The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Thermal performance assessment of steel pipe heat exchanger (SPHX) energy slab embedded in underground space

*Hizb Ullah[1)], Wonjae Ha[2)], Annas Fiaz Abbasi[3)], Sangwoo Park[4)] and Seokjae Lee[5)]

[1), 2), 3), 5)] *Department of Civil Engineering, Kunsan National University, Gunsan, 54150, Korea*
[4)] *Department of Civil Engineering and Environment Sciences, Korea Military Academy, Seoul, 01805, Korea*
[5)] *seokjae@kunsan.ac.kr*

ABSTRACT

Energy slab is hybrid geothermal structure that incorporates heat exchange pipes within concrete slabs. Conventional energy slabs typically use plastic pipes as heat exchangers, which offer relatively low thermal performance compared to other types of ground heat exchangers. Additionally, the ambient air lowers the thermal performance of conventional energy slabs constructed above the ground. To address this limitation, this study proposes an underground-embedded energy slab integrated with a steel pipe heat exchanger (SPHX). Installing the energy slab in the underground space minimizes the thermal influence of ambient air temperature, thereby enhancing the heat exchange ability of the system. Additionally, the superior thermal conductivity of steel pipes contributes to the improved heat exchange performance of the SPHX energy slab. To validate the proposed approach experimentally, a series of thermal performance tests (TPT) were conducted by constructing testbed. Then, the thermal performance of the proposed energy slab was compared to that of a conventional energy slab using plastic pipes. As a result, the thermal performance of the energy slab improved by 11% with the integration of the SPHX. Furthermore, the SPHX energy slab embedded in the underground space exhibited approximately twice the thermal performance compared to the conventional energy slab.

1. INTRODUCTION

With change in global climate and the depletion of energy resources, there is a growing demand for the utilization of renewable energy sources, and geothermal energy interests are increasing worldwide (Wang 2024). A widely adopted method for utilizing geothermal energy is the Ground Source Heat Pump (GSHP) system. GSHP system utilizes geothermal energy by circulating a heat-transfer fluid through ground heat

---

[1), 2), 3)] Graduate Student
[4), 5)] Professor

exchangers (GHE), thus reducing the electricity consumption associated with heat pump systems. Compared to conventional coal-based heating and cooling systems, GSHP systems can reduce environmental and social damage costs by approximately 85%, and their overall environmental effects can be lowered by 65% to 95%. Moreover, after two to three years of operation, GSHP systems often outclass conventional coal-based systems in terms of environmental benefits and cost efficiency (Zhang 2022). However, the vertical closed-loop GHE commonly used in GSHP systems requires high investment due to the additional construction site and borehole drilling. These can reduce their economic feasibility compared to other renewable energy technologies, depending on site conditions (Boennec 2008). To address this, recent studies have focused on the integration of heat exchange pipes into the civil structures (such as foundations and slabs). This approach allows the GHE to achieve improved thermal performance as well as cost-effectiveness (Park 2021; Tian 2024; Lee 2023; Zhao 2025).

Energy slab is one of the methods using the civil structure as a GHE by embedding horizontal heat exchange pipes into wall and floor slabs of the building. As the energy slabs are typically installed in shallow ground, where the ground has lower thermal conductivity and is significantly affected by ambient air temperature, their thermal performance tends to be lower than the conventional GHE (Moon 2015; Lee 2018). To resolve this drawback, (Lee 2018) proposed fabricating the thermal insulation layer in the energy slab, specifically above the heat exchange pipes. This modification significantly improved the thermal performance of energy slab by mitigating the effect of ambient air temperature. In addition, (Lee 2023) introduced an energy slab system designed for underground spaces, where ambient air conditions are more stable and the thermal conductivity of ground is higher. Field tests showed that the energy slab installed in underground space was evaluated to have higher thermal performance than the energy slab in (Lee 2018). These findings indicate that incorporating insulation layer and installing the energy slab in the underground space can enhance the thermal performance of energy slabs.

To use civil engineering structures as ground heat exchangers, it is essential to install heat exchange pipes—typically made of high-density polyethylene (HDPE). Installing heat exchange pipes into such structures usually requires additional construction processes and costs beyond the typical building process (Park 2015). However, if the conventional reinforcing steel bars in the civil structure are replaced with steel pipes having a hollow circular cross-section, fluid can be circulated directly through them. In other words, by using steel pipes heat exchanger (SPHX) as the primary reinforcement, the structure can simultaneously provide both load bearing capacity and heat exchange functionality, eliminating the need for separate heat exchange pipe installation procedure (Lee 2021; Lee 2023). This approach is particularly promising because the thermal conductivity of steel pipes (i.e., 33.6 W/m·K) is significantly higher than that of HDPE (i.e., 0.4 W/m·K), offering clear advantages in terms of thermal performance (Lee 2021). Therefore, implementing this method to energy slabs could significantly enhance their functionality and broaden their potential applications.

This study presents an experimental investigation into the applicability of SPHX energy slab embedded in the underground space. First, a testbed containing a SPHX energy slab was constructed in the Saemangeum. Additionally, an energy slab with the same dimensions as the SPHX energy slab was installed by equipping the HDPE heat exchange pipe in the testbed for the thermal performance comparison. Then, a series of in-situ Thermal Performance Tests (TPTs) was conducted to evaluate the thermal performance of both energy slabs. Finally, the test result from SPHX energy slab was compared with that from conventional energy slab to assess the potential and effectiveness of using SPHX energy slabs embedding underground space.

2. CONSTRUCTION OF ENERGY SLABS

2.1 Energy Slab Configuration

The schematic diagrams of the energy slabs installed on the testbed are shown in Fig. 1 and 2. As shown in Fig. 1, the SPHX energy slab was designed with dimensions of 5 m × 5 m. The steel pipes (outer diameter: 25.4 mm, thickness: 3.7 mm) were arranged with a 250 mm offset from the slab's edges. The pipes were spaced at intervals of 400 mm, resulting in a total pipe length of 55 m, and each pipe was connected using U-shaped aluminum tubing to allow fluid circulation. In parallel, an energy slab using HDPE pipes (outer diameter: 25 mm, thickness: 2.5 mm) as heat exchange pipe were also designed (i.e., HDPE energy slab). This slab was designed with the same surface area and pipe spacing as the SPHX energy slab and used deformed bars (diameter: 25 mm) for primary reinforcement. To simulate a subsurface installation, both energy slabs were placed 3 m below the ground surface, as shown in Fig. 2. Each energy slab was 0.4 m thick and included a 0.07 m insulation layer made from PF board installed above the heat exchange pipes. In addition, T-type thermocouples were installed at the center of each energy slab (as shown in Fig. 2) to monitor temperature changes in both the energy slabs during the field tests.

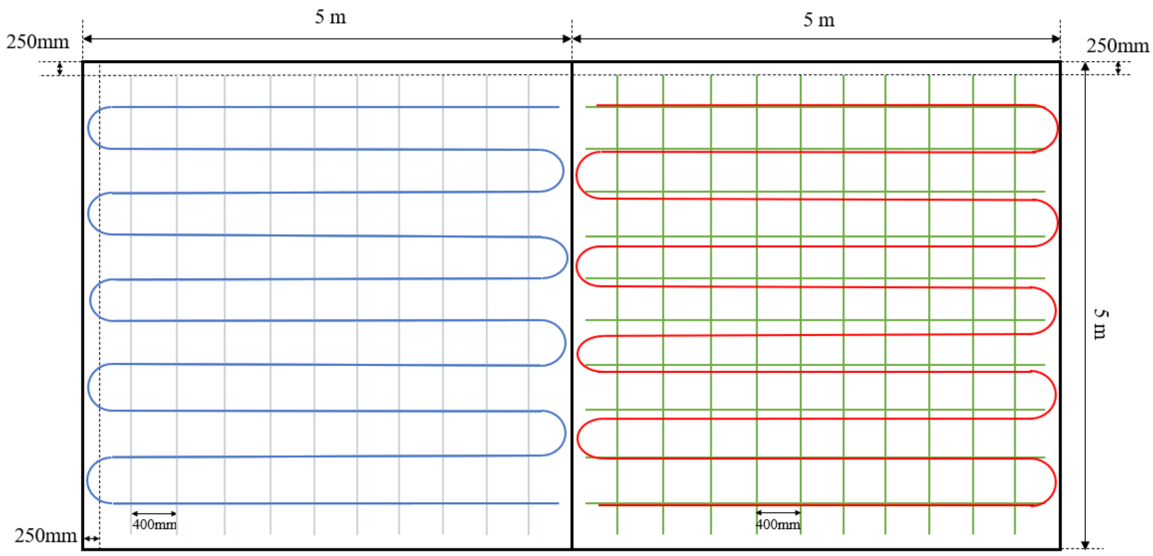


Fig. 1 Plan view of energy slabs

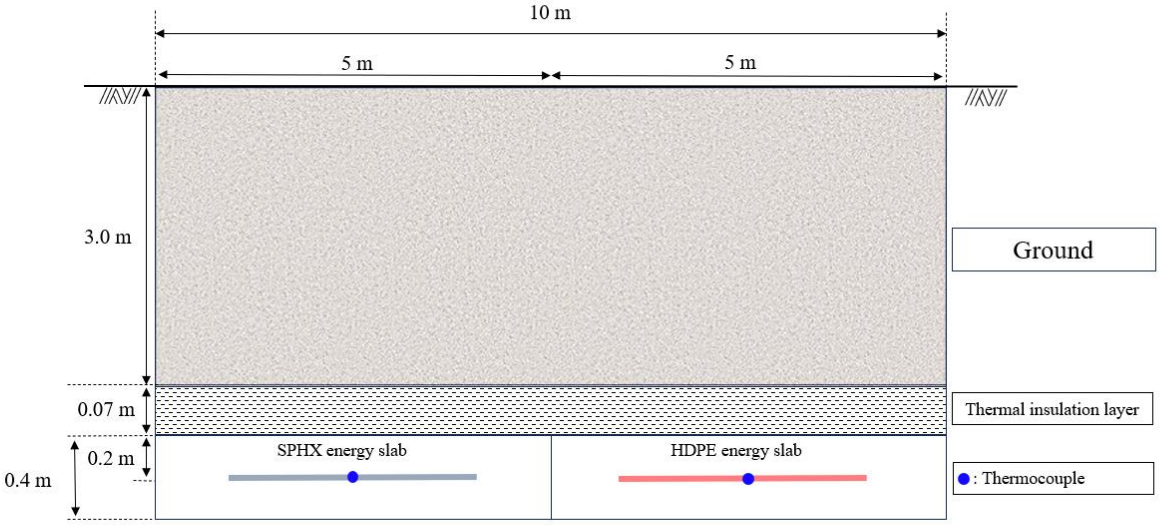


Fig. 2 Sectional view of energy slabs and location of thermocouples

2.2 Overview of the Testbed

The testbed is in the Agricultural and Bio-Industrial Complex of the Saemangeum district, Gunsan-si, Jeollabukdo. Before installing the energy slabs, a geotechnical investigation including Standard Penetration Test (SPT) was carried out to recognize the geotechnical profile of the testbed. As shown in Table 1, the subsurface consists of sandy soil down to a depth of 24.5 m, followed by clayey soil extending to 33.8 m. Beneath this, a weathered rock is present up to 35.4 m, with soft rock encountered between 35.4 and 37.6 m. The investigation was finished at the bedrock, which was reached at a depth of 37.6 m. The SPT results indicated that the testbed was formed through past land reclamation. Notably, groundwater is present within the sandy soil layer, with the water table located at 1.05 m below the ground surface, as shown in Table 1.

Table 1. Results of geotechnical investigation.

Type	Depth (m)	N-value (count/cm)	Note
Weathered soil	0.00~24.50	13/30~13/30	Ground water level -1.05 m
	24.50~33.80	25/30~29/30	
Weathered rock	33.80~35.40	50/4	
Soft rock	35.40~37.60	50/1	
Hard rock	37.60	-	

The construction process of the energy slabs in the testbed is illustrated in Fig. 3. Initially, the testbed area was excavated to facilitate the installation of the energy slabs, after which temperature sensors were embedded. Concrete was then poured up to the designated level for the placement of HDPE and steel pipes. Following this, deformed reinforcing bars and steel pipes were assembled, and the HDPE pipe was installed. Once the geothermal loops were completed, a second concrete pour was conducted, and a thermal insulation layer was installed. Finally, the excavated ground was backfilled, and a monitoring chamber was constructed to support system observation and data acquisition.


(a) Excavation of test bed


(b) Temperature sensor installation


(c) First concrete pouring


(d) Assembling deformed rebar and steel pipe


(e) Installing HDPE pipe


(f) Second concrete pouring


(g) Thermal insulation layer installation


(h) Backfilling


(I) Construction of monitoring chamber

Fig.3 Comprehensive construction process of energy slabs

3. IN-SITU THERMAL PERFORMANCE TEST AND RESULTS

To evaluate the thermal performance of the energy slabs installed at the testbed, a series of in-situ TPTs was conducted. The TPT simulates the operation of the heat pump in the GSHP system to determine the heat exchange capacity of GHE. It is widely employed in the previous studies to evaluate the thermal performance of GHE integrated with civil structure (Lee 2017; Park 2015; Lee 2023). In typical heat pump operation, water is circulated into the ground heat exchanger at approximately 30°C for cooling and 5°C for heating. In the TPT, this is replicated using a constant-temperature water bath.

During the test, the flow rate of the circulating fluid is kept constant, and the temperature of the returning fluid is measured to calculate the heat exchange rate using Eq. (1) (Lee 2017).

$$Q= C \cdot m \cdot \Delta T \tag{1}$$

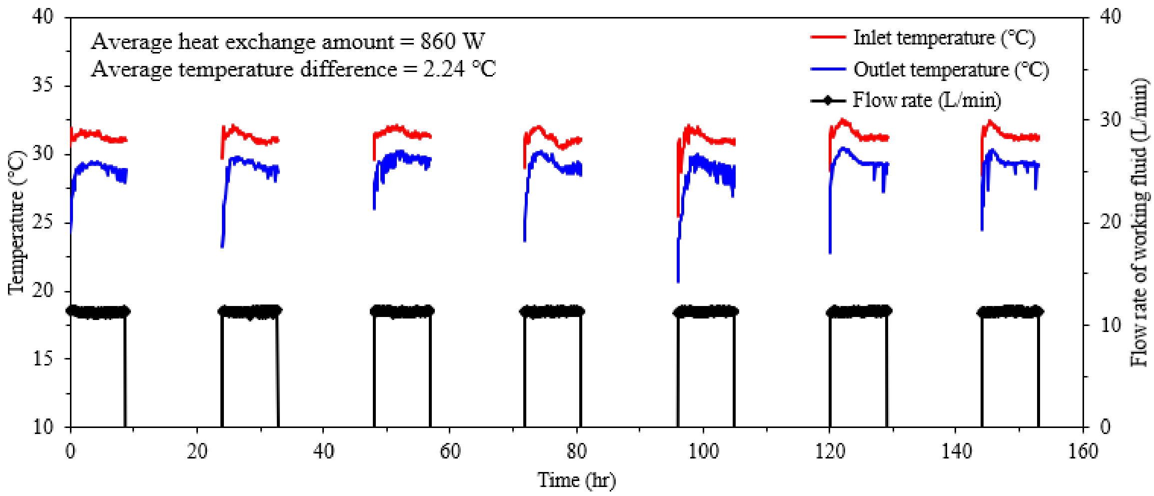
Where, C represents the specific heat of the circulating fluid (J/(kg·K)), m is the mass flow rate of the fluid (kg/s), and ΔT denotes the temperature difference between the inlet and outlet (K).

To promote effective heat transfer with the surrounding soil, the flow velocity of the fluid circulating through the ground heat exchanger is set to induce turbulent flow, as determined by the Reynolds number (Re) in Eq. (2).

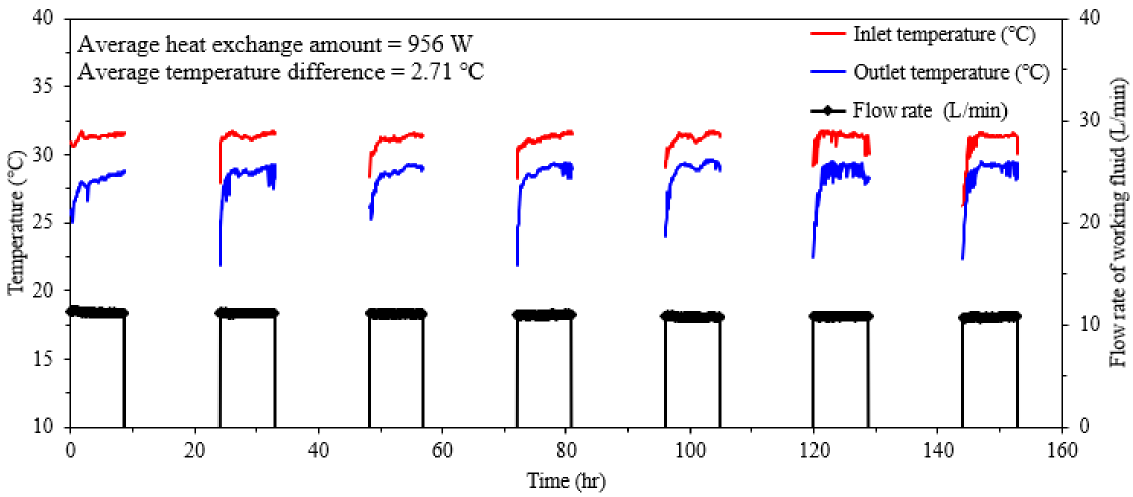
$$Re= \frac{D \cdot V \cdot \rho}{\mu} \tag{2}$$

Where, D represents the pipe diameter (m), V is the average velocity of the fluid (m/s), ρ denotes the fluid density (kg/m^3), and μ represents the fluid viscosity (kg/(m·s)).

In this study, the temperature of the constant-temperature water bath was maintained at approximately 30 °C to simulate cooling operation. Here, ethanol was employed as the circulating fluid because of its antifreeze properties, which were necessary to prevent freezing during cooling process in the constant-temperature water bath. The flow rate was set to 11.2 L/min to ensure a Reynolds number exceeded 4000, thereby establishing fully turbulent flow conditions within the heat exchange pipes. Because turbulent flow is essential to promote efficient convective heat transfer between the circulating fluid and the pipe walls. To replicate the operational characteristics of Heating Ventilation and Air Conditioning (HVAC) systems in commercial buildings, an intermittent flow pattern was implemented, 8 hours of activation followed by 16 hours of deactivation.



(a) HDPE energy slab



(b) SPHX energy slab
Fig. 4 Thermal performance test (TPT) results

The TPTs were conducted for 7 and the results according to the types of energy slab were illustrated in Fig. 4. In the case of the SPHX energy slab (refer to Fig. 4 (b)), the average temperature difference between inlet and outlet was 2.71 °C, indicating that the stable heat performance was exhibited by the SPHX energy slab. In addition, the average heat exchange amount of the SPHX energy slab was 956 W, which was 11% higher than that of the HDPE energy slab (i.e., 860 W).

Fig. 5 illustrates the temperature variations of internal energy slab recorded by the embedded thermocouples (refer to Fig. 2). The temperatures in both energy slabs fluctuated in accordance with the intermittent operation. Notably, the thermocouple embedded within the SPHX energy slab recorded consistently higher temperatures than that of the HDPE energy slab. This implies that heat transfer from the circulating fluid was more effectively induced by the SPHX than by the HDPE pipe. These results confirm that the high thermal conductivity of SPHX significantly improves the thermal performance of energy slabs.

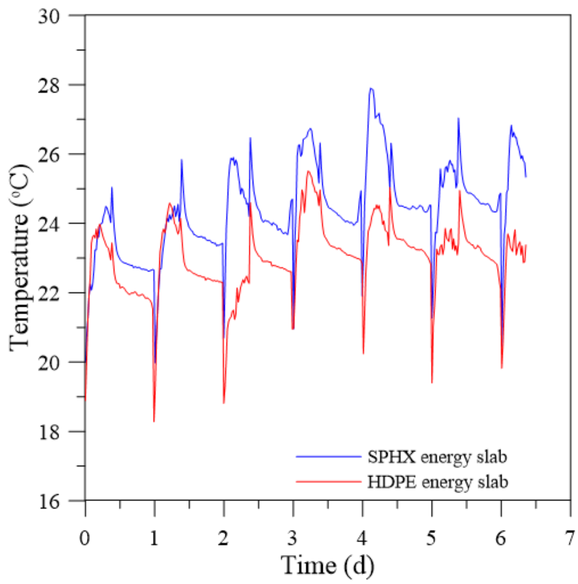


Fig. 5 Temperature variation in energy slabs

To evaluate the applicability of the SPHX energy slab embedded in the underground space, the result of the present study was compared with that of previous study, which performed the TPT in the conventional energy slab (Lee 2018). As summarized in

Table 2, although both energy slabs were constructed at the same size (i.e. 5 m × 5 m), there were significant differences in installation conditions. The conventional energy slab was exposed to the surface, which resulted in greater thermal losses due to ambient air temperature (Lee 2018). In contrast, the SPHX energy slab was embedded in 3 m of subsurface, minimizing the effect of ambient air temperature. Furthermore, the SPHX can enhance the thermal performance of energy slab compared to HDPE pipes. As a result, the SPHX energy slab had approximately 2 times higher heat exchange amount than the conventional energy slab, although the conventional energy slab was equipped with longer heat exchange pipe. Therefore, utilizing the SPHX in the energy slab and installing the energy slab in the underground space can serve as a significant construction method to enhance the low thermal performance of conventional energy slabs.

Table 2. Comparison of construction condition and TPT results between conventional energy slab (Lee 2018) and SPHX energy slab.

Type	Conventional energy slab (Lee 2018)	SPHX energy slab
Material of heat exchange pipe	HDPE	Steel
Thermal conductivity of heat exchange pipe	0.4 W/m·K	33.6 W/m·K
Installation area of energy slab	25 m^2	
Total length of heat exchange pipe	85 m	55 m
Diameter of heat exchanger pipe	40 mm	25.4 mm
Average heat exchange amount of energy slab	430 W	956 W

4. CONCLUSIONS

In this study, the SPHX and HDPE energy slabs were constructed in the testbed. Then, a series of in-situ TPT was conducted to evaluate the thermal performance of constructed energy slabs. The main findings are summarized as follows:

1) As a result of TPTs, the average heat exchange amount for SPHX energy slab was approximately 11% higher than the HDPE energy slab. In addition, the thermocouple embedded within the SPHX energy slab recorded consistently higher temperatures than that of the HDPE energy slab. That is, the high thermal conductivity of SPHX significantly improves the thermal performance of energy slabs.
2) By comparing the TPT of SPHX energy slab with that of conventional energy slab, the SPHX energy slab had approximately 2 times higher heat exchange amount than the conventional energy slab, although the conventional energy slab was equipped with longer heat exchange pipe. This suggests that the thermal performance of energy slabs can be improved through the utilization of the SPHX and the underground space.

The present study conducted the TPT only in cooling operation. Therefore, in order to comprehensively evaluate the thermal performance of SPHX energy slabs embedded in the underground space, the heating and long-term operations should be considered in future studies.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (RS-2022-NR072224 and RS-2021-NR060134)

REFERENCES

Boennec, O. (2008), "Shallow Ground Energy Systems", *Proceedings of the Institution of Civil Engineers - Energy*, Vol. 161(2), 57-61.

Lee, S. Han, T. Park, S. Hwang, C. and Choi, H. (2023), "Thermal performance design and analysis method for energy cast-in-place piles (E-CIPs) installed in diaphragm walls", *Energy Build.*, Vol. 296, 113372.

Lee, S. Park, S. Kim, D. Ahn, D. and Choi, H. (2021), "Dual performance of novel steel pipe heat exchangers equipped in cast-in-place energy pile", *Energy Build.*, Vol. 234, 110725.

Lee, S. Park, S. Kang, M. and Choi, H. (2018), "Field Experiments to Evaluate Thermal Performance of Energy Slabs with Different Installation Conditions", *Appl. Sci.*, Vol. 8(11), 2214.

Lee, S. and Choi, H. (2017), "Evaluation on in-situ Heat Exchange Efficiency of Energy Slab According to Pipe Materials and Configurations", *J. Korea Soc. Geotherm. Energy Eng.*, Vol. 13(4), 1-7.

Moon, C.E. and Choi, J.M. (2015), "Heating Performance Characteristics of the Ground Source Heat Pump System with Energy-piles and Energy-slabs", *Energy*, Vol. 81, 27-32.

Park, S. Lee, S. Sung, C. and Choi, H. (2021), "Applicability evaluation of cast-in-place energy piles based on two-year heating and cooling operation", *Renew. Sustain. energy Rev.,* Vol. 143, 110906.

Park, S. Sung, C. Jung, K. Sohn, B. Chauchois, A. and Choi, H. (2015), "Constructability and heat exchange efficiency of large diameter cast-in-place energy piles with various configurations of heat exchange pipe", *Appl. Therm. Eng.*, Vol. 90, 1061-1071.

Tian, W. Cheng, X. Liu, Z. Wei, Q. Wang, T. and Guo, H. (2024), "Heat exchange performance of an energy-pile group in a hybrid GSHP system and effects of pile spacing", *Energy Build.*, Vol. 316, 114347.

Wang, X. Zhou, Y. Yao, W. Xia, Y. Xu, T. Yang, H. Xie, H. and Gao, W. (2024), "The challenge of the ground heat exchangers: A review of heat transfer efficiency", *Energy Convers. Manag.,* Vol. 302, 118115.

Zhang, T. Zhai, Y. Feng, S. Tan, X. Zhang, M. Duan, L. Shi, Q. Meng, J. and Hong, J. (2022), "Does it pay to develop a ground source heat pump system? Evidence from China", *J. Environ. Manage.*, Vol. 305, 114378.

Zhao, H. Zhu, P. Wang, C. Kong, G. and Hu, X. (2025), "Effect of thermal load distribution types and ratios on the long-term thermal response of energy diaphragm walls", *Comput. Geotech.*, Vol. 179, 107045.