2) If part of the sand was replaced by clay, both the water and ground temperatures would be decreased significantly in operation period and slightly in recovery period.

(3) The ground temperature distributions in layered subsurface were different in operation and recovery periods, where the material with low thermal diffusivity had a smaller temperature variation and longer recovery time.

(4) Insufficient heat transfer of GHEs can amplify the influence of layered subsurface, especially materials with low thermal diffusivities.

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