Advanced Thermal Response Testing and Its Relevance to Complex UTES Arrays

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Borehole heat exchanger
CLOSED LOOP
BOREHOLE HEAT EXCHANGERS
Closed Loop
Vertical BHE Insertion
Single U-pipe BHE
Multipipe coaxial type
Basic types of borehole heat exchangers

U-tube

Coaxial
Ground-source heat pump operating conditions

Heat extraction rate
40 W/m

Typical operating conditions in central Sweden

Borehole wall
+2.5

Undisturbed ground
+8.5
Ground-source heat pump operating conditions

40% of temperature difference between heat carrier fluid and surrounding ground within the borehole

Undisturbed ground

Borehole wall

+2.5

-3

0

+8.5
Ground-source heat pump operating conditions

40% of temperature difference between heat carrier fluid and surrounding ground within the borehole

TRT used to measure performance of borehole heat exchangers

Borehole wall

Undisturbed ground
Ground-source heat pump operating conditions

40% of temperature difference between heat carrier fluid and surrounding ground within the borehole

TRT used to measure performance of borehole heat exchangers

Borehole wall

Thermal conductivity of ground

Undisturbed ground
Ground-source heat pump operating conditions

40% of temperature difference between heat carrier fluid and surrounding ground within the borehole.

TRT used to measure performance of borehole heat exchangers.

Borehole wall: +2.5

Undisturbed ground: +8.5

Thermal conductivity of ground
<table>
<thead>
<tr>
<th>Location</th>
<th>Material</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany, several</td>
<td>Bentonite</td>
<td>0.10-0.13</td>
</tr>
<tr>
<td>Germany, several</td>
<td>Thermal grout</td>
<td>0.06-0.08</td>
</tr>
<tr>
<td>USA, several</td>
<td>Bentonite</td>
<td>0.13-0.15</td>
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<tr>
<td>USA, several</td>
<td>Thermal grout</td>
<td>0.09-0.10</td>
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<tr>
<td>Sweden, several</td>
<td>Water, heating</td>
<td>0.06-0.08</td>
</tr>
<tr>
<td>Studsvik</td>
<td>Ice</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Field measurements of borehole thermal resistance
UNDERGROUND THERMAL ENERGY STORAGE
BTES - Luleå

Borehole heat store: 120 boreholes depth 65 m
Measured temperature in center of store
Measured and simulated energy balance 1983-1988

BTES - Luleå

Measured and simulated energy balance 1983-1988
Estimated ground temperature after charging

Heat losses proportional to the thermal conductivity of ground
Estimated ground temperature after charging

Heat losses proportional to thermal conductivity of ground

(Influence of groundwater flow)
THERMAL PROCESSES
What is the relation between fluid temperatures and heat transfer rates for a specific borehole exchanger design?
Method of analysis

Common approach:
- Determine a thermal response function!

Two basic parts:
- Response of the thermal process in the borehole
- Response of the thermal process in the ground surrounding borehole
Temperature change when constant heat injection rate is supplied
(Similar to thermal response test)
Thermal response

Superpositioning of response functions
Thermal response

Superpositioning of response functions
Superpositioning of response functions

Thermal response

Fluid temperature

Time
Thermal response

Superpositioning of response functions
Thermal response

Superpositioning of response functions
Character of heat transfer process

Short term

Transient radial heat conduction

Long term

Steady-state heat conduction
Numerical methods

Example of numeric grid (Chiasson)
Simulation models

**SBM – Superposition Borehole Model**

- homogeneous ground properties
- borehole heat exchanger (depth, material, filling material)
- arbitrary placement of boreholes (vertical or graded)
- Validated against field experiments

**Results:**

- fluid temperature variation
- temperature in the ground
- energy balance
Design tool

**EED – Earth Energy Designer**

- easy and fast to use (GUI)
- ground properties
- borehole heat exchanger (type, depth, material, filling material)
- 800 predefined borehole configurations
- heat carrier fluid

*The model provides databases for the input data and also relies on a database of pre-calculated response functions*

**Results:** fluid temperature variation and required borehole length
Non-dimensional response functions

Non-dimensional thermal response function – so-called g-functions
THERMAL RESPONSE TEST
Thermal Response Testing (TRT)
Brief history of Thermal Response Testing

- 1975, Gothenburg: GSHP in clay
- 1981, Luleå: 19 borehole pilot trial BTES installation
- 1983, Stockholm: GSHP in rock
- 1984, Luleå: 120 borehole high-temperature BTES installation
- 1986, Stockholm: 25 borehole low-temperature BTES
- 1992, Linköping: 100 U-pipes high-temperature heat storage in clay

These TRT tests were performed after the installations were already completed to verify ground loop performance.

In order to influence the ground loop sizing it would be desirable to make an in-situ TRT before the detailed design.
Mobile thermal response test equipment

First mobile TRT rig (1996)
1996, Sweden: First mobile TRT in operation
1998, USA, Independent development
1997, Netherlands: Mobile TRT with heat pump
2008, Sweden: TRT with optic fibres
Thermal Response Testing (TRT) - Procedure

- **Test Procedure**
  - Minimum 3Hrs circulation without heating
  - Minimum 50hrs circulation with constant heat input
  - Optional 24hrs recovery with heater switched off

- **Data Logger**
  - Flow rate of carrier fluid (m³/s)
  - Heat input (kW)
  - Inflow temperature (°C) to BHE
  - Return temperature (°C) from BHE
  - Ambient air temperature (°C)
Thermal Response Testing (TRT)

Measured injection rate, heat carrier fluid temperatures and ambient temperature
Site investigation of heat transfer properties

- **Thermal response test (TRT)**
  - Estimates the effective thermal conductivity along the borehole
  - Estimates the thermal resistance between heat carrier fluid and borehole wall

- **Logging of vertical temperature profile in the borehole**

- **Geohydrological conditions**
  - Groundwater level
  - Permeable layers

- **Sampling of cuttings**
  - Analysis of mineral composition gives further information on thermal properties of the ground

- **Drilling conditions**
  - Soil depth, geological stratification, production capability
Thermal response test considerations

- Planning of drilling and TRT test
  - Allow 3-5 days between end of drilling and start of TRT test
  - Allow for initial period with only circulation (no heat input)
  - Test duration at least 50 hours
  - Avoid drilling activities in the vicinity
  - Measure vertical temperature profile before and after test

- Number of boreholes to test
  - For large projects sometimes several test boreholes drilled and number of TRT chosen depending on variability of geology

- Borehole heat exchanger depth and design
  - Should be similar to chosen design

- Heat injection rate and heat carrier flow rate
  - Should be similar to expected load conditions
Evaluation method

- Measured heat input
- Measured average fluid temperature
- Measured ambient air temperature

- Radial heat conduction in rock
- Line-source model
- Two node borehole model
  - Borehole heat capacity included
  - Heat carrier fluid capacity included

- Parameter fitting using Nelder-Mead minimization of quadratic error

- Results: Effective thermal conductivity and borehole thermal resistance
Experiences – equipment

Electric power from grid
- Easy to use
- Sometimes unreliable (power cuts, vandalism, etc)
- Some diurnal fluctuation

Electric power from generator
- Independent of grid (required at undeveloped sites)
- Stable power
- Needs refueling
- Heavy rigs difficult to handle outside paved areas
- Thermal insulation of flow path very important
- Full remote control practical
Experiences – evaluation

- Evaluation methods used:
  - Line-source method
  - Numerical parameter fitting method with radial heat conduction and heat capacity of fluid and grout

- Important to use the same model and parameters when applying the results to the design case

- Borehole thermal resistance may have to be modified from measured conditions due to changes in flow rate and temperature
Fitting procedure of measured and calculated fluid temperatures gives effective ground thermal conductivity and borehole thermal resistance.
Long-term thermal response test evaluation

Oskarshamn, Sweden
1996-07-05 --- 1996-08-10
870 hours

Borehole depth 161 m
Borehole diameter 135 mm
Undisturbed ground temperature 10.5°C
Single U-pipe

Measured fluid temperature
Air temperature
Calculated fluid temperature

Long-term test (35 days) in Sweden (1996)
Initial thermal response

Short-term response (residence time)

- Borehole outlet temperature
- Borehole inlet temperature

Start of heating

Residence time (400 seconds)
Thermal response test

Comparison of Borehole Heat Transfer for Five Grout and Pipe Configurations
Oklahoma State University T&F Building Loop Field

- 27% Bentonite Grout and Standard Pipe Installation
- 27% Bentonite Grout and Spacer Clips on Pipe (3.05 meters interval)
- 27% Bentonite Grout and Spacer Clips on Pipe (1.52 meters interval)
- Thermally Enhanced Grout and Standard Pipe Installation
- Thermally Enhanced Grout and Spacer Clips on Pipe (1.52 meters interval)

Fluid capacity
Thermal response test

Comparison of Borehole Heat Transfer for Five Grout and Pipe Configurations
Oklahoma State University T&F Building Loop Field

Fluid and grout thermal capacity
Undisturbed ground temperature

Temperature as function of borehole depth
Undisturbed ground temperature

Temperature as function of borehole depth
Temperature as function of borehole depth
The boreholes are located in the centre of Stockholm
Undisturbed ground temperature

Borehole 1 disturbed by groundwater flow
Temperature profile at different times

The evolution of the profiles indicate a zone with groundwater flow around 25 m depth.
Experiences – effective thermal conductivity

- About 150 measurements performed in Sweden
- About eight of those strongly affected by groundwater flow
  - Values influenced by vertical groundwater flow through borehole
  - At one location the system was changed from borehole heat extraction to groundwater-source heat pump after the TRT result
  - Warning – flow conditions may change with more boreholes in the vicinity
  - Nearby drilling activities disturbs the groundwater flow
- Effective thermal conductivities in the range 2.5-6.8 W/m,K
- Values influenced by vertical groundwater through borehole
Experiences – borehole thermal resistance

- Estimation of borehole thermal resistance requires good estimate of undisturbed ground temperature
- Groundwater-filled boreholes
  - Borehole thermal resistance depends on heat injection rate and temperature level
- Method to estimate borehole heat exchanger performance
  - Site-specific conditions may influence values (base reference values on measurements on several boreholes)
Experiences – undisturbed ground temperature

- Measure undisturbed vertical temperature profile
- Estimate undisturbed ground temperature based on initial period with only circulation of heat carrier fluid
- “Undisturbed” ground temperature profile may be disturbed by heat flow from buildings, paved areas and tunnels (and changes in local climate)
- Interpreting vertical variations in thermal conductivity by using the profile may be difficult
- Measuring vertical temperature profile before and after the TRT may indicate zones of groundwater flow and/or layers with differing thermal conductivity
THERMAL RESPONSE TEST
Groundwater-filled boreholes
Groundwater-filled boreholes

- Better heat transfer than grouted or sand-filled boreholes

- Water movement
  - Natural convection between pipes and borehole wall
  - Vertical flow in borehole

- Freezing of borehole water
Active borehole depth

Groundwater-filled part of the borehole
TRT with varying heat injection rates

<table>
<thead>
<tr>
<th>Case</th>
<th>Power [kW]</th>
<th>Dur [h]</th>
<th>( \lambda_e ) [W/m K]</th>
<th>( R_h ) [Km/W]</th>
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<td>M1</td>
<td>6</td>
<td>70</td>
<td>3.4</td>
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<td>Circulation pump</td>
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TRT measurements at Luleå

High injection rates and high temperatures give lower borehole thermal resistance due to natural convection within the borehole.

Ground-water filled boreholes
Simulations of natural convection in borehole

The water close to the pipes will rise during heat injection.

Water velocity depends on temperature (viscosity).

Heat injection rate 75 W/m

12 C results in maximum velocity of 0,006 m/s
24 C results in maximum velocity of 0,009 m/s
38 C results in maximum velocity of 0,011 m/s

Single U-pipe in groundwater-filled borehole

Cartesian coordinates \((x, y, z) = (0, 1.5, [-0.0518, 0.0518]) \) [m]
Thermosiphon effect

Vertical groundwater flow through borehole due to natural convection
Thermosiphon – heat injection
Thermosiphon – heat extraction
Groundwater flow between permeable layers with different hydrostatic pressure
Thermal response test and artesian flow

Thermal response influenced by groundwater flow
THERMAL RESPONSE TEST
Groundwater flow
Regional groundwater flow

Simulation of thermal process in low permeable layer
(Dähne and Kaiser, 2004)
Regional groundwater flow

Simulation of thermal process in high permeable layer
(Dähne and Kaiser, 2004)
Thermal response test and groundwater flow

Influence of groundwater flow (Witte, 2001)

Separation point where influence of groundwater flow can be seen
Thermal response test and groundwater flow

Separation at later time with lower groundwater flow

Influence of groundwater flow - simulation (Witte, 2001)
THERMAL RESPONSE TEST
Freezing boreholes
In 2004 a new TRT equipment was built at Luleå Technical University. It contains both an electric heater and a heat pump.

Övertorneå

162 m groundwater-filled borehole, single U-pipe

- 5 days heat injection 12 kW
- 7 days rest,
- 6 days heat extraction 7.3 kW

Results

\[ \lambda_e = 4.2 \, \text{W/m,K} \]

\[ R_{b1} = 0.066 \, \text{Km/W} \] (heat injection)

\[ R_{b2} = 0.094 \, \text{Km/W} \] (heat extraction, unfrozen)

\[ R_{b3} = 0.075 \, \text{Km/W} \] (heat extraction, frozen)
Thermal response test with freezing

Temperature decrease in heat carrier fluid with freezing borehole water
Thermal response test with freezing

Stockholm, 1983
Freezing of borehole water

Danger of squeezing the pipe

A survey in Sweden showed that incidence of pipe damage is very small (estimated to 1 in 5,000-10,000)
THERMAL RESPONSE TEST
Optic Fibre
TRT with optic fibre

TRT with optical fibre (DTRT)
Acuna, Hill, Mogensen, Palm (Royal Institute of Technology, Stockholm)
TRT with optic fibre

Borehole depth 260 m
Diameter 140 mm
Single U-pipe PE80 40 mm
Ethanol/water mixture (16%)
Flow rate 1.87 m³/h

Temperature profile and flow log
TRT with optic fibre

Vertical temperature profile before and during initial circulation of fluid

Average fluid temperatures during heating phase
Distributed Thermal Response Test - DTRT

Measurement of heat balance in sections
Distributed Thermal Response Test - DTRT

Power supplied in each section of the borehole
Distributed Thermal Response Test - DTRT

Fluid temperatures in each section during injection
(Borehole thermal resistance evaluated from this curve)
Distributed Thermal Response Test - DTRT

Fluid temperatures in each section during recovery
(Ground thermal conductivity evaluated from this curve)
Evaluated thermal conductivity and borehole thermal resistance in each section

Distributed Thermal Response Test - DTRT

DTRT results (average values)
- Ground thermal conductivity $\lambda_{\text{ground}} = 3.10 \, \text{W/m.K}$
- Borehole thermal resistance $R_b = 0.063 \, \text{K/(W/m)}$

TRT results
- Ground thermal conductivity $\lambda_{\text{ground}} = 3.08 \, \text{W/m.K}$
- Borehole thermal resistance $R_b = 0.079 \, \text{K/(W/m)}$

Undisturbed ground temperature
- Based on vertical profile $T_{\text{vertical}} = 9.10 \, \text{C}$
- Based on initial circulation $T_{\text{initial}} = 9.19 \, \text{C}$
  (Difference attributed to circulation pump work)
Borehole heat exchanger comparison

Four different designs tested
(3-pipe, U-pipe with and without spacer, U-pipe with internal turbulence promoter (fins))
Figure 8: Average temperatures along the borehole during the first month of operation

Single U-pipe: Vertical temperature profile in fluid

(Acuna et al, 2008)
Figure 8: Average temperatures along the borehole during the first month of operation.

Single U-pipe: Vertical temperature profile in fluid

(Acuna et al, 2008)
Current activities

- **Chalmers Technical University, Gothenburg**
  - Analytical and numerical modelling of short-term responses

- **Royal Institute of Technology, Stockholm**
  - Borehole heat exchangers – field measurements using optic fibre

- **Luleå Technical University**
  - Numerical simulations of groundwater filled borehole heat exchangers
Thermal response test

The thermal response test is an established standard procedure for large projects.
Thank you!