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Development of energy textile to use geothermal energy in tunnels

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ABSTRACT

A novel textile-type ground heat exchanger, a so-called "energy textile", is introduced in this paper. The energy textile to be assembled in a tunnel lining is devised to function as a ground-coupled heat exchanger (GHE) to operate a ground source heat pump (GSHP) system in tunnels. A test bed of six pilot energy textile modules with various configurations was constructed in an abandoned railroad tunnel in South Korea. Long-term field monitoring was performed to measure the heat exchange capacity of each energy textile module by applying artificial heating and cooling loads on it. In the course of monitoring, the inlet and outlet fluid temperatures of the energy textile, the pumping rate, the ground temperature, and the air temperature inside the tunnel were measured continuously. Each type of energy textile modules was compared in terms of its heat exchange efficiency, which appears to be sensitive to fluctuation of air temperature in the tunnel. In addition, three-dimensional computational fluid dynamic (CFD) analyses were carried out, employing FLUENT, to simulate the field test for each energy textile module. After verification of the numerical model with the field measurement, the influence of a drainage layer on the performance of the energy textile was parametrically examined. A conventional design procedure for horizontal GHEs was used in a preliminary design of an energy textile module, taking into consideration the air temperature variation inside the tunnel over the course of one year.

1. Introduction

This paper introduces an unprecedented geothermal energy source exploited from a tunnel structure. Geothermal energy entrapped underground and adjacent to a tunnel is extracted via a novel textile-type ground-coupled heat exchanger (GHE), named "energy textile", that is fabricated between a shotcrete layer and a guided drainage geotextile. Efforts are being made in many European countries to couple geothermal energy extraction systems with civil infrastructures (Brandl, 2006).

A typical ground-source heat pump (GSHP) system mainly consists of a conventional water-source heat pump unit coupled with a group of GHEs where heat exchange occurs between a working fluid circulating through the GHE and the ground formation. The overall system performance for cooling and heating is mainly governed by the thermal performance of GHE. Among the various types of GHE, the most popular GHE in practice is the closed-loop vertical GHE because of its unmatched efficiency (Johnston et al., 2012; Park et al., 2016). The closed-loop vertical GHE is commonly equipped with a single U-type or a double U-type heat exchanger pipe in a borehole of 100–300 mm diameter and 50–200 m drilling depth. However, the closed-loop GHE will demand a relatively high construction cost due to the requirement of drilling and additional space for construction (Laloui et al., 2003; Bourne-Webb et al., 2009; Loveridge, 2012; Park et al., 2016). Thus, a novel type of GHE has recently attracted public attention on the thermo-active underground structures such as piles, diaphragm walls, concrete slabs and tunnels (Brandl, 2006; Nam et al., 2007; Pasquier and Marcotte, 2012; Choi et al., 2015; Park et al., 2015, 2016).

The energy textile is a good example of utilizing a civil structure as a GHE. Since it is expected that the ground temperature surrounding a tunnel is relatively constant and not affected by seasonal temperature fluctuations, geothermal energy can be extracted from the underground tunnel structure, to be used in heating and cooling of public facilities such as subway stations. In Austria, Markiewicz (2004) installed an "energy fleece" for the first time on the wall of the Lanze tunnel. Other trial versions of GHE were constructed in the tunnel lining, segment or cut-and-cover tunnels in European countries (Franzius and Pralle, 2011; Mimouni et al., 2014). In addition, Zhang et al. (2014) reported the heat transfer performance of the GHE assembled in the tunnel lining applied to Linchang tunnel in Inner Mongolia.

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Nomenclature

q	amount of heat exchange (W)
C	specific heat (J kg^{-1} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
T	temperature (K)
α	thermal diffusion coefficient (m^2 day^{-1})
t	time (sec or day)
A	average between maximum annual temperature and minimum annual temperature (K)

Subscripts

t	total amount
a	air
g	ground
i	inlet
o	outlet
m	mean
s	soil
0	initial time

Abbreviations

GHE	ground heat exchanger
GSHP	ground-source heat pump
CWB	constant-temperature water bath
CFD	computational fluid dynamics
KMA	Korea Meteorological Administration
PE	polyethylene
GLD	ground loop design
HVAC	heating, ventilation, and air conditioning

In South Korea, a great number of highway and railroad tunnels have been constructed. In addition, numerous metro tunnel projects are being carried out in major cities, which gives more chances in development and utilization of the geothermal energy from tunnel structures. Besides, the energy textile has a constructional advantage over the conventional vertical closed-loop GHE: it is attached to the tunnel wall during the installation of the tunnel support systems, without any need for additional drilling of boreholes. Thus, the energy textile seems to be a promising alternative to conventional geothermal-energy extraction systems.

Although tunnels have an intrinsic advantage in terms of the geothermal heat source in installing the GHE as a thermo-active underground structure, the applicability and design concept for constructing the GHE in tunnels has not been well established. In order to bridge such gap in this paper, a series of long-term field monitoring and numerical analyses for parametric study was performed to examine the performance of the energy textiles constructed in a test bed, and then the conventional design procedure for the horizontal GHE was reviewed for its applicability to the energy textile.

A test bed of six pilot energy textile modules with varying heat exchange pipe layouts was constructed in an abandoned railroad tunnel in South Korea. With reference to a preliminary analysis of short-term performance of the pilot modules considering various influencing factors (Lee et al., 2012), this paper reports on the field monitoring carried out to estimate the heat exchange capacity of each energy textile module with the application of artificial cooling and heating loads on it. The field monitoring results were analyzed to compare the long-term thermal performance of the energy textiles. In addition, three-dimensional CFD analyses, employing a commercial code FLUENT, were carried out to simulate the field test for each energy textile module. With the verified numerical model, a parametric study was conducted to determine the influence of a drainage layer on the performance of the energy textile. Lastly, a conventional design procedure for horizontal GHEs was employed as a preliminary design for the energy textile modules, taking into consideration the variation in air temperature inside the tunnel over the course of a year.

2. Test bed construction

A test bed of six pilot energy textile modules with various layouts of heat exchange pipe was constructed in an abandoned railroad tunnel located in Seocheon, in the western area of South Korea (Lee et al., 2012). The length of the abandoned railroad tunnel is approximately 200 m. The energy textile modules were installed in the middle of the tunnel, at a distance of 100 m from the entrance. There are three different arrangements of heat exchange pipe embedded in the energy textile module. Each of the exchange pipe layouts is represented as a transverse (T), longitudinal (L), and slinky (S) type (refer to Fig. 1). Considering the location of heat exchange pipe within the concrete lining, the heat exchange pipes are fixed either to the tunnel wall (i.e., wall-attached type, as Cases 1 and 2) or at the center of the concrete lining (i.e., centered type, as Cases 3, 4, 5 and 6) as shown in Fig. 2. In addition, a drainage layer that envelopes the heat exchange pipe was installed in Cases 1, 2 and 4. In this way, a total of six energy textile modules with varying heat exchange pipe configurations were installed in the test bed to investigate the thermal performance of each module. The rectangular dimension of the energy textile modules was 10 m in length and 1.5 m in height. The polyethylene (PE) pipe used as a heat exchanger was 15 mm in diameter and 2.5 mm in pipe wall thickness. The total length of heat exchange pipe was 60.2 m for the transverse type modules, 61.2 m for the longitudinal type modules, and 173.0 m for the slinky type module. The drainage layer, PE pipe and concrete lining were then sequentially constructed on the existing surface of the tunnel wall.

3. Long-term field monitoring

3.1. Monitoring equipment and procedure

A series of long-term monitoring tests was performed to estimate the heat exchange capacity of each energy textile module, taking into consideration a typical daily heating operation (that

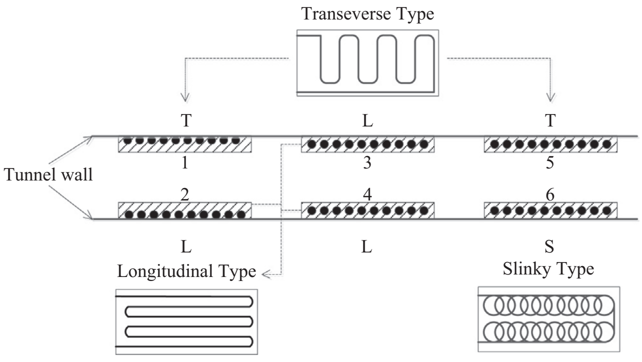

Fig. 1. Test bed configuration with six energy textile modules.