QUANTIFYING GROUND WATER EFFECTS ON HEAT TRANSPORT AROUND A BOREHOLE HEAT EXCHANGER

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SOME BACKGROUND

• Ground Source Heat Pumps are among the most energy efficient heating and cooling systems available
• Testing is needed to establish the critical soil thermal parameters, for borehole heat exchanger system design
• GRT developed in the 90’s in Sweden, USA and the Netherlands
  – Sweden & USA: using electrical heater element (Type I test)
  – Netherlands: using reversible heat pump (Type II test)
• Principle of ‘Classical Test’ is to apply constant energy forcing and estimate conductivity from Temperature - Time relationship

• New test protocol
• Results experiment with forced groundwater flow
THE GRT MACHINE

• Built into a rugged container with full telemetry

Power range: -5 kW to +5 kW
Temperature range: -5 to 45 °C
Flow rate range: 0.3 - 3 m³ / hour
Accuracy:
  sensor error: ± 0.1 K (ΔT) 0.2% (flow rate)
  experiment error: ± 2 - 5% of Q selected
THE CLASSICAL ANALYSIS METHOD

- With constant energy-pulse, use the line source method

Lord Kelvin’s Line Source Theory

\[
T_f = \frac{-q_v \rho c (T_{out} - T_{in})}{4\pi \lambda H} \left[ \ln \left( \frac{4at}{r_0^2} \right) - \gamma \right] + \frac{q_v \rho c (T_{out} - T_{in}) R_b}{H} + T_g
\]

\[
\lambda = \frac{-q_v \rho c (T_{out} - T_{in})}{4\pi H k}
\]

\[t \geq \frac{5r_0^2}{a}\]
LIMITATIONS OF CURRENT TEST

Assumptions (line source method):
- Energy rate needs to be constant
- Soil thermal conductivity considered homogeneous
- Soil temperature considered homogeneous
- Only heat transport mechanism considered is conduction

! THESE ARE NOT NECESSARILY TRUE!

Furthermore
When conditions are unknown, difficult to select optimal test conditions:
1. High energy flux (large $\Delta T$) = higher accuracy
2. Test duration: when $\lambda$ low: quick saturation
HEAT TRANSFER BHE

- **Local process**
  - Fluid properties
  - Flow conditions
  - BHE construction, backfill
  - Convection (T-dependent)

- **Global process**
  - Properties layers
  - Anisotropy
  - Ground water flow
  - Ground temperature
• Using the line source analysis, ground water advection can be recognized, but not quantified
• Especially examining the constancy of the regression is usefull

Witte, 2001: European workshop about Geothermal Response Tests, EPFL, Lausanne, 2001
NEW PROTOCOL: MPL-HCP

- Using heating and cooling pulses, at different energy levels
  - Improve accuracy
  - Retrieve more information
    - Ground water flow (advection)
    - Temperature gradient
    - Convection
  - Ground water effects are temperature dependent

- Estimate based on parameter estimate
  - Started using DST (NATO – TESSEC, 2005)
  - Now using SBM

- Results of Enhanced Groundwater Flow Experiment

![Graph showing fluid temperature change over time](image-url)
NEW PROTOCOL: MPL-HCP

Pulse 1: Line Source

Pulse 2: Increase Accuracy

Recovery

Pulse 3: Invert Energy Flux

Time (hr)

Fluid Temperature (°C)
NEW PROTOCOL: MPL-HCP

- Of interest are the differences between the pulses
  - Conductivity pulse 1 <-> pulse 2: advection & convection
  - Conductivity pulse 1, pulse 2 <-> pulse 3: convection, T-gradient ground

- Calibration with TRNSYS - SBM, adapted to allow different $\lambda$ during different pulses
NEW PROTOCOL: MPL-HCP

- Sensitivity analysis shows calibration procedure finds global minimum of parameter combinations
**EXPERIMENT SETUP**

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- **Clays, peat and fine silty sand**
  - (clay fraction < 2 micrometer 15%)

- **medium sands**
  - (125-250 micrometer)

- **fine sands**

- **medium to coarse sands**
  - (125-500 micrometer)

- **aquifer continues to 60 meters depth**

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**TEST RIG**

- **3 m³/hour**

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**GEOTHERMAL RESPONSE TESTS WITH MULTI-POWER LEVEL HEATING AND COOLING PULSES (MPL-HCP)**

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## EXPERIMENT

### Experiment

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Pulse duration (hour)</th>
<th>Flow rate (m³/hour)</th>
<th>AT (K)</th>
<th>Energy Recovered (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF - PULSE 1</td>
<td>0.24</td>
<td>0.71 ±0.0074</td>
<td>2.04 ±0.195</td>
<td>1602 ±104.5</td>
</tr>
<tr>
<td>REF - PULSE 2</td>
<td>0.47</td>
<td>0.72 ±0.0053</td>
<td>3.02 ±0.145</td>
<td>2466 ±119.4</td>
</tr>
<tr>
<td>REF - RECOVERY</td>
<td>0.71</td>
<td>0.70 ±0.0124</td>
<td>0.36 ±0.125</td>
<td>4.3 ±23.72</td>
</tr>
<tr>
<td>REF - PULSE 3</td>
<td>0.93</td>
<td>0.70 ±0.0066</td>
<td>-4.51 ±0.113</td>
<td>-1947 ±173.65</td>
</tr>
<tr>
<td>GW - PULSE 1</td>
<td>0.24</td>
<td>0.69 ±0.0061</td>
<td>2.09 ±0.144</td>
<td>1606 ±108.8</td>
</tr>
<tr>
<td>GW - PULSE 2</td>
<td>0.48</td>
<td>0.68 ±0.0066</td>
<td>2.29 ±0.084</td>
<td>2477 ±157.2</td>
</tr>
<tr>
<td>GW - RECOVERY</td>
<td>0.82</td>
<td>0.68 ±0.0151</td>
<td>0.02 ±0.092</td>
<td>11 ±70.05</td>
</tr>
<tr>
<td>GW - PULSE 3</td>
<td>0.95</td>
<td>0.70 ±0.0067</td>
<td>-4.22 ±0.117</td>
<td>-1935 ±191.52</td>
</tr>
</tbody>
</table>
## Calibration Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Pulse duration (hours)</th>
<th>Soil conductivity (W/mK)</th>
<th>Boreshole Resistance (K/(W.m))</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>5 - 95</td>
<td>2.09</td>
<td>0.086</td>
<td>14.75</td>
</tr>
<tr>
<td>REF - Pulse 1</td>
<td>5 - 23</td>
<td>2.11</td>
<td>0.148</td>
<td>0.264</td>
</tr>
<tr>
<td>REF - Pulse 2</td>
<td>27 - 47</td>
<td>2.01</td>
<td>0.126</td>
<td>0.384</td>
</tr>
<tr>
<td>REF - Pulse 3</td>
<td>55 - 95</td>
<td>2.18</td>
<td>0.038</td>
<td>1.428</td>
</tr>
<tr>
<td>GW Extraction</td>
<td>5 - 95</td>
<td>2.31</td>
<td>0.09</td>
<td>15.8</td>
</tr>
<tr>
<td>GW - Pulse 1</td>
<td>5 - 23</td>
<td>2.03</td>
<td>0.146</td>
<td>0.299</td>
</tr>
<tr>
<td>GW - Pulse 2</td>
<td>27 - 47</td>
<td>2.22</td>
<td>0.130</td>
<td>0.321</td>
</tr>
<tr>
<td>GW - Pulse 3</td>
<td>55 - 95</td>
<td>2.32</td>
<td>0.045</td>
<td>1.54</td>
</tr>
</tbody>
</table>
Dividing the pulses further in early and later times

- Plot estimate of conductivity with respect to difference fluid - undisturbed ground temperature
Geothermal response tests with multi-power level heating and cooling pulses (MPL-HCP)

Reference: Groundwater

Estimated borehole resistance (K/W/m)

Difference with T-ground (K)
CONCLUSIONS

- MPL-HCP test reduces uncertainty concerning quick saturation and enhances accuracy of the measurement
- Using parameter estimation several important parameters can be estimated concurrently ($\lambda$, $R_b$ or $B_{\text{topol}}$, $T$,..)
- **MPL-HCP and groundwater flow: different effective $\lambda$ found**
  - Effect of gw flow should increase as temperature difference increases, the different estimates of $\lambda$ therefore quantify the effect of groundwater flow. The ‘true’ $\lambda$ is found for the pulse with small difference between fluid temperature and groundwater temperature
- **MPL-HCP and convection**
  - Convection should be stronger at higher temperatures, and weaker at lower temperatures, affecting $R_b$
- **MPL-HCP and temperature gradient**
  - With heating / cooling, effect is expected to be inverted (Signorelli et al, 2004)
FURTHER WORK

- Repeating experiment with order of pulses inverted
- Augmenting experimental data with further numerical models:
  - Simulating different groundwater flows with MPL-HCP GRT
  - Simulating thermal gradient (surface & deep) with MPL-HCP GRT
  - Investigating optimal temperature levels
  - Investigating optimal pulse duration
  - Developing nomograms for effective ground water advection rates from MPL-HCP GRT conductivity estimates
  - Comparing different models with reference dataset
    - DST
    - SBM
    - Yavuzturk
    - Gehlin & Hellstrom
    - ...

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