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Characterization Method about the Vadose Zone for Modeling Long-term Geological Evolution on the Safety of Deep Geological Disposal

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1. Introduction

Nuclear power is one of the essential energy, and it is responsible for 9.18% (Nuclear: 2,632.03 TWh, Total: 28,660.98 TWh) [1] of electricity generation worldwide in 2022, with the largest Nuclear share of electricity among European countries being France (63.3%), Finland (34.5%), Sweden (29.8%), and Switzerland (38.5%). South Korea also accounts for 29.6% of electricity generation produced by nuclear energy [2].

When nuclear fuel is used, spent nuclear fuel should be disposed of and wholly sequestrated from the human and the environment (Figure 1). In addition, continuous efforts are needed to ensure the safety of the disposal repositories. It is necessary to remain in the disposal repositories for tens of thousands to tens of millions of years for spent nuclear fuel to decrease to natural radioactivity levels. Thus, several researchers are trying to develop a comprehensive interacting model (CI model), such as groundwater, surface water, precipitation, etc., to predict the duration of the disposal repositories.

Especially the determination of input parameters for the vadose zone for the CI model is crucial because the properties of the unsaturated zone are related to the flow of all water budget (i.e., rainfall, stream, and groundwater) and are expected to have the most influence on the change in long-term geological evolution. One reasonable method that could be standard should be determined for deriving the input values as representative parameters for simulating the CI model, and it is appropriate to apply the same to obtain the others consistently.

In the present study, we conducted field and laboratory tests to understand the characteristics of the vadose zone in the Unsaturated In-situ Test (UNIT) facility near the KEARI Underground Research Tunnel (KURT). There are three purposes of this study. First, to obtain strategic data fitted on Korea's geologic characteristics by applying the verified research ways (e.g., POSIVA); second, to check the primary data for evaluating natural barrier stability near the future; and lastly, to secure the suitable technique for Korea's geological characteristics. This study included the methods, the results, and what was discussed for determining the representative method for determining the vadose zone input data, which will be utilized in the CI model.

2. Study site

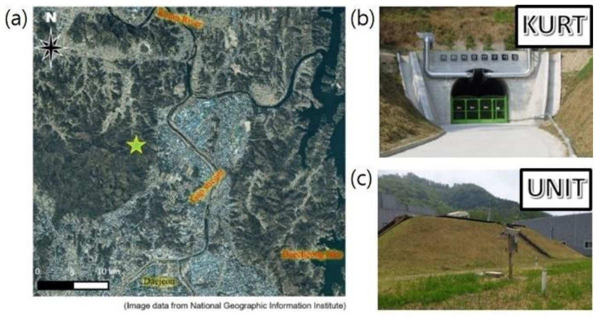

Fig. 1. (a) Study site location (star mark with green color), (b) the front gate of the KURT, and (c) the UNIT facility for infiltration test with small scale

The study area is located in the north part of Daejeon City. Keum River and Gap stream flow along the right side of the study area, and high and low-level mountains surround them. The study facility is called the UINT facility, and it was built 0.6 km from the KURT. Most areas around the UNIT facility were observed with two mica granite outcrops, and the weathered soil layer was developed over them. The purpose of the UNIT facility is to perform infiltration tests on a small scale, and various examinations are being conducted to understand the overall hydraulic and geological characteristics of saturated/unsaturated zones, such as tracer tests, pumping tests, and injection tests.

3. Real-time monitoring

Two real-time monitoring systems were constructed at the UNIT facility. One is on the ground surface, and the other is in the unsaturated zone. The monitoring parameters on the ground surface were temperature (℃), relative humidity (%), precipitation (mm), wind speed (m/s), and wind direction (point of the compass, North = 0°). In the unsaturated zone, soil temperature (T), electrical conductivity (EC), barometric pressures (BP), and water contents (WC) were observed with three different depths such as 30, 60, and 90 cm below ground surface (bgs). The groundwater level was also monitored continuously. Data collection of all parameters was set at

10-minute intervals, and all observing sensors were synchronized with one reference time (universal time, UTC) to be measured simultaneously.

4. Laboratory tests

Non-disturbed soil samples were collected at the UNIT facility at three depths, 30, 60, and 90 cm bgs. The collected soil samples were analyzed to obtain the physical parameters such as the soil bulk density (BD), the porosity(θ), the saturated soil conductivity (Ks), and van Genuchten model values (water retention curves). The soil Bulk density can be calculated using the following equation:

$$(1)\ \text{BD}\ (\text{g}/cm^3) = \frac{mass\ of\ dry\ soil\ (g)}{voulum\ of\ soil\ (cm^3)}$$

When pressure is applied to the soil, the porosity is relatively reduced, and the Bulk density increases. The mass of dry soil per unit volume of soil, including pores, is called Bulk density, and it can be calculated as a specific volume of soil weight divided by the total volume of the soil.

The porosity is calculated using Bulk density and particle density as physical characteristics that can measure the ratio of gaps in which water or air can enter between particles in the unsaturated zone using the following formula.

$$(2)\ \theta\ (\%) = (1 - \frac{bulk\ density\ (g/cm^3)}{particle\ density\ (g/cm^3)}) \times 100$$

The saturated hydraulic conductivity can be estimated using a constant head test or falling head test. In most cases, if a lot of sand is included in the soil sample, it has a non-cohesive property, and the constant head test is applied in this case. Conversely, if the ratio of clay is high, it has cohesive properties, and the falling head test is utilized for this soil sample. K-SAT (METER Group, Inc., USA) [3] can analyze the saturated hydraulic conductivity for non-disturbed soil samples with both methods. This study selected the falling head test because it allows repeated tests within a short period. Characteristic values representing fluid flow in the unsaturated zone include the coefficients related to the saturated volume function ratio(θ_s), the residual volume function ratio(θ_r), the airflow (α), the slop of inflection points (n), and residual function ratio (m) [4]. These values can be estimated using the soil water characteristic curve (SWCC). HYPROP2 (METER Group, Inc., USA) can measure the tension change inside the soil sample in real-time during the naturally evaporating moisture from the soil samples, and the soil moisture characteristic curve is estimated by converting the monitored values using a coding program [3]. This instrument uses two different lengths of tension meters, and it automatically measures and records the tension of water in the non-disturbed soil sample. The hydraulic conductivity of the unsaturated pore section in the soil sample could be predicted using the observed data and the support program provided by METER Group Company.

5. Statistical analysis

Correlation analysis was performed on meteorological variables to analyze their correlation strength. The results value is expressed as the Pearson correlation coefficient. It is the value obtained by dividing the covariance of two variables in the observed data by the product of the standard partiality. The expression can be represented as the following equation,

$$(3)\ \rho = \frac{\sum_i^n (X_i - u_x)(Y_i - u_y)}{\sqrt{\sum_i^n (X_i - u_x)^2}\sqrt{\sum_i^n (Y_i - u_y)^2}}$$

where ρ is the Pearson correlation coefficient, n is the number of populations, X and Y are the populations, and u is the average of the populations.

Regression analysis can check the influence of the independent variable on the dependent variable after obtaining a regression model between two variables for observed continuous variables. It helps to set the variable in the linearly established equation and determine the relationship between the independent and dependent variables. The standard regression model can be expressed as follows.

$$(4)\ y_i = \beta_0 + \beta_1 X_i + e_i$$

where y_i is the independent variable, X_i is the dependent variable, and β_0 and e_i are the predicted coefficients by the regression model.

6. Results

6.1. Real-time monitoring

Real-time monitoring was continuously operated for about 16 months (April 01, 2022, ~ July 21, 2023) using weather observation equipment constructed in the UNIT facility. The monthly average and maximum/minimum values of the observed data were summarized in Table 1. The highest temperature was 35.62 ℃, and the lowest was -18.69 ℃. The most increased monthly precipitation in the study site was in August 2022 at 457.37 mm and July 2023 at 675.42 mm. Most of the precipitation was concentrated during the summer season. The average monthly range of atmospheric pressure was 998.2 – 1017.62 mb, the maximum monthly average was observed to be 1030.44 mb in February 2022, and the minimum was 986.31 mb in September 2022. The relative humidity range was observed from 11.84% to 100%. The southwest wind dominates the wind direction, and the wind speed range mainly was observed from 0.1

to 0.5 m/s. The wind speeds of over 0.5 to 1.0 m/s were also monitored during specific periods (Fig 2).

Table 1: The observed data's monthly average, maximum, and minimum values for about 16 months.

년도	월		기온(℃)	상대습도(%)	풍속(m/s)	*풍향(°)	대기압(mb)	**강수량(mm)
		Max.	28.10	94.00	5.30	360.00	1022.30	
	4월	Min.	1.40	15.00	0.00	0.00	993.40	69.70
		Avg.	14.81	52.29	1.92	202.49	1008.99	
		Max.	31.00	94.00	6.00	360.00	1013.00	
	5월	Min.	5.90	19.00	0.00	0.00	992.60	8.10
		Avg.	19.34	49.86	2.12	222.42	1004.65	
		Max.	35.50	96.00	7.30	360.00	1006.40	
	6월	Min.	14.90	15.00	0.00	0.00	986.80	117.60
		Avg.	24.05	66.44	2.40	192.60	999.54	
		Max.	35.40	95.00	6.30	360.00	1007.30	
	7월	Min.	21.00	41.00	0.00	0.00	990.10	195.00
		Avg.	26.95	75.13	1.89	188.74	998.03	
		Max.	34.20	96.00	6.40	360.00	1009.50	
2022	8월	Min.	15.50	34.00	0.00	0.00	992.50	496.10
		Avg.	25.73	78.65	1.92	201.26	999.55	
		Max.	32.60	96.00	8.20	360.00	1011.80	
	9월	Min.	11.40	23.00	0.00	0.00	985.60	90.20
		Avg.	21.85	68.75	2.15	164.25	1005.22	
		Max.	27.80	96.00	6.30	360.00	1022.20	
	10월	Min.	2.50	17.00	0.00	0.00	999.60	89.30
		Avg.	14.29	67.98	1.66	214.18	1013.67	
		Max.	24.60	97.00	6.60	360.00	1025.40	
	11월	Min.	-5.40	14.00	0.00	0.00	1000.60	45.80
		Avg.	9.53	64.18	1.49	225.06	1013.40	
		Max.	11.50	96.00	6.20	360.00	1025.50	
	12월	Min.	-13.20	16.00	0.00	0.00	1000.50	17.70
		Avg.	-2.01	61.55	1.62	228.16	1016.86	
		Max.	15.40	96.00	7.40	360.00	1025.50	
	1월	Min.	-17.70	18.00	0.00	0.00	1000.50	28.40
		Avg.	-0.90	59.69	1.65	211.21	1016.56	
		Max.	14.20	96.00	7.50	360.00	1030.30	
	2월	Min.	-6.20	12.00	0.00	0.00	1007.10	5.40
		Avg.	2.33	53.77	1.47	174.14	1017.39	
		Max.	25.00	94.00	6.10	360.00	1022.30	
	3월	Min.	-4.10	9.00	0.00	0.00	996.70	23.80
		Avg.	9.96	43.53	1.61	170.03	1012.26	
		Max.	27.90	95.00	7.70	360.00	1016.90	
2023	4월	Min.	1.70	8.00	0.00	0.00	995.10	54.50
		Avg.	13.73	54.39	1.97	159.22	1006.99	
		Max.	31.20	97.00	6.10	360.00	1016.40	
	5월	Min.	5.20	14.00	0.00	0.00	990.90	192.90
		Avg.	18.96	60.79	1.30	118.84	1005.21	
		Max.	33.50	96.00	6.90	360.00	1007.10	
	6월	Min.	15.80	24.00	0.00	0.00	990.80	147.50
		Avg.	23.62	65.28	1.56	156.57	999.34	
		Max.	33.90	97.00	6.10	360.00	1006.10	
	7월	Min.	18.80	37.00	0.00	0.00	985.90	776.30
		Avg.	25.36	81.97	1.28	132.62	997.53	

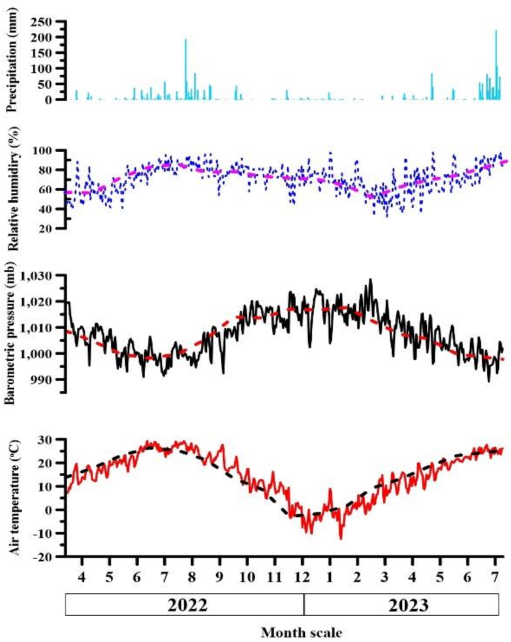

Fig. 2. Meteorological parameters were monitored at the UNIT facility.

6.2. Statistical analysis

Fig. 3 shows the correlation between all meteorological observation variables and the distribution of the monitoring data simultaneously. The correlation coefficient between atmospheric temperature and pressure was -0.77, and those two variables had a negative correlation. Then, the relative humidity and wind speed had a high correlation with a coefficient of -0.62.

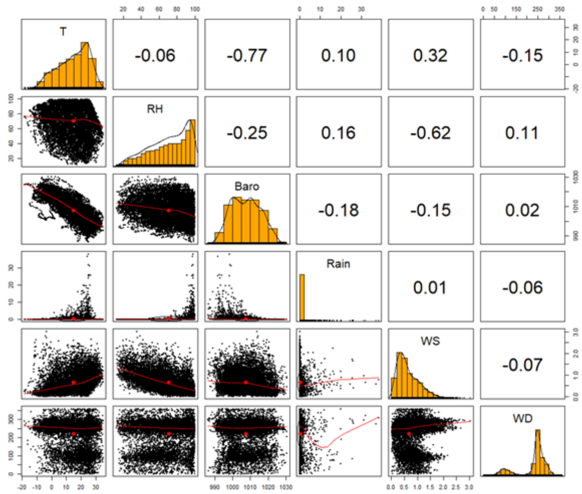

Fig. 3. Data distribution and correlation analysis results of meteorological observation data.

A regression analysis was conducted to better explain the relationship between temperature and atmospheric pressure, which have the highest negative correlation. Temperature was set as an explanatory variable, and atmospheric pressure was selected as the response variable. The analysis was performed by setting the confidence level to 95%. As a result, the coefficient of determination was 0.6, and the standard error was calculated as 5.25. The total data used in the regression analysis was 11,416, and the p-value was very small, close to zero. The estimation equation (5) suitable for the regression model was expressed as follows.

$$(5)\ Y = 1016.361 - 0.604X$$

Based on the established regression equation, it can be explained that if the temperature changes by 1, the atmospheric pressure changes by 0.604. in addition, as a result of the variance analysis between the two variables, the p-value is close to 0 and very small, so the estimated regression model equation is interpreted to be reasonable in explaining the monitored data.

6.3. Laboratory tests

6.3.1. Bulk density

The Bulk density can have various values depending on the mineral composition or status of the soil. The normal Bulk density range of the cultivated soil is 1.1 – 1.4 g/cm^3. As a result of analyzing the three soil samples, the Bulk density was 1.71, 1.60, and 1.68 g/cm^3. It is considered that the weathered soil covering the UNIT facility has accumulated for a long time at a deeper depth and has a higher Bulk density than the cultivated place.

6.3.2. Porosity

The porosity of the sampled soils is calculated using the derived Bulk density and the particle density. Thus, the porosity was derived as 0.361, 0.346, and 0.338.

6.3.3. Saturated hydraulic conductivity

Using the K-SAT equipment [3], the saturated hydraulic conductivity was measured by repeating 5, 16, and 7 times according to 30, 60, and 90 cm depth, respectively. As a result of the repeating test, the saturated hydraulic conductivity was obtained as 5.32E-06 – 6.49E-06 cm/s for 30 cm depth, 7.94E-03 – 9.49E-03 cm/s for 60 cm, and 4.67E-06 – 6.33E06 cm/s for 90 cm. the average Ks for each depth is 5.77E-06 cm/s, 8.73E-03 cm/s, and 5.32E-06 cm/s respectively. The saturated hydraulic conductivity was maintained within a specific range for each depth. Compared with the hydraulic conductivity reference table, 30 cm, and 90 cm are evaluated as clay soil, and 60 cm is clean sand. As a result of different hydraulic conductivity being confirmed depending on the depth, it seems that heterogeneity of various scales has developed vertically and horizontally at the UNIT facility.

6.3.4. Water retention curve

As a result of estimating the soil retention curve for each depth soil sample, it could be represented as shown in Fig. 4. The curve's starting point differs depending on the initial soil moisture content. It can be seen that the three soil samples have different characteristics, but if the soil moisture contents are converted to saturation, the 30 cm and 90 cm depth soil sample's water retention curves showed similar. On the other hand, the soil sample at a depth of 60 cm was drawn with a sharper curve, unlike the other two depths. This is interpreted to be due to the different ratios of the particle size constituting the 60 cm sample of soil and the others [5].

Even if the same analysis is performed using the same sample, the experiment could be carried out that wetting and draining curves can be varied each time (hysteresis). This is a fundamental rule in selecting the model parameters, and it should be remembered that the results can be changed with unreasonable errors. To overcome a negative aspect, it is expected that many repeating laboratory tests and various samples are needed.

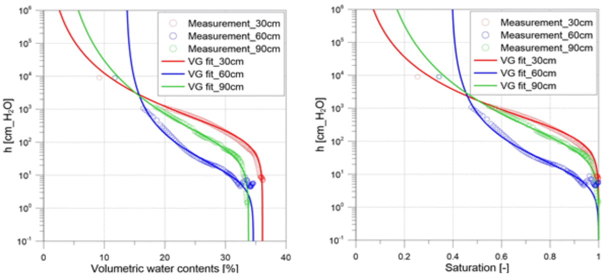

Fig. 4. Comparison of soil retention curve and optimized model results of soil sample for each depth

7. Further study

Based on the previously acquired data, we intend to conduct an infiltration test in the small-scale field (UNIT facility). Tracer and injection/pumping tests are also performed to understand the flow characteristics through the unsaturated zone from the surface ground to the water table. Through all field tests, sufficient data would be obtained. We intended to apply the representative values to the CI model to predict the safety influenced by long-term geological evolution.

We intend to continuously develop methodologies until the selection of a demonstration site to dispose of the spent nuclear fuel and obtain the most appropriate and meaningful guidelines for Korea's geological characteristics.

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