Feasibility Analysis of Utilization of Shallow Geothermal Energy through LNG Tank Pile Foundation

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Abstract. Liquefied Natural Gas (LNG) needs an additional heat source to meet its heat demand in the process of gasification. Based on the background of using shallow geothermal energy, the feasibility of using LNG tank piles as heat exchangers for LNG gasification was studied. A two-dimensional finite element heat transfer model of energy piles was established, and the heat transfer capacity and long-term stability of different buried pipe options were analyzed. The results show that the LNG tank energy piles can meet part of the heat demand for LNG gasification to a certain extent.

1. Introduction

With the advancement of ground source heat pump technology, the energy underground structure based on shallow geothermal energy, especially the energy pile technology, has been greatly developed in the past ten years[1-6]. With the in-depth research on the performance of the heat exchanger itself, some scholars have found that the imbalance of cooling and heating load has a great influence on the heat transfer capacity of the borehole heat exchanger: Abdelaziz S L et al.[7] found that the unbalanced heating and cooling load will reduce the output level of the system. It is very obvious in the first few years of the operation. With the operating time goes by, the reduction will gradually decrease. Rybach L et al.[8] conducted a ground-source heat pump system with only the building heat load. And found that the temperature near the borehole heat exchanger was significantly reduced during long-term operation, and its impact on the ground temperature will take about 30 years to recover. In addition, many scholars have found that the seepage of groundwater can significantly improve the recovery of ground temperature[9-11].

Liquefied natural gas (LNG) needs heat in the process of gasification. If heat exchange pipes are arranged inside the pile foundation of the LNG tank, these energy piles can not only provide part of the heat required for LNG gasification, but also be used for air conditioning and heating of buildings.
near the LNG receiving station. Groundwater seepage under LNG tanks is benefit for the long-term stability of heat exchangers.

Based on the heat supply problem of a certain LNG storage tank in the process of gasification and transportation, the utilization of shallow geothermal energy to provide heat through the piles of the LNG tank is considered. By the finite element analysis, the attenuation of the heat transfer capacity of the energy piles during the long-term heat extraction process is studied, the feasibility of using shallow geothermal energy to provide stable heat for the LNG gasification is evaluated.

2. Theory and model

2.1 Finite element model

The LNG tank located in Anhui Province has a radius of 36.1 meters and the foundation contains 300 piles. The diameter of the pile is 1.2 meters and the depth is 50 meters. The piles are divided into two types: external piles and internal piles. The external piles are divided into inner and outer layers, which are evenly distributed in a ring shape. 64 outer piles form a circle with a radius of 36.1 meters; 56 inner piles form a circle with a radius of 32.5 meters. The internal piles are 4 meters apart, distributed in a rectangular shape, with a total of 180.

In order to reduce the time consumption, the two-dimensional finite element model is used to simulate the heat transfer of the energy pile group. Due to the symmetry of the distribution of piles, one quarter model is adopted when the influence of seepage is not considered, and one half model is adopted when the influence of seepage is considered. The diameter of the pile foundation is 1.2m, which is in the same order of magnitude with the distance between the pile center 4m. Therefore, the energy pile can not be regarded as a line heat source for simulation. The cross section of the pile foundation should be meshed, and the position of each branch pipe in the pile should be set according to the form of the buried pipe. A constant temperature boundary was set 60 meters away from the center of the pile foundation to simulate the influence of the remote stratum on the simulation area. The finite element mesh map without considering seepage is shown in Fig. 1 (a). The value of thermophysical parameters of pile come from concrete, and there is no seepage in the pile. In order to facilitate modeling, the pile foundation is set as a square pile with a side length of 1.2 meters. The local grid near the pile is shown in Fig. 1 (b).
The double U-shaped buried pipe in an energy pile is divided into four branch pipes, and a calculation model is established according to the connection relationship between the branch pipes. The heat exchange between the fluid in branch pipe and the pile foundation considers the convective heat exchange except the heat conduction. The pipe is assumed to be a high-density polyethylene material with a thermal conductivity of 0.42 W/(m·K), which is much smaller than common geotechnical materials. Its thermal resistance effect in heat transfer is considered. The thermal resistance between the fluid in the pipe and the inner wall of the borehole includes the convective heat transfer resistance and the thermal resistance of the pipe wall material, as shown in equation (1).

\[ h' = \frac{1}{1/h+d/(2\rho \ln (D/d))} \]  

(1)

Here, \( h' \) represents the thermal resistance between the fluid in the tube and the inner wall of the borehole, \( h \) represents the convective heat transfer resistance between the fluid in the tube and the tube wall, \( D \) and \( d \) represent the outer and inner diameters of the tube, respectively, \( \rho \) represents the fluid density, and \( \lambda \) represents the fluid thermal conductivity. The 4 branch pipes in the double U-shaped buried pipe are divided into two pairs, each pair of branch pipes are connected in series, and the two pairs of branch pipes are connected in parallel. The heat exchangers (pile) are all connected in parallel, and the inlet water temperature is the same. The finite element simulation is based on the part of the pile foundation area, but the heat transfer capacity of the energy piles in Section 3 is the overall heat transfer capacity.

2.2. Parameters of material
According to the ground survey, the stratum where the LNG tank is located contains gravel, sand and clay layers. In order to analyze the upper limit of the heat transfer capacity of the energy pile group, the thermophysical parameters of the gravel layer are selected as the equivalent soil thermal physical parameters. According to the code[12], its specific heat capacity is 2.4 MJ/(m³·K), and the thermal conductivity is 3.3 W/(m·K). The specific heat capacity of the pile foundation concrete is 2.0 MJ/(m³·K), and the thermal conductivity is 2.32 W/(m·K). The initial ground temperature is 17°C. According to the load demand provided by the owner, the annual average load is about 467kW. In the following analysis, it will be used as the reference to evaluate the heat transfer capacity of pile foundation buried pipe. In order to determine the maximum heat exchange capacity of the pile group, the inlet water temperature is set to 5°C. And the ground temperature changes of the buried pipe area and the characteristics of the heat exchange capacity in the operation process under this extreme condition are predicted.

2.3 Simulation duration
A longer period of time will be chosen as simulate duration to evaluate the long-term stability of the ground source heat pump system. But that is usually for systems that have both heating and cooling loads. For systems that only have heating or cooling load, the output level of the system will drop
significantly in a relatively short period of time. Therefore, one year of simulation duration is set. Subsequent studies have shown that under non-seepage conditions, when the simulation time reaches a year, the heat extraction capacity of the system has been significantly attenuated; while with groundwater seepage, under the given groundwater flow rate, the change in the system's heat extraction capacity will reach a relatively stable state within a year.

3. Analysis

3.1. Without groundwater seepage

3.1.1. All piles occupied  A one-year simulation is carried out according to the operation mode of constant inlet water temperature of 5 ℃. During the simulation period, the distribution of ground temperature and the change of heating power are shown in Figure 2.

![Figure 2a](image1.png)  ![Figure 2b](image2.png)  ![Figure 2c](image3.png)

a) Ground temperature in buried pipe area during operation for half a year  
b) Ground temperature in buried pipe area during operation for a year  
c) Heat extraction rate of energy pile group

**Figure 2.** Simulation results of heat extraction with all piles occupied

During the one-year simulation, the ground temperature in the buried pipe area decreased significantly, as shown in Figure 2a) and b). After the system has been in operation for half a year, the temperature
of the pile group drops below 6 °C, the temperature of the soil between the piles drops below 8 °C, and the influence region beyond the buried pipe area increases. When the simulation runs for a year, the temperature of the pile foundation and the soil between the piles in the buried pipe area is close to 5°C, and the ground temperature within about 10 meters beyond the buried pipe area drops by more than 1°C.

The total heat transfer power of pile group has gradually decreased within a year, as shown in Figure 2c). The average heat extraction rate of energy pile group in a year is 258kW, which can reach 55% of the need of LNG gasification. The heating power is very high at the beginning of operation, but as time goes by, the heat extraction rate of the pile group is seriously attenuated. The total heat transfer power of the 300 energy piles is only 50kW at the end of a year, and only in the first 64 days can meet the gasification heat need, and the first 111 days are higher than the average heat extraction rate. The temperature in the buried pipe area is close to the inlet water temperature, and the temperature outside the boundary of the buried pipe gradually rises to the initial ground temperature. Therefore, it can be inferred that the heat extraction power of the internal piles is very small, and the later heat exchange mainly depends on the external piles.

3.1.2. Partial piles occupied The occupied internal piles spacing is 8 meters, only the outer layer of external ring are occupied, and the buried pipes are placed at intervals. A total of 84 piles are set as energy piles. Figure 3 and Figure 4 show the distribution of ground temperature after a year and the change of heat extraction rate in the year.

![Figure 3. Ground temperature distribution in interval occupancy scheme](image)
Figure 4. Simulation results of heat extraction rate in interval occupancy scheme

The temperature range of the buried pipe area is 6~11℃, and the temperature difference between the soil and the pile foundation is 2~3℃, as shown in Figure 3. The ground temperature in the buried pipe area has dropped significantly and the temperature difference between the piles and the soil is small, indicating that the "cold accumulation" phenomenon in the buried pipe area is more serious, the local heat extraction is too large, and the heat exchange capacity of the pile group is seriously reduced. The average heating power is 134kW, as shown in Figure 4, which can supply 29% of the heating demand, and the average heating power per pile is 1.60kW. Planning energy piles at intervals will still reduce the ground temperature in the buried pipe area, and the heating power during operation will also be seriously attenuated.

3.1.3. External piles occupied Only using the total of 120 external piles for heat exchange can optimize the temperature distribution in the buried pipe area, avoid the "cold accumulation", and promote the heat transfer from the external soil to the buried pipe area. Figure 5 and Figure 6 show the distribution of ground temperature after a year of operation and the change of heating power in the year.

Figure 5. The distribution of ground temperature in external piles occupancy scheme
Figure 6. Simulation results of heat extraction rate in external piles occupancy scheme

The temperature in the area where the buried pipe is located has dropped significantly, and the local ground temperature has dropped to 6°C, as shown in Figure 5. There are some areas with relatively high ground temperature inside and outside the boundary of the pile foundation region, which is beneficial to the long-term stability of the energy pile.

The average heating power for a year is 157kW, which is shown in Figure 6, and the average heating power for each pile is 1.31kW. The heat extraction rate at the end of the year is 77kW, which is higher than the aforementioned plan. After a year of heat extraction, the instantaneous heat extraction power is the highest among the above three schemes, indicating that such a buried pipe scheme has good long-term stability and can maintain a certain output power under a longer period of operation. However, the heat extraction capacity of this scheme is relatively low. There are two main reasons: the number of buried pipes is less and the distance of the energy piles is small. Because the buried pipe needs to be laid in the pile foundation, the energy pile is actually restricted by the pile position, and the external pile spacing is actually less than 4 meters required in the code[12], therefore, when the whole external piles are occupied, the energy piles are too close, which is not good to the long-term heat exchange.

3.2. With groundwater seepage

3.2.1. All piles occupied The seepage velocity is assumed 0.1m/d and 0.5m/d, the heat transfer of the buried pipe of the pile foundation is simulated for a year, the ground temperature distribution after a year and the heating power in the year are shown in Figure 7 and 8.
After a year, the pile foundation area and some of its downstream areas were affected by the heat extraction through energy piles, as shown in Figure 7. When the seepage velocity is small, the downstream affected area is also small, and the soil temperature in the affected area decreases more. Where there is a temperature gradient in the reverse seepage direction, and the temperature drops significantly. The heat transfer capacity is suppressed by the effect of seepage. When the seepage velocity is high, more heat is transferred from the upstream of the buried pipe area, so that the soil temperature around the upstream pile foundation is restored, and the corresponding heat transfer capacity of the buried pipe is improved; meanwhile the increase of the seepage velocity increases the
affected range of ground temperature. The "cold accumulation" phenomenon in the downstream area is alleviated, and the attenuation of heat exchange capacity is reduced. When the seepage velocity is 0.1m/d, the temperature of the downstream part of the buried pipe is close to 5°C, and the heat transfer capacity of the buried pipe in the "cold accumulation" area is basically lost, as shown in Figure 8a; when the seepage velocity is up to 0.5m/d, the temperature of the downstream part of the buried pipe is above 6°C, the temperature of the upstream part will further increase, and the attenuation of the heat transfer capacity of all buried pipes will decrease, and it will gradually stabilize with the time.

The simulation results of the heat transfer power of the energy pile group under different seepage conditions are shown in Figure 8. When the seepage velocity is 0.1m/d, the heat extraction rate still decays with the running time, but when the running time is long enough (about 250 to 300 days), the heating power gradually stabilized at 224kW, which can supply 47.9% of the gasification heating load, and the average heating power per pile is 0.75kW. With the increase of the seepage velocity, the attenuation of the heat transfer power of the buried pipe still exists, but the stable output power increases, the running time to reach the stable output power decreases. When the seepage velocity is 0.5m/d, after about 50 to 100 days of operation, the stable output power is reached and the value is 797kW, which is greater than the heating load of gasification, and the average heating power per pile is 2.66kW.

3.2.2. **External piles occupied** When only the external piles are occupied, the overall heat transfer capacity will also be improved to a certain extent due to the influence of groundwater seepage. Set the seepage velocity to 0.1m/d and simulate for a year. The simulation results of the ground temperature distribution and the heating power are shown in Figure 9 and Figure 10.

![Figure 9. Distribution of ground temperature with only external piles occupied](image-url)
The heat transfer influence range of the buried pipe is approximately elliptical from the original ring shape (see Figure 6) to the downstream direction, as shown in Figure 9. The soil temperature between the piles within the influence range of the buried pipe is not less than 10°C, which is 4°C higher than that under the condition of no seepage. Most of the annular area formed by the energy pile is affected by the lower temperature of the energy piles in the upstream direction, but due to the low seepage velocity, there remains a higher temperature area inside the downstream buried pipe after a year operation. If the system continues to run, the temperature in this area will drop below 10°C, and at the same time it will affect the heat transfer power of the buried pipe at the downstream location, resulting in a further reduction in the heat extraction capacity of the buried pipe.

The final output power of the pile group in the end of a year is 207kW, as shown in Figure 10, and the average heating power per pile is 1.73kW. The heat exchange capacity of a single pile is higher than that of all pile foundation heat exchange schemes under the same seepage conditions. The overall heat transfer capacity of the external piles gradually decreases during operation, and the attenuation range does not decrease with time, but shows the characteristics of first decrease and then slightly increase. This is affected by the relationship between the placement of occupied piles and seepage. Projecting the buried pipe onto a plane perpendicular to the seepage direction shows that the projection density is small near the axis of symmetry (the upper boundary in Figure 9), and the projection density is greater at places farther from the axis of symmetry. The high projection density means that the downstream buried pipe is greatly affected by the upstream buried pipe under seepage conditions. In the initial stage of energy pile heat exchange, the impact of heat extraction in the downstream direction is relatively small, mainly concentrated in several piles. The adjacent upstream buried pipes near the symmetry axis have little effect on the downstream piles, and the heat transfer capacity of the downstream piles is less attenuated; the occupied piles are more densely distributed along the seepage direction at places far from the symmetry axis, and the downstream buried pipe is affected by multiple upstream buried pipes at the same time, and the heat exchange capacity attenuates greatly.

With the operation time of the heat extraction goes by, the influence range of the energy piles in the downstream direction is enlarged, causing the heat transfer capacity of the downstream energy piles to
continue to attenuate, especially when the influence range of the energy piles close to the symmetry axis exceeds the circular area in the middle of the piles, the heat transfer capacity of the downstream energy piles will be suppressed, and the overall attenuation of the heating power will increase. However, with the heat exchange time of the energy piles goes by further, the attenuation amplitude will gradually decrease, and the downstream influence range will be further expanded. But the pile foundation area is approximately steady, and the heat extraction rate of the pile group will no longer decrease thereafter.

3.3. Discussion
3.3.1. Schemes comparison without seepage Long-term heat extraction from ground is very unfavorable for the use of shallow ground energy. Long-term extraction of heat from the ground without adding heat to the soil will result in a larger net heat output of the soil, which will reduce the ground temperature in the energy pile area and cause the heat extraction capacity of the energy pile to continue to decline. Regardless of how many piles are occupied as heat exchanger, the total heat transfer of the buried pipe pile group will drop below 100 kW in a year, and the average heat transfer power of each scheme can supply 29%~55% of heating demand. The greater the number of energy piles, the stronger the short-term heat exchange capacity, but as the heat exchange time increases, the greater the attenuation amplitude. For the all piles occupied scheme, the end heat exchange mainly depends on the heat exchange of the external piles; for the partial piles occupied scheme, in addition to relying on the heat exchange of the external piles, the internal piles also retain a certain heat exchange capacity in the final stage; for the external piles occupied scheme, all the piles keep a relatively high efficiency. Comparing these three schemes, it is found that the heat transfer capacity of the external piles occupied scheme is weaker, but the long-term stability is better; the average single-hole heat transfer capacity of the partial piles occupied scheme is better, but due to the small number of buried pipes, the overall heat extraction capacity is not ideal; the short-term heat exchange capacity of the all piles occupied scheme is very good. The system can fully meet the heating demand for the gasification of liquefied natural gas in the storage tank in the early stage of operation, but the heat extraction capacity has a large attenuation and the long-term stability is weak.

3.3.2. Schemes comparison with seepage The effect of seepage on the ground temperature and the heat transfer capacity of the pile foundation is very significant. When the seepage velocity is 0.1m/d, the heat extraction rate of the energy pile group gradually stabilizes at 224kW, which can supply 47.9% of the heating load of gasification. When the seepage velocity is up to 0.5m/d, the final stable output power of energy pile group is 797kW, which is greater than the heating load of gasification. Under the same groundwater seepage conditions, the average single-pile heat transfer capacity of the external piles is stronger than that of the entire energy piles. For the groundwater seepage, the interaction of the energy piles upstream and downstream becomes greater. When the energy piles are laid too close under the seepage flow, the heat transfer capacity of the energy piles in the downstream
direction may be greatly reduced. Therefore, the groundwater seepage direction and other relevant data should be obtained before design.

4. Conclusion
In this paper, the feasibility of heat transfer of energy pile group of LNG tanks for heating during gasification and transportation was studied. The heat transfer capacity and long-term stability of different energy piles occupied schemes were compared, and the influence of groundwater seepage on the heat transfer of energy piles is analyzed. The main conclusions are as follows:
1) Under the condition of no seepage, the long-term heat extraction for the LNG gasification will cause the ground temperature of the energy pile area to drop, and the phenomenon of "cold accumulation" will appear, and the heat extraction capacity will gradually decrease with time. The average power of the three schemes described in a year is only 29% to 55% of the required power.
2) Groundwater seepage will significantly increase the heat extraction capacity and long-term stability of the energy piles. The greater the seepage velocity, the greater the increase in the heat extraction capacity and long-term stability of the energy pile group. Groundwater seepage will cause a relatively ideal steady-state power for the heat transfer of the energy piles, which makes the utilization of shallow geothermal energy of greater value.
3) Considering the long-term performance of each energy piles scheme with and without seepage, the long-term stability of the external piles occupied scheme is the best, and the average heat transfer capacity for a single pile is also high, which is a feasible scheme for LNG gasification.

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