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Assessment of Radionuclide Release from a High-Level Radioactive Waste Repository under a Cumulative Earthquake Scenario Using GoldSim

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1. Introduction

High-level radioactive waste (HLW) must be isolated from humans and the biosphere for many tens of thousands of years. The internationally accepted solution is deep geological disposal, in which engineered barriers are emplaced within a stable host rock to form a multi-barrier system that retards radionuclide migration. Earthquakes, however, can fracture the host rock and alter groundwater flow, potentially degrading the containment performance of the engineered barriers. Although single-event seismic effects have been studied, quantitative analyses of repeated or cumulative earthquakes are still scarce-particularly for Korean conditions.

This study therefore applied the Feature, Event, and Process (FEP) screening methodology to a set of abnormal scenarios. Non-seismic events, such as typhoons and lightning, were excluded due to their extremely low probability or negligible impact, identifying earthquakes as the principal disruptive event [1]. A bounding sequence of magnitude 5, 6 and 7 earthquakes occurring in succession was adopted. The scenario was implemented using the GoldSim software, which couples models for fracture growth, groundwater flow, and radionuclide transport. The resulting simulations quantify how such cumulative seismic loading could affect barrier integrity and the release of five key radionuclides over geological timescales, thereby providing a basis for demonstrating the long-term safety of the proposed repository.

2. Methods and Results

2.1 *Scenario Selection and Assumptions*

Among the 2,161 historical earthquakes recorded on the Korean Peninsula, events of intensity 2–4 account for 62 % of the total, whereas those of intensity 8–10 represent only 0.7 % (15 events). Earthquakes with a magnitude of 4.75 or greater comprise just 5.5 % of all cases, indicating that high-intensity events are very rare. Nevertheless, their potential consequences are severe, and they must therefore be explicitly considered in the design and safety assessment of radioactive-waste repositories.

Table 1. Number of historical earthquakes depending on the Earthquake intensity and magnitude [2]

Intensity	2~4	4	5	6	7	8	8~10	Total
Number	1,340	381	321	59	25	20	15	2,161
Ratio(%)	62.0	17.6	14.9	2.7	1.2	0.9	0.7	100
Magnitude	<3.75	3.75	4.25	4.75	5.25	5.75	>5.75	

This study conservatively evaluates potential radionuclide releases under the assumption that strong earthquakes of magnitude 5 or greater occur within their probabilistic recurrence interval.

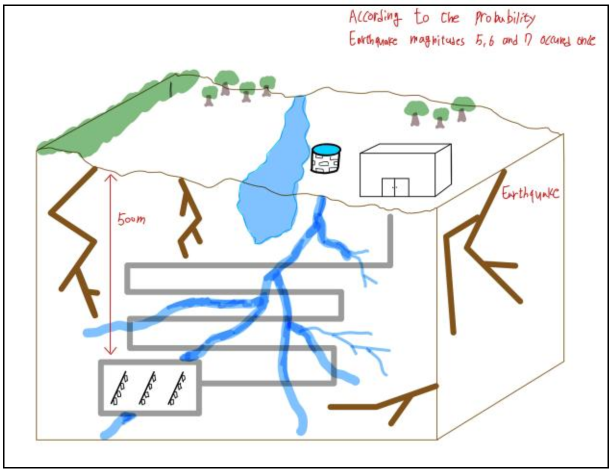

Fig 1. Schematic of the Earthquake Scenario

2.2 *Input Parmeter*

To represent conditions beyond the design-basis accident (DBA), the earthquake scenario assumes three successive earthquakes of magnitudes 5, 6, and 7 occurring on the same fault segment, with respective recurrence intervals of approximately 200, 1,000, and 5,000 years. This sequence allows fractures produced by the first event to be further propagated by the second and third, deliberately over-estimating rock deformation and the resulting perturbations in groundwater flow. Seismic input parameters peak ground acceleration, fault displacement, and hypocentral depth were taken from the National Seismic Hazard Map. The simulation was initiated at repository closure and run for 10,000 years under this highly conservative assumption of successive earthquakes.

Radionuclide selection was carried out in two stages. First, radionuclides with half-lives exceeding 10 years and high mobility in groundwater were selected, including C-14, Tc-99, I-129, and the long-lived transuranic Pu-239[3]. Second, the fissile isotope U-235 was included as mandated by spent-fuel safety-assessment guidelines, yielding a final set of five radionuclides.

Model development employed the GoldSim-RT module, integrating an earthquake-driven fracture-propagation model with radionuclide leaching and transport sub-models. This configuration allows the entire sequence earthquake-induced fracture growth, consequent groundwater-flow perturbations, and the resulting radionuclide release and migration to be evaluated conservatively within a single simulation framework.

Table 2. Half-lives of the selected radionuclides

Nuclide	Half-life
C-14	5.73E + 03
Tc-99	2.11E + 05
I-129	1.57E + 07
U-235	7.04E + 08
Pu-239	2.41E + 04

2.3 *GoldSim Modeling*

Modelling was carried out with GoldSim, a code optimised for simulating mass- and volume-transport processes—such as radionuclide migration and groundwater flow—within complex disposal systems that include both engineered and natural barriers. The base model (Fig. 2) consists of a silo and canister. It explicitly models an underlying aquifer that becomes hydraulically connected to the repository upon barrier fracture. Key input parameters include hydraulic conductivity, distribution coefficients (Kd), and groundwater flow rates.

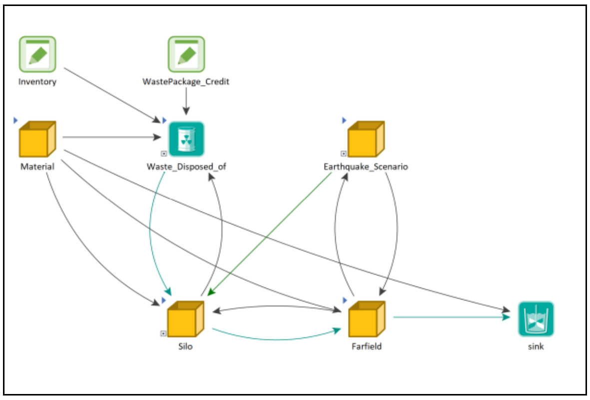

Fig 2. Basic GoldSim Modeling of a High-Level Radioactive Waste Repository

The earthquake scenario (Fig. 3) was implemented with GoldSim's EVENT module. Magnitude and occurrence probability were assigned to three earthquakes, each defined as a separate event. These events were linked in sequence by Status elements and combined with an AND gate so that fractures are generated only when all events occur in the prescribed order. The mechanical, hydraulic, and radionuclide-transport sub-models were then coupled, and the fully integrated simulation was executed to evaluate repository performance under the cumulative earthquake scenario.

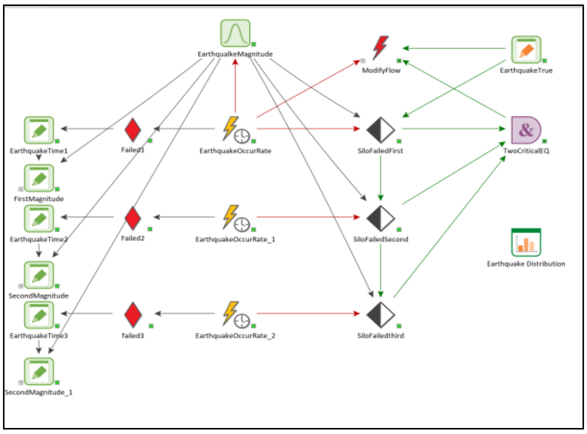

Fig 3. Modeling Earthquake Scenarios

2.4 *Results*

The modeling results (Fig. 4) indicate that even under this extreme scenario, the third and final earthquake does not occur until approximately 3,800 years after repository closure. The first (magnitude 5) and second (magnitude 6) earthquakes are triggered at 170 and 450 years post-closure, respectively, followed by the magnitude-7 earthquake at approximately 3,800 years. As illustrated in Fig. 5, radionuclide release begins only after this third event. Accordingly, no release to the geosphere is predicted for the first 3,800 years, and the releases that do occur thereafter remain below the applicable regulatory limits.

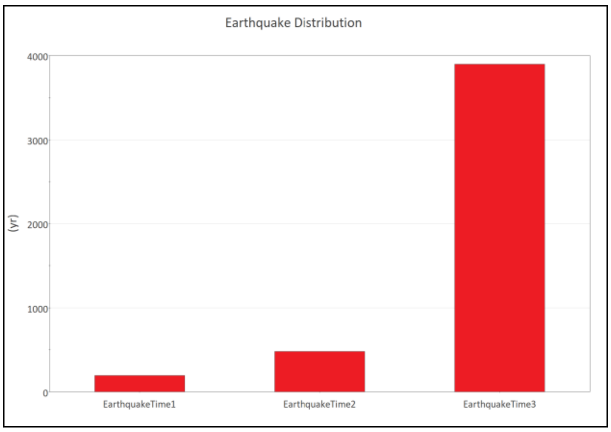

Fig 4. Earthquake Occurrence Results

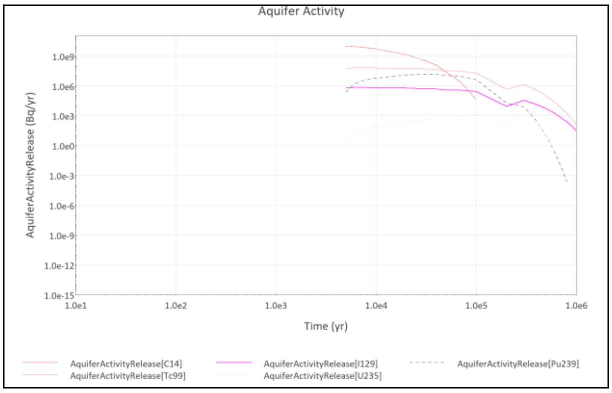

Fig 5. Results of the Radionuclide Release Scenario

Table 3. peak release amount

Nuclide	**peak release amount (Bq/yr)**
C-14	8.178 E+09
Tc-99	6.347 E+05
I-129	1.341 E+07
U-235	6.184 E+07
Pu-239	1.520 E+03

3. Conclusions

The results demonstrate that the engineered-barrier disposal system maintains a substantial safety margin for approximately 3,800 years after closure. Beyond that time, however, cumulative seismic loading may degrade barrier integrity, indicating the need for additional measures to ensure very-long-term safety. Future work will refine the model by discretising additional transport pathways—groundwater flow, gas diffusion, and biotic transfer—and by incorporating post-disaster ingestion and inhalation scenarios for local residents, thereby enabling a more comprehensive assessment.

Acknowledgements

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