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Study of the Ground Water Permeation's Influence on Energy Pile Heat Exchange in Porous Medium Soil

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Energy pile heat storage technology is a typical soil source heat pump system, and features and parameters of soil have great influence on the heat storage of energy pile. Ground water permeation will take heat in soil away directly and if the permeation speed is too fast, the heat storage system of the energy pile even cannot store heat. In order to guarantee that the heat storage system of the energy pile can function well in practical working conditions, it is necessary to do further quantitative study of the ground water permeation's influence on soil source heat pump. This study focuses on soil permeation's influence on energy pile heat exchange through establishing the energy pile heat storage model and finds that when the permeation speed is less than 3×10^{-7}m/s, it is the desirable heat storage condition; when the permeation speed is more than 1×10^{-6}m/s, the energy pile heat storage system cannot store heat at all.

1. Introduction

Energy pile heat storage technology is a typical soil source heat pump system, (Zhao and Lu, 2015; Zarrella, 2013). and features and parameters of soil have great influence on the heat storage of energy pile. Ground water permeation will take heat in soil away directly and if the permeation speed is too fast, the heat storage system of the energy pile even cannot store heat. In order to guarantee that the heat storage system of the energy pile can function well in practical working conditions, it is necessary to do further quantitative study of the ground water permeation's influence on soil source heat pump (Singh, 2013; Taoufik and Abdelmajid, 2012; Brandl, 2006).

2. Establishment of the Model

2.1 Theoretical Model

Momentum equation of porous medium model
If the porous medium is isotropic (Zhao and Chen, 2014; Zhao and Fu, 2016), the formula is:

$$S_i = -\left(\frac{\mu}{\alpha}v_i + C_2\frac{1}{2}\rho|v|v_i\right) \tag{1}$$

In this formula, S_i is the source term of $i(x, y, z)$ momentum equation; $|v|$ is the scalar of the speed; α is the permeability coefficient; C is the matrix and C_2 is the simplified diagonal matrix of C.
Effective thermal conductivity of the porous medium
The effective thermal conductivity of the porous medium is the average of all porous medium effective thermal conductivities (Pinel et al., 2011). The following one is the calculation formula:

$$k_{eff} = \gamma k_f + (1-\gamma)k_s \tag{2}$$

In this formula, γ is the porosity of the porous medium; k_f is the thermal conductivity of the fluid; k_s is the thermal conductivity of the solid.
Darcy's law in Porous Medium Soil

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$$\nabla p = \frac{\mu}{\alpha}\vec{v} \tag{3}$$

2.2 Single Pile Heat Exchange Model

There are mainly 3 calculation domains of the single pile heat exchange model: first, U heat exchange tube domain. The tubing material is pp-r and the heat exchange medium in the tube is water. This domain is mainly for the calculation of water turbulence flow process and heat exchange; second, concrete energy pile domain. This domain is only for the calculation of heat exchange; third, soil domain with porous medium model as a core. This domain is for the calculation of ground water permeation and heat exchange in soil.
The geometric dimension of this model is 3m×3m×12m, in which the outermost layer is soil. Because that domain is set to be porous medium, it is calculated as the fluid domain. The length of the energy pile is 12m and the pile diameter is 0.6m. Single U heat exchange tubes are buried within the energy pile, and the distance between heat exchange tubes is 0.12m and the tube diameter is 0.032m. The flow speed of the intake of the heat exchange tube is 2m/s and the temperature is 315K.

Table 1: Physical parameters

	Thermal conductivity (w/m^2. K)	Specific heat (J/kg)	Density (kg/m^3)	Permeability (%)	Porosity (%)
Heat exchange tube	0.3	2000	940	—	—
Concrete	1.74	970	2500	—	—
Water	0.6	4200	998	—	—
Sand	0.74	1645	1800	1	37
Clay	0.46	2200	1500	1	47
Silt	0.54	700	2000	1	40

3. Ground Water Permeation's Influence on Single Pile Heat Exchange of Energy Piles

3.1 Soil Temperature Fields of 10d Heat Exchange under Different Permeation Speeds

Table 2 are different permeation speeds of ground water in the soil. The researcher simulated soil temperature fields of 10d, 20d and 30d heat storage of the energy pile under 7 different permeation speeds while other physical parameters were kept fixed.

Table 2: Different permeation speeds

Serial number	1	2	3	4	5	6	7
Permeation speed(m/s)	1×10^{-7}	1.5×10^{-7}	2×10^{-7}	2.5×10^{-7}	3×10^{-7}	3.5×10^{-7}	1×10^{-6}

Figure 1 are soil temperature fields of 10d heat exchange under different permeation speeds. From Figure 1, the researcher finds that temperature fields have deviations of different degrees in the direction of y axis, which means that temperature fields are influenced by ground water permeation in different degrees. In terms of heat exchange, ground water permeation makes the heat exchange increase, and the faster the ground water permeation is, the higher the heat exchange is. This indicates that ground water permeation increases the convective heat exchange efficiency between the energy pile and the soil. Comparing figures from a to f, the researcher finds that with the increase of permeation speed, there are 2 obvious changes in the thermal influence radius of the soil: first, the thermal influence radius becomes smaller and smaller in the inlet direction of permeation, while the thermal influence radius becomes bigger and bigger in the outlet direction of permeation; second, under the function of permeation, the soil temperature field becomes to oval from circle.

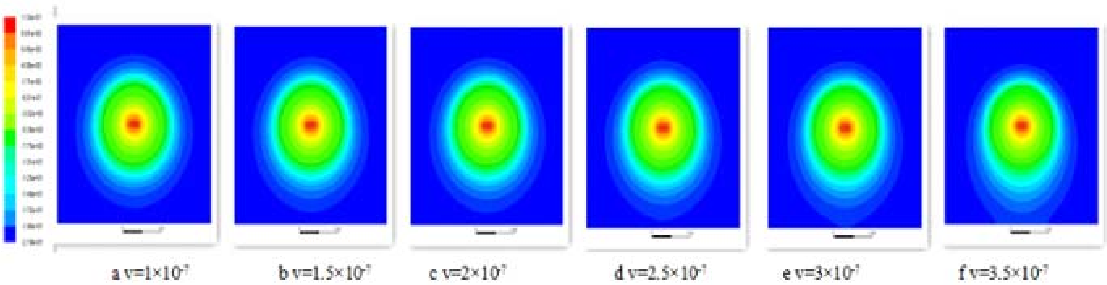

Figure 1: Soil temperature fields of 10d heat exchange under different permeation speeds

From Figure 1-e and 1-f, the researcher finds that after 10d heat exchange, when the permeation speeds are $v=3\times10^{-7}$ and $v=3.5\times10^{-7}$ respectively, the maximum thermal radius of the energy pile heat storage model reaches 1.5m, and the heat has flown away out of the model with the permeation.

3.2 Soil Temperature Fields of 20d Heat Exchange under Different Permeation Speeds

Figure 2 are soil temperature fields of 20d heat exchange under different permeation speeds. Comparing with Figure 1, the researcher finds that with time elapsing, the permeation has already influenced the temperature distribution within the energy pile. Except that the energy pile temperature fields of $v=1\times10^{-7}$ and $v=1.5\times10^{-7}$ maintain in obvious circles, the temperature fields of other models distribute like ovals. None of the temperature fields of all models influences the boundary at the inlet direction of the permeation. It is notable that the temperature fields of $v=3\times10^{-7}$ model and $v=3.5\times10^{-7}$ model have high temperatures in the boundary at outlet direction of the permeation, but those 2 models almost have no influence on wall temperatures of 2 sites of soil which are perpendicular to the permeation direction. This shows that the permeation speed is fast at that moment and the heat storage is influenced greatly.

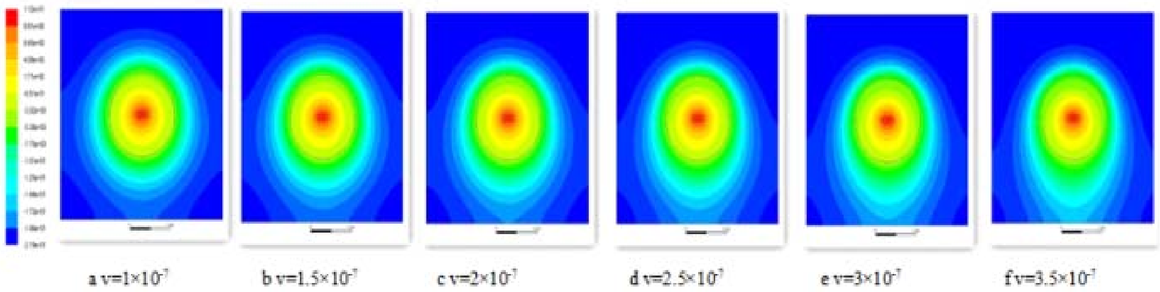

Figure 2: Soil temperature fields of 20d heat exchange under different permeation speeds

3.3 Soil Temperature Fields of 30d Heat Exchange under Different Permeation Speeds

Figure 3 are soil temperature fields of 30d heat exchange under different permeation speeds. From Figure 3, the researcher finds that $v=1\times10^{-7}$ model and $v=1.5\times10^{-7}$ model have good heat storage, which accelerate the heat exchange speed under the function of permeation and maintain relatively stable heat storage temperature fields as well. Shapes of temperature fields of $v=2\times10^{-7}$ model and $v=2.5\times10^{-7}$ model change greatly, but these 2 models can still store heat stably. Shapes of temperature fields of $v=3\times10^{-7}$ model and $v=3.5\times10^{-7}$ model change greatly and there is 30d heat storage, but these 2 models still have no influence on wall temperatures of 2 sites of soil which are perpendicular to the permeation direction. This shows that the permeation speed reaches $3\times10\text{-}^{7}$m/s, the heat storage is out of function.

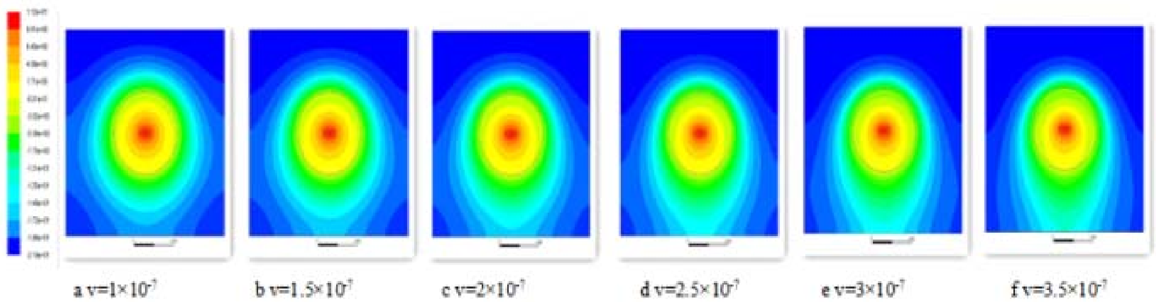

Figure 3: Soil temperature fields of 30d heat exchange under different permeation speeds

4. Ground Water Permeation’s Influence on Pile Group Heat Exchange of Energy Piles

4.1 Soil Temperature Fields of 10d Heat Exchange under Different Permeation Speeds

From Figure 4, the researcher finds that there’s no obvious difference between pile group heat exchange models and single pile heat exchange models under same working conditions in the early stage of simulation. The temperature fields are distributed like ovals as well, and the thermal influence radius is relatively small in the permeation inlet direction while the thermal influence radius is relatively big in the permeation outlet direction. In the early stage of heat exchange, there's no obvious shape change in each model's temperature field, which means that models have good performance in heat storage in this stage.

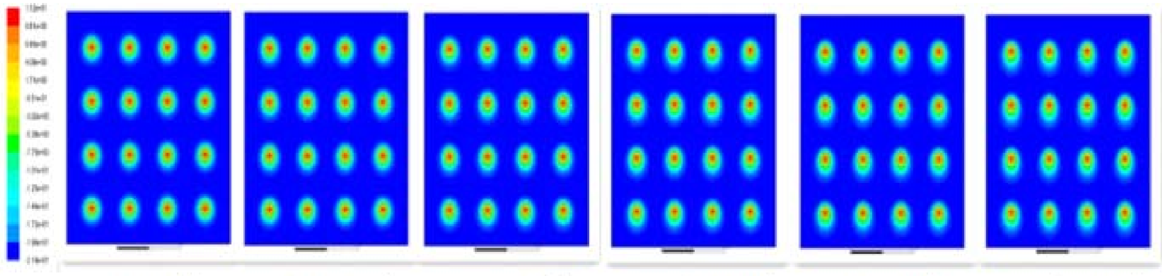

Figure 4: Soil temperature fields of 10d heat exchange under different permeation speeds

4.2 Soil Temperature Field of 20d Heat Exchange under Different Permeation Speeds

From Figure 5, the researcher finds that after 20d heat exchange, for $v=1\times10^{-7}$ model and $v=1.5\times10^{-7}$ model, each single temperature field of pile group models is still in accordance with that of single pile models under same working conditions. For 4 models with the speed $\geq 2\times10^{-7}$, in the permeation direction, there are overlaps in different degrees of thermal influence domains of different piles. When thermal influence domains overlap, the soil temperature field of pile group models is no longer similar to that of single pile models.

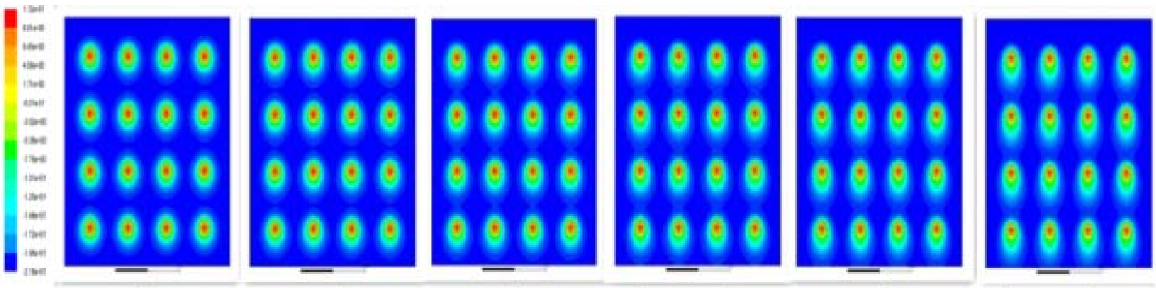

Figure 5: Soil temperature fields of 20d heat exchange under different permeation speeds

4.3 Soil Temperature Field of 30d Heat Exchange under Different Permeation Speeds

From Figure 6, the researcher finds that under the mutual influences and functions of porous medium and different piles, there are complex changes in temperature fields of each energy pile in the pile group. Though energy piles are adjacent, their temperature fields are different. However, $v=1\times10^{-7}$ model and $v=1.5\times10^{-7}$ model can still maintain relatively stable heat exchange rate. From Figure 6-a and 6-b, the researcher finds that there is no obvious difference between the thermal influence domain in the permeation direction and the thermal influence domain in the direction perpendicular to the permeation direction, which means that when the permeation speed is lower than $v=2\times10^{-7}$, the ground water permeation has no negative influence on energy pile heat exchange, on the contrary, it accelerates the heat exchange rate to some degree. From Figure 6-c and 6-d, the researcher finds that there are obvious differences between the thermal influence domain in the permeation direction and the thermal influence domain in the direction perpendicular to the permeation direction and mutual influences of adjacent energy piles are strong in the permeation direction, which means that when the permeation speed is between 2×10^{-7} and 3×10^{-7}, the energy pile heat exchange is influenced a lot. But the heat is mainly distributed around energy piles, which indicates that heat storage can still work. From Figure 6-e and 6-f, the researcher finds that the thermal mutual influences between piles are mainly in the permeation direction, while the mutual influences are weak in the direction perpendicular to the permeation direction. As a whole, these two models are influenced greatly by the permeation, which means that when the permeation speed is higher than 3×10-7, it is unsuitable for heat storage.

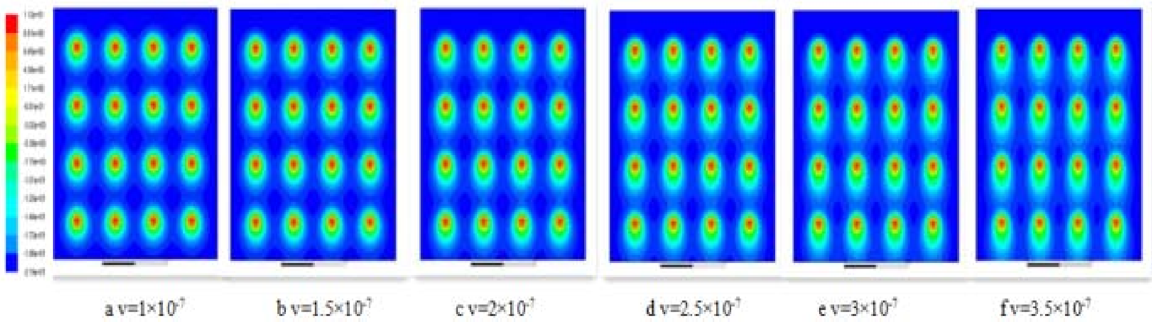

Figure 6: Soil temperature fields of 30d heat exchange under different permeation speeds

From Figure 7, when the flow rate of 1 x 10^{-6}, pile temperature field in a direction perpendicular to the direction of seepage discrete, that is to say, the pile model no heat exchange between different columns or thermal influence each other, in this case, the temperature loss too fast, not suitable for thermal storage.

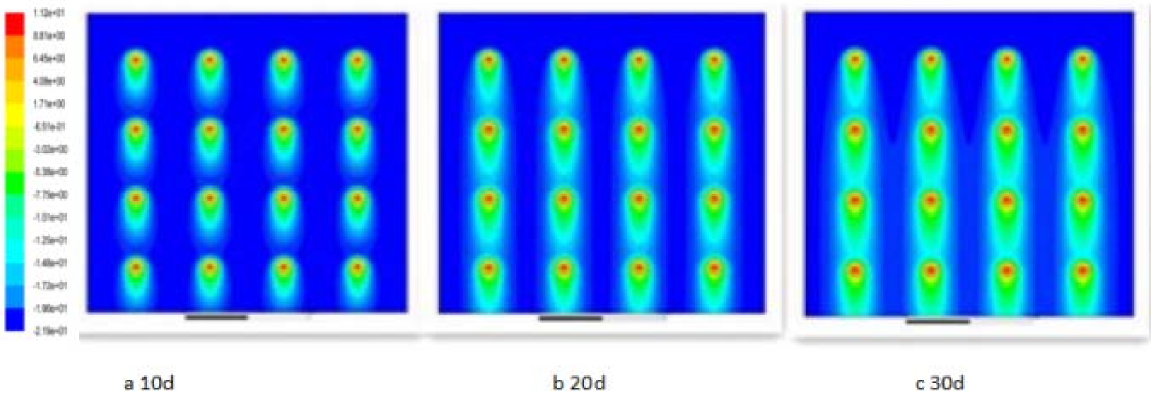

Figure 7: Permeation speeds of 1×10^{-6}m/s the soil temperature fields under different heat exchange time

5. Conclusions

Energy pile heat storage technology is a typical soil source heat pump system, and features and parameters of soil have great influence on the heat storage of energy pile. Ground water permeation will take heat in soil away directly and if the permeation speed is too fast, the heat storage system of the energy pile even cannot store heat. it is necessary to do further quantitative study of the ground water permeation's influence on soil source heat pump.

The soil permeation's influences on energy pile heat exchange of single pile model study and pile group model study are similar: when the permeation speed is lower than 3×10^{-7}m/s, it is the desirable heat storage condition; when the permeation speed is between 3×10^{-7}m/s to 4×10^{-7}m/s, the heat storage will be influenced but the heat storage is still relatively stable; when the permeation speed is higher than 4×10^{-7}m/s, it cannot store heat as normal, especially when the permeation speed is higher than 1×10^{-6}m/s, it cannot store heat at all.

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