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A Study on Rock Properties Acquisition using Deep Boreholes for High-Level Radioactive Waste Disposal Site Characterization

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Abstract

High-level radioactive waste (HLW) is expected to be disposed of in rock masses at depths of approximately 300 meters or more. In Korea, the tentative disposal depth is considered to be 500 meters. Site characterization requires the assessment of over 100 evaluation parameters. This study focuses on acquiring key evaluation parameters such as uniaxial compressive strength, in-situ stress, rock mass elastic modulus, hydraulic conductivity, and joint characteristics using a 750-meter deep borehole and recovered core samples in granite area.

The uniaxial compressive strengths evaluated in this study were generally above 200 MPa, except in altered sections, and showed no significant dependence on depth. The maximum horizontal stress (S_H) was found to be (S_H) = 0.0257 × (depth) + 3.8092, with a direction of 101° ± 36° clockwise from true north. The deformation moduli of the deep rock mass, measured using a high-pressure dilatometer (HPD), ranged from 20.2 to 37.8 GPa. Hydraulic conductivity values, obtained through constant pressure injection and pulse tests, ranged from 1.6E-10 to 2.05E-8 m/s. Regarding joint characteristics, low-dip joints were predominantly observed at shallow depths, while high-dip joints became more prevalent with increasing depth. Overall, high-dip joints were more common. Alteration and calcite precipitation within joints, caused by groundwater flow, were also observed at depths below 500 meters.

This study provides critical baseline data for understanding the geological and rock properties necessary for the site characterization of high-level radioactive waste disposal and contributes to establishing a scientific foundation for selecting an appropriate disposal site.

Keywords

High-level radioactive disposal, Uniaxial compressive strength, In-situ stress, Hydraulic conductivity, rock mass deformation modulus

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1 Introduction

The status of nuclear power generation in Korea has been continuously increasing since the operation of Kori Unit 1 in April 1978, and the amount of high-level radioactive waste has also been accumulating accordingly. Currently, the waste is temporarily stored on-site at nuclear power plant facilities. According to Korea Hydro & Nuclear Power (KHNP), which is responsible for operating nuclear power plants, on-site storage facilities at Hanbit, Hanul, and Kori plants are expected to reach capacity sequentially starting in 2030. Disposal of radioactive waste is defined as ‘permanently isolating radioactive waste from human habitation,’ and high-level radioactive waste, i.e. spent nuclear fuel, must be stored in a disposal system and isolated for at least 100,000 years. The most realistic method is to construct a disposal facility in deep rock and dispose of it. Site investigations for selecting a site for the disposal of high-level radioactive waste are usually conducted in stages (IAEA 1984). After conducting a nationwide survey to exclude unsuitable areas, a basic survey is conducted on the candidate site. Through the basic survey, site characterization and suitability evaluation are performed, and the intention of the residents of the target area is confirmed to conduct the next step, which is a detailed survey. In the step-by-step site survey, 33 evaluation parameters were presented in the rock engineering field (Kim et al. 2020), and among them, uniaxial compressive strength and in-situ stress can be classified as key evaluation parameters.

In this study, the characteristics of key evaluation parameters related to rock engineering were examined using deep boreholes conducted in granite areas among crystalline rocks, so that they can be utilized when the high-level radioactive waste project begins in Korea in the future.

2 Study area

The study area is Wonju, Gangwon Province, located to the east of Seoul. The rock type in the study area is Jurassic hornblende-biotite granite from the Mesozoic era. Before conducting a 750 m deep borehole drilling, a geological field survey was carried out at sites where granite outcrops were well developed around the drilling site. The granite in the Wonju area has been dated to approximately 174 Ma and exhibits very dense rock fabric with a strength higher than hard rock. It displays a homogeneous texture of medium- to coarse-grained structure (Cheon et al. 2024a). In addition, strike-slip faults with a sense of left-handed motion in the NE-SW direction, which are consistent with the most dominant linear structure around the Wonju drilling site, are developed, and accompanying faults in the N-S direction are secondarily developed (KIGAM 2021, Cheon et al. 2022). The joint sets developed in the Wonju area are sequentially developed in the directions of NE-SW, NE-SW, NW-SW, and E-W, and are developed similarly to the linear structures developed around in the Wonju area (KIGAM 2021). Figure 1 presents the geological map and linear structures around the drilling site.

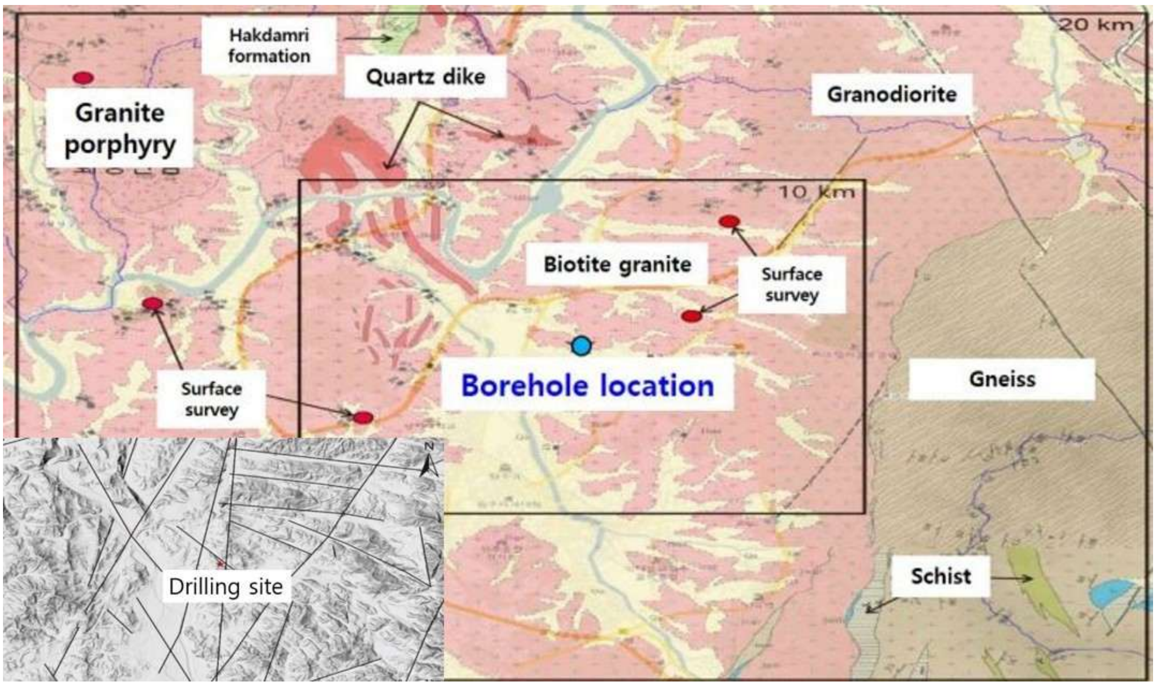

Fig. 1 Geological map and linear structure in Wonju study area

3 Rock properties of the study area

3.1 Physical and mechanical properties from drilled core

Physical and mechanical analyses were conducted at 50 m intervals using intact rock samples from granite in the Wonju area. Fig. 2 shows the physical and mechanical properties with depth. As shown in Fig.2, The change in strength with depth was not significant, and the average uniaxial compressive strength was 205 MPa. However, deviations from the expected trend were observed at depths of 450 m and 700 m, which correspond to alteration zone. This indicates that the bedrock's mechanical properties were degraded due to groundwater flow through high-dip joints. It was also confirmed that calcite was deposited on the joint surfaces in these sections (Fig. 3).

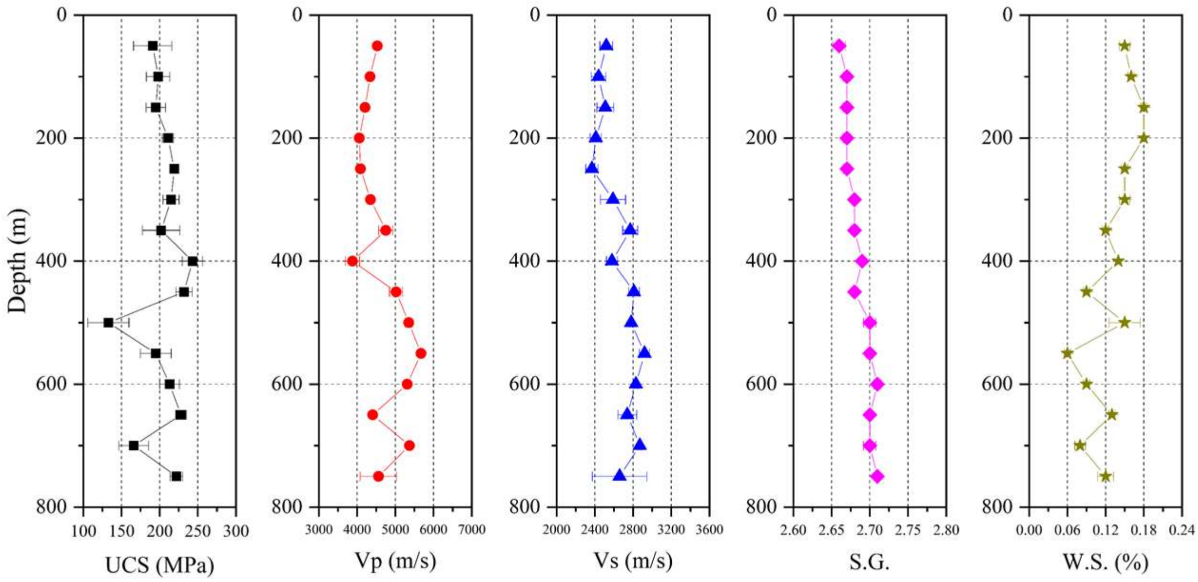

Fig. 2 Physical and mechanical properties with depth in study area (Cheon et al. 2022)

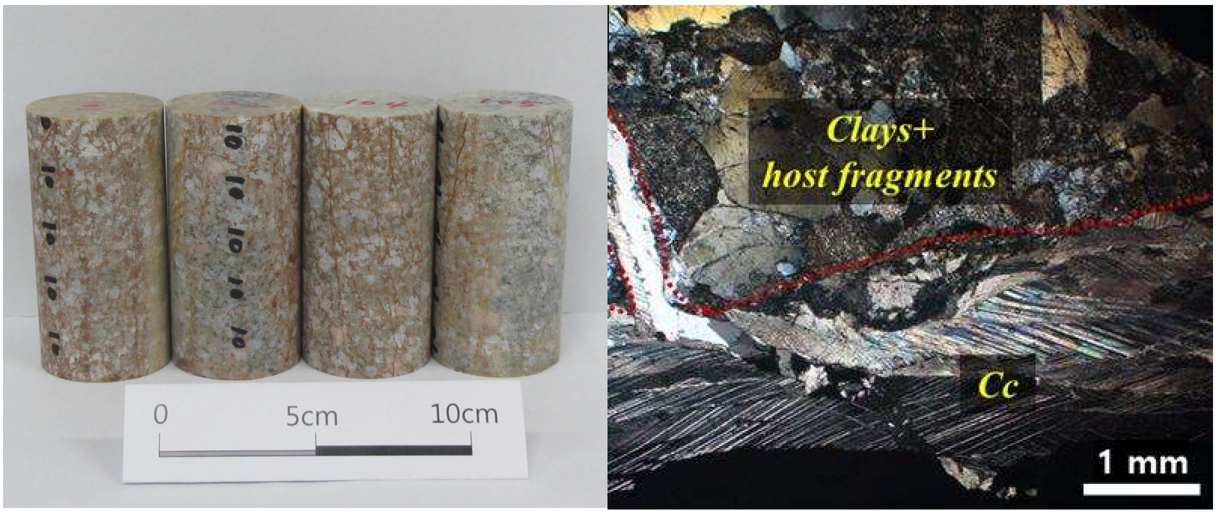

Fig. 3 Core samples(left) and calcite (Cc) precipitation on the joint surface(right) from the alteration zone (approx. 450 m depth)

3.2 In-situ stress from hydraulic fracturing test

After hydraulic fracturing tests were performed in more than 20 non-fractured sections, the magnitudes and directions of in-situ stress were evaluated as shown in Fig. 4. Consistent with general in-situ stress trends, the magnitude of in-situ stress increased with depth. The maximum horizontal stress (S_H) was found to be (S_H) = 0.0257 × (depth) + 3.8092. The directions of the maximum horizontal stress in the study area is 101° ± 36° within the NE-SE range as calculated from the Korean stress map. The stress ratio, K, is approximately 1.3.

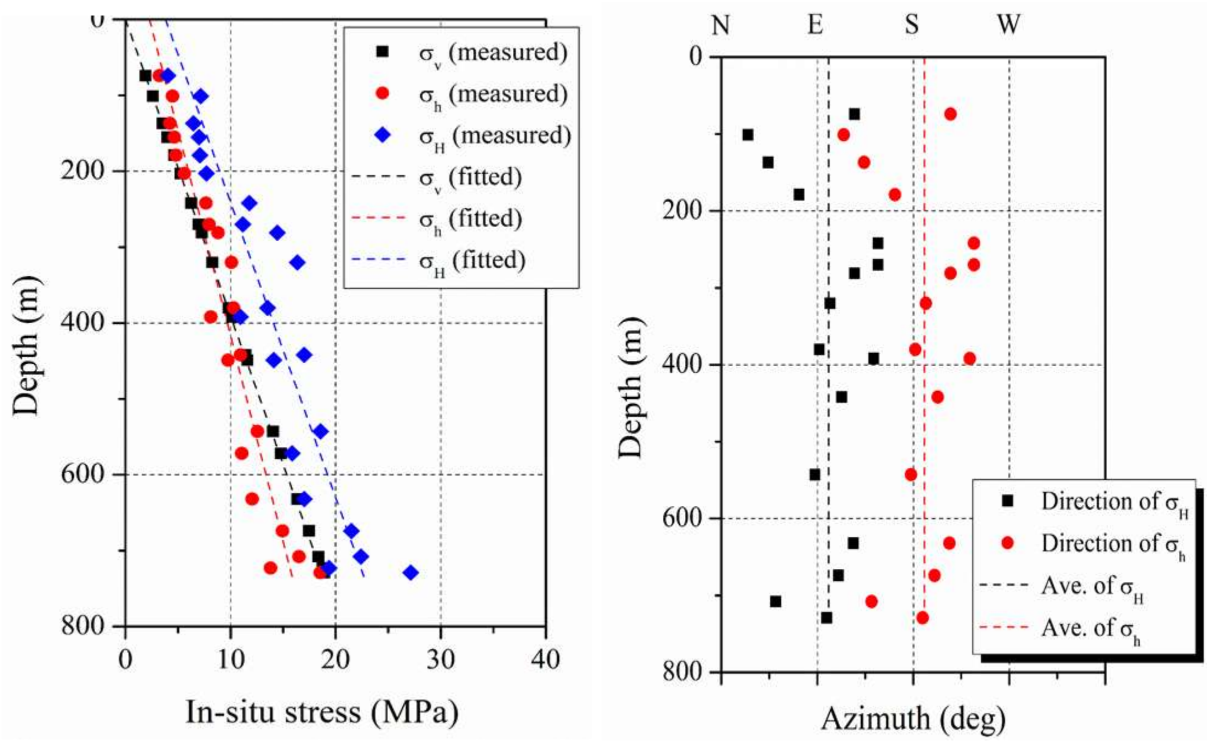

Fig. 4 The magnitudes and directions of in-situ stress (KIGAM 2021, Cheon et al. 2022)

3.3 Hydraulic conductivities

To obtain hydraulic conductivity, field hydraulic tests were conducted in 13 test intervals above a depth of 710 m, taking into account potential permeable discontinuities identified through drilled rock cores and BHTV borehole images, as well as the mechanical condition of the borehole wall. Among the 13 test intervals, constant pressure injection tests were performed in 10 intervals, and pulse tests were conducted in 3 intervals. Figure 5 shows the distribution of hydraulic conductivity values as a function of depth. The hydraulic conductivity of the test borehole in the Wonju area was found to be generally low, ranging from 1.6 x 10^{-9} to 2.05 x 10^{-8} m/s, indicating low permeability of the rock mass. Within the test intervals, the difference in hydraulic conductivity values between the lowest and highest permeability points was up to 128 times (approx. 2 orders of magnitude). Although no strong trends indicating significant variation in hydraulic conductivity with depth were observed, the lower region below a depth of 600 m showed slightly lower values compared to the upper region (Lee et al., 2024).

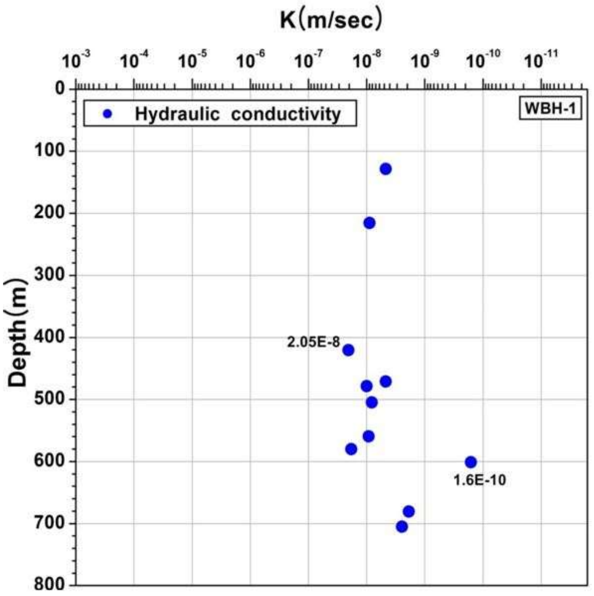

Fig. 5 Hydraulic conductivity measured in Wonju study area (Lee et al. 2024)

3.4 Rock mass deformation modulus

High-level radioactive waste disposal facilities are located at depths of at least 300 m underground, necessitating the measurement of the in-situ rock mass deformation modulus in the section where the waste disposal facility is located. However, conventional methods, such as the Goodman jack, are generally applicable only at relatively shallow depths. In this study, a high-pressure dilatometer (HPD) from Cambridge Insitu Ltd. was used to measure the deformation modulus of deep rock mass. Tests were conducted at depths of 101.5 m, 200 m, 301.8 m, 404.5 m, and 449 m. Figure 6 shows the pressure-displacement curves obtained for the entire testing interval. The deformation modulus calculated from these tests ranged from 20.2 to 37.8 GPa. The lowest value, 20.2 GPa, was measured at the 101.5 m depth, while the highest value, 37.8 GPa, was observed at the 449 m depth.

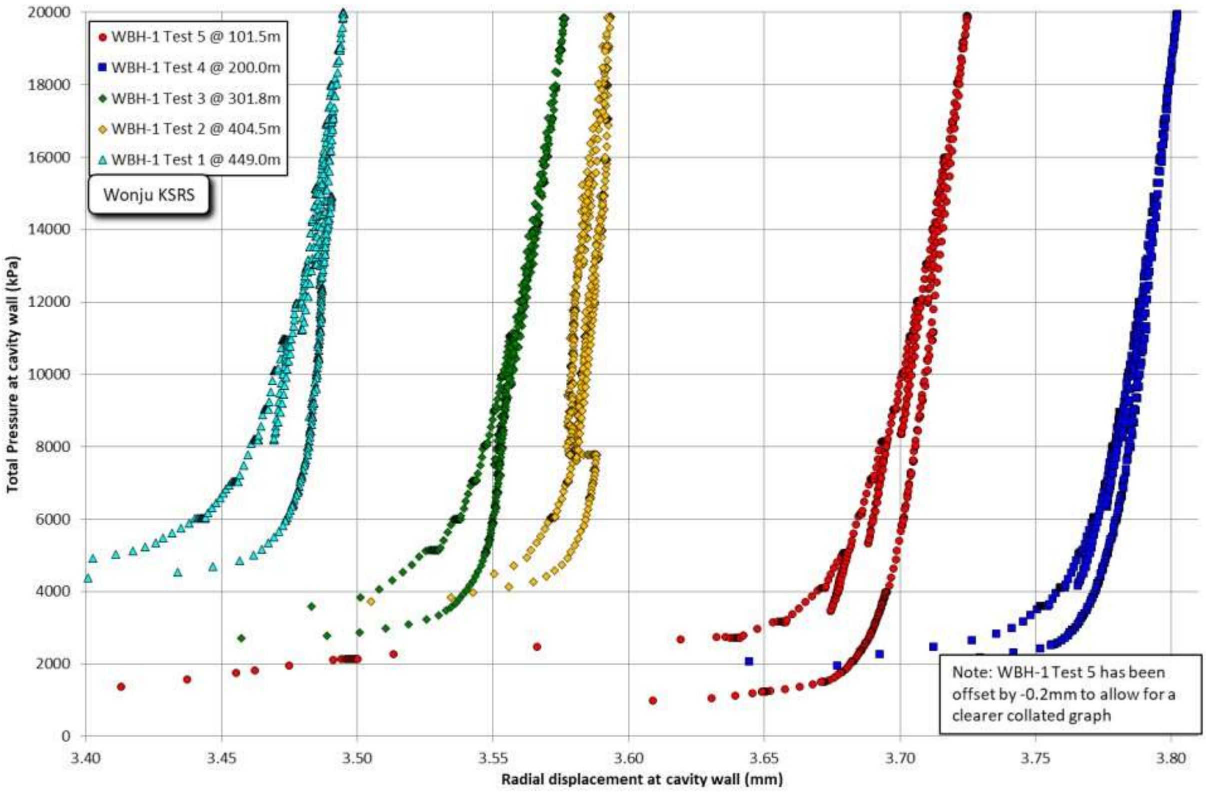

Fig. 6 Pressure versus displacement from HPD tests

3.5 Fracture features in the borehole

Various discontinuities exist in the rock mass, and they are critical factors in characterizing high-level radioactive waste disposal sites, as they affect both mechanical stability and pathways for radionuclide migration. This section utilizes joint information obtained from ATV analysis. Additionally, borehole deviation was considered to accurately calculate the orientation of the joints, including dip and dip direction.

The distribution of joints in the granite of the study area by depth is shown in Fig. 7. A total of 518 joints were detected below a depth of 50 m (Cheon et al. 2024b). These were categorized based on dip into low-dip (~30°), medium-dip (30–60°), and high-dip (60–90°) joints, and their distribution by depth was visualized. High-dip joints were the most frequent, with 284 occurrences, followed by medium-dip joints (231), and low-dip joints (61), which were the least common. Overall, joint frequency exhibited a relatively linear trend with depth, but a slight increase in frequency was observed beyond 400 m. When all joints identified throughout the borehole were projected onto a stereo net and clustered, as shown in Fig. 8, the primary joint sets had dip/dip directions of 68/171 and 35/42.

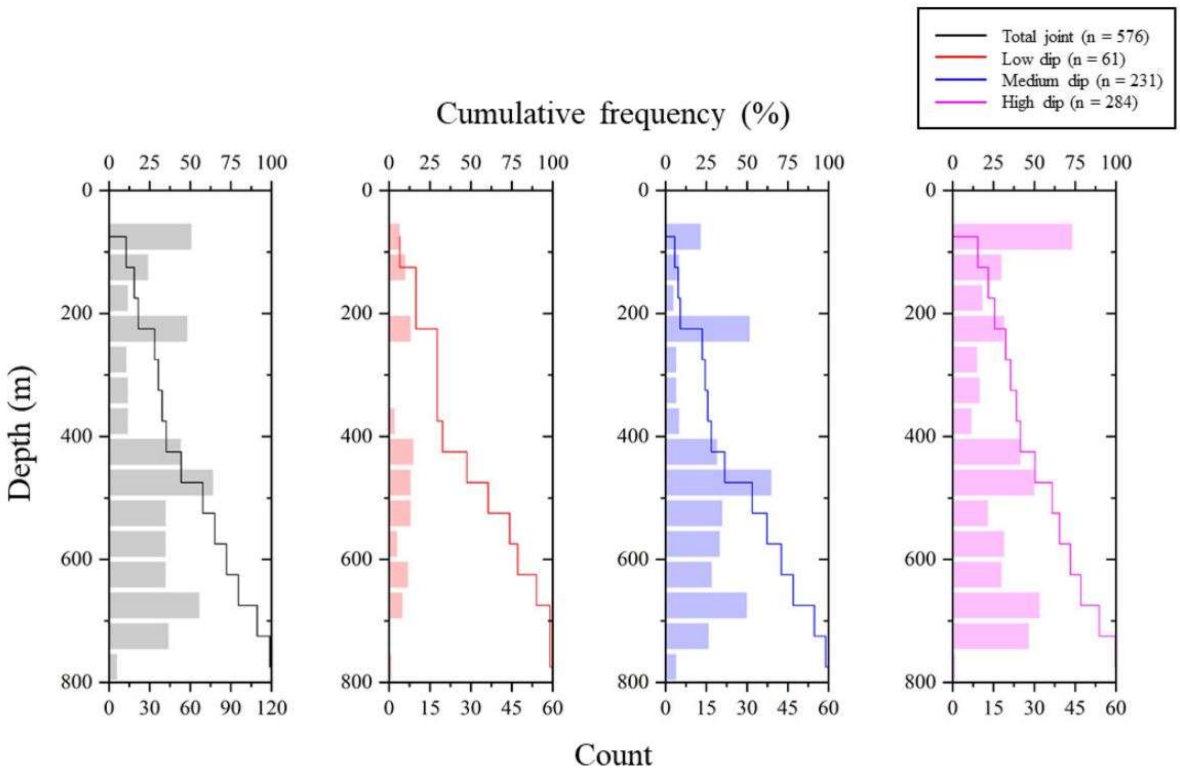

Fig. 7 Joint distribution with depth and dip

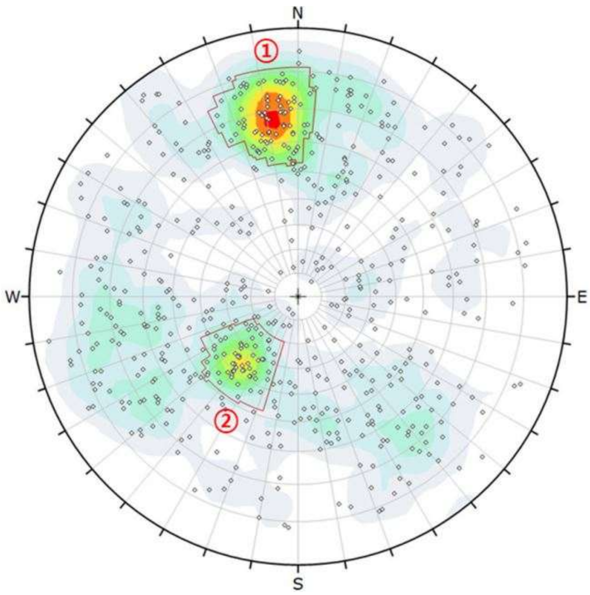

Fig. 8 Joint clustering and main joint sets in study area

4 Conclusion

This study focuses on the deep borehole investigations conducted in the Wonju granite area, part of the Jurassic period of the Mesozoic era, and evaluates the mechanical and hydraulic properties of the deep subsurface. Key evaluation parameters related to the selection of high-level radioactive waste disposal sites were obtained, including major mechanical properties such as uniaxial compressive strength, in-situ stress, fracture characteristics, and rock mass deformation modulus, as well as key hydrogeological properties like hydraulic conductivity.

The methods for obtaining these properties primarily involved deep borehole testing techniques such as hydraulic fracturing tests, constant pressure injection tests, borehole expansion tests, and geophysical logging methods like ATV. Some properties were also determined through laboratory testing of recovered borehole cores. It was observed that groundwater flow through high-dip joints, which are predominantly developed in the granite of the study area, can generate alteration zones and precipitates such as calcite, potentially weakening the mechanical properties such as strength. The direction of in-situ stress aligns with the overall stress orientation of the Korean Peninsula, and the range of hydraulic conductivity, which provides pathways for radionuclide migration, was identified.

The testing methods and data acquired through this study can serve as essential baseline information for site selection projects for high-level radioactive waste disposal.

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