Investigation on the thermal performance of the diaphragm wall in deep buried engineering: a simulation study

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Abstract: Ground source heat pump technology is widely used in buildings to meet the cooling and heating demand. As a special form of the buried pipe, diaphragm wall has received increasing interests due to high energy-efficiency and relatively low costs. Previous studies investigated the thermal behavior of diaphragm wall in underground tunnels or underground parking while very few studies were carried out on deep-buried engineering with the air-conditioned adjacent indoor environment. In this study, the effects of buried pipes on the heat transfer regulation of the diaphragm wall and the indoor load are analyzed. Simulation results indicated that average energy exchange through the pipe in the diaphragm wall is 78.1% compared with that of the conventional buried pipe for the ground heat pump. The heat exchange capacity of the buried pipe in the diaphragm wall in intermittent mode is 1.2 times of that in the non-intermittent mode in 14h. For the underground engineering boundary with pipes buried in the concrete layer, heat transfer through the inner surface reduced 3.8W/m², which would consequently add to the indoor cooling load. In order to reduce the heat transfer back to the indoor environment through the inner surface, insulation of the diaphragm wall are analyzed. This study can provide a reference for the analysis of the feasibility and application of diaphragm wall in deep-buried engineering.

1. Introduction
Diaphragm wall is a special form of buried pipe which is embedded in the foundation of the building (pile, slab, retaining wall or tunnel lining). It can achieve thermal activation by installing an absorber tube in the geological structure through the circulating fluid extracts or injects heat from the ground. The pipe inlet/outlet of each panel is connected to the main circuit, which connects them to the heat pump [1]. The technology can play an important role in the current challenges facing the growing demand for clean and renewable energy, effectively avoiding drilling costs [2]. In recent years, it has aroused increasing interests in the research community worldwide, especially in Europe and Asia [3, 4].

Previous research on the application of diaphragm walls mainly focused on subway tunnels or underground garages. Since there is a large amount of air disturbance in the underground space adjacent to the tunnel, and heat of the diaphragm wall is partially taken away by the air. The underground parking’s indoor temperatures are closely related to the outdoor temperature. Large area of excavation exists in the early stage of construction, and the surrounding rock’s is constant. The excavation conditions at the beginning of the project construction provide a good innate condition for the application of diaphragm walls. However, its heat transfer effect is mainly affected by boundary conditions, adjacent air temperature and convective heat transfer coefficient.

This paper presents a study on the thermal performance of a diaphragm wall in underground engineering in China, especially for the deep-buried engineering with air-conditioned adjacent indoor
environment. The effects of buried pipes on the heat transfer law of the diaphragm wall and the indoor load are analyzed, and the heat transfer effects of the diaphragm wall and the common buried pipe are compared. In order to explore the thermal recovery characteristics, intermittent working mode for both common buried pipes and pipes in diaphragm wall are explored.

2. Model and methodology

2.1 Mathematical model

Temperature field model around buried heat exchanger in underground diaphragm wall are list as follows:

\[ k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} + q_0(t)\delta(x-a)(y-b) = \rho C_m \frac{\partial T}{\partial t} \]  

In the calculation model, the right side of the underground diaphragm wall is convective boundary, and the left side of the underground diaphragm wall is in close contact with the soil. The soil temperature at the left boundary can be considered not affected by the buried pipe, thus is considered to be adiabatic boundary. The upper and lower boundaries of the calculation unit are assumed to be adiabatic boundaries. The specific expression is as equations (3)-(6):

Initial condition:

\[ T_{i,j}(x,y,t) = T_\infty, i = 1,2,0 \leq X \leq L_4, 0 \leq y \leq H, t = 0 \]  

\[ -K_i \frac{\partial T_{i,j}}{\partial x} + h[T_{i,j} - f(t)] = 0, x = L_3, 0 \leq y \leq H, t > 0 \]  

\[ T_{0,j} = T_\infty, x = 0, 0 \leq y \leq H, t > 0 \]  

\[ -K_i \frac{\partial T_{i,j}}{\partial y} = 0, 0 \leq x \leq L_4, y = 0, t > 0 \]  

\[ K_i \frac{\partial T_{i,j}}{\partial y} = 0, 0 \leq x \leq L_4, y = H, t > 0 \]  

Continuity condition are shown in equation (7-8):

\[ T_{0,1} = T_{0,2}, x = L_1, L_2, L_3, 0 \leq Y \leq W, t > 0 \]  

\[ K_i \frac{\partial T_{0,j}}{\partial x} = K_{i+1} \frac{\partial T_{0,j+1}}{\partial x}, x = L_1, L_2, L_3, 0 \leq y \leq W, t > 0 \]  

Where Qin and Qout are the inlet and outlet heat respectively.

2.2 Model assumption and physical parameters

The diaphragm wall numerical model is an explicit 2-D finite volume model with a rectangular non-uniform grid that is applied in ANSYS v19.0. The grid diagram is shown in the Fig.1. The two-dimensional having a plane perpendicular to the tube, assuming no heat transfer through the soil along the length of the tube. Additionally, corner effects are not considered in the model. The influence of surface air temperature is ignored since the shelter is deep buried.
In order to explore the boundary conditions’ influence on the thermal performance of the diaphragm wall exactly, only above excavation portion performance are studied. In this simulation, the wall structure parameters are based on the Chinese code [5], and the specific parameters and construction are shown in Table 1. The pipe was buried 0.02m next to the left boundary of the reinforced concrete layer with a spacing of 0.37m, ignoring thermal interference between adjacent pipes. What’s more, the effect of water flow on heat transfer is ignored. Step size and minimum grid verification, select step size is 0.5s, minimum mesh size Mesh is 0.001m. The pipe’s length in the simulation is 100m, and the indoor temperature are set as 299.15K. Fluid velocity in the buried pipe is set as 0.08m/s. Inlet temperature was set as 305.15 K.

**Table 1.** Thermophysics parameters of materials.

| No. | Material            | Thickness (m) | Conductivity (W/m.k) | Specific heat capacity (J/kg.K) | Density (kg/m³) |
|-----|---------------------|---------------|----------------------|-------------------------------|-----------------|
| 1   | Soil                | 2             | 1.41                 | 1840                          | 1850            |
| 2   | Reinforced concrete | 0.6           | 1.54                 | 840                           | 2400            |
| 3   | Polystyrene board   | 0.05          | 0.03                 | 1500                          | 25              |
| 4   | Cement mortar       | 0.01          | 0.9                  | 1050                          | 1800            |

**2.3 Model verification**

**Figure 1.** Schematic of the buried pipe and wall’s layer structure

**Figure 2.** Temperature versus elapsed time on the left-hand side at different coordinates from experiment and numerical study.
In fig. 2., numerical results using the method in this study were compared with the experiment result of Dong’s et al. [6]. Numerical results refers to the result in this validation, experiment value and numer. orig refers to the results of Dong’s et al. As can be seen from fig. 2, results show that the curves match well with each other. The soil temperature at a depth of 0.33 m is slightly higher than the height of 1.67 m due to convective heat transfer on the upper surface. At the same time, comparing to the simulation results of this paper with Dong’s et al. experiment, the maximum temperature difference was 0.2°C. Therefore, it can be concluded that the model assumptions, etc. have little influence on the results. And the 2-d model’s setting is reasonable.

3. Results and discussion

3.1 Temperature distribution in the wall

![Figure 3. Temperature versus distance from the pipe at various elapsed times (Length=50 m)](image)

Fig. 3 shows the temperature of the diaphragm wall with different distance from the inner surface. It can be seen that at a given time, the temperature at a location closer to the pipe is higher. And affected by the indoor temperature (299.15K) as well as the hot water in the pipe, temperature between the inner surface and pipe is higher than the temperature on the other side of the pipe. As can be seen in Fig. 3, temperature of the pipe at the length of 50m changes to 303.31K after 2h, and then there’s slight rise. After 2 days, the temperature at 1.2m keeps steady as the initial temperature, therefore, a distance as 2.2m could be considered the far boundary in the paper.

3.2 Influence of buried pipes on the cooling load

![Figure 4. Comparison of the inner surface temperature and heat flux between the diaphragm wall and conventional wall. (T_no_dia: inner surface temperature without buried pipe, T_dia: inner surface temperature of the diaphragm wall, H_dia heat flux of the diaphragm wall, H_no_dia: heat flux of the diaphragm conventional wall)](image)
Fig. 4 shows the inner surface temperature and inner surface heat flux with or without pipes in the concrete layer. Indoor temperature is controlled around 26°C. Result shows that, when the heat flux in the inner surface tends to be stable, the heat flow is around 6.8 w/m², which is 3.8 w/m² more than that in the walls without pipes. There will be more 140.6W heat flux to indoor environment because of a single pipe buried in the wall which will lead to the extra cooling load. Meanwhile, the time-by-time injected heat from the pipes to the surrounding concrete is 632.0w. Therefore, there will be 13.1w/m² favorable cooling.

3.3 Energy efficiency of different pipes

The aim of this part of the study was to evaluate the energy efficiency of the diaphragm wall. Thermal performance of the conventional pipes and embedded pipes in the diaphragm wall are compared. In order to explore the soil heat recovery characteristics, simulation about intermittent and continuous operation modes were carried out. Fig. 6 shows outlet temperature of the diaphragm wall and conventional buried pipe separately.

According to the results, outlet temperature of pipes have similar variation trend. As the outlet temperature become stable after 10h, the heat exchange of the outlet temper 85 % compared to that of the conventional pipes.

Figure 5. Relationship curves of outlet temperature and time in intermittent and continuous operational modes (a) diaphragm wall (b) conventional buried pipe

In the intermittent operation mode, the water pump circulated from 8:00am to 10:00pm per day for commercial buildings, i.e., intermittent ratio is 1.4:1. Outlet temperature are relatively low because of
the initial temperature, then the increase becomes slowly with time goes on, especially after around 10h. In intermittent mode, when the heat exchanger runs again after 10h ceasing, the variation trend of outlet temperature has big difference from that in continuous mode in the first 6h and it is much lower than the value in continuous mode. However, it turns to be similar to that in continuous model then. Taking 14h as a heat exchange cycle, the heat transfer amount for the two operation mode of diaphragm wall are 10.7kWh and 8.9kWh separately (average value). And the results for conventional buried pipe are 13.7Kw.h and 11.2kw.h. Therefore, the energy transfer efficiency of diaphragm wall is less than the conventional buried pipe, and the intermittent mode provides better performance.

4. Conclusion
The diaphragm wall, a special form of buried pipe, is embedded in the building foundation to effectively avoid drilling costs. Feasibility of the diaphragm wall applied in deep-buried engineering was studied. When the heat flux in the inner surface tends to be stable, the heat flow is 6.8 W/m², which is 3.8 W/m² more than that in the walls without pipes. Consequently, this part of heat will add to the extra indoor cooling load. Injected heat through the pipe in the diaphragm wall is 78.1% compared with that through the conventional buried pipes for the ground heat pump in the continuous mode. Taking 14h as a heat exchange cycle, the heat transfer amount in the intermittent mode and continuous mode of diaphragm wall are 10.7kWh and 8.9 kWh separately (average value). And the results for conventional buried pipe are 13.7kWh and 11.2kWh Therefore, the energy transfer efficiency of diaphragm wall is less than the conventional buried pipe, and the intermittent mode provides better performance.

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