A Comparative Study on Factors Affecting Thermal Response Test Analysis

Hae-Rim Oh[1], Byeong-Hak Park[2], Ji-Young Baek[1], Kang-Kun Lee[1*]
[1]School of Earth and Environmental Sciences, Seoul National University, Republic of Korea
[2]Disposal Performance Demonstration Research Division, Korea Atomic Energy Research Institute, Republic of Korea
*e-mail: kklee@snu.ac.kr

ERE2.5
EGU22-7678

This presentation participates in OSPP
Outstanding Student & PhD candidate Presentation contest

Sharing not permitted

Experimental data

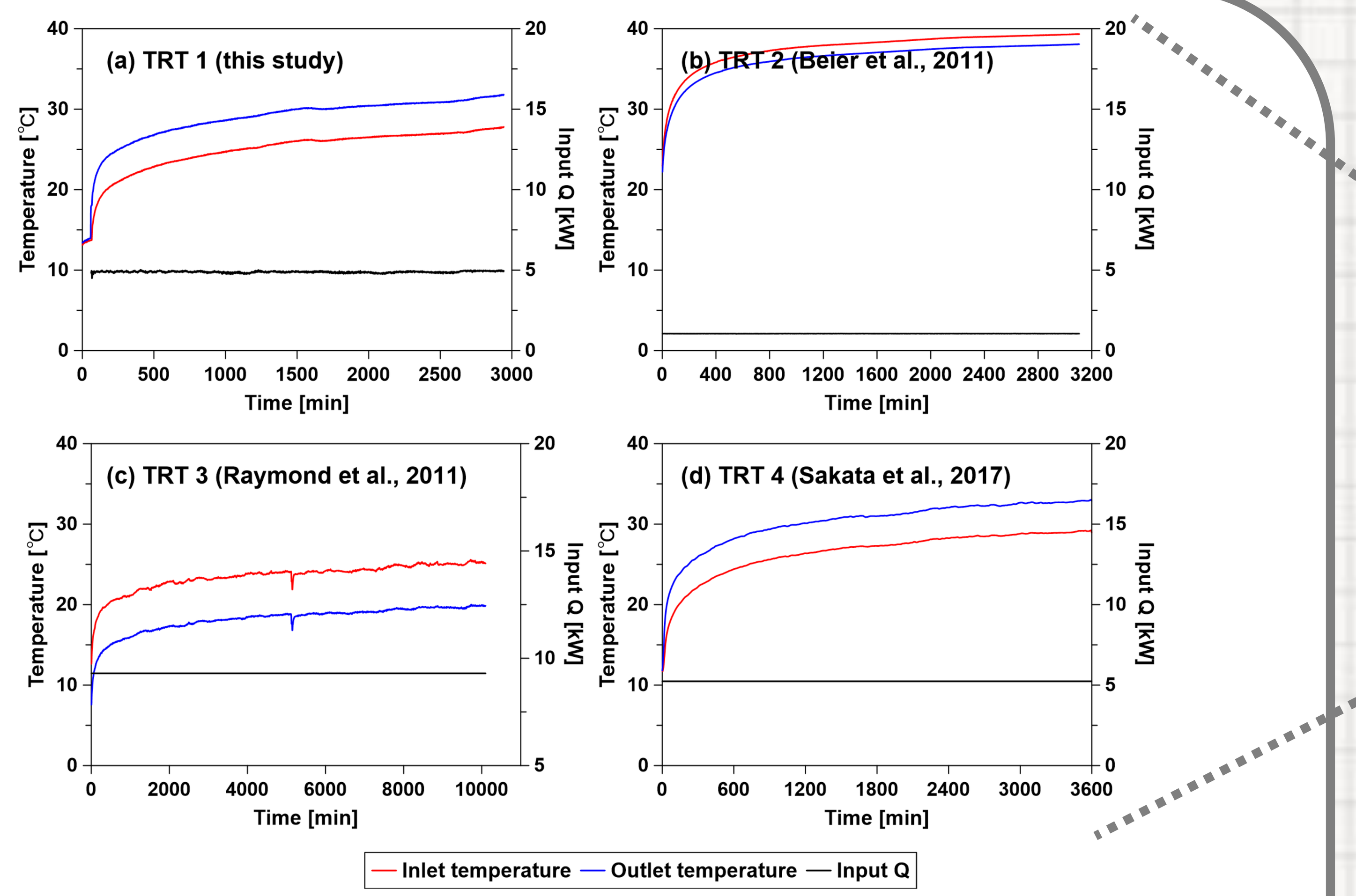

Figure 2. Measured inlet and outlet fluid temperatures and the heat flow rate during TRTs.

	TRT 1	TRT 2	TRT 3	TRT 4
	(in-situ)	*(laboratory)*	*(in-situ)*	*(in-situ)*
Borehole diameter [m]	0.152	0.126	0.152	0.134
Test duration [h]	48	52	168.3	60
Data acquisition interval [min]	1	5	1	1
Borehole length [m]	76	18.3	140	80
Initial temperature [℃]	13.64	21.95	7.5	12.1
Average temperature difference [℃]	3.94	1.28	5.31	3.75
Heat flow rate per unit length of borehole [W m^{-1}]	64.22	57.71	66.49	65.41

Table 1. Geometric and experimental parameters of TRT 1-4.

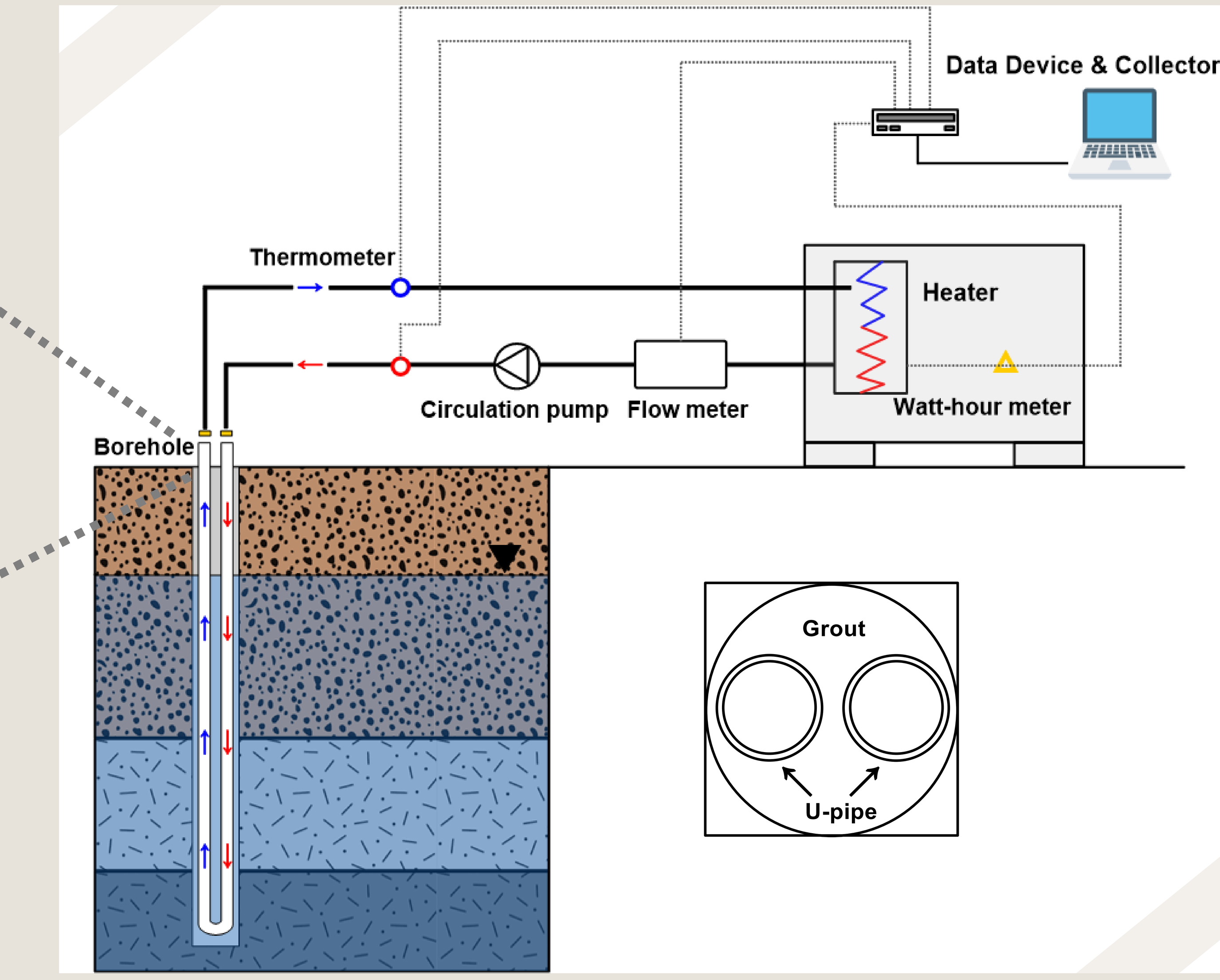

Figure 1. Schematic diagram of thermal response test (TRT) (modified from Bae et al., 2019)

Summary

- We investigated the influences of three factors (**starting time, test duration, and DAI**) for **the accurate thermal conductivity estimation** in the process of TRT analysis.
- **Four TRT data** (3 field test and 1 laboratory test) were used to analyze.
- The results showed that the three factors can affect the thermal conductivity estimation **in the order of starting time, test duration, and DAI**.

Analytical models

① Infinite line source (**ILS**) model
(Carslaw & Jaeger, 1959)

$$T(r,t) = T_0 + \frac{q}{4\pi\lambda}\cdot\left(ln\frac{4\alpha t}{r^2} - \gamma\right) + q\cdot R_b$$

$$T_f = a\cdot ln\,t + b$$

$$\lambda = \frac{q}{4a\pi} = \frac{q}{4\pi}\cdot\frac{ln(t_2)-ln(t_1)}{T_f(t_2)-T_f(t_1)}$$

Linear regression

Parameter estimation

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(T_{model}(t_i) - T_{meas}(t_i))^2}{N}}$$

② Infinite cylindrical source (**ICS**) model
(Ingersoll et al., 1954)

$$T(r,t) = T_0 + \frac{q}{4\pi\lambda}\int_0^{\pi} Ei\left(-\frac{r^2+r_0^2-2rr_0\cos\varphi_r'}{4\alpha t}\right)d\varphi_r' + q\cdot R_b$$

T_f : mean fluid temperature [℃]
T_0 : initial undisturbed ground temperature [℃]
λ : thermal conductivity [W/m/K]
q : heat flow rate per unit length of borehole [W/m]
t : time [s]
α : thermal diffusivity [m^2/s]

③ Moving infinite line source (**MILS**) model
(Sutton et al., 2003)

$$T(x,y,t) = T_0 + \frac{q}{4\pi\lambda}\int_0^t exp\left(-\frac{\{(x-v_t\cdot(t-t'))\}^2+y^2}{4\alpha\cdot(t-t')}\right)\frac{dt'}{(t-t')} + q\cdot R_b$$

r : radial distance [m]
R_b : thermal borehole resistance between the BHE fluid and the borehole wall [K/(W/m)]
γ : Euler's constant (=0.5772)
r and φ_r' : radial and angular coordinates

④ Finite line source (**FLS**) model
(Eskilson, 1986)

$$T(x,y,z,t) = T_0 + \frac{q}{4\pi\lambda}\left\{\int_0^H \frac{erfc(r'/\sqrt{4\alpha t})}{r'}dz_0 - \int_{-H}^0 \frac{erfc(r'/\sqrt{4\alpha t})}{r'}dz_0\right\} + q\cdot R_b$$

r_0 : radius of the BHE [m]

$$-Ei(-x) = \int_x^{\infty} e^{-u}\frac{du}{u}$$

v_t : groundwater velocity [m/s]
H : length of the BHE [m]

Base case
- Starting time = 720 min (MOTIE, 2019)
- Test duration = 2880 min (MOTIE, 2019)
- Data acquisition interval (DAI) = 5 min

		TRT 1		TRT 2		TRT 3		TRT 4	
		λ [W m^{-1} K^{-1}]	RMSE [K]	λ [W m^{-1} K^{-1}]	RMSE [K]	λ [W m^{-1} K^{-1}]	RMSE [K]	λ [W m^{-1} K^{-1}]	RMSE [K]
ILS model	Linear regression	2.10	0.1260	2.93	0.0303	2.90	0.1119	1.98	0.0986
ILS model	Parameter estimation	1.90	0.1423	2.69	0.0541	3.48	0.1669	2.00	0.1029
	ICS model	2.00	0.1280	2.71	0.0513	3.48	0.1669	2.00	0.1029
	MILS model	1.99	0.1278	2.71	0.0436	3.49	0.1652	1.99	0.1073
	FLS model	2.00	0.1286	2.82	0.0341	3.50	0.1883	2.00	0.1029

Table 2. The results of thermal conductivities estimated by analytical models in four TRTs.

Results

Comparison criterion
10%
Kavanaugh (2000)

Comparison between the **base case** and the **analysis scenarios**
→ Starting time : 0 – 1000 min (10 min increments)
→ Test duration : 1880 – 2880 min (10 min increments)
→ DAI : 5 – 60 min (5 min increments)

① Starting time

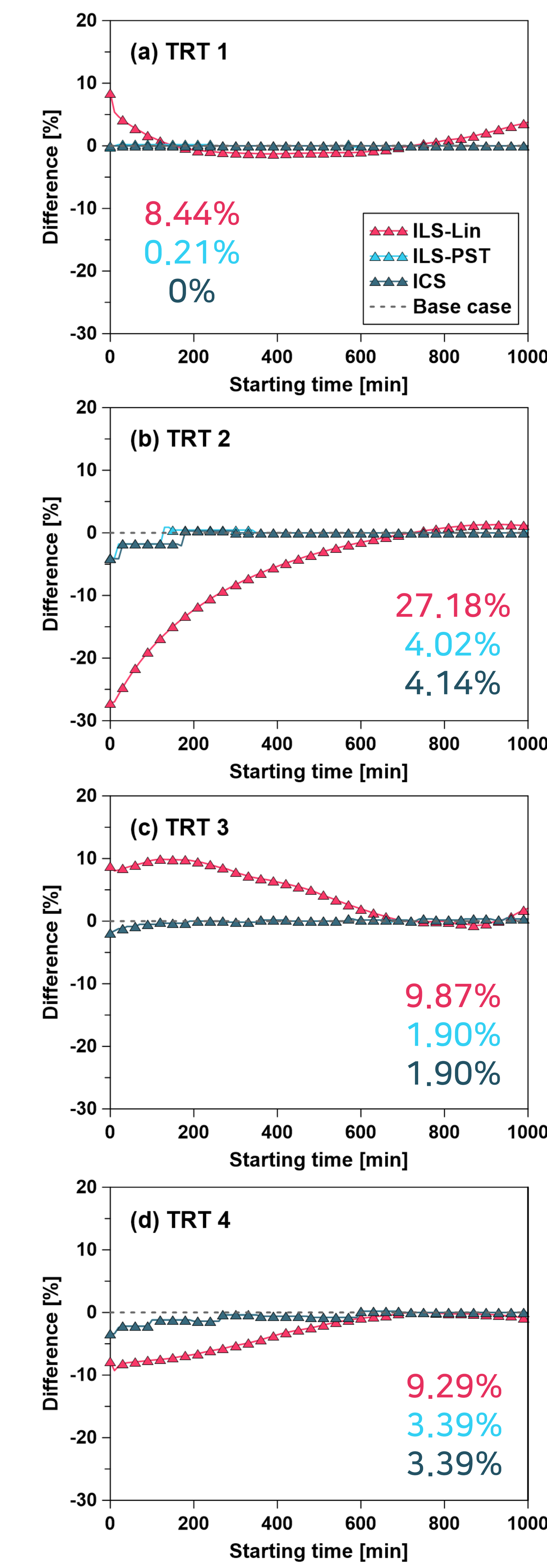

Figure 3. The change in thermal conductivity caused by varying the starting time.

② Test duration

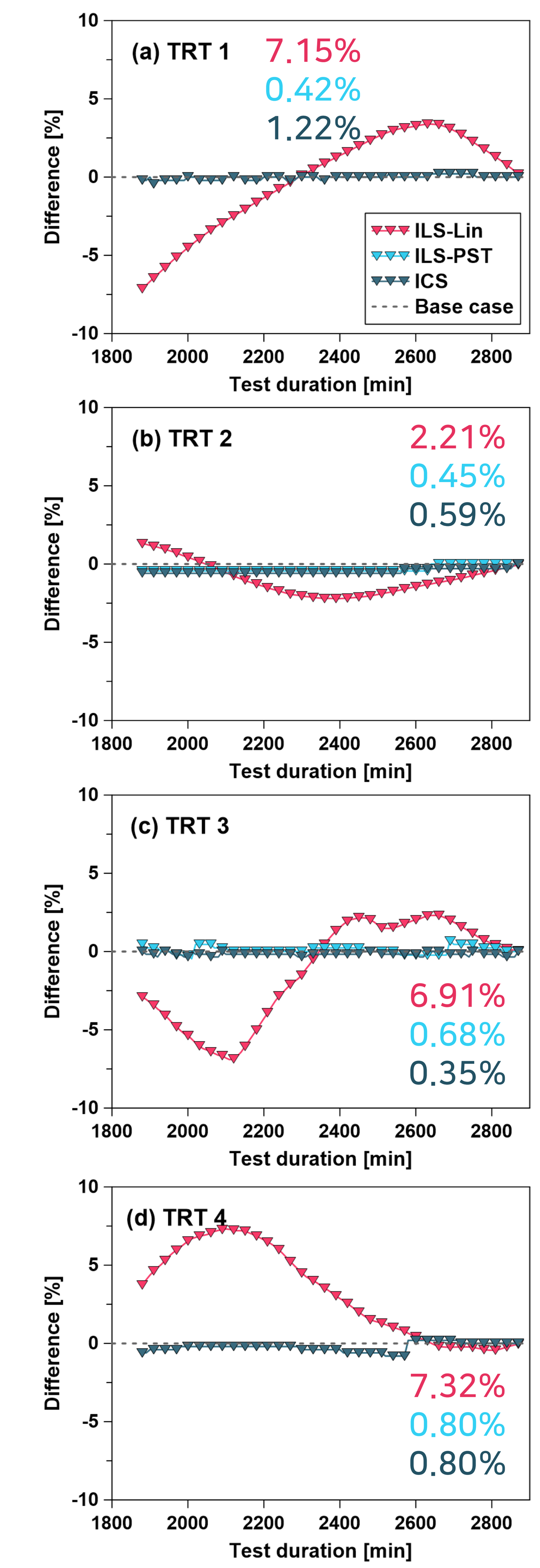

Figure 4. The change in thermal conductivity caused by varying the test duration.

- Maximum difference from the base case
  Starting time (27.18% in TRT 2) > Test duration (7.32% in TRT 4) > DAI (1.07% in TRT 3)
- **The impacts of each factor** differed for four different tests under **different environments**.

References
1. Bae, S. M., Nam, Y., Choi, J. M., Lee, K. H., & Choi, J. S. (2019). Analysis on thermal performance of ground heat exchanger according to design type based on thermal response test. *Energies*, *12*(4), 651.
2. Beier, R. A., Smith, M. D., & Spitler, J. D. (2011). Reference data sets for vertical borehole ground heat exchanger models and thermal response test analysis. *Geothermics*, *40*(1), 79-85.
3. Raymond, J., Therrien, R., Gosselin, L., & Lefebvre, R. (2011). A review of thermal response test analysis using pumping test concepts. *Groundwater*, *49*(6), 932-945.
4. Sakata, Y., Katsura, T., Nagano, K., & Ishizuka, M. (2017). Field analysis of stepwise effective thermal conductivity along a borehole heat exchanger under artificial conditions of groundwater flow. *Hydrology*, *4*(2), 21.
5. Carslaw, H. S., & Jaeger, J. C. (1959). Conduction of heat in solids, Clarendon.
6. Ingersoll, L. R., Zabel, O. J., & Ingersoll, A. C. (1954). Heat conduction with engineering, geological, and other applications.
7. Sutton, M. G., Nutter, D. W., & Couvillion, R. J. (2003). A ground resistance for vertical bore heat exchangers with groundwater flow. *J. Energy Resour. Technol.*, *125*(3), 183-189.
8. Eskilson, P. (1987). Thermal analysis of heat extraction boreholes. Sweden.
9. MOTIE (2019). Standards of Support, Installation, and Management of New and Renewable Energy system.
10. Kavanaugh, S. P. (2000). *Field tests for ground thermal properties--methods and impact on ground-source heat pump design*. Univ. of Alabama, Tuscaloosa, AL (US).

Acknowledgement
This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science and ICT (MSIT) of South Korean government (No. 2017R1A2B3002119). This work was also supported by Korea Environment Industry & Technology Institute(KEITI) through "Activation of remediation technologies by application of multiple tracing techniques for remediation of groundwater in fractured rocks" funded by Korea Ministry of Environment (MOE) (Grant number: 20210024800002/1485017890). This work was also supported by the Institute for Korea Spent Nuclear Fuel (iKSNF) and National Research Foundation of Korea (NRF) grant funded by the Korean government (Ministry of Science and ICT, MSIT) (Grant number: 2021M2E1A1085200).