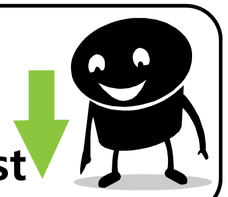
Outline of Thermal Response Test (TRT)

◆ 1 . Problems in TRT

Unknown Parameters and Information for GSHP Design

- Ground thermal conductivity
- Ground Initial temperature
- Ground Heat capacity
- Borehole thermal resistance
- Groundwater flow

Inverse Parameter Estimation via Thermal Response Test



Uncertainty in TRT

- TRT duration
- Experimental configuration

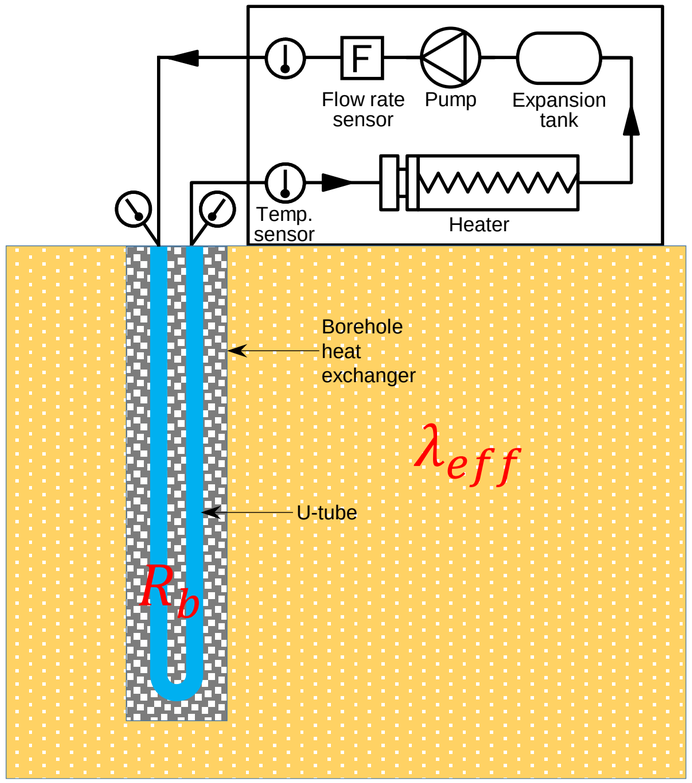
Disturbances

- Contextual disturbances
- Aboveground heat transfer

→Wrong design of GHE

- ✓ **Examine disturbances**
- ✓ **Propose solutions**
- ✓ **Suggest new guideline**

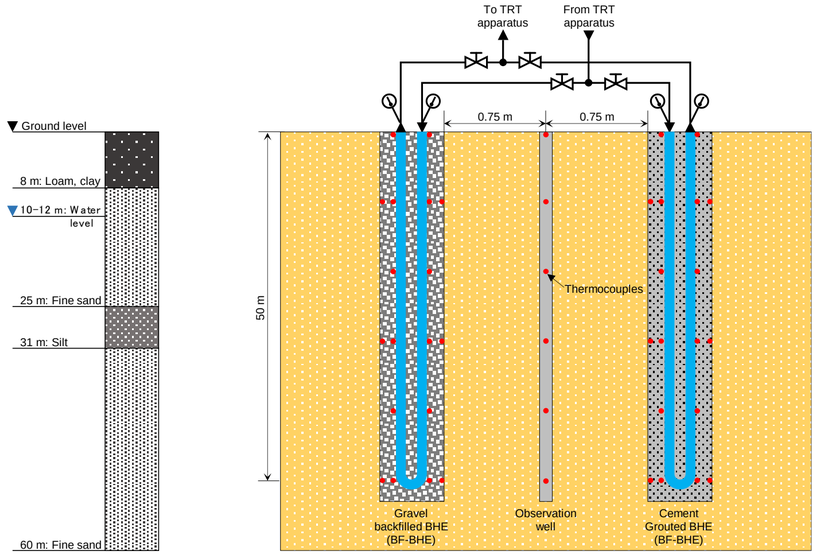
◆ 2 . What is TRT?



Schematic of TRT setup

TRTs are conducted to estimate the effective ground thermal conductivity and borehole thermal resistance which are needed to decide the required length of ground heat exchanger

◆ 3. Outline of experimental setup



(a) Drill log (b) Setup of two borehole heat exchangers

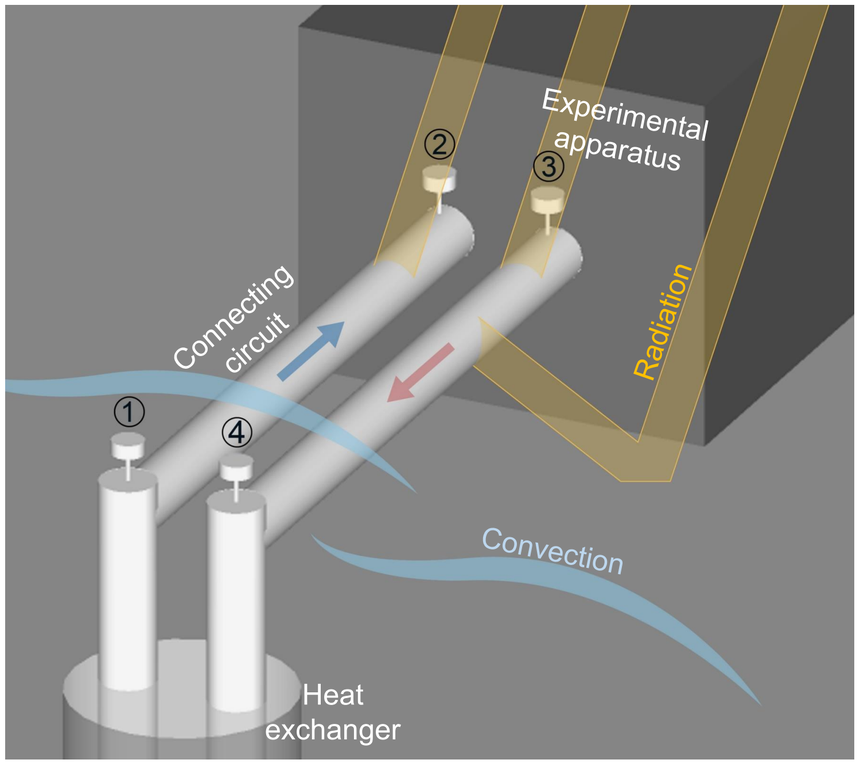
Schematic of ground heat exchangers and drill log of experimental site

Photo of experimental setup

Disturbance considered TRT estimation method

◆ 1 . Causes of error in TRT

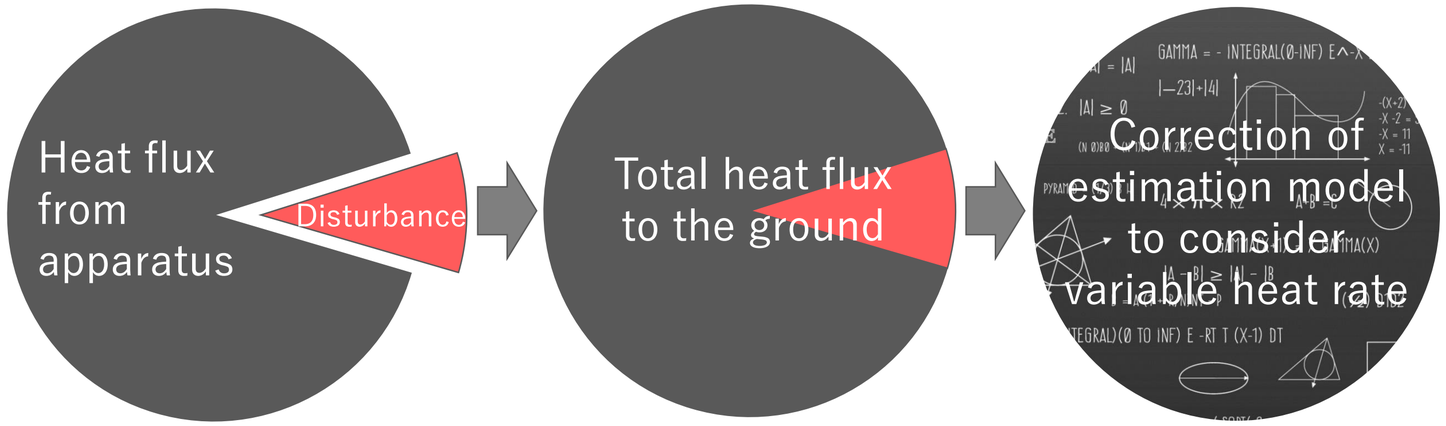
- Unstable voltage supplied to heaters in TRT apparatus
- Contextual disturbances: heat exchange between TRT setup and outdoor environment
- Inconsistency between the TRT and physical model for estimation



Heat exchange between aboveground TRT setup and outdoor environment (flow sequence 1→2→3→4)

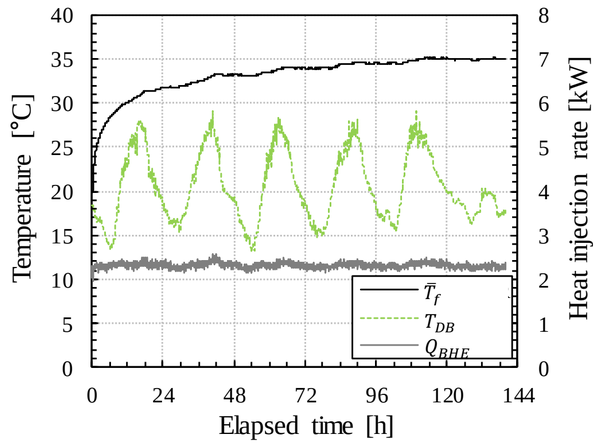
◆ 2 . Principle idea of developed estimation method

Fluctuating disturbed heat injection rate is known boundary condition. Thus, the disturbed portion is not a part to be removed: it is a part of the total heat injection rate.

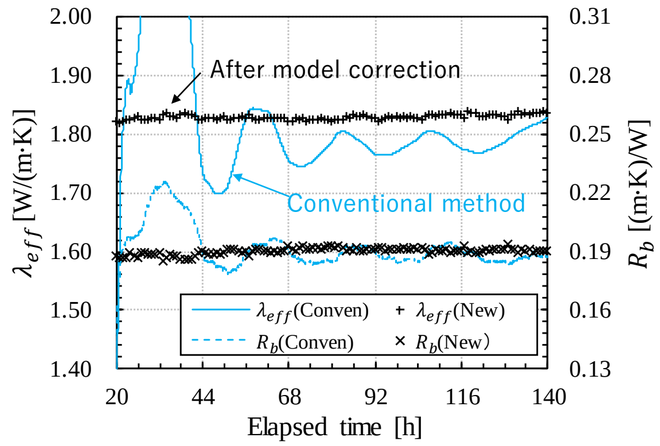


New idea to consider disturbed thermal response test data in parameter estimation

◆ 3 . Comparison between conventional and developed method



Disturbed thermal response test data



Comparison between conventional and new estimation methods

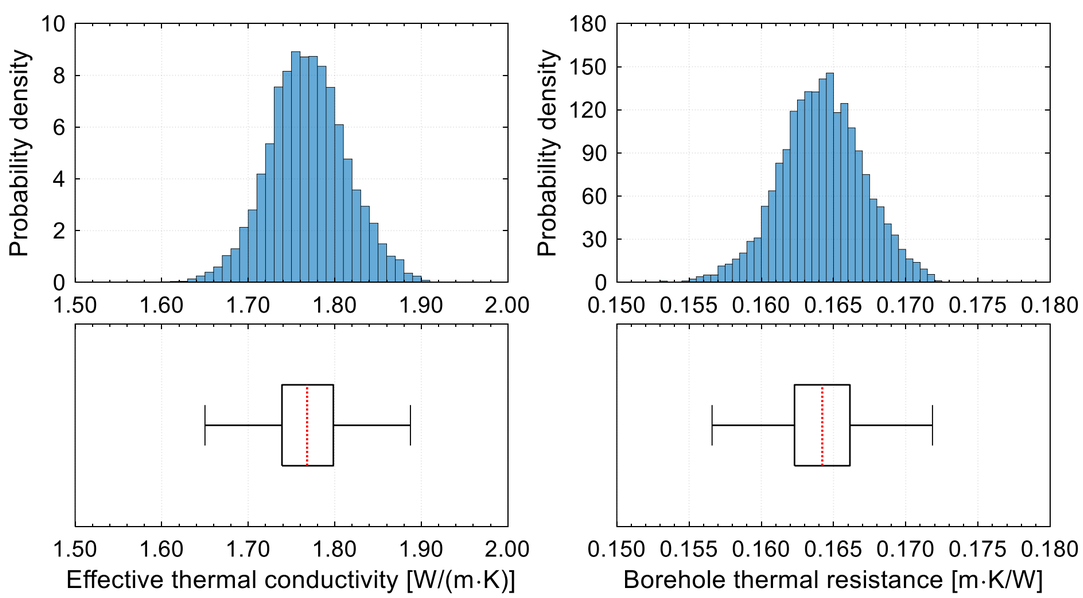
Development of Bayesian Inference for Thermal Response Test

◆ 1 . Bayes' theorem

$$\underbrace{P(\theta|d)}_{Posterior} \propto \underbrace{P(\theta)}_{Prior} \times \underbrace{P(d|\theta)}_{Likelihood}$$

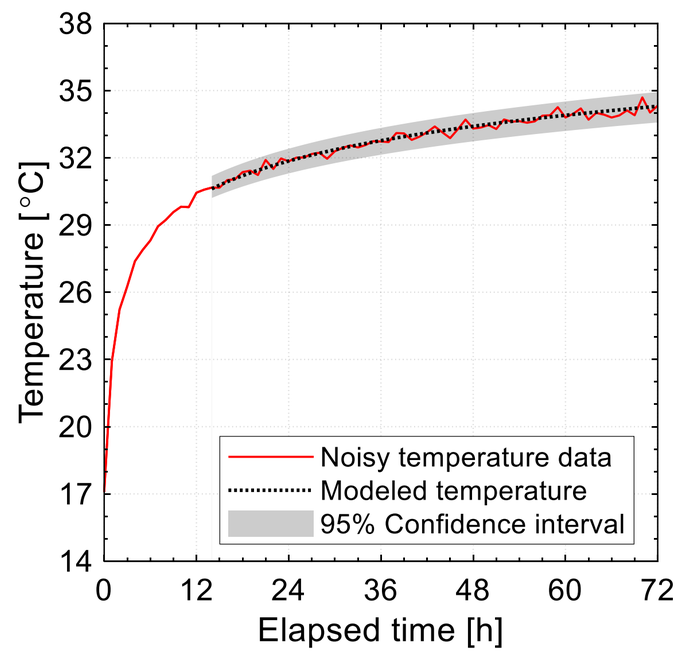
- Unknown parameter(θ) is handled as a probability distribution. Thus estimated results is also probability distribution (posterior)
- Prior：Expert's knowledge, experience, hunch, and available information are used in setting a prior distribution
- Likelihood：It is updated based on the data. Thus it is objective probability distribution

◆ 2 . Estimated probability

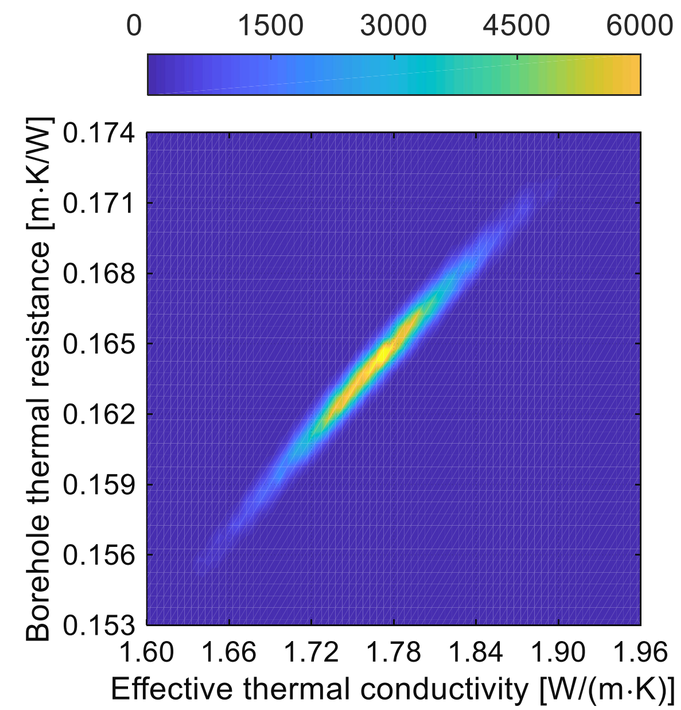


◆ 3 . Advantages of Bayesian inference

- Uncertainty caused by contextual disturbances during TRT (heat exchange between aboveground TRT setup and outdoor environment) can be evaluated by extracting statistical indices from posterior
- Credible intervals of unknown parameters and reliability of estimates can be evaluated
- By constructing a joint probability distribution, the correlation between two parameters can be confirmed



Measured temperature, modeled temperature, and uncertainty range using 95% credible intervals of estimates



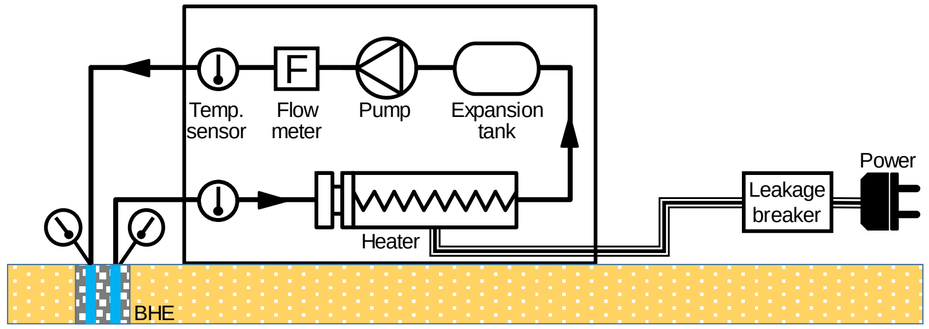
Joint probability distribution of GSHP design parameters

Development of Cost-effective Thermal Performance Test Apparatus

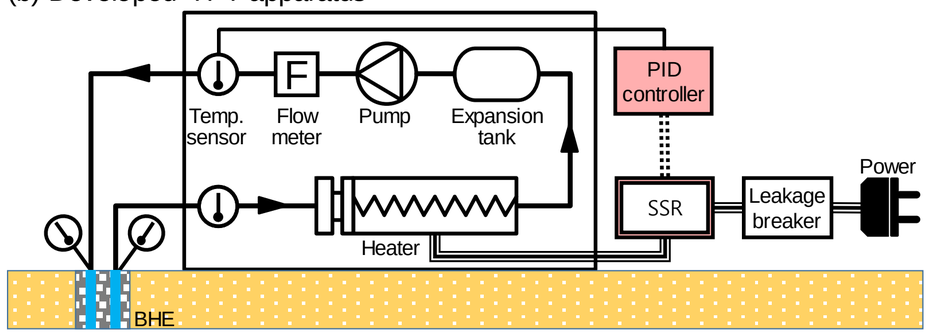
◆ 1 . Background of TRT

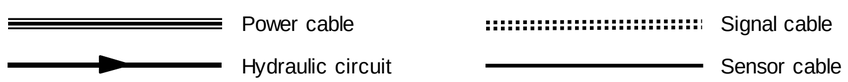
- Unlike TRT, thermal performance tests has a constant inlet temperature as the experimental boundary condition.
- Conventional TPT apparatus requires a massive hot water tank and complex control logic
- Proposed TPT apparatus just requires two additional control components compared to TRT apparatus: Solid state relay and PID controller

(a) General TRT apparatus



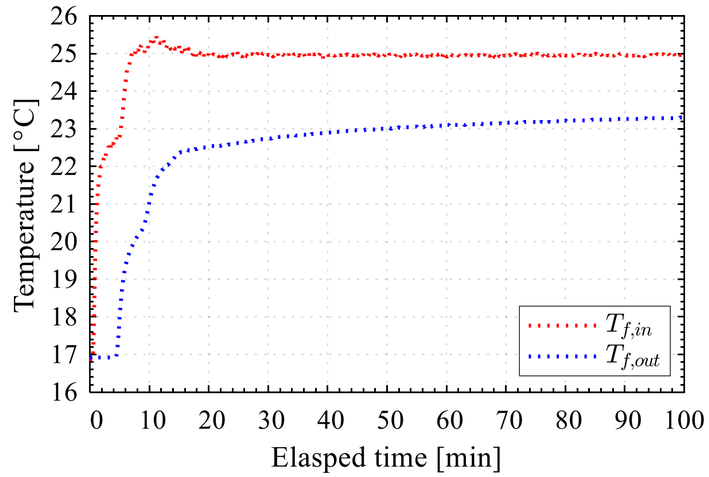
(b) Developed TPT apparatus



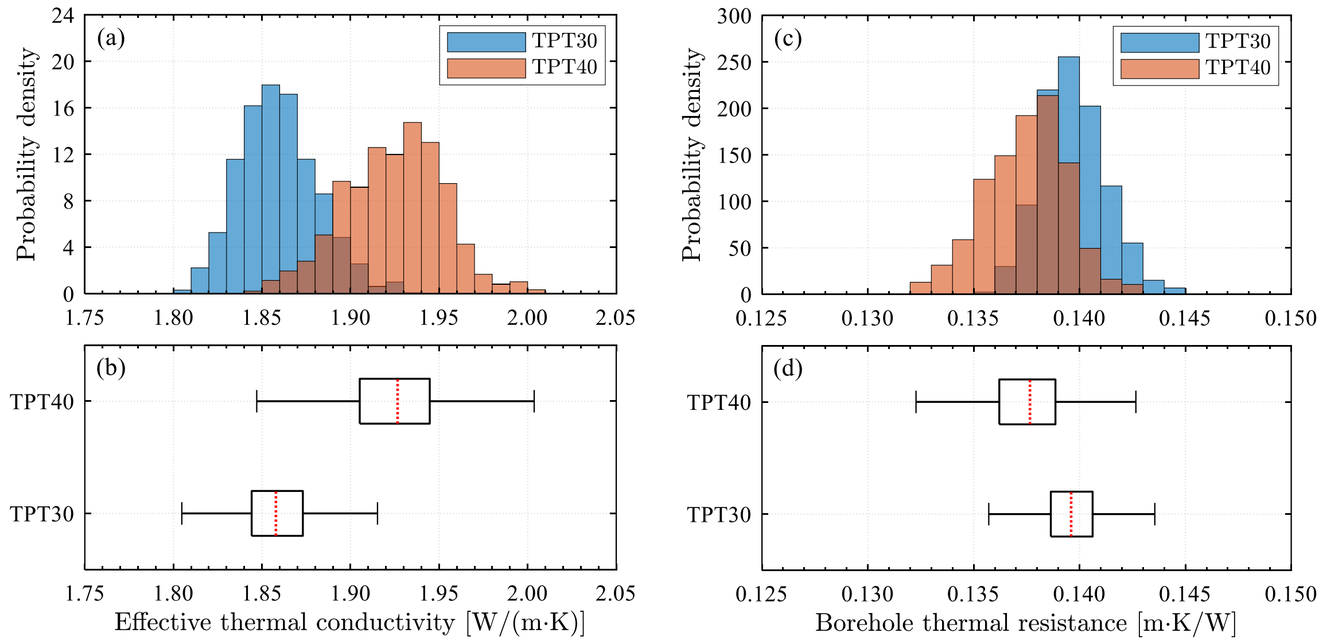


◆ 2 . Performance of developed TPT apparatus

- When inlet setpoint temperature was 25 °C, rise time from the initial ground temperature of 17 °C was approximately 7 min
- Overshoot after reaches the setpoint was just 0.44 °C
- After the elapsed time of 13 min, the control error was 0.2 °C and 1 h, it was less than 0.1 °C.



◆ 3 . Bayesian inference for two TPT datasets (inlet setpoint temperatures of 30 °C, 40 °C)



Bayesian inference of GSHP design parameters using two TPT datasets