Ground properties evaluation for the design of geothermal heat pump systems and uncertainty measurement during the Thermal Response Test

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Geothermal Energy
Geothermal Energy (Low Enthalpy)

Ground offers favorable and constant temperature throughout the year.

\[
COP_{\text{max}} = \frac{T_H}{T_H - T_C}
\]
Geothermal Energy (Low Enthalpy)

GSHPs allow COP value to be high (COP > 4)

Ground thermophysical properties have to be estimated accurately.
<table>
<thead>
<tr>
<th>Country</th>
<th>Number of GSHPs Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italy</td>
<td>12,357</td>
</tr>
<tr>
<td>Germany</td>
<td>205,150</td>
</tr>
<tr>
<td>Sweden</td>
<td>378,311</td>
</tr>
<tr>
<td>Total (EU)</td>
<td>1,014,436</td>
</tr>
</tbody>
</table>

**Source:**
www.eurobserv-er.org
Ground Response Models
Hypothesis:

1D Conduction
Constant heat transfer rate
Constant thermophysical properties
Homogeneous medium
No underground water flow

1D Analytical Solutions

\[ T(r = r_b, \tau) - T_{gr,\infty} = \frac{\dot{Q}'}{Ck_{gr}} \Gamma(Fo) \]

\[ Fo = \frac{\alpha t}{r^2} \]
Ground Response Models II

**Infinite Cylindrical Source (ICS)**

\[
\Delta T = \frac{Q'}{k} G(F_0, p) \\
p = \frac{r}{r_0}
\]

\[
G(F_0, p) = \frac{1}{\pi^2} \int_0^\infty \frac{\exp(-F_0 \cdot \beta^2) - 1}{J_1^2(\beta) + Y_1^2(\beta)} [J_0(p\beta)Y_1(\beta) - J_1(\beta)Y_0(p\beta)] \frac{1}{\beta^2} d\beta
\]

**Infinite Linear Source (ILS)**

\[
\Delta T = T_r - T_\infty = \frac{\dot{Q}'}{4\pi k} \cdot E(X) \\
X = \frac{1}{4 \cdot F_0}
\]

\[E(X) = \text{Exponential Integral}\]

Approximated solution
(Abramowitz e Stegun)
For periods between a few hours to one year, ILS model is suitable to describe the ground response to heat load pulses.

M. Bernier (2009)

M. Fossa (2009)
Thermal Response Test
Thermal Response Test I

**Base principle:** constant heat rate injection into the ground through hot fluid circulation

**TRT apparatus**

Components

- Heater
- Temperature sensors
- Circulation pump
- Flow meter
- Data logger
Thermal Response Test II

ILS solution allows the fluid temperature evolution to be predicted and the corresponding ground thermal conductivity $k$ and borehole resistance $R_{bhe}$ to be estimated.

\[
T_f(t) = \frac{\dot{Q}'}{4\pi k} \left( \ln \left( \frac{4\alpha t}{r_b^2} \right) - \gamma \right) + \\
+ \dot{Q}' \cdot R_b + T_{g,\infty}
\]

\[
\Delta T_f = S \ln(t) + p
\]
Thermal Response Test III

Under constant heat flux assumption, ILS solution suggests a log correlation between temperature and time. Conductivity is hence estimated from temperature profile slope.

\[ \Delta T_f = S \ln(t) + p \]

\[ k = \frac{\dot{Q}'}{4\pi S} \]

\[ R_{bhe} = \frac{1}{\dot{Q}} (T_f - T_g) - \frac{1}{4 \cdot \pi \cdot K} \cdot \left( \ln(t) + \ln \left( \frac{4\alpha}{r^2} \right) - \gamma \right) \]
Thermal Response Test IV

In situ test first developed in Sweden (Mogensen 1983) and widespread diffused today for GCHP plant design

Lack of standards about:

- Apparatus characteristics
- Test duration
- Undisturbed ground temperature measurement
- Data analysis

Uncertainty estimation

\[ k = k \pm ? \quad [W/(m K)] \]

\[ R_{bhe} = R_{bhe} \pm ? \quad [(m K)/W] \]
TRT: Sensitivity Analysis I

\[ k = \frac{Q \pm \delta Q}{4\pi(H \pm \delta H)(S \pm \delta S)} \]

\[ R_b = \frac{H \pm \delta H}{Q \pm \delta Q} \left( T_m - (T_{ind} \pm \delta T_{ind}) \right) - \frac{1}{4\pi(k \pm \delta k)} \left[ \ln(t) + \ln\left( \frac{4(k \pm \delta k)}{(\rho c \pm \delta \rho c)r^2} \right) - \gamma \right] \]

| \(\delta Q\) | 1.96\(\sigma(Q)\) |
| \(\delta H\) | 0.5 m |
| \(\delta T_{ind}\) | 0.5°C |
| \(\delta \rho\) | \(\rho \pm 0.2\rho\) |
| \(\delta c\) | \(c \pm 0.2c\) |
| \(\delta k\) | “calculated” |

Heat flux variation reveals to be the main source of uncertainty under standard ILS approach. Methods able to cope with variable heat transfer rates are advisable.
Measurement uncertainties: variable heat transfer rate situations

External temperature influences measured inlet and outlet fluid temperature.

**Determination of the external temperature effect on k and $R_b$ evaluations is needed.**
Variable heat transfer rate possible cases

Notice: Power failure under standard ILS analysis requires a new test in a different BHE.
Superposition of basic solutions in time

Temporal superposition is here applied to obtain the fluid temperature as a function of time as the result of N different thermal pulses, describing the real TRT thermal history.

\[ T_{r=rb}(\tau) - T_{gr,\infty} = \sum_{i=1}^{N} \frac{Q_i'}{ck_{gr}} \Gamma(\tau_N - \tau_{i-1}) \]
Variable heat transfer rate: results

Voltage drop effect

Power failure

Custom heat flux variation
Superposition applied to real TRT measurements I

Real TRT heat transfer rate measurement.

Results with proposed temporal superposition method.
The superposition method allows the fluid temperature evolution to be estimated, even in case of variable heat transfer rate.

Calculated and measured data are fit through optimum search on ground conductivity value, which is hence estimated without any hypothesis on constant heat flux.
Conclusions

*Thermal Response Test* is a widely used method for estimating the ground and borehole thermal properties.

Uncertainties evaluation reveals that heat transfer rates variations (not included in standard ILS approach) are the most important source of error in ground parameter estimation.

A novel procedure has been implemented in order to take into account non constant heat transfers to the ground.

The procedure, to be further developed and coupled with proper optimization algorithms, seems to be a promising technique for improving the TRT accuracy and controlling disturbances that typically happen during real TRT sessions.
THANK YOU!