Thermal Efficiency of the Borehole Heat Exchanger Built with Drilling Mud.

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ABSTRACT: To reduce CO_2 emissions and thus global warming, the use of renewable energy has become increasingly common worldwide. An analysis of household energy use indicates that heat energy occupies nearly half of the energy consumption. The direct use of available heat energy for air-conditioning, heating and hot-water supply is expected to be a more efficient use of energy than converting electric energy to heat energy, and is also expected to reduce the consumption of electric power. Ground source heat is one of the most commonly available renewable energy sources. Although ambient air can also store heat, the ground is a much better medium for heat storage because the input and output of thermal energy are much easier and more stable. The advantages of ground source heat as a stable supply of heat are: 1) the ground has a huge capacity to store heat and 2) the temperature of the ground is stable year round. Reducing power consumption has become a pressing need in Japan since The Great East Japan Earthquake, with the use of ground source heat greatly increasing. The geological structures in Japan are many and very complex, with an abundance of groundwater.

To utilize ground source heat, a borehole is generally drilled and two U-tubes installed. A heat transfer medium such as water flows through the U-tubes to extract heat from the ground.

The flow of groundwater greatly contributes to enhancing extraction and storage of heat in the ground. When cold water flows through the tubes, groundwater, which maintains a temperature of 13 to 14 degrees Centigrade throughout the year, comes into contact with the tubes. The cold water in the tubes then acquires heat from the groundwater. The groundwater transfers ground source heat to the cold water. The constant flow of groundwater maintains a constant flow of fresh water coming into contact with the tube, and thus a constant transfer of heat.

Muddy water or grout is circulated throughout the borehole. Muddy water has a higher specific gravity than groundwater, therefore groundwater cannot penetrate the boreholes, and the borehole wall does not collapse. The muddy water does not penetrate very far into the ground. After circulating through the borehole, a thin layered mud wall is formed around the circumference of the borehole. The mud wall hinders groundwater from coming into direct contact with the tubes. Thus, the mud wall is considered to work as heat insulation. Until now, there has been no conventional study on the heat insulation effects of the mud wall. In this study we developed a numerical model using FEFLOW6.2 software to examine the heat insulating effects of the mud wall.

INTRODUCTION

In order to extract/inject heat from/to the ground, various types of heat exchangers have been developed. For example, if the site has a large area, horizontal-type heat exchangers have been buried in the comparatively shallow ground (Fujii et al., 2012).However, in general, because usable area is restricted at locations such as residential areas, vertical type heat exchangers have been most widely adapted in Japan.

The vertical type heat exchangers are constructed by the drilling of a borehole. Then, heat exchanger pipes (U-tube) are installed in the borehole and a heat carrier, such as water, flows through the U-tube. The space in the borehole is filled with silica sand or a similar material. During drilling, in order to prevent the borehole wall from collapsing due to groundwater pressure and fragile soil, grout or muddy water mixed with additives is circulated through the borehole. The muddy water has a higher specific gravity than groundwater, and keeps the pressure inside the borehole higher than the surrounding ground.

After circulating the borehole for some time, the muddy water forms a mud layer on the wall. This mud layer is referred to as a mud wall or mud cake and keeps the borehole wall from collapsing. The thickness of such a mud wall is about 3 to 5 mm (Groundwater Handbook 1998). Due to the mud wall, the flow of groundwater which carries ground heat is not able to directly contact the U-tubes. Consequently, the mud wall is considered to reduce heat exchange efficiency.

In this study we developed a numerical model of a borehole with U-tubes using EFLOW 6.2 software. The model was verified with the measured data of heat exchanger at an actual borehole. Using the model, we estimated the temperature variations of the outlet water which flowed through the heat exchanger, power output and temperature distributions in the ground surrounding borehole to evaluate the thermal effects of the mud wall.

NUMERICAL MODELING

Borehole Type Heat Exchanger

Model Domain

We developed a numerical model of a borehole with the following dimension: 10 m long, 10 m wide and 100 m deep (Figure 1). The center of the model is set at the center of the borehole. In order to estimate the insulation effects of the mud wall, we developed models with and without mud walls. For the model with a mud wall, the mud wall was made along the outer circumference of the borehole. Two loops of heat exchanger pipes were set (double U-tube) in the borehole. The ground is assumed to be made of homogeneous and isotropic material.

The groundwater levels of the east side border(x=xl) and the west side border (x=-xl) were given as constant values. The hydraulic gradient of the groundwater was set as 0.02 m/10 m from the east to the west.

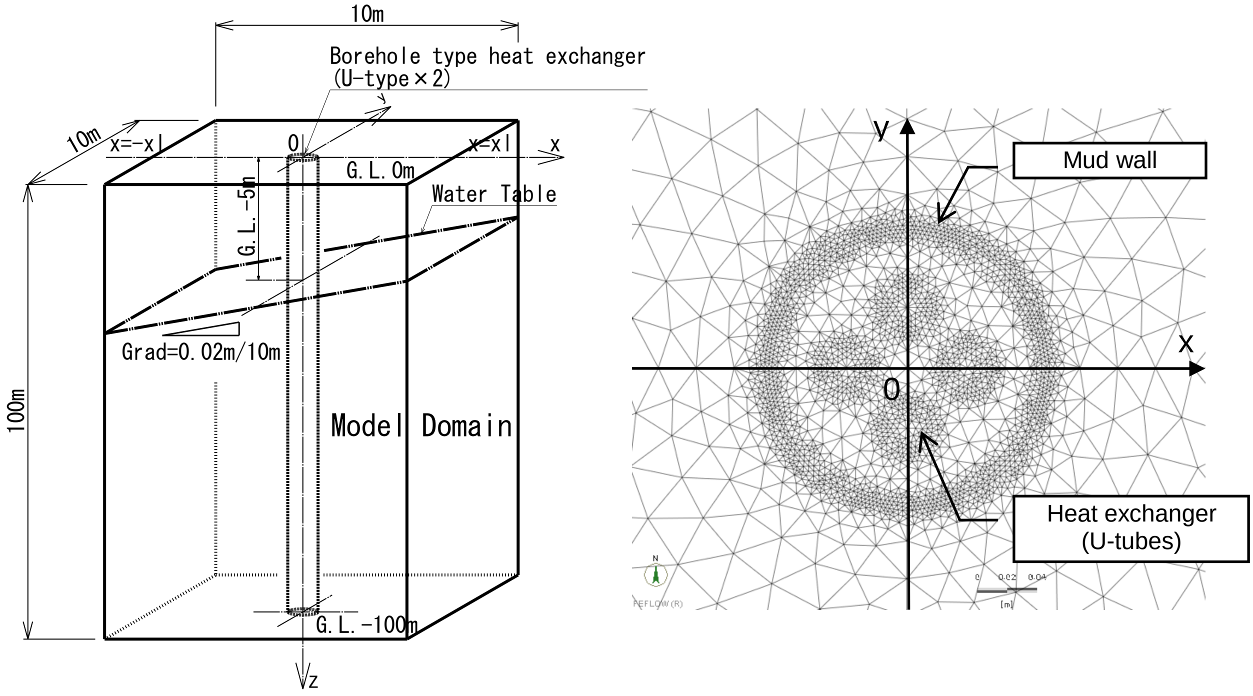

Figure 1: Model domain (left) and structure of borehole heat exchanger (right)

Initial and Boundary Conditions

The initial temperature was set at uniform for the model domain. For the heat boundary conditions, constant value was given to the upstream of the groundwater flow (at east side border: x=xl), while a heat insulation condition is given to other borders. The initial groundwater distribution was given as the hydraulic gradient of 0.02 m/10 m from the east border to the west border of the borehole.

Other Parameters

Table 1 gives the properties of the U-tube and borehole fillings.

Table1: Material Property.

	Heat exchanger pipe (U-tube)	Fillings
Material	Polyethylene	Silica sand
Heat conductivity [W/m/k]	0.38	2.1
Heat capacity [MJ/kg/K]	1.81	1.62

RESULT AND DISCCUSION

Model Validation

A measured thermal response test (TRT) data was applied to verify the developed numerical model. From a field test, we obtained a thermal conductivity for the ground of 2.09 [W/m/K] and the hydraulic conductivity of 5.61×10^{-5}[m/s] and applied them to the model. We set the ground temperature at 17.6 [deg. C] to match the condition of the measured data. The volume of water that was circulated through the U-tubes and the temperature when the water was inlet to the U-tubes were given as the inlet conditions. The other parameters were determined on a trial and error bases and also based on the literature (JSME Data Book: Heat Transfer 2009).

We made a hysteresis comparison of measured values and model estimated values. The model calculated outlet water temperatures matched up well with the measured temperatures (Figure 2), and thus the validity of the model was confirmed.

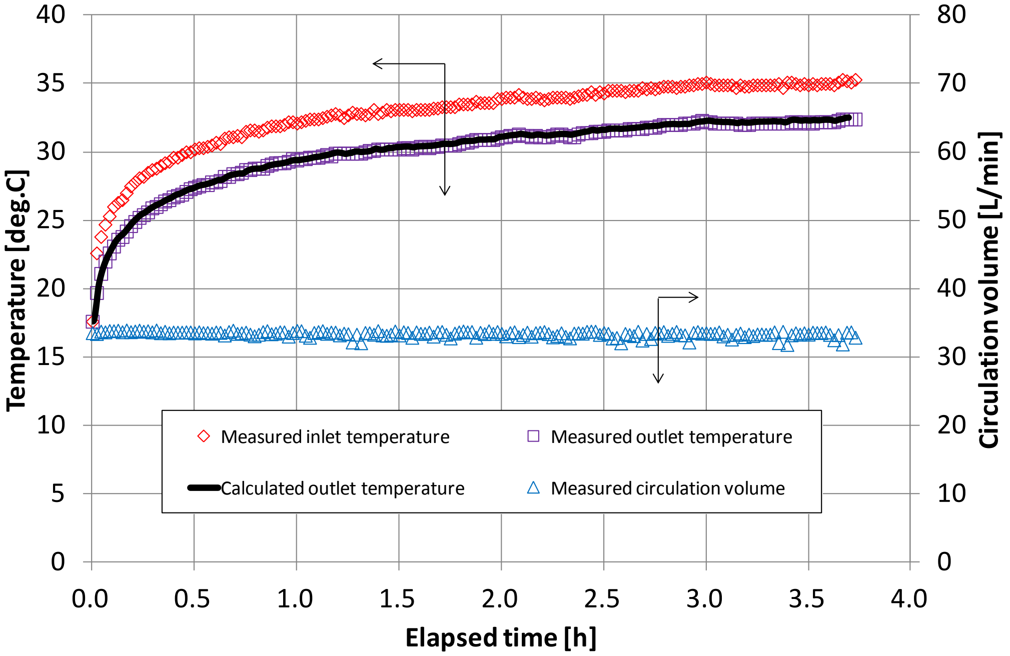

Figure 2: Hysteresis matching of measured and simulated outlet water temperatures

Simulations

Common Set Parameters

Considering the common subterranean conditions in Japan, the initial ground temperature was set at 15 [deg. C].The thermal conductivity of the ground of λ_g=2.0 [W/m/K]) and volumetric heat capacity of $c\rho_g$=3.06 [MJ/m^3/K] were given to the model based on the literature (Ground Source Heat Pump System 2007). While keeping the hydraulic gradient (0.02 m/10 m), the groundwater velocity was set by changing the hydraulic conductivity.

Assuming the mud wall is a-5 mm-thick clay layer, a thermal conductivity of λ_m=1.2 [W/m/K],volumetric heat capacity of $c\rho_m$=3.06 [MJ/m^3/K] and hydraulic conductivity of K_x, K_y, K_z = 1X10^{-9} [m/s] were given, and circulating water volume was set at 30 [L/min/borehole].

Uninterrupted Operation

For the purpose of extracting the ground source heat, cold water at 7 [deg. C] was supplied to the U-tubes continuously. Changes in the outlet temperature and power output are shown in Figure 3.

When the model has a mud wall (Figure 3 left), trends of outlet temperatures and power output agree and are stable regardless of ground water flow velocity. This indicates that the outlet temperature, power output, and the efficiency of the heat exchanger, do not depend on the groundwater flow velocity.

On the other hand, when the model is without a mud wall (Figure 3 right), for a faster groundwater flow velocity, a slightly higher outlet temperature and power output are simulated. This means that the outlet temperature and power output are larger for a higher groundwater flow velocity. Consequently when there is no mud wall, the groundwater comes into direct contact with the U-tube, and therefore, more heat exchange can occur, when compared to the model with a mud wall. This indicates that the mud wall works as heat insulation and the model with a mud wall is more heat resistance than the model without a mud wall.

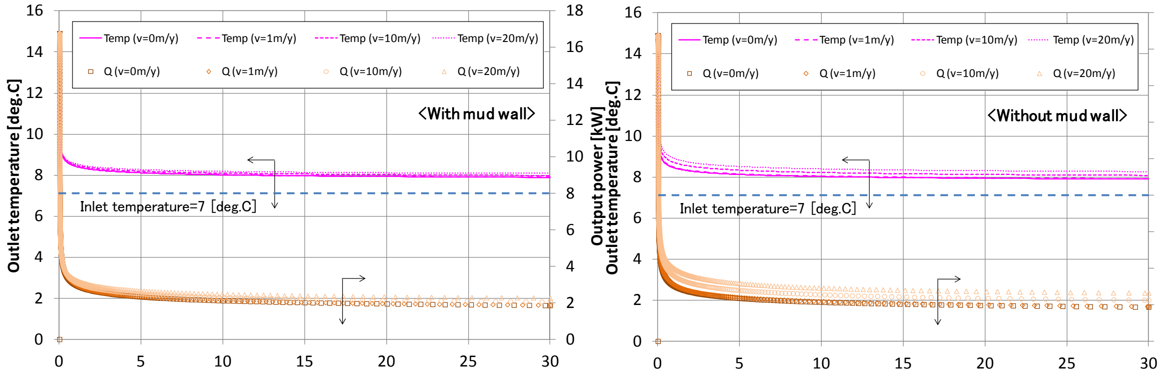

Figure 3: Changes in outlet temperature and power output under the uninterrupted heat exchanger operation.

Cycle Operation

Generally, an office air-conditioning system is not running all day but for a limited time period. Therefore, we simulated the operation of a heat exchanger by setting a-12 hour-cycle operation (running from 6:00 a.m. to 21:00 p.m.) for 30 days. While running the heat exchanger, a constant heat extraction of about 4.2 [kW] was assumed.

The temperature difference between outlet temperature and inlet temperature was set at 2 [deg. C]. Figure 4 (with mud wall) and Figure 5 (without mud wall) showing the changes in temperature of outlet water from the U-tubes.

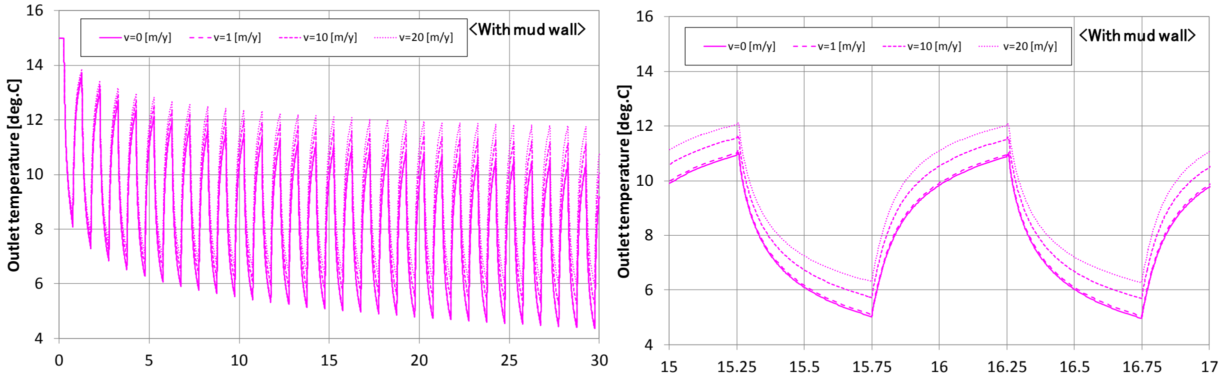

Figure 4: Changes in outlet temperature under the cyclic operation (with mud wall).

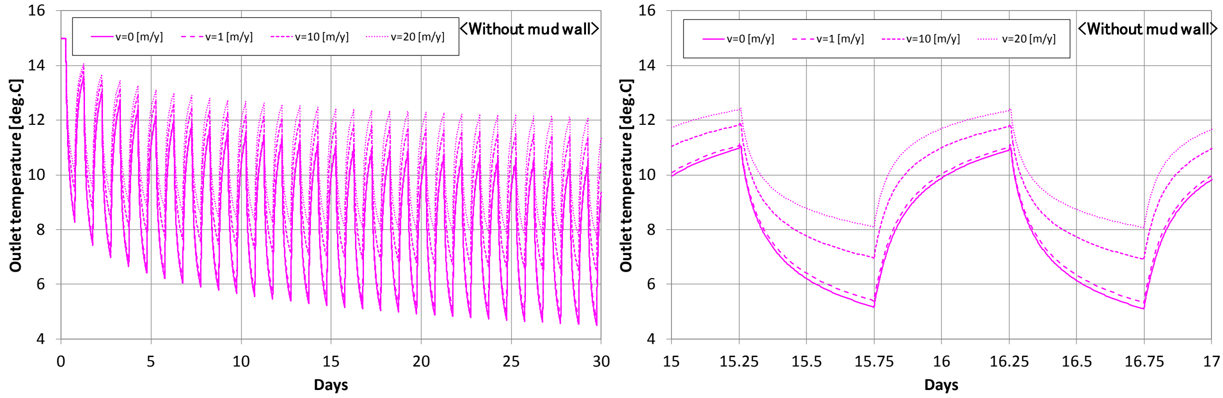

Figure 5: Changes in outlet temperature under the cyclic operation (without mud wall).

Regarding the daily operation, Figure 4 and Figure 5 show that regardless of mud wall existence, outlet temperature decreases every day as time elapsed. The temperature drop of the outlet water of the heat exchanger without a mud wall is less than that of the heat exchanger with a mud wall. When the groundwater flow velocity is faster, the temperature drop is smaller.

Figure 6 and Figure 7 show the ground temperature distributions in y direction. Groundwater flows along x-direction (from the east to the west).When groundwater flows at a velocity of v=0 [meter/year] (Figure 6), there is no difference in ground temperature distributions between the heat exchangers with and without a mud wall. In this case, heat transfer is governed by heat conduction. However when groundwater flows at a velocity of v=20 [m/year] (Figure 7), temperature in the borehole is much higher without a mud wall than with a mud wall. Low temperature resigns are limited to at around the borehole. The temperature at the center of the borehole is the lowest.

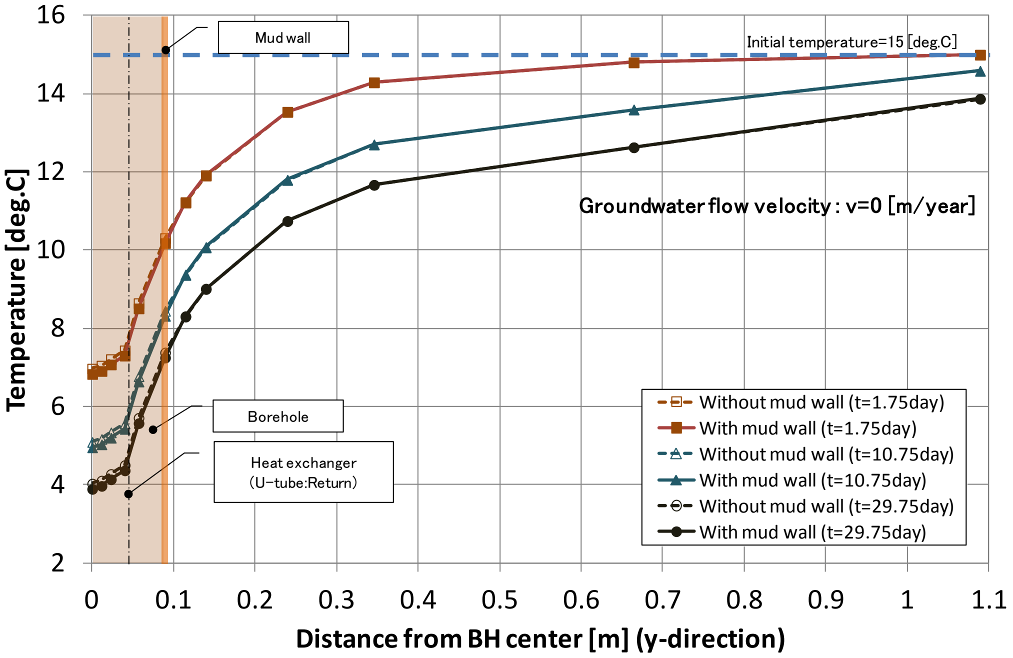

Figure 6: Distributions of ground temperature (Groundwater flow velocity v=0 [m/y]).

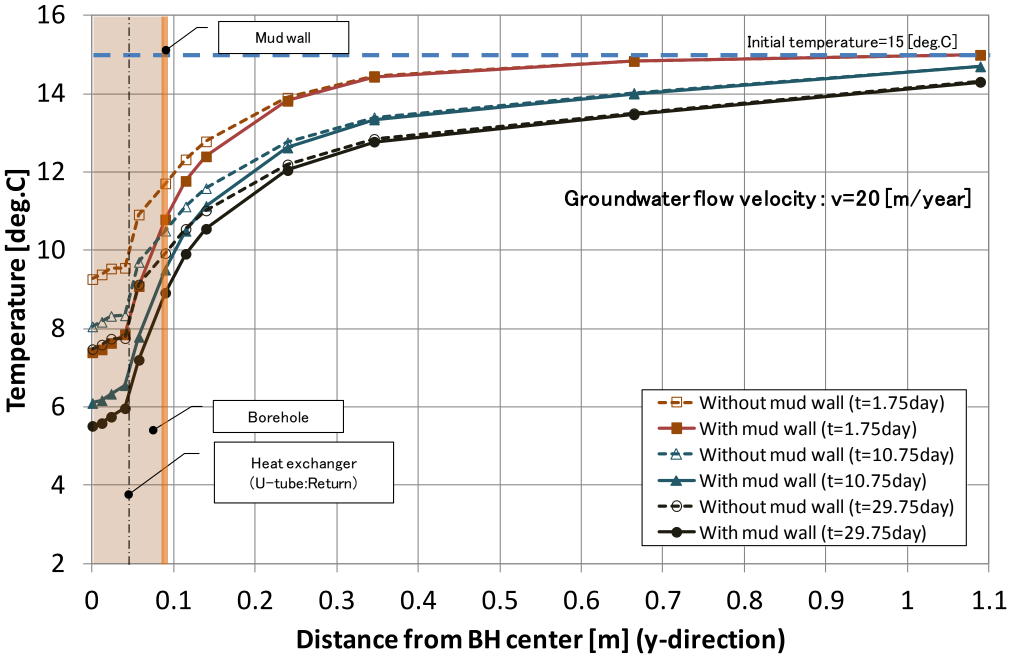

Figure 7: Ground Temperature distribution (Groundwater flow velocity v=20 [m/y]).

Thermal Efficiency in Terms of Comparison of Heating COP

A borehole heat exchanger is often connected to a heat pump for further utilization of the heat. The performance of the heat pump can be evaluated in terms of the coefficient of performance (COP). Referring to the relationship between COP and heat-pump output temperature included in technical documents of the heat pump manufacturer, we calculated COPs and input temperatures to the U-tubes (the same temperature as the heat pump output temperature). The average COP over the 30-day cycle operation is shown in Table 2. The model without a mud wall was simulated to have a COP of about 5% higher than that of the model with a mud wall at the maximum.

Table 2: Comparison of Heating COP

	Without a mud wall			With a mud wall		
	35 [deg. C]	40 [deg. C]	45 [deg. C]	35 [deg. C]	40 [deg. C]	45 [deg. C]
v=0 [m/y]	3.72	3.18	2.76	3.72	3.19	2.77
v=1 [m/y]	3.74	3.20	2.78	3.71	3.18	2.76
v=10 [m/y]	3.91	3.34	2.90	3.77	3.28	2.80
v=20 [m/y]	4.02	3.43	2.98	3.81	3.26	2.83

CONCLUSIONS

While boring for a vertical type heat exchanger, muddy water is circulated to prevent ground from collapsing. The muddy water gradually forms a thin clay layer, which may be left after completion of the heat exchanger. The mud wall has a possibility of reducing heat efficiency of the system because the mud wall may act as heat insulation. In this study, we developed a numerical model of borehole heat exchanger with and without a mud wall using EFLOW 6.2 software and verified with measured data at an actual borehole. Then we made simulations of outlet temperature and ground heat distributions with the model and fund as follow:

1) When the groundwater flow velocity is low: The mud wall has little effect on the output temperatures and temperature distributions in the ground, because the heat is transferred manly by conduction.
2) When the groundwater flow velocity is high: With a mud wall, there is a large ground temperature drop from heat capturing in the borehole. Without a mud wall, the ground temperature drop is less and the borehole temperature is higher than for a borehole with a mud wall. A heat exchanger without a mud wall is more advantageous in terms of heat efficiency than that with a mud wall.
3) Regardless of the groundwater flow velocity or whether the borehole has or does not have a mud wall, the effects of heat capturing by a heat exchanger on ground temperature are limited to the borehole and its adjoining ground.

When a vertical borehole is built, it is recommended to thoroughly wash out any mud on the circumference wall in order to make the ground heat extraction system as efficient as possible.

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