What is the potential for pipe to pipe interactions in energy piles?

Fleur Loveridge\textsuperscript{1} & Francesco Cecinato\textsuperscript{2}

\textsuperscript{1}Faculty of Engineering & the Environment, University of Southampton, Southampton, UK. \\
\textsuperscript{2}Dept. of Civil, Environmental & Mechanical Engineering, University of Trento, Trento, Italy.

\textbf{Background}

Borehole heat exchangers are one of the most common means of executing ground energy storage. Borehole thermal resistance is an important parameter since the resistance controls the temperature change between the heat transfer fluid and the ground for a given heat input according to the expression \( \Delta T = qR_b \), where \( q \) is the heat transfer rate per unit depth (W/m) and \( R_b \) is the borehole thermal resistance in mK/W. \( R_b \) is normally calculated on the basis of a two dimensional slice through the borehole and accounts for both borehole geometry and material properties. Minimising the resistance is a desirable target since it will help improve heat transfer to the ground. With respect to borehole geometry it is now well established that maximising the pipe spacing (U-tube shank spacing) will reduce the resistance\textsuperscript{[1]} due to two mechanisms. One is the simple 2D separation of the pipes which places the two heat sources further apart and closer to the borehole edge. However, the second mechanism is three dimensional. If the pipes are placed too close together then they will potentially exchange heat with each other rather than the ground, thus introducing axial effects. This can be accounted for within boreholes containing a single U-tube by determining a quasi-three dimensional resistance (for details see the review by Lamarche et al\textsuperscript{[2]}).

Energy piles are often taken as analogous to borehole heat exchangers as they are both axisymmetric in external form. However, piles are both larger in diameter than boreholes and have the potential to contain many more heat transfer pipes. Typically it would also be expected that those pipes would have a larger spacing than in a borehole. But does energy pile design also need to consider three dimensional resistances, or would two dimensional computation be sufficient? To investigate this question two sets of analysis have been carried out. First, existing analytical tools for single U-tube heat exchangers are used to explore the theoretical potential for interactions. Secondly, fluid temperature profile data from numerical simulations are examined to determine whether interactions are occurring in double and triple U-tube connected in series.

\textbf{Single U-Tube Scenarios}

The multipole method\textsuperscript{[3]} has been used to determine the steady state pile resistance \( R_b \) and the internal resistance \( R_a \) for a range of typical pile geometries. \( R_b \) is the pipe to pipe resistance between the two shanks of the U-tube. In this case, for simplicity, the contribution of the pipes and fluid to the steady state resistance \( R_b \) was neglected. This will lead to an underestimation of the resistance, but will be conservative when it comes to determining the interaction potential as described below. Two geometry scenarios are considered (i) a pile with a diameter of 1000mm with variable concrete cover to the pipes, and (ii) variable pile diameter with a fixed concrete cover to the pipes of 50mm. The first scenario shows the difference between installing pipes within the centre of a pile as would be typical for contiguous flight auger (CFA) construction and installing pipes near the edge of the pile as would be typical for rotary bored construction. The second scenario shows the effect of increasing the pipe shank spacing for rotary piles as their overall size increases.

The calculated resistances are shown in Figure 1, for three ratios of the concrete to ground thermal conductivity (\( \lambda_c/\lambda_g \)). The results are plotted as normalised values, where the resistance has been multiplied by the concrete conductivity. For the 1000mm diameter pile normalised \( R_b \) reduces as the shank spacing is increased, from approximately 0.5 to 0.25. For the constant concrete cover pile \( R_b \) increases slightly with pile size increases, from approximately 0.2 to 0.3. The internal resistance, \( R_a \), is low (<0.1) for the 1000mm diameter pile with small shank spacing (e.g. a typical CFA pile), but it increases rapidly as the shank spacing is widened. For the other case, as the shank spacing is always greater, the internal resistance is larger than 0.7 in all cases. The worst case for interactions will be
when the internal resistance is smallest, i.e. the CFA arrangement in the 1000mm pile or the smallest diameter rotary pile.

Figure 1 Calculated resistance for single U-tube energy piles with different \( \lambda_c/\lambda_g \) ratios, a) 1000mm pile with variable concrete cover; b) variable pile diameter with fixed 50mm cover.

The method of Diao et al\cite{4} was used to calculate the potential for pipe to pipe interactions for the two worst case scenarios identified above. The parameter \( \delta \) is defined as the relative error between the two dimensional pile resistance and a quasi-three dimensional resistance which takes into account pipe to pipe interactions. \( \delta \) is calculated based on \( R_a, R_b \) and the fluid mass flow rate, \( m \). Figure 2 shows how \( \delta \) varies with \( m \) for the two worst case geometries. In general the values are very low except at small mass flow rates. In reality \( m < 0.075 \) kg/s would be unlikely so practically it can be concluded that pipe to pipe interactions would be insignificant. Counter to expectations, the values of \( \delta \) for rotary piles are greater than for CFA piles, despite the larger shank spacing. It is possible that this results from the assumption that the temperature is uniform around the edge of the heat exchanger which underlies the physical models for determination of both the resistances and \( \delta \); however, this point requires further investigation.

**Single & Multiple U-Tube Scenarios**

Of course most energy piles have more than a single U-tube installed. For such cases quasi-three dimensional resistance models are not readily available. Hence to make an initial investigation of interaction potential the results of three dimensional numerical simulations have been examined. The simulations were conducted using the numerical model developed by Cecinato et al.\cite{5} A constant temperature was used as a boundary condition at the inlet to the ground heat exchanger and the fluid temperature at the outlet was calculated. The profile of the fluid temperatures around the pipe circuit was determined after four days of continuous heat exchange and used to test two models:

1. The quasi-three dimensional model of Diao et al.\cite{4} which is based on \( R_a, R_b, m \), the length of the heat exchanger, \( H \), and the temperature of the outer edge of the pile (assumed to be uniform), \( T_b \).

   In this case \( R_b \) was calculated according to the multipole method,\cite{3} \( m \) and \( H \) are known from the model inputs and \( R_a \) and \( T_b \) are fitted. The model is only applicable to single U-tube cases.

2. A two dimensional model which also assumes a uniform value for \( T_b \).\cite{6} The model differs from 1 above by not including \( R_a \). As above \( T_b \) was a fitted parameter, while the others are known or calculated. It is applicable to multiple U-tube cases.

When there are no pipe to pipe interactions, models 1 and 2 are equivalent.\cite{2}

For single U-tube simulations both models fitted the numerical results well. The root mean square error (RMSE) for the model fit was in the range \( 5 \times 10^{-4} \) to \( 3 \times 10^{-2} \). The errors were the same for the two models suggesting that no interactions were occurring. This was confirmed by calculating \( \delta \), with the resulting value always less than 1% for the rotary piles and less than 2% for the CFA piles. This confirms the earlier theoretical results.

Numerical simulations were also carried out for rotary piles with three U-tubes and CFA piles with two U-tubes. In these cases it is not possible to apply model 1 and only model 2 was fitted. The range of root mean square error values for the model fits were \( 9 \times 10^{-4} \) to \( 5 \times 10^{-2} \) which is similar overall compared to the single U-tube cases. Examples of the fits are given in Figure 3, which shows an overall acceptable fit quality, suggesting that pipe to pipe interactions may not be significant.
Additional observations can be made by considering the relationship between the RMSE values and the total pipe circuit length, pipe centre to centre spacing and fluid mass flow rate (Figure 4). For the CFA pile simulations the fit quality appears to depend mainly on the fluid mass flow rate. For the rotary pile simulations, total pipe circuit length and pipe spacing are also important, with reduced fits for longer circuits and smaller spacings. The results also highlight that the least good fit occurs for rotary piles with multiple U-tubes. This may be related to total circuit length, the jump to three rather than two U-tubes, or may be a reflection of deviation from the underlying physical model in these cases. In fact Lamarche et al.[2] have shown that these models can break down when pipes are close to the edge of the heat exchanger. These factors can be investigated further by more in depth interrogation of the results of the numerical simulations.

Figure 4 Variation of model 2 fit quality for a) pipe circuit length; b) pipe spacing; c) mass flow rate. Diamonds = rotary; circles = CFA; solid symbol = single U-tube; open symbol = double (CFA) or triple (rotary) U-tube.

Conclusions & Further Work

Initial studies suggest that for the range of pipe spacing that are typical for energy piles the potential for significant pipe to pipe interactions is low. For single U-tube scenarios the potential appears insignificant. For some multiple U-tube scenarios, the quality of model fits for fluid temperature profiles is reduced, but not to an unacceptable degree. It is possible that this reduction in fit quality is caused by other deviations from the physical model itself, for example the assumption of a constant and uniform temperature around the edge of the heat exchanger. This can be investigated further by numerical simulations.

If the potential for pipe to pipe interaction can be shown to be low for all energy piles then there are important consequences for further simulation and analysis. In particular the absence of significant axial effects may mean that, at least for short term analysis, two dimensional modelling may be sufficient in some cases. This will save significantly on computational effort for further research, but also for routine analysis and design approaches. Of course for longer term analysis, where the surface boundary condition is important, three dimensional approaches will still be required.