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An Experimental Performance Comparison between Different Shallow Ground Heat Exchangers

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ABSTRACT

For ground source heat pump applications, shallow ground heat exchangers (SGHEs) are cheaper and easier to apply in comparison with the vertical borehole heat exchangers. The main disadvantage of SGHEs is the requirement for large application area. To decrease the application area and initial cost of the system, different kinds of designs are developed for SGHEs. In this study, common and widely used designs (snail, slinky and helix types) are experimentally investigated and their unit heat transfer rates (HTR) as well as unit cost per HTR values are compared. Results show that snail design is the best if the heat transfer rate per unit length is considered while the vertical helix design becomes the best if the application area is considered. On the other hand, if the minimization of initial cost is the target, then slinky design is the best solution. Also unit cost per HTR values of SGHEs are compared with that of vertical borehole heat exchangers.

1. INTRODUCTION

Heat pumps have the capability to be integrated with geothermal and renewable resources for heating and cooling load of buildings. They have considerable advantages besides the conventional heating and cooling systems. Ground source heat pumps (GSHPs) have great importance because the ground has stable temperature throughout the year.

The main disadvantage of GSHPs is their high initial cost. The cost of vertical boreholes has an especially large contribution to the total cost. Horizontal Ground Heat Exchangers (GHE) have a relatively lower cost. Horizontal GHE are easy to install and much cheaper than the vertical ones. On the other hand, there are some criticisms on horizontal GHE, like requiring wide spaces and giving poor performance in cold winter times.

In this study, different kinds of horizontal GHE are investigated experimentally.The main types of horizontal GHE like slinky, snail and helix are installed and tested. In addition, the performance of slinky and helix types are compared for both vertical and horizontal configurations. All types are compared based on unit pipe meter, unit installation area, and unit cost. Snail design seems the best for HTR value per unit pipe length while vertical slinky is the best one for HTR value per unit application area and initial cost.

2. EXPERIMENTAL STUDY

Snail, slinky (Bose and Smith, 1992) and helix types are generally used for shallow type GHE (Figure 1). They are buried inside the ground at a shallow depth. The burying depth of GHEs has crucial significance. The depth of burial should be as deep as not to be affected by seasonal changes of weather temperature and should be as shallow as to renew its temperature in summer time (Banks, 2008). The depth of burial is also affected by the length of the heating and cooling seasons and the insolation time of the ground throughout the year. For instance, in a place where the summer insolation time is short, shallower installation should be performed. Generally, the burying depth is between 1.2 m and 2.5 m.

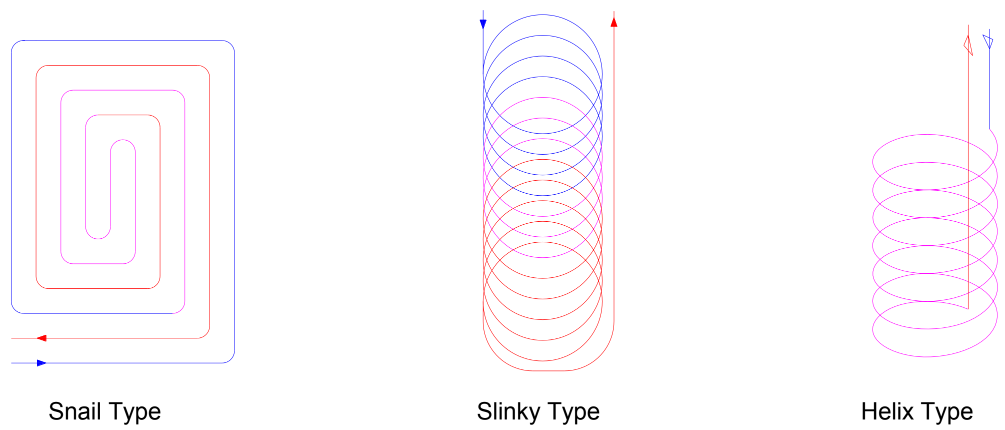

Figure 1. Shallow GHE types.

To find the best depth of burial, ground temperature data given in Figure 2 and Figure 3 by Aydin et. al (2013) is used. These figures show monthly temperature curves of ground in the test area in Istanbul. As can be seen in Figure 2, at the depth of 2 m a temperature change of only 6 °C is observed along the year. On the other hand, at depth of 1 m, the temperature change is almost 13 °C, and at a depth of 3 m the change is 4 °C. At the depth of 2 m, the lowest temperature is around 12.5 °C in February and March and the highest temperature is around 20 °C in August and September. These temperatures are adequate temperatures for cooling and heating processes. In the test region, the heating season starts from mid-October with small loads and reaches to full load in December, January and February. Following this period, the loads begin to decrease and eventually end in mid-April. This means that if the system is used in one way, namely for just heating, the ground has six months to renew itself. If the GSHP system is used in two ways, namely heating and cooling, there will be no problem, because heat will be extracted and injected to the ground in winter and summer times, respectively. If the renovation rate of ground is examined in detail, the renovation time can precisely be determined in a future work.

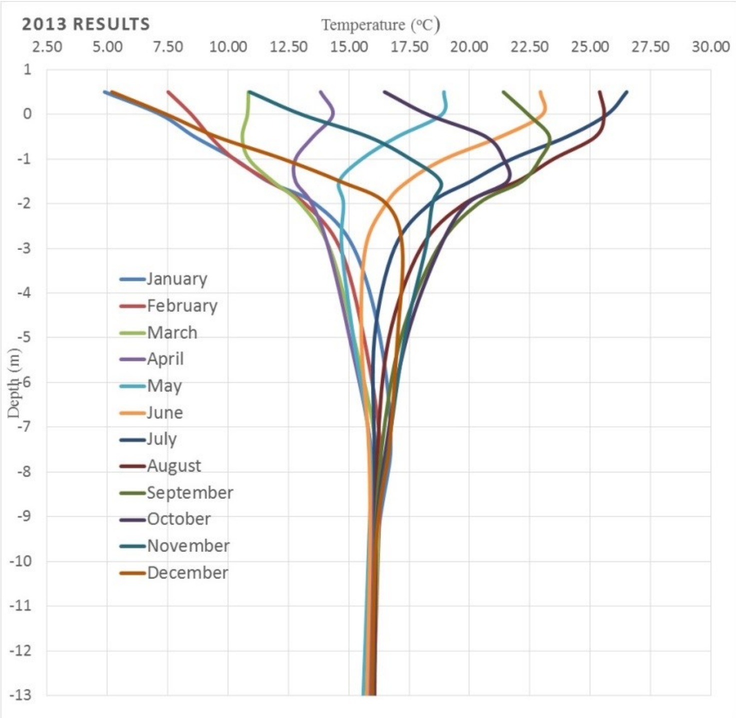

Figure 2. Ground temperature variation with depth at different months for Maslak/Istanbul/Turkey region.

Due to the considerations above, the depth of 2 m is chosen for burying of pipes. Snail and horizontal slinky GHE are buried at 2 m depth. The vertical slinky's top is under 1.7 m below the surface while the bottom is 2.7 m (Figure 3). Helix pipes are installed between 1.5 m and 4.5 m (Figure 4). The dimensions of the slinky GHE are chosen by considering the results given in the study by Chong et.al. (2013). For snail and helix GHE, modulation dimensions are taken from manual of GHE's manufacturer based on the standard of VDI4640.

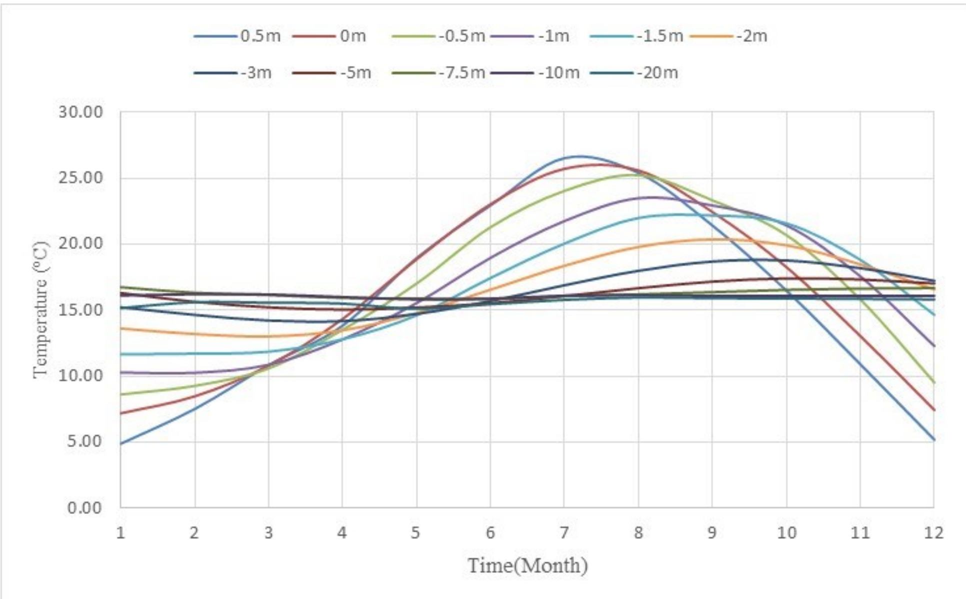

Figure 3. Monthly ground temperature variation at different depths for Maslak/Istanbul/Turkey region-year 2013.

Before the installation of the snail and horizontal slinky pipes, thin quartz sand is placed on the surface of the ground. Pipes are then installed, and another thin layer of quartz sand is placed top of the pipes. Thin soil is placed and all trenches are closed with soil. After installation of vertical slinky and helix GHE, thin soil is used to close the gaps. On every pipe circuit, a temperature sensor is located. Before the trench is closed, the pipes are tested at 2-3 bar to ensure that there is no leakage in the installations. Then, all edge of all pipes are connected to thermal response test system in the laboratory, Figure 5. The properties of the pipes are given in Table 1.

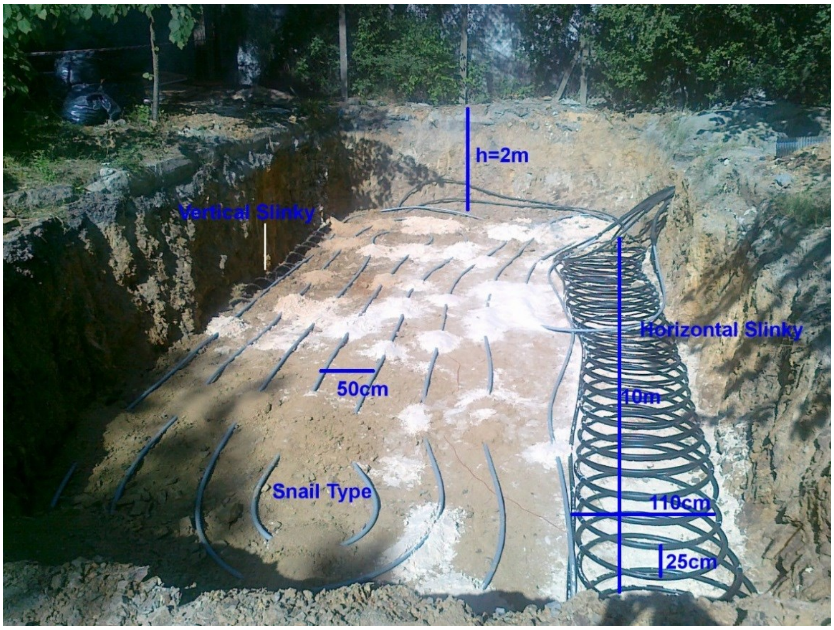

Figure 3. Snail, horizontal and vertical slinky GHEs in application field of Energy Institute-ITU/Istanbul/Turkey.

Figure 4. Vertical Helix GHEs in application field of Energy Institute-ITU/Istanbul/Turkey.

Table 1. Shallow Ground Heat Exchangers' properties.

Slinky and Snail Properties		
Pipe Length	100	m
Pipe Material	HDPE	
Pipe Inner Diameter	26.2	mm
Pipe Outer Diameter	32	mm

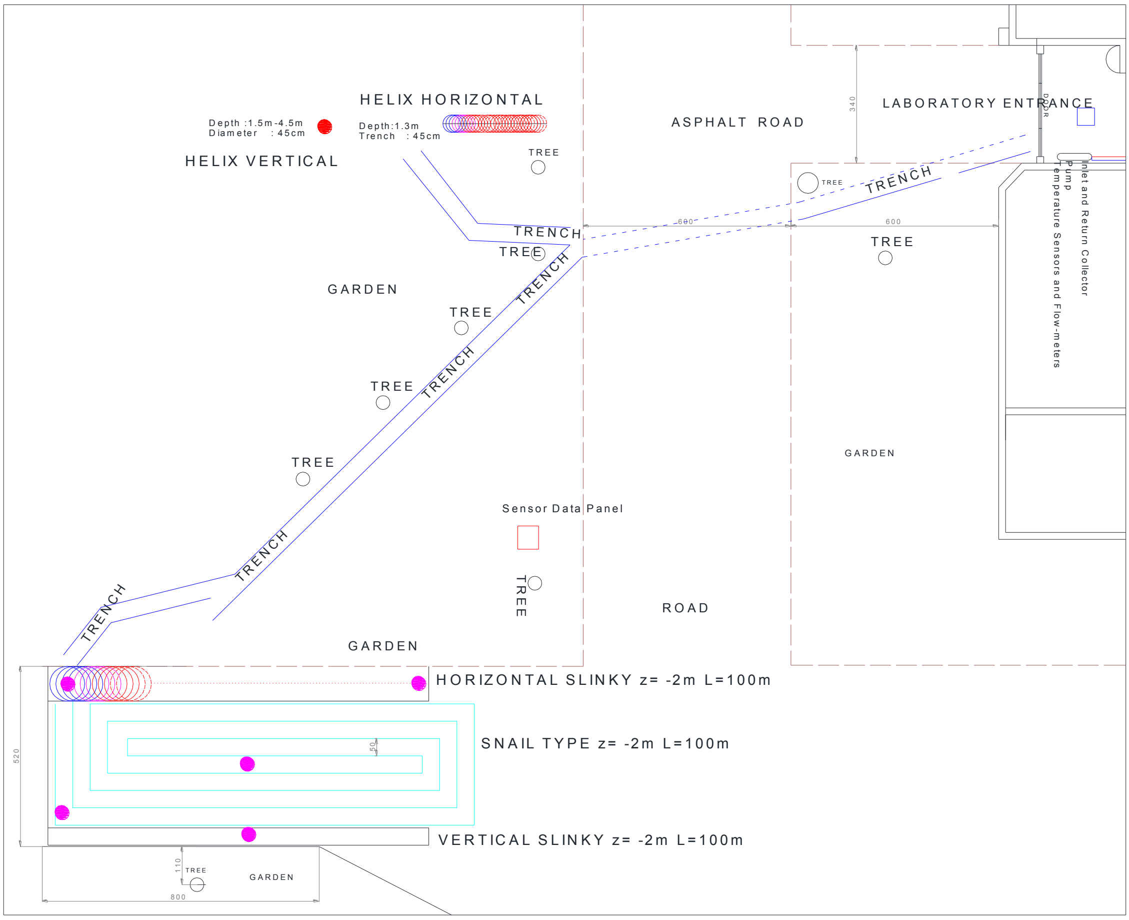

Figure 5. Schematic view of shallow GHEs and laboratory connections.

3. TEST SYSTEM

For test process, Constant Temperature Method (CTM) is used (Wang et.al. 2010 and Aydin et.al. 2014). CTM has some important advantages including better accuracy, shorter time to achieve steady state regime, and a wider range for testing temperature. However, this test system is more expensive due to its temperature control requirements. The constant temperature TRT system mainly consists of an electrical resistance connected to water tank, hydraulic circulating pump, PID control unit, and data logger (shown in Figs. 6 and 7). By using this system, more than one circuit can be tested simultaneously and also get more accurate results.

Figure 6. Thermal response test system.

In the test system, the flow rate and inlet and outlet temperatures are measured and recorded in real-time for each pipe by turbine flow-meter and Pt1000 temperature sensors. Properties of the temperature sensor and flow meter are given in Table 2. Before the test system is operated, the temperature sensors are calibrated in a calorimetric container to get the same results from each sensor for the temperature range of from 2 °C and 55 °C . Flow-meters are also calibrated by Siemens Mag5000 flow-meter.

Table 2. Specifications of Flow-meter and Temperature Sensors.

Flow meter		
Nominal Diameter	15	mm
Repeatability	±0.2	%
Accuracy - Standard	±1	%
Temperature Sensor		
Type	Pt1000	
Precision	±0.15	K

To measure the HTR of GHE, edges of pipes are connected to the test system. After the air is purged from the system, the undisturbed ground temperature has to be measured before the test is started. To determine undisturbed ground temperature, the valves 3, 5, 6, 7 are closed (in Fig. 7) and pump is operated, circulating water temperature after 15-20 minutes gives the information about the undisturbed temperature as Gehlin (2002) stated in his work. Similarly, it can be determined by considering the average outlet temperature of water from borehole for first couple of minutes. Later, valves 2, 3, 7 and boreholes' valves are closed, mini pump and electrical resistances with PID control are operated to heat the water in the tank up to the test temperature.

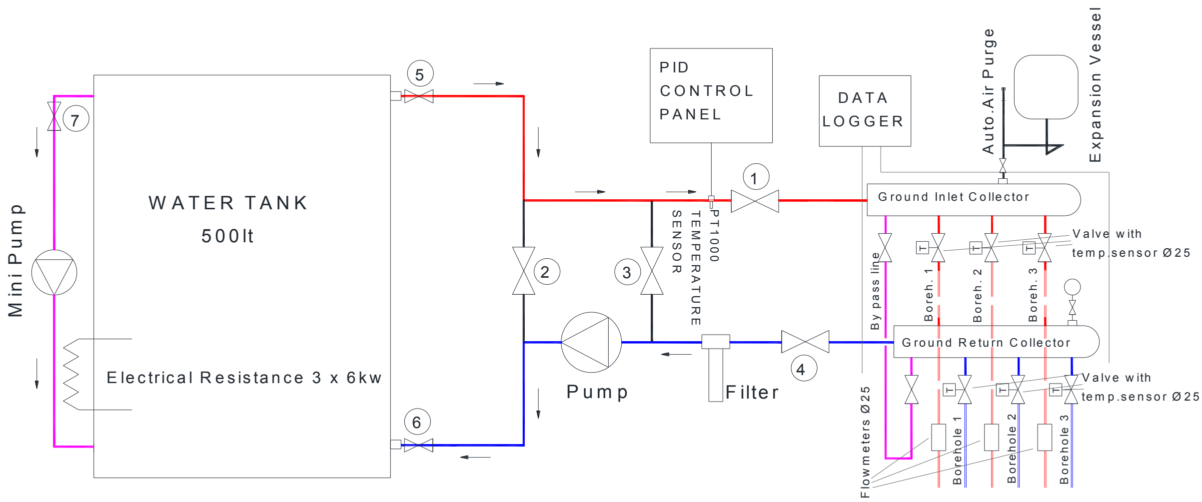

Figure 7. Constant temperature TRT system.

When the water temperature in the tank reaches the test temperature, a by-pass line and valves 2 and 3 are closed, the others are opened and then test is started. Mini pump on left hand side of the tank provides homogeneity of water temperature in the tank. Inlet temperature is measured and controlled by PID controller.

4. RESULTS

As given Table 1, helix GHE has different properties than other ones. Snail and slinky GHE are compared first. Then all results are compared with that of helix one in terms of cost. During test process, each GHE is tested for 70 hours by pumping the constant temperature fluid to the GHE. Testing fluid temperature is chosen as 40 °C to simulate summer conditions for non-stop working. To get reliable results all tests are done twice in different times. To avoid effect of previous tests, at least two weeks is allowed to pass between the tests. Figure 8 shows test results of snail, vertical, and horizontal slinky GHE. Inlet and outlet temperatures as well as mass flow rate are measured in the laboratory and HTR value is calculated with following equation:

$$\dot{Q} = \dot{m} c_p \left(T_{in} - T_{out}\right) \tag{1}$$

where $\dot{m}$, and c_p are mass flow-rate and heat capacity of fluid, respectively.

In Fig. 8, variation of total heat transfer rates from start to end of the test can be seen. The vertical slinky starts higher HTR and then after period of time (about 12 hours) decrement of HTR with time becomes linear. Horizontal slinky shows similar behavior while snail one shows different behavior. Its HTR value decrement is nearly linear during the whole test period. In order to understand their difference from each other, their normalized values are shown in Figure 9.

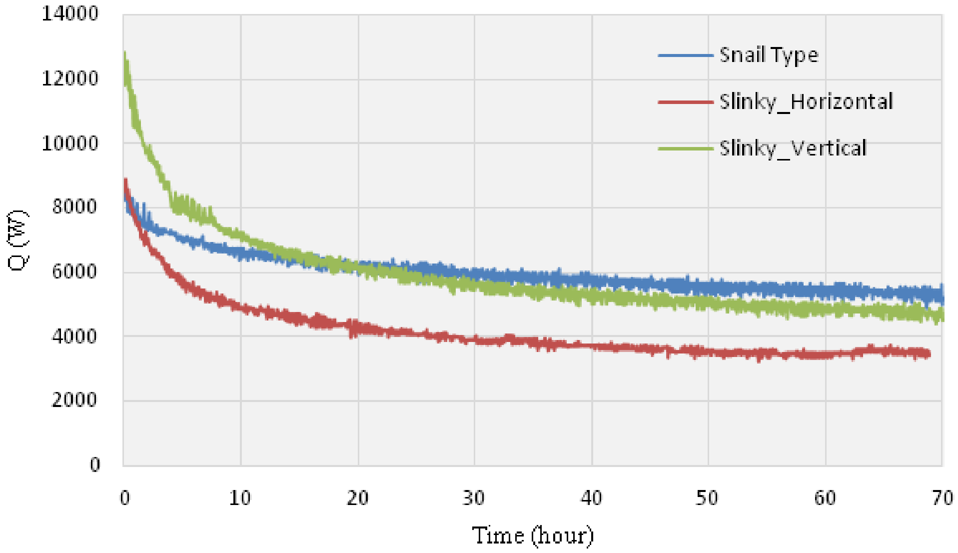

Figure 8. Test results for snail, vertical and horizontal slinky GHE.

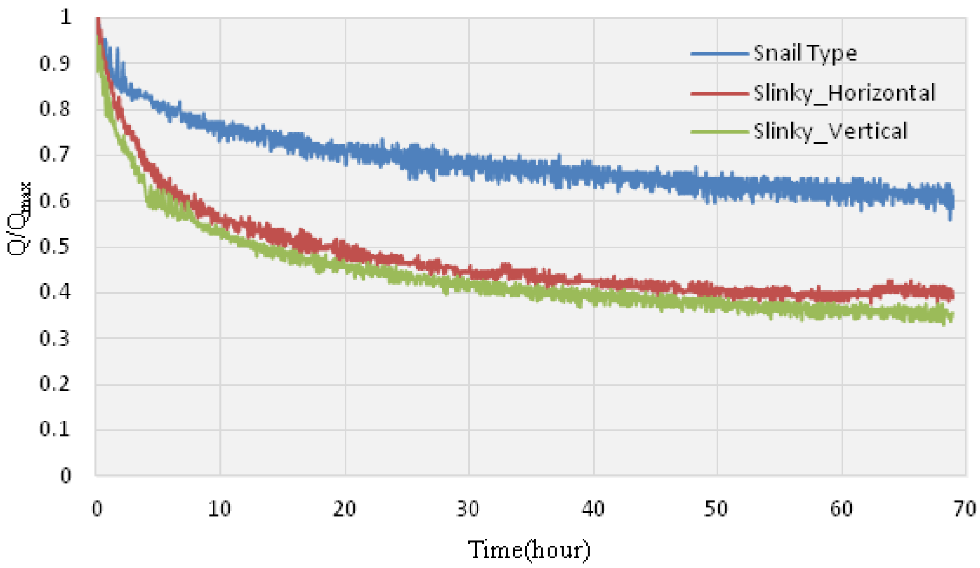

Figure 9. Normalized rest results for snail, vertical and horizontal slinky GHE.

Since there are enough distance between pipes for snail GHE, thermal shortcut is very low. Then decrement of HTR is lower than the others. All test results are summarized in Table 3.

Table 3. Summary of Test Results.

Type	Application Area	Flow-rate	T_{in}	T_{out}	Q_{avg}	$Q_{avg-12h}$
	m^2	lt/min	°C	°C	W	W
Slinky Horizontal	12.1	16.0	40.1	36.4	4161	3810
Slinky Vertical	1.1	16.0	40.0	35.0	5882	5374
Snail Type	42.0	15.9	40.0	34.6	5971	5748

The last column shows the average of heat transfer rates in linear decrement region, which excludes initial 12 h data. If average total heat rates are compared, the order of performance is snail, vertical slinky, and horizontal slinky. Depending on projects, however, either cost or area might be more important, and therefore comparisons in terms of unit length, unit area and unit cost are needed.

4.1 Comparison in Terms of Unit Pipe Length

Each GHE has 100m pipe length and if we compare the results in terms of unit pipe length we get results as shown in Table 4.

Table 4. Comparison in terms of unit length.

Type	$q_{total-12h}$	% Difference
	W/m	
Slinky Horizontal	38.1	0
Slinky Vertical	53.7	41
Snail Type	57.5	51

Pipes do not touch each other in snail GHE while there are lots of contact points in slinky GHE and thermal shortcut is higher than that of snail one. Therefore snail GHE give the best result if heat rate per unit length is considered.

4.2 Comparison in Terms of Unit Application Area

Generally in the majority of projects, application space is limited. If we compare the GHEs in terms of unit area we get the results as shown in Table 5.

Table 5. Comparison in terms of unit application area.

Type	$q_{total-12h}$	Multiple
	W/m^2	
Slinky Horizontal	314.9	2.3
Slinky Vertical	4885.5	35.6
Snail Type	136.9	1

As shown in Table 5, slinky is definitely the best. The worst option is snail because it needs wide application area. Horizontal slinky needs 2.3 times smaller area than the snail one.

4.3 Comparison in Terms of Initial Cost

If the same technology is used, initial costs of horizontal and vertical slinky are approximately equal. Costs of material and installation might change from country to country and region to region. For generalizing the comparison, an imaginary currency, x, is used. Thus in the region where application is installed, costs can be listed as follows:

Vertical and horizontal slinky cost

Trench opening and closing	:	38x
PE pipes	:	100x
Fittings	:	5x
Ground side installations	:	24x
Plumbing Installations	:	30x
Total	:	197x

Snail Cost

Trench opening and closing	:	95x
PE pipes	:	100x
Fittings	:	5x
Ground side installations	:	45x
Plumbing Installations	:	48x
Total	:	293x

A summary of the cost values and comparison of initial cost per heat rate is given Table 6.

Table 6. Comparison in terms of investment cost.

Type		Initial Cost	Initial Cost / Power
	W	Cost	Cost / W
Slinky Horizontal	3810	197x	0.052x
Slinky Vertical	5374	197x	0.037x
Snail Type	5748	293x	0.051x

As seen in Table 6, vertical slinky GHE has the highest heat transfer rate per initial investment cost.

4.4 Helix Study

Helix GHE can be placed either in a channel or in a borehole vertically or horizontally. In the study here helically prepared pipes have been applied horizontally and vertically. Helix GHE properties are given in Table 7.

Table 7. Helix GHE properties.

Pipe Length	40	m
Pipe Material	PE-Xa	
Inner Diameter	20.4	mm
Outer Diameter	25	mm
Helix Diameter	360	mm
Helix Length	3	m

Helix GHE are tested by the test system pumping constant temperature fluid during the test. Inlet and outlet fluid temperatures and flow rates are recorded and HTR vs. time plots are obtained (Figure 10).

In Figure 10, it is seen that similar to other GHE, the heat transfer rate starts with higher values and decreases linearly after about 12 hours. Average heat transfer rate obtained from horizontal helix is 785W while it is 1056W for vertical helix. If the linear decrement region is considered, the average heat transfer rates 728W and 1019W for the horizontal and vertical configurations, respectively.

When a cost analysis is done for vertical helix GHE, the following results are obtained:

Trench opening and closing	:	30x
PE pipes	:	55x
Fittings	:	5x
Plumbing Installations	:	15x
Total	:	100x

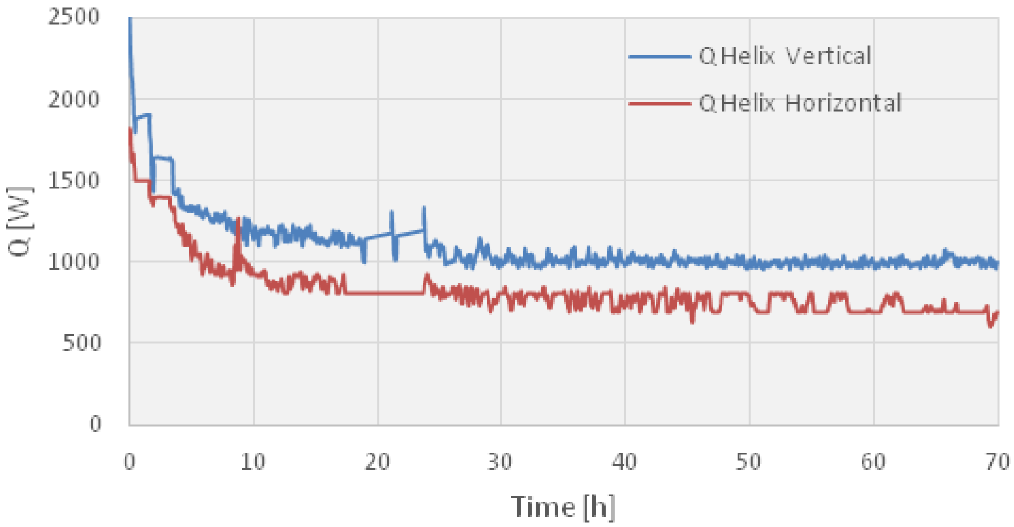

Figure 10. Vertical and Horizontal Helix Test Results.

Thus the cost of initial investment for helix application is 100x/1019 = 0.098x. Then, if we compare this result with the results in Table 6, we see that investment cost of helix GHE is higher than the others.

Because dimensions of helix application are different from slinky and snail, it is not possible to compare the results in terms of unit pipe length. But in the study of Congedo (2012) it has been shown that helical GHE is the best option in terms of HTR per unit pipe length. Furthermore vertical helix application needs a borehole with 40cm diameter and 5m length. If we compare the results of vertical helix (8108 W/m^2) with the results given in Table 5, vertical helix gives the best heat transfer rate per unit application area.

5. CONCLUSION

In this study shallow ground heat exchangers are investigated experimentally. Different shallow GHE (snail, slinky and helix) are compared. Results show that snail GHE is the best in terms of HTR per unit pipe length, while vertical helix give the best results for HTR per unit application area. In the cost analysis, vertical slinky gives the best result in terms of heat transfer rate per unit investment cost. These costs are based on the prices in the application area, which was Turkey. Since costs may change from region to region the results may also be changed. If we compare these results with those of vertical boreholes, we see that vertical boreholes with U-tubes have better heat transfer rate since they are not affected by seasonal temperature fluctuations. Furthermore, vertical boreholes need very small application area and they are better in terms of unit application area, but their cost is higher than those of all horizontal GHE. Study in this paper presents a comparison between shallow GHEs, but in order to achieve more detailed results, long term predictions of GHE should be done. This may be a future study.

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