

Uncertainty Analysis of Natural Barrier Input Parameters for Safety Assessment of Deep Geological Disposal Facilities and Domestic Application Strategies

Yeeun Choi, Jeongbeen Lee, Donggyu Lee, Hongjun Park*
Department of Nuclear and Energy Systems Engineering(Nuclear Engineering),
Dongguk University WISE Campus, Gyeongju, Republic of Korea
*Corresponding author: hjpark86@dongguk.ac.kr

***Keywords :** High Level Radioactive Waste, Deep Geological Disposal, Uncertainty, Safety Assessment, Natural Barrier

1. Introduction

To ensure the long-term safety of deep geological disposal facilities for high-level radioactive waste (HLW), a safety assessment based on a multiple-barrier system is essential. Of the components of this system, the natural barrier is identified as a key element that delays and mitigates the migration of radionuclides. In particular, input parameters associated with the natural barrier—such as groundwater flow, rock properties, and radionuclide transport coefficients—govern the long-term behavior of the disposal system, and uncertainties in these parameters have a significant impact on safety assessment results.

In leading countries for HLW disposal, including Finland, Sweden, and France, the influence of input parameters has been systematically evaluated through uncertainty and sensitivity analyses [1]. However, within the domestic framework for deep geological disposal safety assessment, endeavors addressing uncertainties in natural barrier input parameters remain insufficient [2].

In this study, the uncertainty characteristics and relative influence of natural barrier input parameters used in safety assessments of deep geological disposal facilities are systematically reviewed. Based on this analysis, a stepwise approach for incorporating uncertainty analysis into the domestic safety assessment framework is proposed.

2. Uncertainty Characteristics of Natural Barrier Input Parameters

Natural barriers inherently exhibit spatial heterogeneity and temporal evolution. As a result, input parameters employed in safety assessments inevitably involve various forms of uncertainty.

2.1 Classification of Input Parameters

Natural barrier input parameters can be categorized into physical properties, hydrogeochemical properties, and radionuclide transport characteristics. Representative parameters include rock permeability, porosity, groundwater velocity, the distribution coefficient (Kd), and diffusion coefficients [3,4]. These

parameters are typically determined based on field investigations, laboratory experiments, and relevant literature.

From a phenomenological perspective, uncertainties associated with natural barriers can be further classified into thermal, hydraulic, mechanical, chemical, and radionuclide transport processes.

2.2 Sources of Uncertainty

Uncertainties in natural barrier input parameters arise from several sources, including data incompleteness, spatial heterogeneity, model simplifications, and reliance on expert judgment.

- Data incompleteness: Limited site investigation data for deep geological environments
- Spatial heterogeneity: Variability in rock properties across spatial scales
- Model uncertainty: Simplifications in conceptual and numerical models
- Expert judgment dependence: Use of empirical estimates based on professional experience

These uncertainties cannot be adequately represented by single deterministic values alone. Therefore, probabilistic approaches based on probability distributions should be applied in conjunction with deterministic analyses.

3. Evaluation of Uncertainty Characteristics of Input Parameters by Major Processes for Domestic Application

Based on the uncertainty characterization of natural barriers, the causes and relative impacts of uncertainties associated with major processes—namely thermal, hydraulic, mechanical, chemical, and radionuclide transport processes—relevant to domestic deep geological disposal systems are systematically summarized in this section.

3.1 Thermal Process

Uncertainties in thermal processes primarily arise from simplifications in heat conduction modeling and the assumption of temperature-independent material properties. The omission of nonlinear effects resulting

from the linear heat conduction assumption introduces temperature deviations of less than approximately 1 °C. In addition, uncertainties associated with freezing effects are considered to have negligible influence under domestic geological conditions. The major sources of uncertainty and their impact characteristics for the thermal process are summarized in Table 1.

Table 1: Major Sources of Uncertainty and Impact Characteristics for the Thermal Process

Category	Major Sources of Uncertainty	Impact and Characteristics
Heat transfer	Model simplification assuming linear heat conduction	Maximum temperature deviation of approximately 0.5–1 °C; relatively small uncertainty
Freezing effects	Use of two-dimensional (2D) models with limited representation of three-dimensional (3D) behavior	Negligible impact under domestic conditions

3.2 Hydraulic Process

Uncertainties in groundwater and gas flow are primarily governed by fracture structures, spatial heterogeneity, and modeling simplifications. In particular, uncertainties in the modeling of two-phase and unsaturated flow, as well as in the estimation of gas generation rates, are identified as major contributing factors. The principal uncertainty factors and their impact levels for the hydraulic process are summarized in Table 2.

Table 2: Major Sources of Uncertainty and Impact Characteristics for the Hydraulic Process

Category	Major Sources of Uncertainty	Impact and Characteristics
Groundwater flow	Fracture network structure; uncertainty in two-phase flow modeling	Significant uncertainty in quantitative modeling results
Gas flow and dissolution	Fracture aperture and connectivity; uncertainty in gas generation rates	Uncertainty in predicting gas migration pathways and velocities; uncertainty in input data

3.3 Mechanical Process

Uncertainties in mechanical processes are primarily associated with fracture zones, stress redistribution, and the development of excavation damaged zones (EDZ). Major sources of uncertainty include the limited scalability of laboratory-scale data to field conditions and the simplification of three-dimensional behavior

into two-dimensional models. The identified sources of uncertainty and their relative impacts in the mechanical process are summarized in Table 3.

Table 3: Major Sources of Uncertainty and Impact Characteristics for the Mechanical Process

Category	Major Sources of Uncertainty	Impact and Characteristics
Rock mass movement / reactivation	Limited scalability of laboratory-scale material models	High uncertainty in predicting the behavior of large-scale fracture zones
Fractures and EDZ	Simplification through two-dimensional (2D) modeling	Potential overestimation of the damaged zone extent
Creep / erosion	Neglect of long-term creep effects	Negligible impact in crystalline rock conditions

3.4 Chemical Process

Uncertainties in chemical processes arise from various factors, including reaction kinetics, diffusion, sorption, microbial activity, and colloid behavior. The primary sources of uncertainty are model simplifications and the limited availability of representative data. The major uncertainty contributors and their relative influence on safety performance in the chemical process are summarized in Table 4.

Table 4: Major Sources of Uncertainty and Impact Characteristics for the Chemical Process

Category	Major Sources of Uncertainty	Impact and Characteristics
Advection and mixing	Difficulty in quantifying reaction–mixing interactions	Possible underestimation of chemical reaction contributions due to model simplifications
Diffusive transport	Neglect of fracture infill materials; assumption of constant diffusion coefficients	Potential underestimation of diffusion resistance; increased diffusivity in the presence of alteration zones
Sorption / distribution	Limited representativeness of experimental data; condition dependency	Large variability depending on mineralogy and groundwater chemistry; structural uncertainty in Kd values due to model simplifications
Groundwater–rock interactions	Uncertainty in reaction kinetics; limitations of equilibrium	Slow reaction rates result in limited short-term changes; equilibrium models

	assumptions	may lead to over- or underestimation
Microbial processes	Uncertainty in microbial parameters	Limited reliability of laboratory data under field conditions; uncertainty in sulfide generation predictions
Colloid and gas-species reactions	Uncertainty in colloid stability and concentration	Uncertain influence on erosion processes; gas generation and dissolution are relatively well understood, although some variability remains

3.5 Radionuclide Transport Process

Uncertainties in radionuclide transport processes arise from the methods used to estimate diffusion resistance, simplifications in sorption coefficient modeling, and uncertainties associated with gas transport pathways. Overall, the influence of these uncertainties on overall safety performance is considered to be limited. The main sources of uncertainty and their impact on safety assessment outcomes for the radionuclide transport process are summarized in Table 5.

Table 5: Major Sources of Uncertainty and Impact Characteristics for the Radionuclide Transport Process

Category	Major Sources of Uncertainty	Impact and Characteristics
Liquid-phase transport	Method used to estimate matrix diffusion resistance	Limited representation of channeling effects; potential underestimation of diffusion resistance
Gas-phase transport	Uncertainty in gas migration pathways; colloid sorption	Negligible overall impact on safety performance

Based on the integrated analysis of uncertainties across all processes, uncertainties associated with chemical processes are identified as having the greatest influence on natural barriers in domestic deep geological disposal systems, whereas thermal processes demonstrate relatively stable behavior. Uncertainties in hydraulic, mechanical, and radionuclide transport processes are largely influenced by model simplifications and parameter variability. The major sources of uncertainty and their relative impacts on safety assessment for each process are summarized in Table 6.

Table 6: Major Sources of Uncertainty and Relative Impact on Safety Assessment by Process for Domestic Application

Process	Major Sources of Uncertainty	Impact Level
Thermal	Simplified heat conduction models	Low
Hydraulic	Fracture structures, spatial variability	Medium-High
Mechanical	Fracture zones, stress redistribution	Medium
Chemical	Reaction kinetics, sorption, microbes, colloids	High
Radionuclide Transport	Diffusion resistance, simplified sorption models	Medium

4. Strategies for Domestic Application

To effectively incorporate uncertainty analysis of natural barrier input parameters into the domestic safety assessment framework for deep geological disposal, a structured and stepwise approach is required. The proposed strategy consists of the following phases:

- **Step 1:** Establishment of input parameter lists and reference ranges that reflect domestic geological characteristics
- **Step 2:** Introduction of probabilistic uncertainty analysis in parallel with deterministic safety assessments
- **Step 3:** Development of analysis and evaluation procedures aligned with regulatory requirements

In addition, clear guidelines are necessary to interpret the results of uncertainty analysis not merely as numerical outputs, but in terms of safety margins and risk implications.

Furthermore, uncertainties associated with natural barriers should not be regarded as issues to be fully resolved at a single stage of the project. Instead, a systematic strategy for managing and progressively reducing uncertainties throughout different project phases is required. In particular, when defining input parameters for safety assessments, a conservative approach that explicitly acknowledges the existence of uncertainty should be integrated with a stepwise refinement strategy.

5. Conclusions

In this study, the uncertainty characteristics of natural barrier input parameters, which play a critical role in the safety assessment of deep geological disposal facilities, were analyzed, and strategies for their incorporation into the domestic safety assessment framework were proposed. A systematic introduction of uncertainty analysis for natural barriers is expected to enhance the

reliability of safety assessment results and to strengthen the scientific basis for demonstrating long-term safety.

Future research should focus on pilot uncertainty analyses using representative domestic geological data, as well as on evaluating their applicability and regulatory acceptability within the domestic framework along with Engineering barrier system.

Acknowledgement

This research was supported by the Institute for Korea Spent Nuclear Fuel under the policy research contract program titled “Investigation and Analysis of the Uncertainty of Natural Barriers Input Variables for Safety Evaluation of Deep Geological Repository.”

REFERENCES

- [1] OECD/NEA Features, Events and Processes (FEPs) for Geological Disposal of Radioactive Waste: An International Database, 2000.
- [2] J. K. Bang et al., JKRWS, Production and Application of Domestic Input Data for Safety Assessment of Disposal, pp 161-170, 2012.
- [3] ANDRA, Dossier 2005 Argile Tome, Safety evaluation of a geological repository, 2005.
- [4] Crawford J, Bedrock Kd data and uncertainty assessment for application in SR-Site geosphere transport calculations. SKB R-10-48, Svensk Kärnbränslehantering AB, 2010.