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Exploration on the reverse calculation method of groundwater velocity by means of the moving line heat source

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A B S T R A C T

The research on the influence that groundwater exerts on borehole ground heat exchanger has been made progress. However, the investigation on how to obtain the groundwater velocity is a little. According to the line heat source model with groundwater flow, a new methodology is explored to obtain the value and direction of groundwater velocity while it flows through borehole. Some points are distributed around borehole and they have the same distance to the center line of borehole, and the temperature responses of these points are significant parameters which lay firm foundation for reverse-reasoning. The reverse-reasoning calculation can be conducted by establishing objective function. The comparisons of temperature responses between theoretical results and the simulative recorded data are made. The impact degree of groundwater flow can be displayed and then the velocity is estimated. Differences among points' temperature responses are made full use of to respectively indicate the direction and value ranges of velocity. The relativity between the points' location and the velocity intensity is investigated and then some cases are chosen as the trials to verify the rationality of reverse calculation method. To a large extent, the research work of this paper provides theoretical guidance or computing mode for getting velocity of groundwater. The methodology can be employed for obtaining the velocity in actual engineering projects or other cases.

1. Introduction

The ground source heat pump (GSHP) system avails itself of underground medium to achieve thermal discharge and heat absorption respectively in summer and in winter, and underground heat exchange occurs between ground heat exchangers (GHEs) and the surrounding medium. It is commonly believed that GHEs are significant components of the whole system, and their heat transfer performance greatly determines the behavior of GSHP technology. Currently the relevant models of GHEs are based on pure conduction; a large number of scholars and engineering technologists have realized that groundwater seepage exerts a considerable degree impact on thermal transmission performance of GHEs, and these researchers suggested a given mass of qualitative analysis. However, a little investigation on this problem has been done due to the calculation complexity. In addition, it is difficult to comprehend the local groundwater velocity and therefore the seepage intensity cannot be obtained even if mathematical models are employed. Borehole GHEs with the depth range from 60 m to 200 m are widely adopted in the GSHP engineering projects [1] and the groundwater seepage phenomenon exists more or less in such a deep strata, especially in coastal areas or groundwater rich areas where the groundwater can flow through underground medium. The heat transfer performance of GHEs can be improved by groundwater seepage due to convection; the stronger the seepage, the better the improvement degree to heat transfer process. In particular, the unbalance of endothermic and exothermic accumulation of GHEs can be alleviated so that the design size of GHEs is reduced.

At present, the research on calculation models of borehole GHEs with groundwater flow has been made progress. Firstly, the energy equations including the Green function were applied to obtain the transient temperature response caused by the line source [2,3]. Secondly, the heat transfer period of borehole GHEs is regarded as a complicated and unsteady process. Thirdly, conduction and convection synthetically constitute the heat exchange style during the time scale which is usually from months to years [4]. There is no doubt that groundwater seepage alleviates heat accumulation around GHEs. Accordingly, heat transfer performance can be

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Nomenclature

x,y,z	rectangular coordinate (m)
X,Y,Z	dimensionless rectangular coordinate
q_l	heating rate per meter line heat source (W m^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
r	distance between point and borehole center (m)
a	thermal diffusivity (m^2 s^{-1})
c_p	specific heat (J kg^{-1} K^{-1})
Fo	Fourier number
t_0	initial temperature (K)
t	temperature (K)
u	value of groundwater velocity (m/s)
U	dimensionless value of groundwater velocity
P	Green function with groundwater convection
S	sum of squared deviation
L	dimensionless distance
Greek symbols	
τ	time (s)
φ	angle of groundwater velocity
Θ	dimensionless excess temperature
θ	excess temperature (K)
Superscript	
$'$	integration parameter
Subscripts	
i	infinite line source seepage model
rec	obtain based on simulative recorded data
cal	obtain based on calculation model
$1,2,3$	order number of points

improved. As for groundwater, it can ensure the sustainability of borehole GHEs even the velocity is low [5]; it can exert influence on the heat transfer of energy pile and improve the corresponding performance either [6]; the coupled conduction and groundwater advection from GHE to the surrounding soil have been studied, and the heat transfer performance is better than that of only pure conduction [7]. However, the test for groundwater velocity is difficult because the velocity always has minor order of magnitude and the underground structure is complicated; the specific value and orientation of velocity are hardly obtained. Thus, some calculations or analyses with the help of mathematical models cannot provide convincing basis, which means that how favorable to heat transfer performance is the groundwater flow cannot be shown. Accordingly, it is necessary to explore how to obtain relatively accurate groundwater velocity.

According to the existing models, a new reverse calculation method is proposed to estimate the value and orientation of groundwater velocity. Groundwater flows through borehole GHE and convection action has non-ignorable influence on the distribution of temperature field [8]. If the temperature responses of some points locating near the borehole GHE can be recorded, the comparisons between recorded data and the temperature response obtained by mathematical models can be made, the recorded data are those measured values. The objective function is established and it aims at comparing the difference between recorded data and theoretical data. Although the accurate velocity is unknown at first, as the iteration proceeds, that is, velocity can be selected continually from the pre-set range sufficiently covering all the possible velocities, the accurate velocity can be determined while the difference reaches the minimal value. Thereby, this is a novel reverse calculation method to acquire groundwater velocity. The experimental data need to be recorded are temperatures of some points which are close to borehole, the thermal resistors can be installed at these points and the data collecting instrument is employed to obtain the corresponding data. The fluid inside U-tube of borehole circulates to emit heat and therefore the temperature response outside borehole can be achieved, but it is not necessary to take fluid temperature into account.

The application significance of the reverse calculation method is to obtain the groundwater velocity by way of testing some points' temperatures, and then the heat transfer performance of borehole GHE can be analyzed while groundwater flows through it.

The study combined with computer programming is conducted in the process of exploration. It is conceivable that the concrete values and orientation of groundwater velocity are respectively achieved. Once the problem of getting velocity is solved, the improvement degree caused by groundwater flow to heat transfer performance of borehole GHEs can be vividly expressed. As a result, the design size of borehole GHEs is reduced so that the initial cost of the whole GSHP system is reduced [9]. From what has been analyzed above, it is necessary to explore the reverse calculation method to obtain the velocity.

2. Interpretation of methodology

2.1. The schematic diagram of distributing points

Underground hydraulic gradient leads to groundwater seepage [10]. The greater the gradient, the larger the velocity value, and the orientation of seepage rests with gradient direction. Groundwater flows along three-dimensional directions or even in rough-and-tumble manner sometimes, but basically the gradient direction is at one plane and therefore the two-dimensional seepage should be taken into account. Three points with the same radius r to the center of borehole are set around borehole GHE to fulfill the reverse-reasoning, and the 120-degree intersection angle between every two neighboring points is defined. It is clear that the effect is better if added points with well-distributed intersection angle are

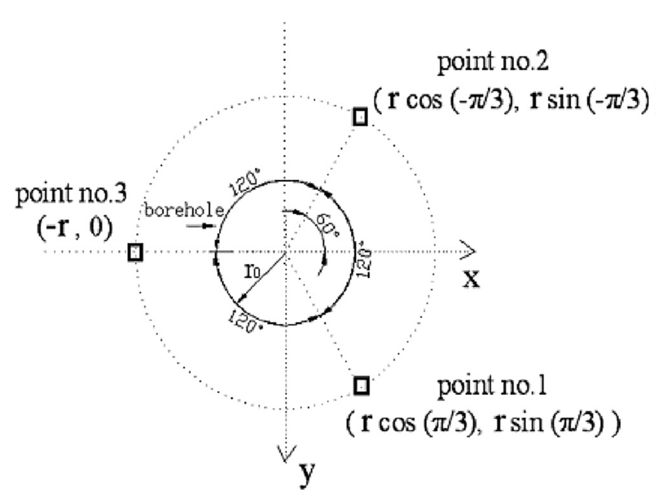

Fig. 1. The schematic diagram on distributing points.