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A novel oscillatory thermal response test for deep U-tube borehole heat exchanger : In situ data

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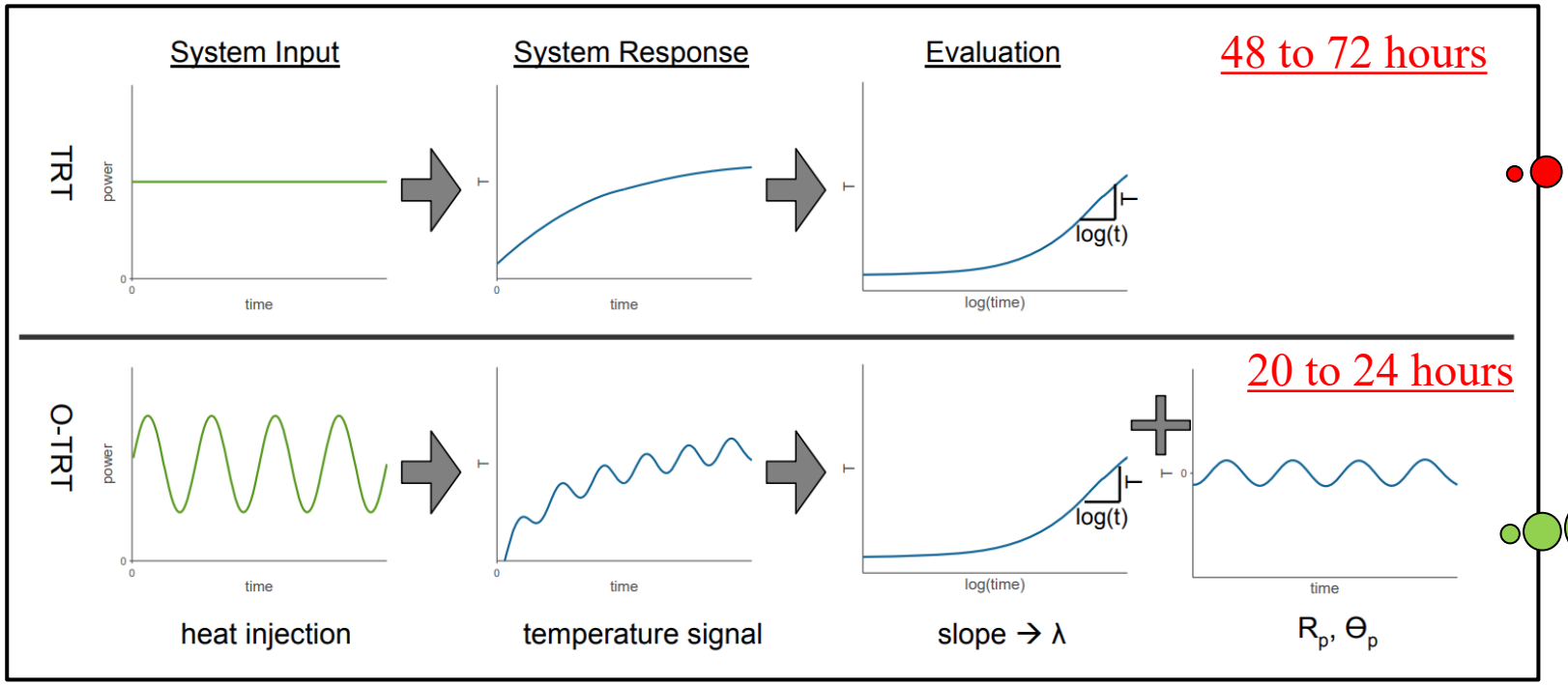
Background, motivation and objectives



1- Long TRT time
2- Hight test cost
3- High labor cost

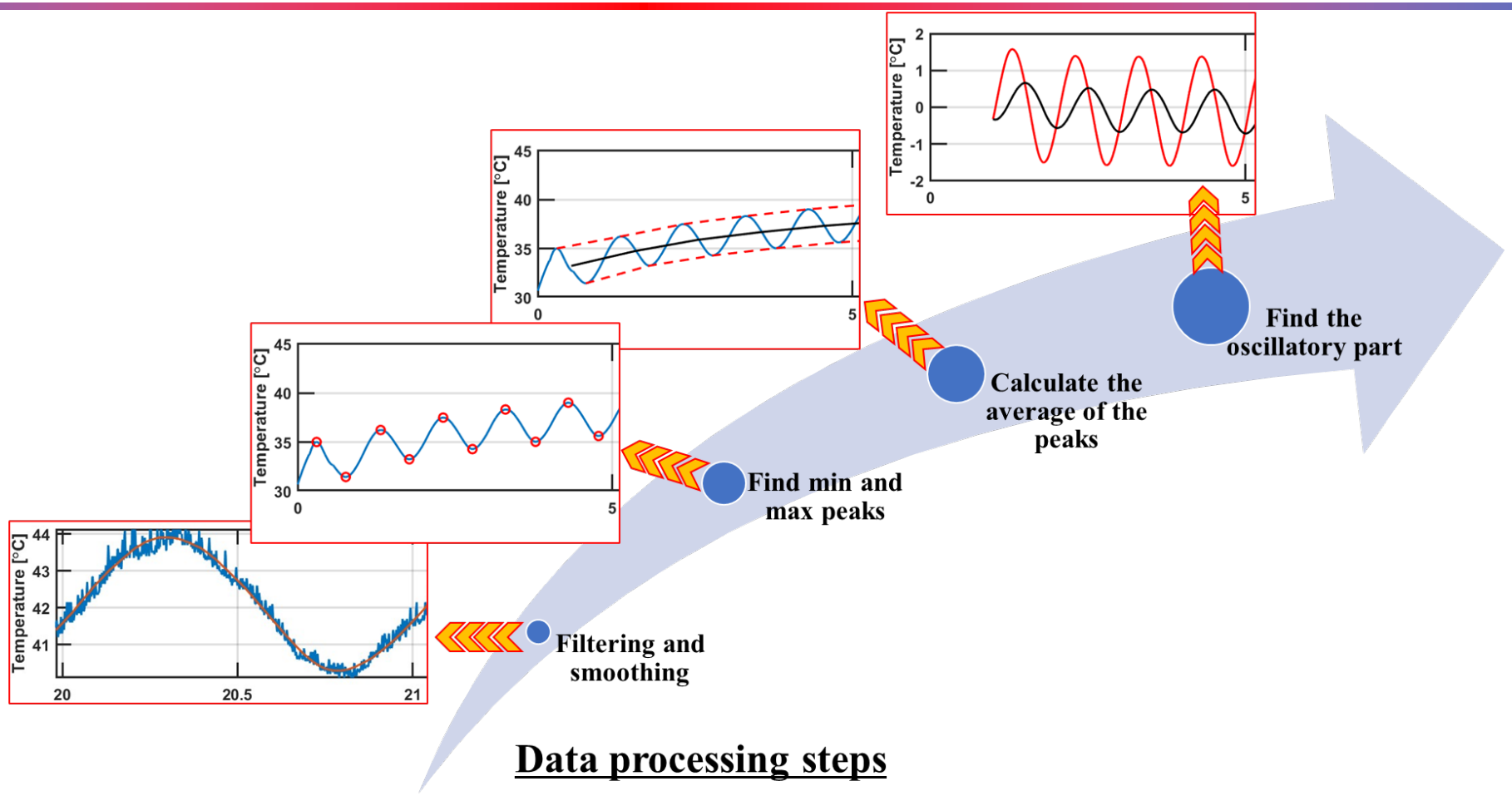
1- Short TRT time
2- Less test cost
3- Less labor cost

$$P(t) = P_0 + P_1.\sin(\omega_0 t), \qquad |P_0| > |P_1|$$

Where P_1 is the amplitude and ω_0 is the angular frequency. And P_0 is a constant heat rate

Analysis method:

1- Data Processing

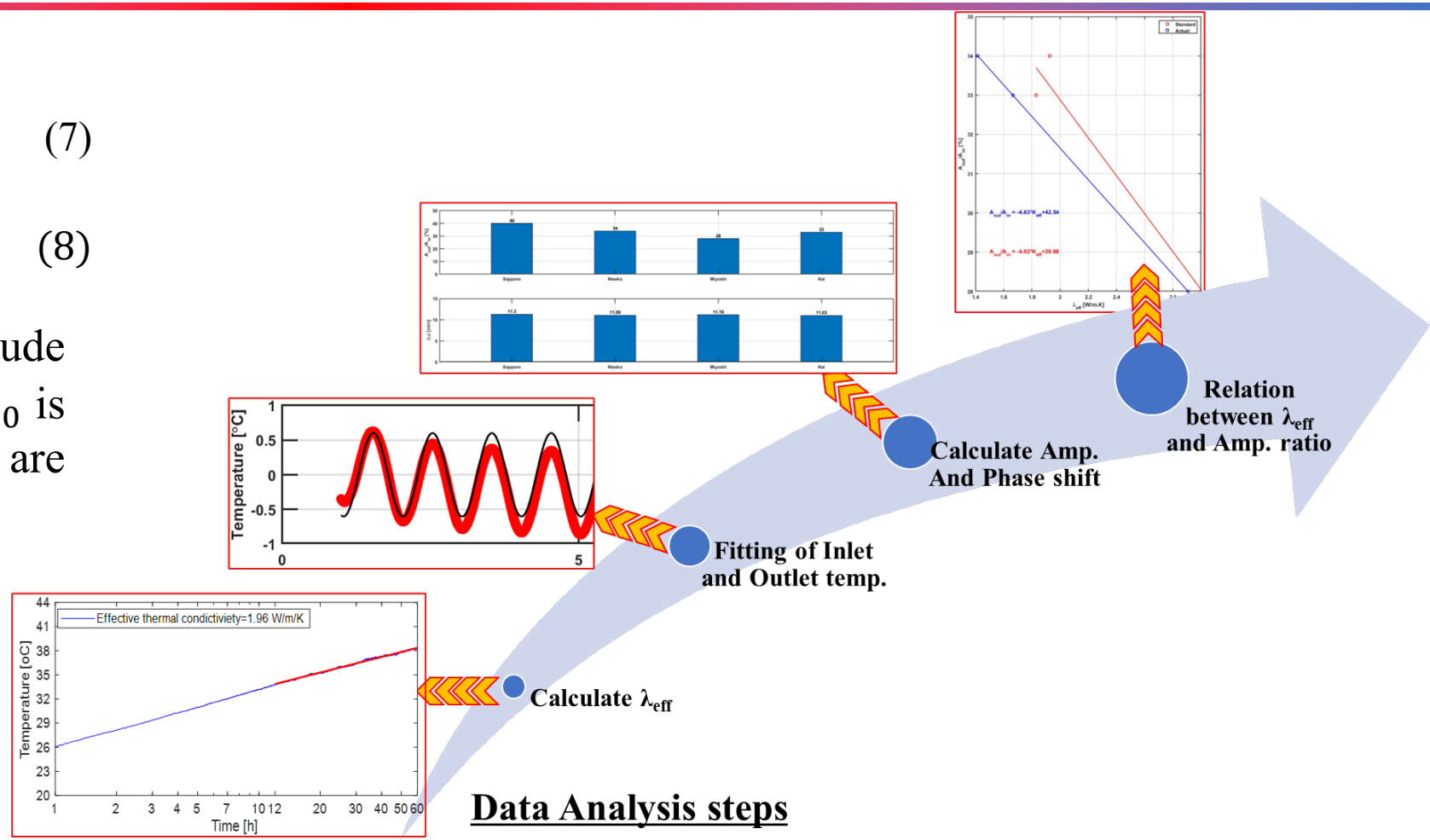


Analysis method:
- Data Analysis

$$T_{in}(t) = A_{\text{in},0}.\sin(\omega_0 t + \varphi_{in}) \quad (7)$$

$$T_{out}(t) = A_{\text{out},0}.\sin(\omega_0 t + \varphi_{out}) \quad (8)$$

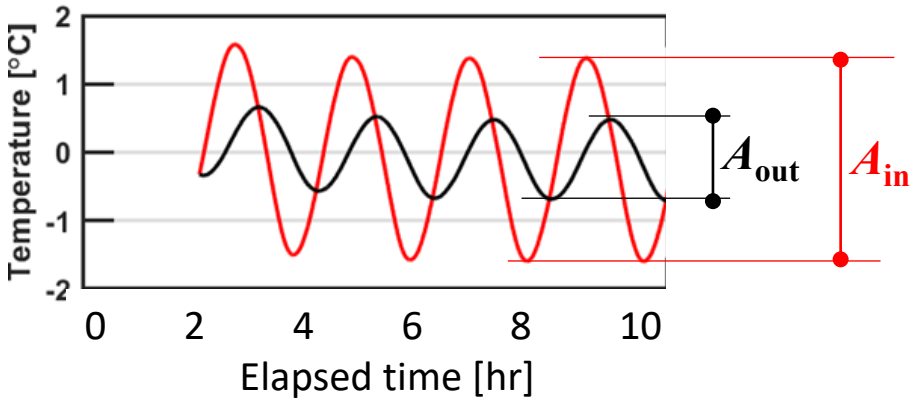
Where $A_{\text{in},0}$, and $A_{\text{out},0}$ are the amplitude of inlet and outlet temperatures (°C), ω_0 is the frequency (Hz), and φ_{in} , $and\ \varphi_{out}$ are the phase shift (sec).

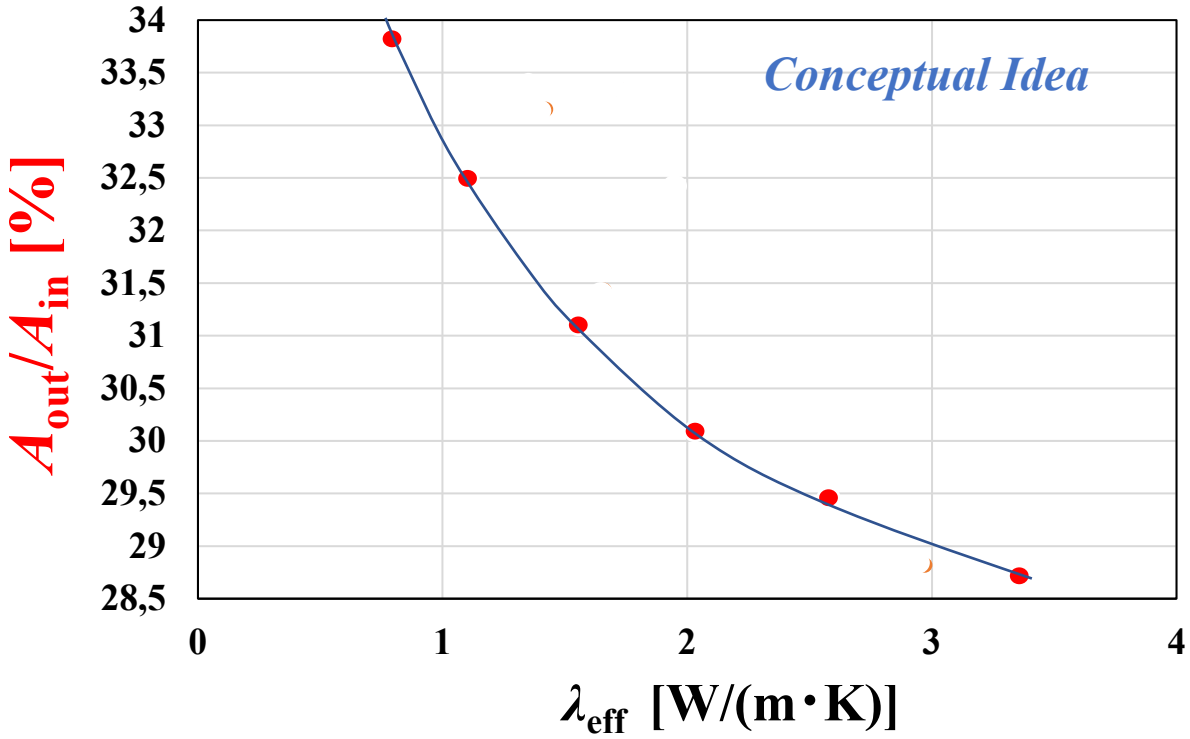


The relationship between the amplitude ratio of inlet and outlet temperatures A_{out}/A_{in} and the effective conductivity λ_{eff}

- In this study, the authors particularly focus on the relationship between the amplitude ratio, A_{out}/A_{in} and the effective thermal conductivity λ_{eff} measured by the standard TRT.

Amplitude ratio, A_{out}/A_{in}

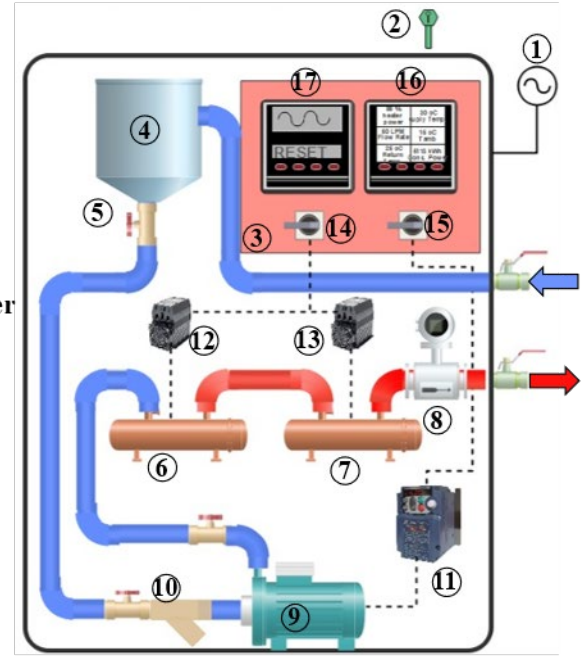




Field test set-up:

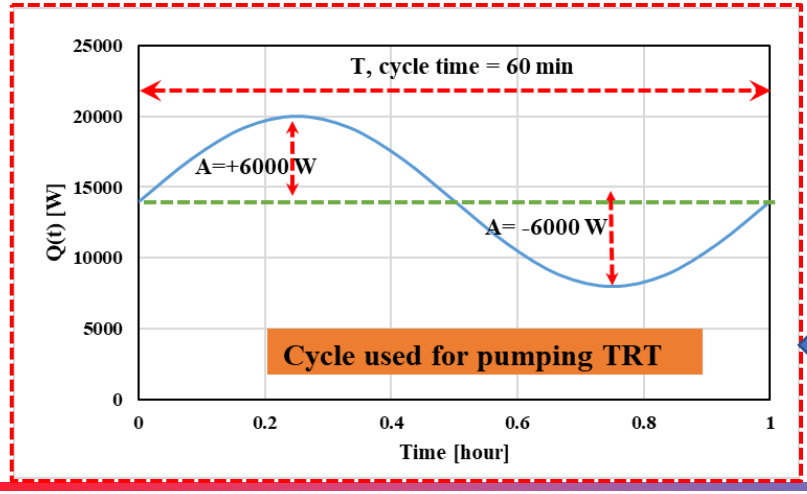
2- OTRT Machine

① 220 V AC supply
② Ambient air temp. sensor
③ Control panel
④ Liquid tank
⑤ Gate valve
⑥ Electrical heater no. 1
⑦ Electrical heater no. 2
⑧ Electro- Magnetic flow meter
⑨ Centrifugal pump
⑩ Y-strainer
⑪ Inverter
⑫ 3-Phase Thyristor no.1
⑬ 3-Phase Thyristor no.2
⑭ Heaters on/off switch
⑮ Pump on/off switch
⑯ Data logger panel
⑰ Heating programing panel



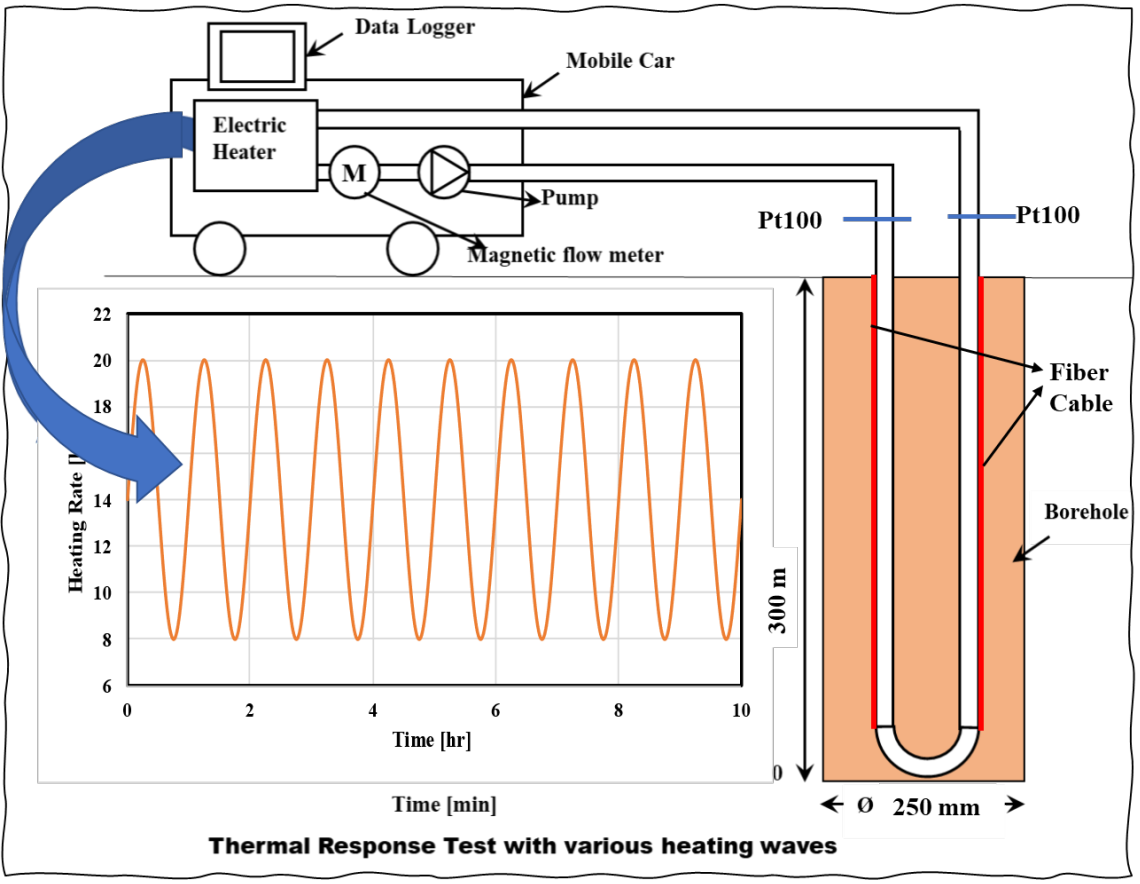
$$P(t) = P_0 + P_1.\sin(\omega_0 t), \qquad |P_0| > |P_1|$$

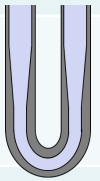
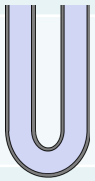
The heat injection rate is supposed to be a sinusoidal function with the amplitude P_1 and the angular frequency ω_0, and a constant heat rate P_0 by using enough capacities of thyristors.



Field test set-up:

3- Operation of the OTRT test

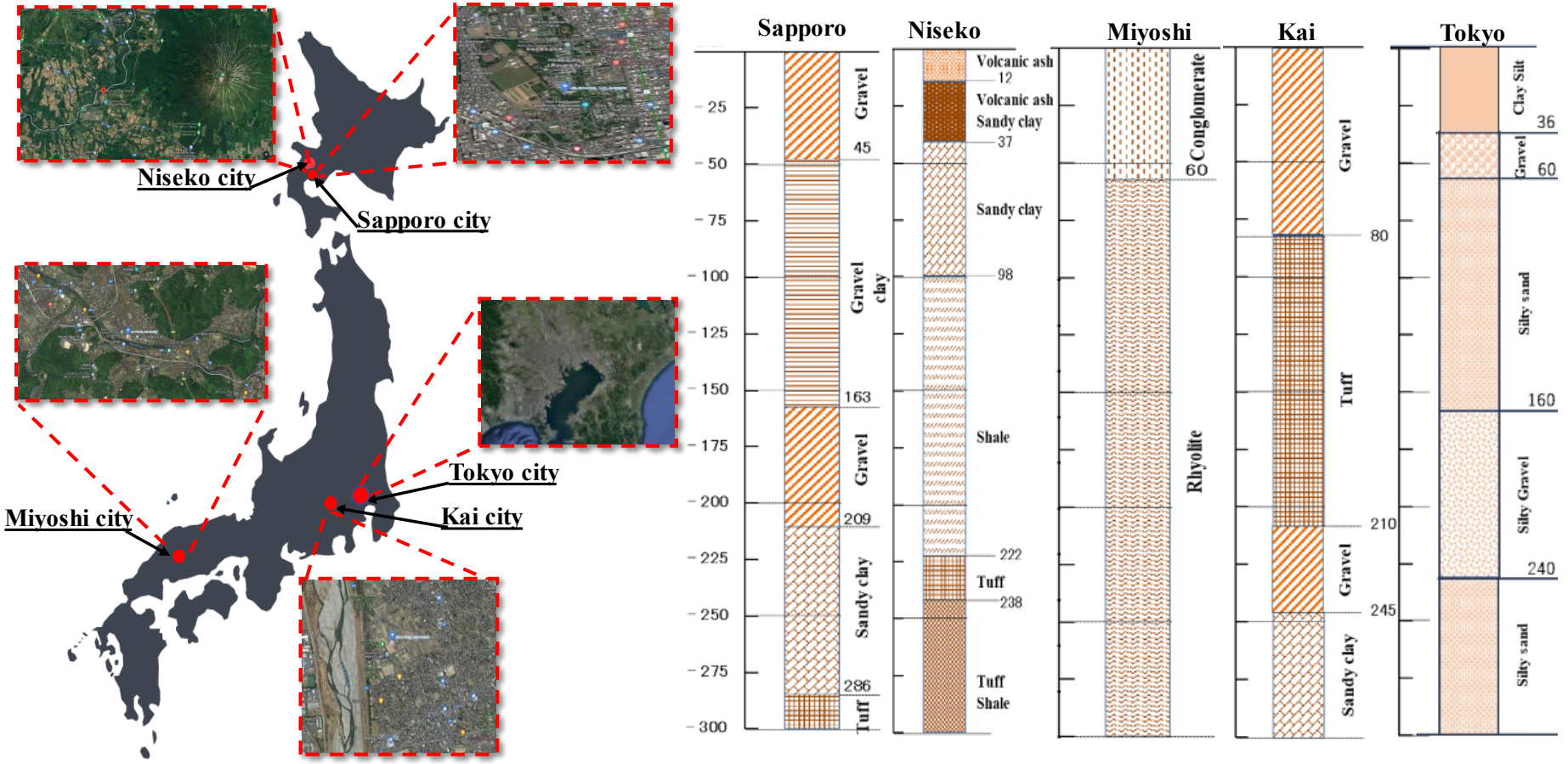


	Sapporo, Niseko, Kai, Miyoshi	Tokyo
Borehole diam.(mm)	250	150
Depth,(m)	300	300
U-tube	single	double
Pipe cross-section	Converged 	Straight 
Di,Do(mm)	36, 43	1st U-tube 31,40 2nd U-tube 27,32
Flow rate [L/min.]	50	37

Test Duration is 24 hours

Field test set-up:

1- Site description



λ_{eff} estimated from geological column in each site

Site	λ_{eff} [W/(m·K)]
Sapporo	1.4
Niseko	1.2
Miyoshi	3.1
Kai	2.1
Tokyo	1.6

Fig. 1 Field study set-up, (a)Experimental sites, (b) Geological column in each site

Results and discussions:

1- Undisturbed soil temp

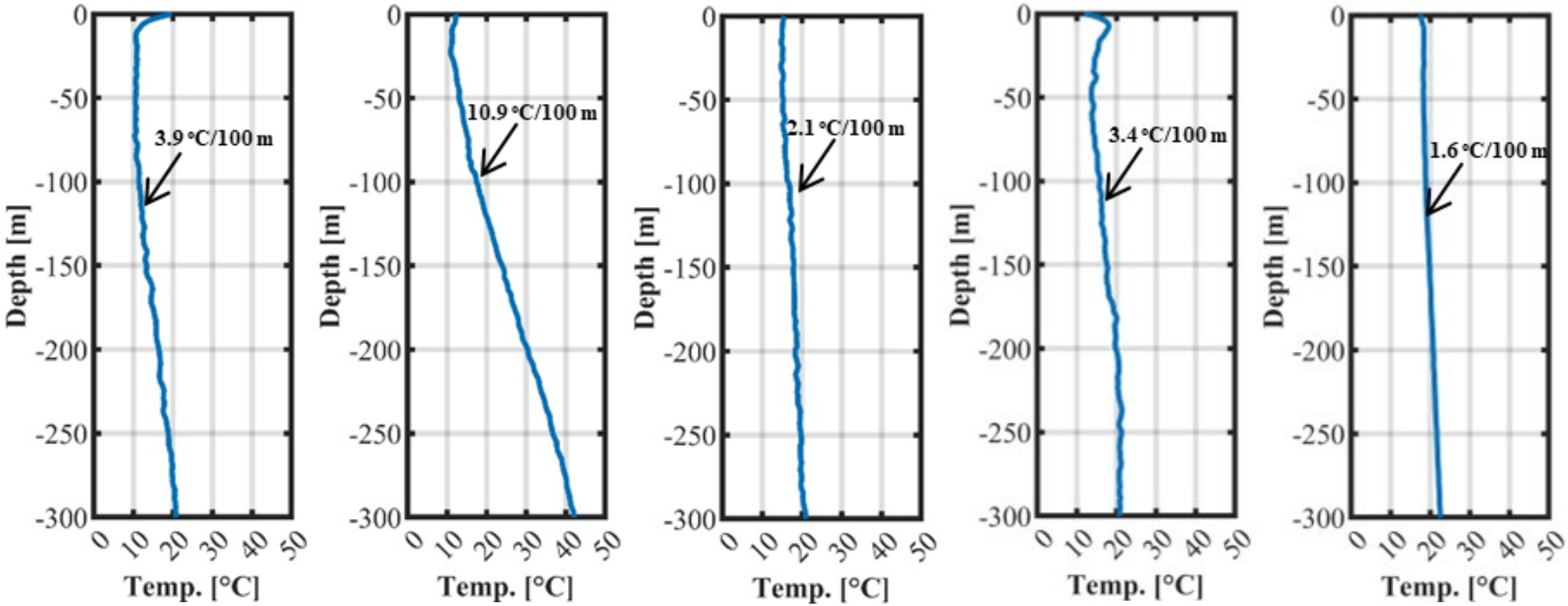


Fig.(6) Undisturbed soil temperature profile at a) Sapporo, b) Niseko, c) Miyoshi, d) Kai, and e) Tokyo cities

Results and discussions:

2- OFS temperature profile

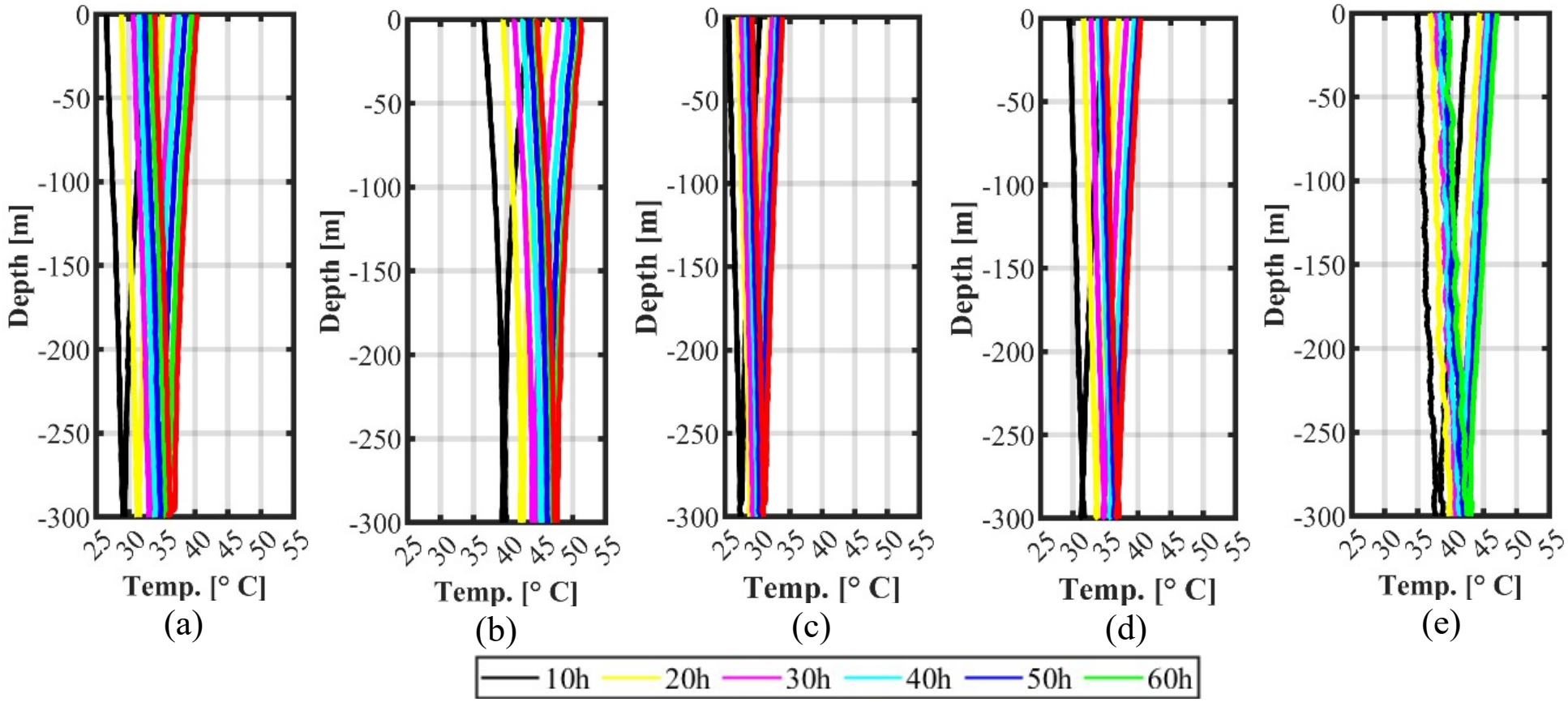
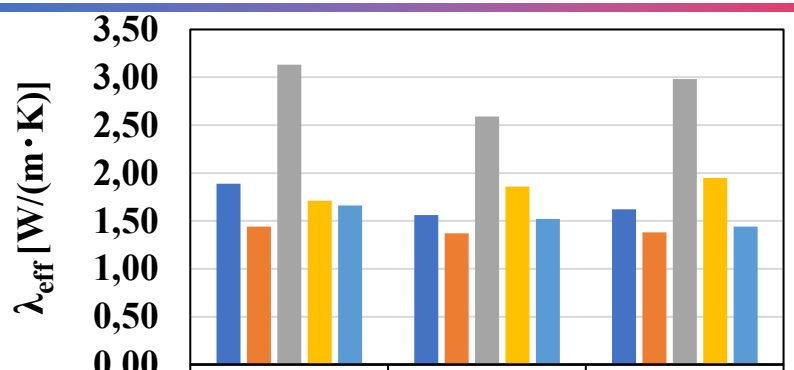


Fig.(8) Fluid temperature profile at a) Sapporo, b) Niseko, c) Miyoshi, d) Kai, and e) Tokyo cities at different time

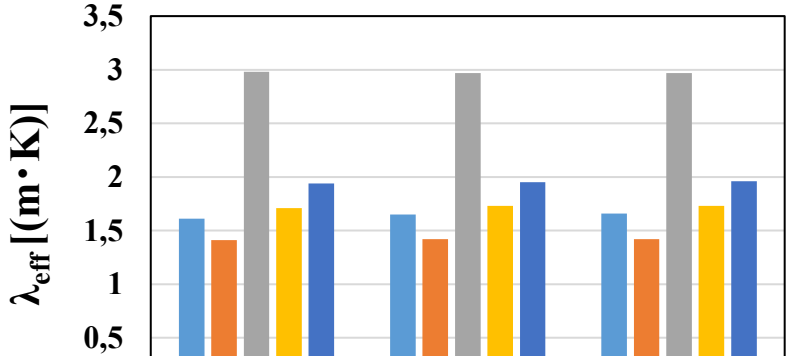
Results and discussions:

3- OTRT



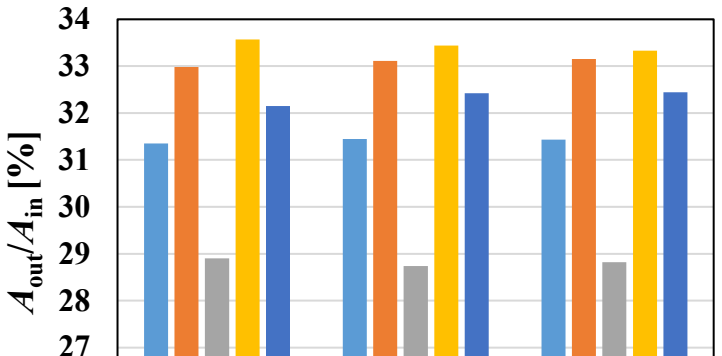
	12~15	12~30	12~60
Sapporo	1,89	1,56	1,62
Niseko	1,44	1,37	1,38
Miyoshi	3,13	2,59	2,98
Kai	1,71	1,86	1,95
Tokyo	1,66	1,52	1,44

λ_{eff} from NTRT



	12~14	12~20	12~24
Sapporo	1,61	1,65	1,66
Niseko	1,41	1,42	1,42
Miyoshi	2,98	2,97	2,97
Kai	1,71	1,73	1,73
Tokyo	1,94	1,95	1,96

λ_{eff} from OTRT



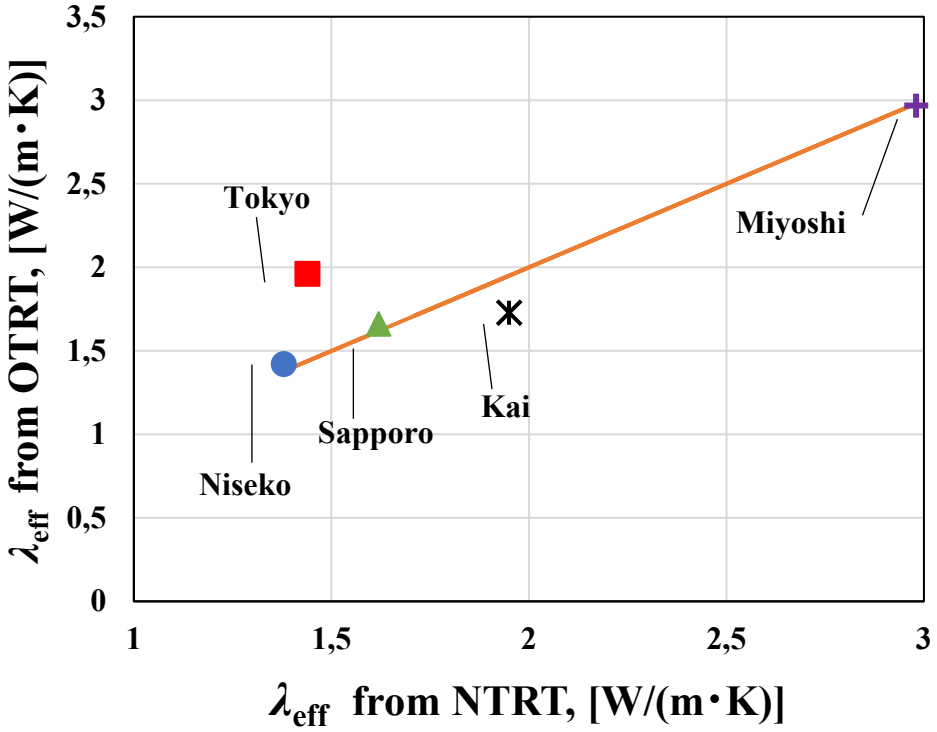
	12~14	12~20	12~24
Sapporo	31,35	31,45	31,43
Niseko	32,98	33,11	33,15
Miyoshi	28,9	28,74	28,82
Kai	33,57	33,44	33,33
Tokyo	32,15	32,42	32,44

Amp. Ratio (A_{out}/A_{in})

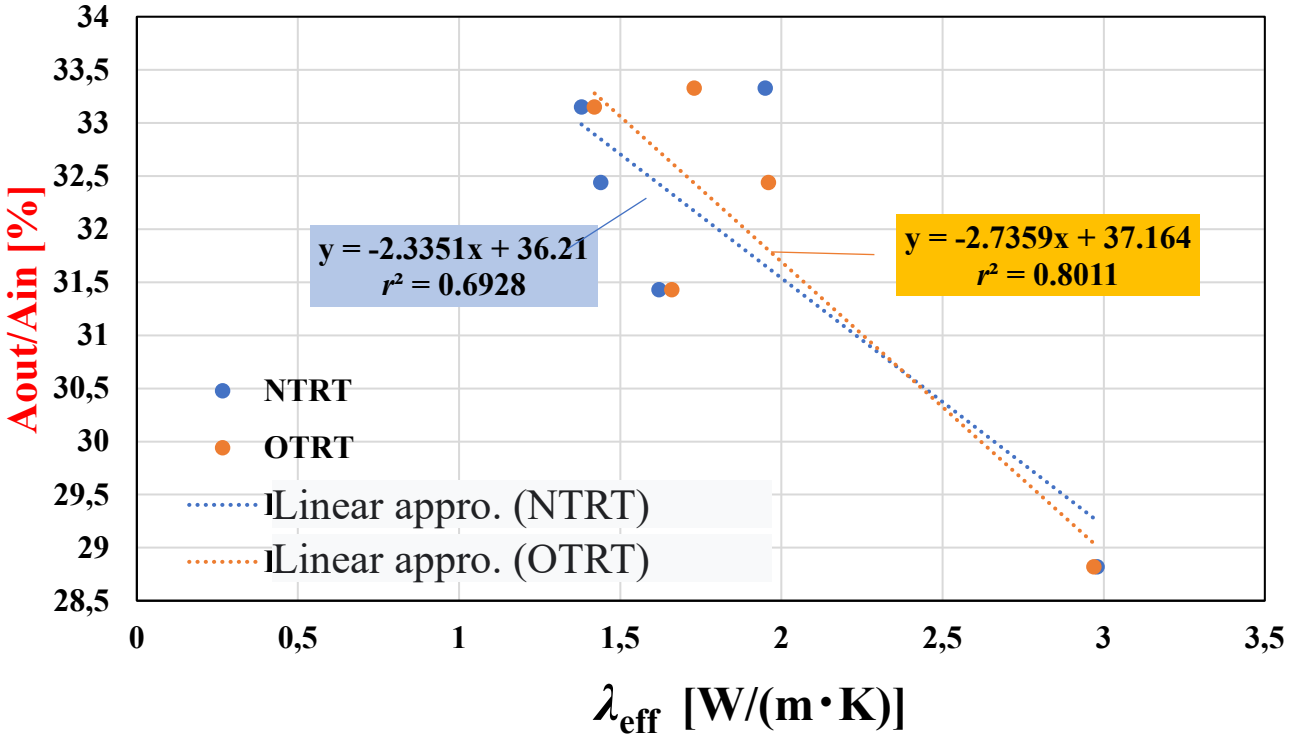
- The **NTRT** results show instability and differences between the three periods with a maximum value of 0.54 W/(m·K) in Miyoshi
- While the results of the **OTRT** show more stability and robustness with a maximum difference of 0.04 W/(m·K)in Sapporo
- The period of **14 hours of an OTRT is enough** to calculate the λ_{eff} with an accuracy of 98 % in three sites (Sapporo, Niseko, and Miyoshi), 87% in one site (Kai city) and 74% in one site (Tokyo city).
- Hence the **OTRT** has a promising potential to save more than 77 % of the time needed for NTRT.

Results and discussions:

4- Comparison between NTRT and OTRT



The root means square error **(RMSE)** between the two results is **0.25 W/(m·K)** with a square error maximum value of 0.27 W/(m·K) in Tokyo.



The relationship between the **amplitude ratio** of inlet and outlet temperatures and the **effective conductivities**

Conclusions

1. A new OTRT is proposed to **decrease the TRT time from 60 hours to 14 hours** and save test and labor costs by 77 %.
2. The effective conductivity, which the new OTRT calculates, has an RMSE of 0.25 W/(m·K) compared with the NTRT.
3. The **new TRT machine has been built and tested successfully.**
4. A **new analysis method is developed**.
5. **A new key parameter** (Amp. Ratio between Inlet and Outlet temperatures) is proposed for future investigation
6. A **linear relationship** is defined between the **effective conductivity and amplitude ratio**,

   which shows a good potential to generalize this method in future work.

Although the OTRt shows promising potential using the experimental measurements in different hydrological, geological, and thermal conditions, **this method needs a comprehensive investigation** to explore and clarify the impact of these parameters on the response and amplitude ratio. These goals are the main objectives of **future studies** using inclusive computational fluid dynamics simulations and artificial intelligence.

Thank you for your attention