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# Numerical Assessment of Repository Stability Based on Preliminary Disposal Concept for High-Level Radioactive Waste in Korea

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## Abstract

The operation of nuclear power plants inevitably generates spent nuclear fuel, and its disposal is principally managed within national borders. Disposal concepts vary depending on the geological characteristics of each country. In Korea, the High-Level Radioactive Waste Management Act took effect in 2025, under which the Korea Radioactive Waste Agency (KORAD) leads the development and implementation of disposal strategies. As part of this effort, KORAD has proposed a preliminary disposal concept tailored to domestic conditions, which will be further refined through successive research and project phases.

This study presents a numerical stability assessment of the proposed high-level radioactive waste repository concept, incorporating in-situ stress data and uniaxial compressive strength measurements compiled by the Korea Institute of Geoscience and Mineral Resources (KIGAM). The evaluation explores three key scenarios: vertical vs. horizontal disposal, mechanical vs. thermo-mechanical analysis, and short-term vs. long-term performance. The dimensions and layout of disposal holes and tunnels used in the simulations are based on repository designs developed bythe KORAD, while geotechnical properties reflect both field measurements and standard input values commonly used in Korean rock engineering. Numerical results indicate that the horizontal disposal configuration offers superior stability over the vertical design. Even when thermal effects are considered, the system remains mechanically stable. Long-term analyses also suggest that stability can be maintained under typical geological conditions, provided the site is not in an extremely unfavourable environment. As this study is based on generalized geological settings rather than a specific site, future efforts should focus on site selection, characterization, and detailed repository design to enable more accurate safety assessments.

## Keywords

Repository, Disposal concept, Numerical assessment, HLW.

# 1 Introduction

Since the commissioning of Kori Unit 1 in 1978, nuclear power has played a major role in electricity generation in the Republic of Korea. Currently, 26 reactors are in commercial operation, and additional units—including large-scale reactors and small modular reactors (SMRs)—are planned to meet the rapidly growing electricity demand driven by advanced industries such as artificial intelligence and high-performance computing.

The operation of nuclear power plants inevitably produces spent nuclear fuel (SNF). Korea's national policy requires the final disposal of SNF within its own territory. After extensive policy development, the High-Level Radioactive Waste Management Act was enacted in 2025, designating the Korea Radioactive Waste Agency (KORAD) as the implementing organization. Based on national geological and technical conditions, KORAD has established a preliminary concept for deep geological disposal, which will be further refined through staged research and implementation.

According to the International Atomic Energy Agency (IAEA, 2023), key tasks in the planning phase of a geological disposal program include the design of the disposal system and the evaluation of design alternatives. The design process should incorporate regulatory and technical requirements and evolve through four stages: Generic Design, Conceptual Design, Technical Design, and Detailed Design. The generic design, developed prior to site selection, must rely on conservative geological information representative of national deep geological conditions. Therefore, to ensure timely implementation of the national HLW program and successful site selection, a conceptual design reflecting Korean geological environments is essential. Such a design also contributes to enhancing public acceptance.

In this study, the stability of the proposed disposal system was evaluated under various conditions based on KORAD's preliminary disposal concept and representative in-situ stress and rock mechanical properties of deep geological formations in Korea.

# 2 Conceptual Design of the Deep Geological Repository and Deep Rock Characteristics

## 2.1 Concept of the Deep Geological Repository

The Korean disposal system conceptually proposed by the Korea Radioactive Waste Agency, referred to as the KORADIS (KOREa Advanced DIposal System), consists of two alternative repository concepts: KORAD-V (vertical disposal system) and KORAD-H (horizontal disposal system).

The engineered barrier system (EBS) of the KORAD-V vertical disposal system consists of a disposal canister emplaced vertically, a bentonite buffer surrounding the canister, and backfill material placed in the disposal tunnel. A horizontally excavated disposal tunnel is connected to multiple vertical deposition holes. Each deposition hole accommodates one disposal canister. The disposal canister is designed to contain four assemblies of pressurized water reactor (PWR) spent nuclear fuel. The KORAD disposal canister consists of a steel channel that holds the spent fuel assemblies, an inner cast iron insert, and an outer copper shell. The deposition hole is filled with block-type bentonite buffer material, while the disposal tunnel is backfilled with a mixture of bentonite and crushed rock excavated from the host rock.A schematic comparison between the KORAD-V vertical disposal canister and the Finnish canister design is illustrated in Fig. 1.

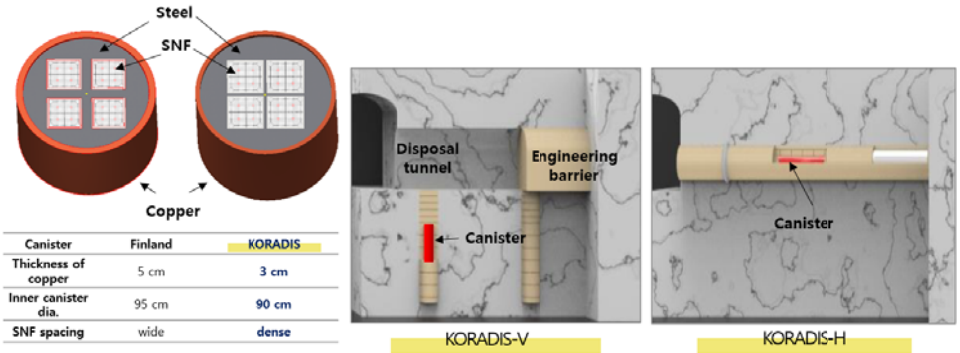



Fig. 1 Comparison of disposal canister designs between Finland and the Korean KORADIS system.

The engineered barrier system of the KORAD-H horizontal disposal system consists of a horizontally emplaced super container (disposal canister surrounded by buffer material), a lower support structure, and a disposal tunnel. A single horizontal disposal tunnel contains multiple super containers, and the surrounding space is filled with backfill material. Each disposal canister accommodates four assemblies of PWR spent nuclear fuel, identical to the canister used in the vertical disposal concept. Within the KORAD super container, the internal disposal canister is identical to that used in the vertical system. The surrounding buffer material consists of block-type bentonite. The lower support structure of the super container is also constructed using block-type bentonite, while the disposal tunnel is filled with granular bentonite backfill material.

## 2.2 In-situ Stress in Deep Geological Environment

To evaluate the stability of a deep geological repository prior to site selection, the in-situ stress conditions in Korea were reviewed. A national stress map of Korea was developed based on more than 1,400 in-situ stress measurements that have been conducted across the country over several decades (Kim et al. 2021). In addition, deep borehole investigations reaching depths relevant to repository construction, typically below 500 m, have been conducted in various rock types in relation to research on high-level radioactive waste repository site selection (KIGAM 2024). By integrating these datasets, correlations for in-situ stresses below a depth of 300 m were derived (Cheon et al. 2024). Figure 2 compares the nationwide in-situ stress correlations and patterns in Korea with those observed in the repository candidate areas of Olkiluoto in Finland and Forsmark in Sweden. The comparison indicates that the Korean Peninsula generally exhibits lower in-situ stress magnitudes and lower lateral stress coefficients compared with those of the Scandinavian Peninsula, while the variation trends with depth show similar patterns.

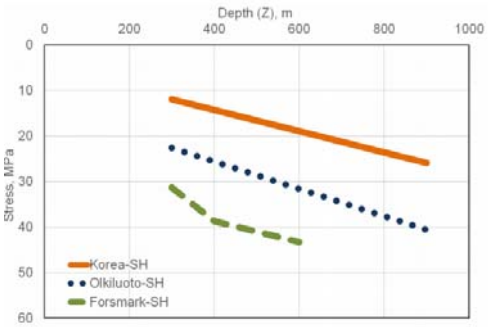



Fig. 2 Comparison of in-situ stress (major horizontal stress) pattern on South Korea, Olkiluoto in Finland, and Forsmark in Sweden at the lower 300 m depth (Cheon et al., 2024).

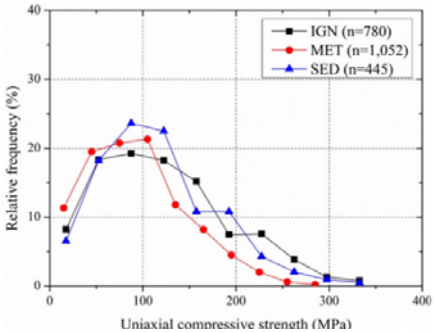



Fig. 3 Distribution of uniaxial compressive strength for igneous rocks (IGN), metamorphic rocks (MET), and sedimentary rocks (SED) (Choi et al., 2021).

The vertical stress applied in this study was determined from the overburden load. In this calculation, the specific gravity of Korean rock masses was assumed to be 2.66. Based on this assumption, the vertical stress at a depth of 500 m was calculated to be approximately 13 MPa. Using the empirical relationships between horizontal stresses and stress ratios derived from nationwide data below 300 m in Korea, the mean, major and minor horizontal stress ratios at a depth of 500 m were estimated to be approximately 1.3, 1.65, and 0.95.

## 2.3 Uniaxial Compressive Strength and Rock Mass Properties

The mechanical properties of rocks distributed throughout Korea have been reported by numerous researchers. Recently, Choi et al. (2021) compiled results from various laboratory rock tests conducted in Korea and presented a statistical analysis in which the data were classified according to rock type, strength range, and regional distribution. Figure 3 illustrates the distribution of uniaxial compressive strength according to rock type. Regardless of rock type, the strength distribution generally shows a peak around 100 MPa and exhibits a roughly symmetric distribution around this value. In most cases, the compressive strength of Korean rocks tends to fall within approximately 200 MPa. Due to the mountainous terrain that characterizes much of Korea, numerous underground structures such as tunnels have been constructed for infrastructure development. Based on site investigation data obtained during the construction of such infrastructure projects, representative rock mass properties corresponding to rock mass classification systems have been widely used in numerical analyses in civil engineering practice (Cheng et al. 2009).

# 3 Numerical Modelling

## 3.1 Governing Equations and Constitutive Model

In this study, the mechanical behaviour of the rock mass surrounding the deep geological repository was analysed using the Solid Mechanics module provided in COMSOL Multiphysics. The mechanical response of the rock mass was governed by the force equilibrium equation, which describes the balance of forces acting within the medium. To represent the relationship between stress and strain in the rock mass, the Mohr–Coulomb elastoplastic constitutive model was adopted. The governing equations and constitutive model were implemented using the built-in functionalities provided within the COMSOL Multiphysics environment.

## 3.2 Geometry of the Numerical Model

The numerical model geometry was developed based on the disposal concept proposed by KORAD. For the vertical disposal concept, the disposal tunnel was modelled as a shape consisting of a rectangular section with a width of 3.5 m and a height of 2.65 m, topped by a semi-circular arch with a diameter of 3.5 m. The total length of the disposal tunnel was set to 28 m. During numerical modelling of the rock mechanical behaviour, the excavation process was simulated by dividing the domain into multiple stages in order to capture the mechanical response of the rock mass during excavation. For computational efficiency and consistency with the tunnel geometry, the excavation of both the tunnel and the deposition holes was simulated using a full-face excavation method with a step length of 2 m.The entire numerical domain for the vertical disposal concept was defined with dimensions of 80 m in width, 120 m in height, and 192 m in length. For the horizontal disposal concept, two deposition holes with a diameter of 1.75 m and a depth of 7.962 m were constructed. These deposition holes were located at a distance of 9 m from the centre of the modelling domain. Preliminary analyses indicated that boundary effects were not significant within the selected domain size. Therefore, the numerical domain was defined with dimensions of 50 m in width, 25 m in height, and 32 m in length in order to minimize boundary effects during the numerical simulations. In the horizontal disposal concept, the disposal tunnel was modelled with a diameter of 2.5 m, and the spacing between adjacent disposal tunnels was set to 25 m. The length of the disposal tunnel was set to 24 m to ensure that the model could accommodate two disposal canisters along with the granular bentonite backfill material. This configuration considered the distance between the ends of the disposal canisters, which is 6.1 m, and the length of each disposal canister, which is 4.802 m. To evaluate the influence of the distance between the deposition holes and the disposal tunnel, a unit module was established as an analysis model featuring a single disposal tunnel and two deposition holes. Numerical simulations were performed only for this unit module in order to represent the mechanical behaviour of the overall repository system.

## 3.3 Boundary Conditions and Input Properties

The thermo-mechanical input properties used in the analysis were determined based on material properties commonly applied in civil engineering projects in Korea while considering conservative design assumptions. The reference case for the numerical simulations adopted the properties summarized in Table 1. For the thermal analysis, a time-dependent analysis was performed to account for the temporal variation of heat generation from the disposal canisters containing spent nuclear fuel. The thermal behaviour of the host rock in response to temperature changes was also incorporated into the model. The initial in-situ stress field was implemented using the Initial Stress and Strain function provided in COMSOL Multiphysics. In the mechanical analysis, the excavation sequence was explicitly considered to simulate the excavation process. However, in the thermo-mechanical analysis, the excavation stages were not modelled sequentially. Instead, it was assumed that the entire repository section was excavated instantaneously. After excavation, the excavated regions were assumed to be filled with engineered barrier components including the disposal canister, buffer material, and backfill material.

Table 1. Mechanical and hydraulic properties of rock masses used in numerical analysis.

| **Material** | **K** | **γ (kN/m³)** | **E (MPa)** | **φ (°)** | **c (kPa)** |
|---|---|---|---|---|---|
| Rock Mass | 1.3 | 26.0 | 11,700 | 40.0 | 1,400 |
| **Material** | **ρ (kg/m³)** | **k (W/m·°C)** | **Cp (J/kg·°C)** | | **α ($10^{-6}$/K)** |
| Cast Iron Insert | 7,850 | 52 | 500 | | 12 |

| Material | K | γ (kN/m³) | E (MPa) | φ (°) | c (kPa) |
|---|---|---|---|---|---|
| Rock Mass | 1.3 | 26.0 | 11,700 | 40.0 | 1,400 |
| **Material** | **ρ (kg/m³)** | **k (W/m·°C)** | **Cp (J/kg·°C)** | **α (10⁻⁶/K)** | |
| Carbon Steel Shell | 7,200 | 36 | 461 | 11.5 | |
| Copper Overpack | 8,940 | 391 | 394 | 16.9 | |
| Bentonite Buffer | 1,330 | 0.906 | 1,287 | 200 | |
| Backfill | 1,720 | 0.544 | 1,208 | 200 | |
| Crystalline Rock | 2,580 | 2.984 | 831 | 7.7 | |

** ρ: density, k: thermal conductivity, Cp: specific heat capacity, α: thermal expansion coefficient, K: in-situ stress ratio, γ: unit weight, E: elastic modulus, φ: friction angle, c: cohesion*

# 4 Stability Assessment Based on Numerical Analysis

The stability assessment of the disposal facility was conducted by comparing several scenarios. The first scenario evaluated the mechanical stability of the repository considering only the mechanical behaviour of the rock mass. The second scenario evaluated thermo-mechanical stability by simultaneously considering the decay heat generated by the spent nuclear fuel. The third scenario evaluated long-term stability by considering the reduction in the strength of the natural barrier over time after the disposal of the spent nuclear fuel. In addition, the stability of the repository was compared between the vertical disposal concept and the horizontal disposal concept. The long-term degradation of the natural barrier due to extended repository operation was represented in the analysis by a reduction in the rock mass classification grade. Figure 5 presents the distribution of equivalent plastic strain obtained from the mechanical analysis and the thermo-mechanical analysis. Although both analyses exhibited generally similar overall patterns, differences were observed in the detailed mechanical behaviour. In the thermo-mechanical analysis, the calculated strain values were generally lower than those obtained from the purely mechanical analysis. This result is interpreted as being due to the assumption that the excavated repository spaces were filled with buffer materials in the analysis model, which resulted in partial redistribution and reduction of the applied loads within the surrounding rock mass.

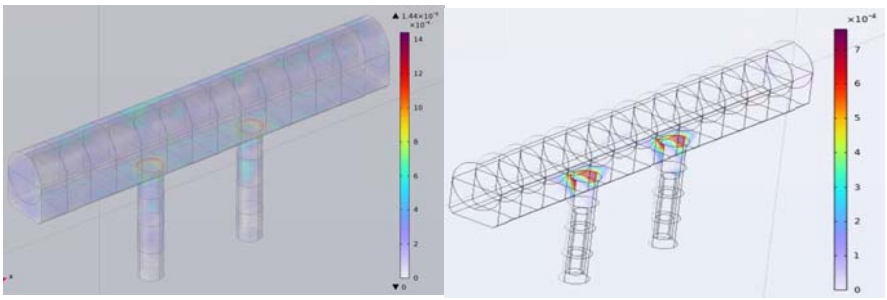


Fig. 4 Comparison of equivalent plastic strain between mechanical analysis (left) and thermo-mechanical analysis (right).

Table 2(a) presents the stress analysis results for the representative vertical disposal model under short-term and long-term conditions, respectively. The results indicate that the equivalent stress was higher under short-term conditions, whereas the maximum principal stress showed higher values under long-term conditions. Table 2(b) presents the analysis results comparing vertical disposal and horizontal disposal concepts considering both mechanical and thermo-mechanical conditions. The results show that the horizontal disposal concept generally exhibits lower stress concentration compared with the vertical disposal concept. In particular, unlike the vertical disposal case, equivalent plastic strain did not occur in the horizontal disposal configuration.

Table 2. Stress analysis results in different conditions.
(a) Short vs. long-term condition

| Analysis Type | Equivalent Stress (von Mises) | 1st Principal Stress | 2nd Principal Stress | 3rd Principal Stress |
|---|---|---|---|---|
| Short-term (Mechanical) | 62.1 | 73.5 | 37.2 | 15.3 |
| Long-term (Mechanical) | 57.8 | 81.9 | 50.5 | 24.0 |

(b) Vertical vs. horizontal disposal condition withthermo-mechanical effect

| Analysis Condition | Equivalent Stress (von Mises) | 1st Principal Stress | 2nd Principal Stress | 3rd Principal Stress |
|---|---|---|---|---|
| KORAD-V (Mechanical) | 62.1 | 73.5 | 37.2 | 15.3 |
| KORAD-H (Mechanical) | 45.4 | 49.1 | 28.9 | 15.4 |
| KORAD-V (Thermo-Mechanical) | 59.6 | 75.8 | 33.2 | 18.4 |
| KORAD-H (Thermo-Mechanical) | 48.7 | 50.6 | 30.3 | 16.9 |

# 5 Conclusion

In this study, the stability of deep geological disposal concepts considered in Korea was evaluated at the conceptual design stage. Numerical analyses were conducted for both vertical and horizontal disposal concepts using in-situ stress conditions derived from the Korean geological environment and rock mass properties based on rock mass classifications commonly used in domestic construction projects.

The results indicate that the horizontal disposal concept generally provides better mechanical stability than the vertical disposal concept under the proposed repository conditions. The horizontal disposal configuration showed lower stress concentration in the surrounding rock mass and did not produce significant equivalent plastic strain, whereas the vertical disposal concept exhibited relatively higher stress concentration around the deposition holes. Thermo-mechanical analyses considering the decay heat of spent nuclear fuel were also performed. The results suggest that the repository system maintains acceptable stability even when thermal effects are taken into account. Furthermore, long-term analyses considering potential degradation of the natural barrier indicate that the disposal system can remain stable under typical geological conditions in Korea unless extremely unfavourable geological environments occur. These results suggest that the proposed disposal concepts, particularly the horizontal disposal concept, are capable of providing stable repository conditions within the Korean geological environment at the conceptual design stage.

# Acknowledge

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