Study on Rainfall Infiltration Into Vault of Near-surface Disposal Facility Based on Various Disposal Scenarios

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(Received August 2, 2021 / Revised September 2, 2021 / Approved October 12, 2021)

In this study, rainfall infiltration in vault of the second near-surface disposal facility was evaluated on the basis of various disposal scenarios. A total of four different disposal scenarios were examined based on the locations of the radioactive waste containers. A numerical model was developed using the FEFLOW software and finite element method to simulate the behavior of infiltrated water in each disposal scenario. The effects of the disposal scenarios on the infiltrated water were evaluated by estimating the flux of the infiltrated water at the vault interfaces. For 300 years, the flux of infiltrated water flowing into the vault was estimated to be 1 mm/year or less for all scenario. The overall results suggest that when the engineered barriers are intact, the flux of infiltrated water cannot generate a sufficient pressure head to penetrate the vault. In addition, it is confirmed that the disposal scenarios have insignificant effects on the infiltrated water flowing into the vault.

Keywords: Rainfall infiltration, Near-surface disposal facility, Vault, Emplacement of radioactive waste, Flux of infiltrated water

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1. Introduction

A low and intermediate level radioactive waste facility in Gyeongju will be developed as a complex disposal facility that has various types of disposal facilities according to the radioactive waste classification to efficiently manage radioactive waste [1]. In December 2014, the first phase disposal facility was completed as underground silos, and the second phase disposal facility will be constructed as a near-surface vault disposal system.

The near-surface disposal facility may include engineered barriers which isolate the waste from human and the environment. The engineered barriers include the waste package and other human made features such as vaults, cover, backfills [2]. When disposal of radioactive waste is completed, the multi-layer cover is installed on the top of the vault. The multi-layer cover consists of different layers and the main function is to minimize the percolation rate of water to the concrete vault [3]. The engineered barriers should be designed to prevent or limit the ingress of water into the facility towards the waste and the migration of radionuclides from the waste to the biosphere for the required period of time [4].

The main transport routes for nuclides from radioactive waste to the biosphere is through the groundwater. In the second phase disposal facility, the transport of radionuclides through water starts by radioactive waste contacting with infiltrated rainfall through the engineering barriers. And the released radionuclides passing through the unsaturated zone reaches to saturated zone along with the groundwater flow.

In the second phase disposal facility, the lower level radioactive waste than the first phase disposal facility will be disposed, but the second phase disposal facility will be built on the near-surface, the possibility of contact with rainfall is greater. Therefore, it is necessary to identify the amount of rainfall infiltrating into the vault. In this study, numerical simulation that reflects the design characteristics of the second phase near-surface disposal facility was performed and the water infiltrating into the vault was quantitatively calculated. In addition, in order to identify more realistic case, various disposal scenarios considered emplacement of radioactive waste containers were composed and the effect of disposal scenarios on the infiltrated water flowing into the vault was evaluated.

2. Design of the Second Phase Near-surface Disposal Facility

The second phase near-surface disposal facility will be constructed with 20 vaults and the multi-layer cover system. The total capacity of the second phase disposal facility is about 125,000 drums based on 200 L drum.

The vault used to dispose low level radioactive waste is a concrete structure and it has dimension of $18.8 \times 18.8 \times 9.7$ m based on the internal clear distance.

When the disposal of radioactive waste and backfilling

| Layer           | Composition       | Function                                                                 |
|-----------------|-------------------|--------------------------------------------------------------------------|
| Surface layer   | Silty sand        | Manage runoff, minimizing erosion, maximizing evapotranspiration          |
| Protective layer| Gravelly sand     | Protect drainage layers from degradation, which can occur by repeated freeze/thaw cycles, repeated excessive wetting/drying, plant, animal, or human intrusion |
|                 | Pea gravel        |                                                                          |
| Drainage layer  | Sand              | Collect water infiltrated through the surface and protective layers and to divert this water laterally |
| Barrier layer   | Clay              | Limit water infiltration into disposal vault                              |

Table 1. Composition and function of each layer
is completed in all vaults, the upper concrete slab will be sealed. And then the multi-layer cover system is installed for maintenance during the post-closure period.

The multi-layer cover system is composed of different layers (surface layer, protective layer, drainage layer and barrier layer) as engineered barrier elements and has a total thickness of 5.5 m. Table 1 shows the composition and functions of each layer. The primary objective of cover of LILW disposal facility is to limit the amount of water that passes through the cover system and the amount of water potentially coming into contact with radioactive waste. The barrier layer is the most critical component because this layer plays a role to limit water infiltration into the vault. Functional requirement of this layer is less than $10^{-7}$ cm·s$^{-1}$. Therefore, the permissible infiltration rate of multi-layer cover system is 32 mm/year. Fig. 1 shows the configuration of the multi-layer cover system.

### Table 2. Specification of disposal containers

| Type            | Size [mm]                        | Maximum weight [ton] |
|-----------------|----------------------------------|----------------------|
| 200 L drum      | $615 (Φ) \times 884 (H)$         | 0.5                  |
| PC-HIC          | $1,200 (Φ) \times 1,288 (H)$     | 2.2                  |
| Small type-2    | $1,452 (W) \times 1,452 (L) \times 950 (H)$ | 12.5 |
| Medium type-2   | $1,000 (W) \times 3,000 (L) \times 1,000 (H)$ | 10 |

### 3. Methodology

The purpose of this study is to evaluate the effect of emplacement of radioactive waste containers in the second phase near-surface radioactive waste disposal facility on the infiltrated water flowing into the vault.

To achieve the objective, numerical simulations of the two-dimensional model composed of multi-layer cover, vault, containers and unsaturated zone was conducted. And the flux of infiltrated water at various interfaces was estimated. The behavior of infiltrated water for each disposal scenario was simulated using FEFLOW (Finite Element subsurface FLOW). FEFLOW is a numerical simulation software to simulate the flow in porous media under saturated and unsaturated condition and it is effective in reflecting the spatial characteristics of complex structures.
Fig. 2. Disposal Scenarios.
3.1 Disposal Scenarios Considered in Numerical Simulation

In order to evaluate the effect of emplacement of the radioactive waste containers on infiltrated water, various disposal scenarios were composed. To compose the various disposal scenarios, containers to be disposed of in the second phase disposal facility were considered. 200 L drum and 860 L PC-HIC (Polymer Concrete High Integrity Container), Small type 2 and Medium type 2 were considered as disposal containers. Small type 2 and Medium type 2 are new types of disposal containers for decommissioning wastes derived from the ‘Development of Waste package, Transportation and Disposal containers for Decommissioning wastes of nuclear power plant’ research [5]. Table 2 is the detailed specification of the containers reflected in the disposal scenarios. Disposal scenarios considered in numerical simulation are set as four scenarios. The first scenario is to stack 6,885 200 L drums in 9 floors (Scenario 1). The second disposal scenario is stacking 600 small type-2 containers in 6 floors and then stacking 1,530 200 L drums in 2 floors on the top of them (Scenario 2). The third disposal scenario is stacking small type-2 containers same as the second scenario, and then stacking 216 PC-HICs on the top of the small type-2 containers (Scenario 3). The last disposal scenario is 420 medium type-2 containers in 6 floors and then stacking 1,530 200 L drums in 2 floors (Scenario 4). Fig. 2 shows the disposal scenario considered for the infiltration assessment.

3.2 Governing Equation

The flow in the unsaturated or variably porous media model is based on the Richard’s equation written in the following [6].

\[ s(\psi) S \left( \frac{\partial \psi}{\partial t} + \epsilon \frac{\partial S}{\partial t} - \nabla \cdot \{ K \nabla \psi + (1 + \chi) \psi \} \right) - Q = 0 \]  

(1)

\[ S_e = \frac{S - S_r}{S_s - S_r} = \begin{cases} \frac{1}{1 + |\alpha \psi|^n} \quad & \psi < 0 \\ \frac{1}{\psi + (1 + \chi)e} \quad & \psi \geq 0 \end{cases} \]  

(2)

\[ k_e = S_e^{\frac{m}{2}} \left[ 1 - (1-S_e^{\frac{1}{m}})^m \right]^2 \]  

(3)

The advantage of equation 1 is only one primary variable (\( \psi \)) remains to be solved for the flow problem. In equation 1, \( S[-] \) is saturation, \( \psi[L] \) is pressure head, \( S_r[L^{-1}] \) is specific storage coefficient, \( t[T] \) is time, \( \epsilon[-] \) is porosity, \( K[-] \) is relative permeability, \( \mathbf{K}[LT^{-1}] \) is tensor of hydraulic conductivity, \( f_u[-] \) is viscosity relation function, \( \chi[-] \) is buoyancy coefficient, \( e[-] \) is gravitational unit vector, \( Q[LT^{-1}] \) is supply (source/sink) mass.

Additionally, the constitutive relationships are required for the saturation as a function of the pressure head and for the relative hydraulic conductivity as a function of either the pressure head or the saturation. The equation 2 and 3 are used for the FEFLOW as empirical relationships.

In equation 2, \( S_e[-] \) is effective saturation, \( S[-] \) is saturation, \( S_r[-] \) is residual saturation, \( S_m[-] \) is maximum saturation, \( \psi \) is pressure head. In equation 3, \( k_e[-] \) is relative conductivity, and \( \alpha[-], n[-], m[-] \) are Van Genuchten law’s coefficients [7].

3.3 Concept Model of Numerical Simulation

The domain of the model designed for the analysis of infiltrated water based on disposal scenarios is shown in Fig. 3. As shown in Fig. 3, the model was set up on the cross-section as a full scale, which is in the center of the second phase near-surface disposal facility. Two-dimensional model is, around a single vault, consist of multi-layer cover at the top, filling materials on the left and right, and an unsaturated zone at the bottom. The radioactive waste containers are placed in the vault according to the four different disposal scenarios. The multi-layer cover was composed of sand and filling materials composed of pea gravel. In addition, the lowest part of the model was located at a
depth of 10 m below the vault in order to exclude external influences in assessing the rainfall infiltration. The width and length of the entire model are 24 m and 22 m, and the total area is 534.129 m².

3.4 Boundary Conditions and Input Parameters

In this study, the multi-layer cover is considered intact, so there is no evolution in it and it performs a function to limit infiltration water less than the permissible infiltration rate (32 mm/year) of multi-layer cover. Therefore, the permissible infiltration rate (32 mm/year) was set as the top of domain so that it was maintained as a constant value during the simulation time. The bottom of domain was set as constant head boundary condition and the others were set as no flow boundary. Fig. 4 shows the applied boundary conditions.

In order to simulate different flow patterns of infiltrated water according to the material compositions of each disposal structure, hydraulic properties of each cover layer and vault were applied. It was assumed that flux of infiltrated water varies according to the flow of vertical direction calculated by numerical simulation. The hydraulic properties of sand, pea gravel and vault are listed in Table 3 [8]. The hydraulic properties of the unsaturated zone are also shown in Table 3.
Table 4. Statistical information of the mesh

|                      | Scenario 1  | Scenario 2  | Scenario 3  | Scenario 4  |
|----------------------|-------------|-------------|-------------|-------------|
| Number of elements   | 38,609      | 38,082      | 37,033      | 38,228      |
| Number of nodes      | 19,446      | 19,176      | 18,652      | 19,252      |
| Min. Elemental Area  | 0.0031      | 0.0019      | 0.0022      | 0.0023      |
| Max. Elemental Area  | 0.3803      | 0.4802      | 0.3490      | 0.3983      |
| Mean Elemental Area  | 0.0138      | 0.0140      | 0.0144      | 0.0140      |
| Std dev. Elemental Area | 0.0218    | 0.0221      | 0.0223      | 0.0219      |

Fig. 5. Mesh configuration of numerical simulation.
Fig. 6. Saturation distribution of scenario 1, 2.
Fig. 7. Saturation distribution of scenario 3, 4.
zone were applied as the result of discrete fracture network modeling [9].

3.5 Mesh

The meshes were generated using triangular elements of various sizes ranging from fine to coarse mesh in reflection of the disposal type in vault. The model domain is subdivided into 5 areas reflecting the design so that characteristics of each area can be applied. The mesh configuration for each disposal scenario is shown in Fig. 5, and it consists of about 38,000 elements and about 19,000 nodes. Table 4 shows the statistical information of the mesh.

4. Results and Discussion

The effect of various disposal scenarios on infiltrated water flowing into the vault were analyzed by extracting the path line of infiltrated water from the top of the sand layer, which is the lowest layer of multi-layer cover, and estimating the flux of infiltrated water. For this analysis,
4.1 Distribution of Saturation

The Figs. 6 and 7 show the change of saturation distribution over 300 years and it is possible to judge the behavior of infiltrated water based on saturation of simulation results (after 0, 30, 150, 300 years). All results of four disposal scenarios show similar saturation distribution patterns as follows. The flow of infiltrated water proceeded at a very slow rate along with time. Most infiltrated water flow laterally along the slope of the top of the vault. For 300 years, the change of saturation in vault is weak and most of the infiltrated flow through the side pea gravel and finally reaches the unsaturated zone. Hence, the difference in the change of saturation according to the disposal scenarios seems to be insignificant.

4.2 Pathways of Infiltrated Water

In order to confirm the detailed behavior of infiltrated water, pathways of infiltrated water were derived for 300 years. Pathways of infiltrated water were derived from using the forward particle tracking method. For this, 65 particles were placed on the top of the domain.

As shown in Fig. 8, results of pathways for four different disposal scenarios show a slight difference, but this is considered to be the difference between the mesh compositions. Similar to the saturation’s results, pathways for four different disposal scenarios show similar trend. For 300 years, pathways of the infiltrated water flowing into the vault have not been observed. And it can be seen that the infiltrated water flows through the pea gravel along the slope of the top of the vault. In line with the results of saturation, there is no significant difference in pathways of infiltrated water according to the disposal scenarios.

4.3 Flux of Infiltrated Water

For the quantitative analysis of the infiltrated water for 300 years, water budget was derived by setting the interfaces of the area which were interesting in model. Then it was divided by the effective area of the interface.
to calculate the flux of infiltrated water. The interfaces for calculating the amount of infiltrated water were set as the same as the flow of infiltrated water. Calculated interfaces are 3 areas as the upper part of the vault, the inner wall of the vault and the bottom of the vault contacting with unsaturated zone. Fig. 9 shows the 3 interfaces and the effective area.

The results of the flux and the amount of infiltrated water derived from the water budget at each interface are Table 5. The flux of infiltrated water according to the four different disposal scenarios show the same trend that the flux of infiltrated water decreases towards the bottom and inner of the vault. For 300 years, the flux of infiltrated water flowing into the upper part of the vault was estimated 0.96 mm/year at scenario 1, 1 mm/year at scenario 2, 0.81 mm/year at scenario 3 and 0.5 mm/year at scenario 4. And the flux of infiltrated water flowing into the inner wall of the vault was estimated 1.81 × 10⁻³ mm/year at scenario 1, 0.52 × 10⁻³ at scenario 2, 0.46 × 10⁻³ mm/year at scenario 3 and 0.17 × 10⁻³ mm/year at scenario 4. These fluxes are impossible to form the pressure head that can penetrate the vault. Therefore, the amount of infiltrated water flowing into the vault during the post-closure period is very insignificant or nonexistent. These results were judged as a phenomenon due to the high capillary force of the vault, not the infiltrated water flowing into the vault. And the difference in the flux of infiltrated water by disposal scenarios seems to be insignificant.

| Face 1 | Face 2 | Face 3 |
|--------|--------|--------|
| Infiltrated water | Flux [mm·yr⁻¹] | Amount [m³] | Flux [mm·yr⁻¹] | Amount [m³] | Flux [mm·yr⁻¹] | Amount [m³] |
| Scenario 1 | 5.76 | 0.96 | 3.06 × 10⁻² | 1.81 × 10⁻³ | 5.70 | 0.95 |
| Scenario 2 | 6.03 | 1.00 | 0.88 × 10⁻³ | 0.52 × 10⁻³ | 5.70 | 0.95 |
| Scenario 3 | 4.87 | 0.81 | 0.77 × 10⁻³ | 0.46 × 10⁻³ | 3.58 | 0.60 |
| Scenario 4 | 2.99 | 0.50 | 0.29 × 10⁻³ | 0.17 × 10⁻³ | 1.44 | 0.24 |

5. Conclusion

In this study, the effect of emplacement of the radioactive waste in the second phase near-surface radioactive waste disposal facility on the infiltrated water flowing into the vault was evaluated. For this evaluation, the numerical simulation reflected the design was performed for the post-closure period (300 years) of the second phase disposal facility. And the flux of infiltrated water was estimated at the interfaces of the vault. The evaluation of rainfall infiltration was conducted for 4 disposal scenarios composed of containers which can be disposed in the second phase disposal facility. The considered containers are 200 L steel drum, PC-HIC, small type-2 and, Medium type-2. The scenarios considered in this study assumed that the engineered barriers (multi-layer cover, vault, containers) are intact, so there are no evolution and degradation in it.

The results for four different disposal scenarios show similar change of saturation and trend of pathways over 300 years. Though these results, when the multi-layers of cover effectively drain and block the infiltrated water according to the purpose of the design, most of infiltrated water flowing through the sand layer which is the lowest layer of the disposal cover, flows through the pea gravel and finally reaches the unsaturated zone. The results of flux of infiltrated water flowing into the inner wall of the vault was estimated 1.81 × 10⁻³ mm/year at scenario 1,
0.5 × 10^{-3} at scenario 2, 0.46 × 10^{-3} mm/year at scenario 3 and 0.17 × 10^{-3} mm/year at scenario 4. The flux of infiltrated water flowing into the vault is very insignificant or nonexistent. So it judged that the flux cannot generate a sufficient pressure head to penetrate the vault. The difference in the results by disposal scenarios seems to be insignificant. Through this study, it was confirmed that, when the engineered barriers are intact, the emplacement of radioactive waste containers in the vault had insignificant effect on the infiltrated water flowing into the vault.

However, this study considered only the intact engineered barriers and the simplified two-dimensional model so assumption for long timescale are very uncertain. Therefore, it is necessary to consider the processes that affect the performance the disposal system, such as degradation of the waste and the barriers and high rainfall event in the future to assessment the long-term safety of the second phase near surface disposal facility.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP Project No.20193210100110) grant funded by the Ministry of Trade, Industry and Energy (MOTIE) of the Republic of Korea.

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