Thermal Behaviour of Piles used as Heat Exchangers

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Contents

• Piles compared to borehole heat exchangers
  – Layout of the heat exchangers
  – Geometry of the heat exchanger
  – Pipe arrangements within the heat exchanger
  – Connection of heat exchanger pipe circuits

• Thermal response testing

• Fieldwork

• Conclusions
Scope

- Bored foundation piles with concrete cast in situ
- Piles, not walls or piled walls
- Thermal behaviour, not thermo-mechanical
Differences to BHs
Pile Layout

- Often irregular in terms of length, diameter & spacing
- Determined by structural engineer
Geometry:
Line and Cylindrical Sources, Ground Response
Geometry: Pile Diameter

<table>
<thead>
<tr>
<th>Error</th>
<th>Fo</th>
<th>r=0.1m</th>
<th>r=0.3m</th>
<th>r=0.6m</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% error</td>
<td>10</td>
<td>28 hours</td>
<td>10 days</td>
<td>42 days</td>
</tr>
<tr>
<td>10% error</td>
<td>5</td>
<td>14 hours</td>
<td>5 days</td>
<td>21 days</td>
</tr>
<tr>
<td>25% error</td>
<td>2</td>
<td>6 hours</td>
<td>2 days</td>
<td>8 days</td>
</tr>
</tbody>
</table>
Pile Geometry : Aspect Ratio

- Aspect ratio = length/diameter
- Borehole AR = 500 to 2,000
- Pile AR = 10 to 50
Aspect Ratio: Thermal Response
Pile Geometry – Pile Length

The graph shows the relationship between pile length and the time (in years) it takes to achieve a 10% error for piles of different diameters: 0.2m, 0.6m, and 1.2m. The graph includes three lines, each representing a different diameter, indicating how the time to reach 10% error increases with the length of the pile.
Aspect Ratio: Thermal Response

- 0.2m diameter
- 0.6m diameter
- 1.2m diameter
Pipe Arrangements

- More pipes
- More widely spaced
- Larger cover

- Lower Resistance
- Higher resistance?
- Higher Resistance
Pile Thermal Resistance

\[ R_b = R_{pconv} + R_{pcond} + R_c \]

- \( R_{pconv} \) & \( R_{pcond} \) relatively “easy” to calculate
- \( R_c \) – complex multipole method or numerical modelling
- Depends on pipe arrangements and thermal conductivity of concrete
- Possibility to determine in situ ??
Numerical Modelling for $R_c$

- Aim to determine shape factor so that $R_c$ can be calculated
- Steady state vs transient
- Lower resistance if:
  - More pipes
  - Pipes closer to edge
- For central pipes number & arrangement matters less
- Still need to know $\lambda_{\text{concrete}}$

\[
R = \frac{1}{S_f \lambda}
\]
Design Chart for $R_c$ with four pipes
Pile Thermal Resistance - Values

\[ R_b = R_{p\text{conv}} + R_{p\text{cond}} + R_c \]

<table>
<thead>
<tr>
<th>Pile Dia mm</th>
<th>Pipes</th>
<th>( R_{p\text{conv}} )</th>
<th>( R_{p\text{cond}} )</th>
<th>( R_c ) ( \lambda=1.25 )</th>
<th>( R_c ) ( \lambda=2.5 )</th>
<th>( R_b ) ( \lambda=1.25 )</th>
<th>( R_b ) ( \lambda=2.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>2 central</td>
<td>0.05</td>
<td>0.04</td>
<td>0.214</td>
<td>0.107</td>
<td>0.304</td>
<td>0.197</td>
</tr>
<tr>
<td>300</td>
<td>2 edge</td>
<td>0.05</td>
<td>0.04</td>
<td>0.148</td>
<td>0.074</td>
<td>0.238</td>
<td>0.164</td>
</tr>
<tr>
<td>600</td>
<td>4 central</td>
<td>0.02</td>
<td>0.02</td>
<td>0.282</td>
<td>0.141</td>
<td>0.322</td>
<td>0.181</td>
</tr>
<tr>
<td>600</td>
<td>4 edge</td>
<td>0.02</td>
<td>0.02</td>
<td>0.090</td>
<td>0.045</td>
<td>0.130</td>
<td>0.085</td>
</tr>
<tr>
<td>1200</td>
<td>4 central</td>
<td>0.02</td>
<td>0.02</td>
<td>0.372</td>
<td>0.186</td>
<td>0.412</td>
<td>0.226</td>
</tr>
<tr>
<td>1200</td>
<td>8 edge</td>
<td>0.01</td>
<td>0.01</td>
<td>0.046</td>
<td>0.023</td>
<td>0.066</td>
<td>0.043</td>
</tr>
</tbody>
</table>
Pile Resistance: Time for Steady State

- 300mm diameter pile: < 1 day
- 600mm diameter pile: up to 2 days
- 1200mm diameter pile: up to 5 days
- Is steady state resistance approach appropriate?
3D: Pipe Interactions

![Diagram showing fluid temperature and mean fluid temperature vs. depth with different temperature patterns: linear, exponential, and interacting.](diagram.png)
3D: Pipe Interactions (modelling)

### 3D: Pipe Interactions (thermal resistance)

<table>
<thead>
<tr>
<th>Flow Rate</th>
<th>Thermal Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m/s</td>
<td>0.05 mK/W</td>
</tr>
<tr>
<td>0.5 m/s</td>
<td>0.07 mK/W</td>
</tr>
<tr>
<td>0.25 m/s</td>
<td>0.09 mK/W</td>
</tr>
<tr>
<td>0.1 m/s</td>
<td>0.15 mK/W</td>
</tr>
</tbody>
</table>
Pile Connections

- 1 No. 50m deep pile with 3 up and down loops
- 3 No. 25m deep piles with 2 up and down loops each

Assumes:
- Flow of 0.75m/s
- Pipe inner diameter of 28mm
- Fluid specific heat of 4200J/kgK
- Thermal resistance of 0.1mKW
Thermal Response Testing
Thermal Response Testing

- Data discarded prior to Fo=5:
  \[ t_{\text{min}} = 5 \frac{r_b^2}{\alpha} \]

- 300mm dia pile ~ 1.3 days
- 600mm dia pile ~ 5 days
- 1200mm dia pile ~ 21 days

- Standard TRT timescale = 60 hrs = 2.5 days
Temperature at edge of concrete

Temperature at pipes (neglecting $R_p$)
Temperature at pipes (neglecting $R_p$)
In reality?

- Few TRTs on piles done so far.
- Recent test by GIL of large diameter pile with central loops gave good results.
- Warning: measuring concrete properties not soil
- Warning: can not determine Rb in this case
Fieldwork
Field Monitoring

• Need to quantify real behaviour

• Instrumentation of a site in East London

• Always looking for more site opportunities
Initial Data
Conclusions & Recommendations

- Care with respect to irregular pile layouts.

- Important to consider larger diameter of piles, especially for small time-step behaviour. A solid cylinder model may be most appropriate.

- Short piles mean an appropriate surface boundary condition is important.

- Probably larger thermal resistance, but also higher range of values.

- A transient model of concrete and ground may be most appropriate for large diameter piles.

- Connecting piles together can lead to temperature and heat flux variations in the pile group.
Conclusions & Recommendations

• Thermal Response Testing:
  – Small diameter piles, standard test ok
  – Large diameter CFA piles, measure concrete properties, but NOT Rb
  – Large diameter piles with pipes at edge, not appropriate (without long timescales)
  – Tests on boreholes during site investigation

• Most design currently conservative due to some of these uncertainties:
  – Scope for improving efficiency in the future