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Mechanical aperture characteristics of rock fractures around the KURT site based on conditioned genetic DFN model

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1. Introduction

The natural barrier must delay the migration of radioactive nuclides over a prolonged period. Therefore, understanding the characteristics of rock fractures, which act as the primary migration pathways for nuclides, is essential. Aperture is one of the key hydro-mechanical parameters of these fractures. This study focused on the mechanical behavior of fractures and analyzed the mechanical aperture characteristics around the KURT (KAERI Underground Research Tunnel) site. The block-scale KURT site model was developed using the conditioned genetic discrete fracture network (DFN) method and integrated with 3DEC, a widely used distinct element method (DEM) program, to analyze the mechanical aperture characteristics. The input data for the DFN model were derived by analyzing face mapping data from KURT, and the mechanical aperture model was constructed using empirical formulas from previous studies and laboratory test results from samples collected around the KURT site. The variation in mechanical aperture with changes in the magnitude of principal stresses was analyzed, and the results were presented in relation to the orientation and size of the fracture sets.

2. Modeling methods

The analysis of mechanical aperture characteristics in the block-scale rock mass involved constructing and utilizing a mechanical behavior model in conjunction with a DFN model. This chapter provides a brief overview of the models used in this study.

2.1. Conditioned genetic DFN model

The DFN generation methods include the conventional stochastic and genetic modeling approaches. The genetic modeling approach is known to be advantageous for reproducing trace distributions observed on actual rock surfaces [1], but effective utilization of this approach requires a conditioning process on growth parameters. Recently, a new conditioning technique that utilizes trace length distribution from sampling windows has been proposed [2]. This technique has the advantage of not requiring assumptions about fracture size distribution; therefore, it was adopted in this study to construct a conditioned genetic DFN model for the KURT site. Figure 1 presents the pseudo-code for the genetic DFN generation process in the technique.

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Algorithm: Genetic DFN generation
Input growth parameters:
growth exponent/rate, nuclei rate/orientation
nuclei length/ exponent, growth time (stepsize*numsteps)
Initialize: fractures
Start
  for step from 1 to numsteps
    Generate nuclei by nuclei rate/orientation and
    nuclei length following probability distribution of:
      p_N(l) = (b − 1)/l_N · (l/l_N)^(−b)
    Add fracture entities to fractures:
    fracture.radius, fracture.arrest
    for Each fracture in fractures
      if not arrested
        l_{t+1} = (l_t^{1−a} + (1 − a)CΔt)^(1/(1−a))
        Update fracture.radius = l_{t+1}
      else continue
    end
    for Each fracture in fractures
      if fracture is in contact with larger fracture
        fracture.arrest = true
        Update fracture.radius =
        [distance to larger fracture]
      end
    end
  end
finish
```

Fig. 1. Pseudo-code of genetic DFN generation [2].

2.2. Mechanical aperture model

The mechanical aperture model was constructed using results from previous studies and laboratory tests. First, a size-dependent initial aperture was applied, based on research indicating a linear relationship between fracture apertures and their size [3]. The linear coefficient was derived from laboratory test results on samples collected from the KURT site, as shown in Equation (1).

(1) $e_0 = 3e^{-3} \times D$

where e_0 is the initial mechanical aperture, D is the diameter of the fracture.

Second, a stress-dependent normal stiffness model was applied, based on the commonly used hyperbolic fracture closure model [4]. The model describes the relationship between normal stress and stiffness and includes two coefficients (a and b), as shown in Equation (2).

$$(2)\quad k_n = \frac{d\sigma_n}{du_n} = \frac{a}{(a - bu_n)^2}$$

where k_n, σ_n, and u_n represent the normal stiffness, applied normal stress, and normal displacement of the fracture, respectively.

The two coefficients are defined by two fracture parameters: the maximum closure (V_m) and the initial normal stiffness (k_{ni}). These parameters were determined from experimental data obtained at the KURT site [5], as detailed in Equations (3) and (4).

$$(3)\quad V_m = \frac{a}{b} = 3.177 \times e_0^{1.291}$$

$$(4)\quad k_{ni} = \frac{1}{a} = 184.601 \times e_0^{-2.244}$$

2.3. Fracture trace data in the KURT

The conditioning technique used in the conditioned genetic DFN model requires trace length distribution data. Accordingly, face mapping data collected from the KURT site were utilized to construct the block-scale KURT site model. Trace maps were extracted from the mapping data of 33 stations, and their length distributions were analyzed. Figure 2 presents an example of the face mapping data analysis from one station.

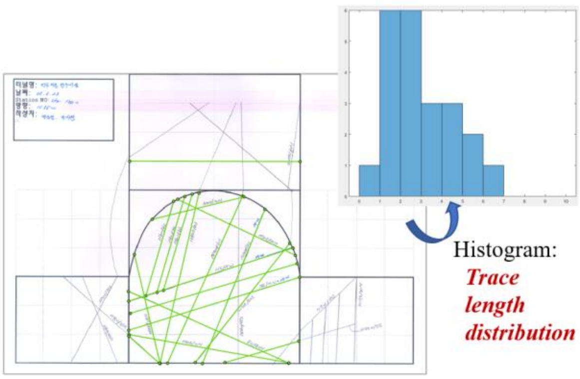

Fig. 2. An example of the face mapping data analysis.

3. Mechanical aperture analysis

The block-scale KURT site model was constructed to analyze the changes in mechanical aperture in response to varying principal stress magnitudes. In this study, the conditioned genetic DFN model was implemented using MATLAB code, while the mechanical aperture model was implemented in 3DEC using FISH functions. Figures 3 and 4 illustrate an example of a model generated using the conditioned genetic DFN model and its mechanical analysis in 3DEC.

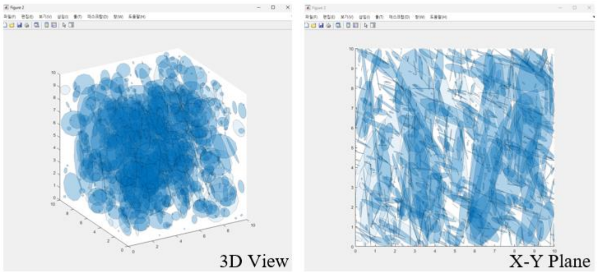

Fig. 3. An example of conditioned genetic DFN model.

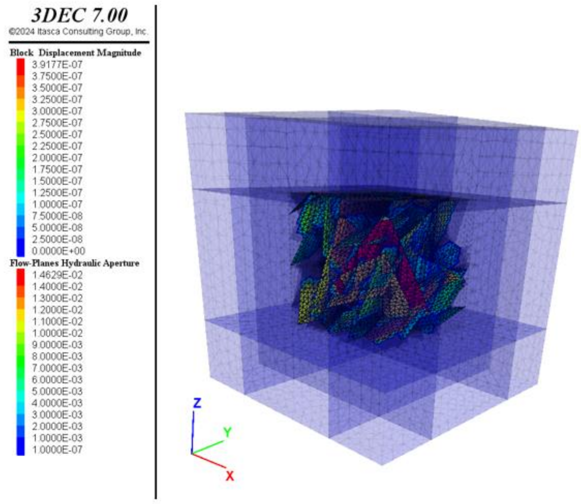

Fig. 4. An example of mechanical analysis in 3DEC.

We examined the mechanical aperture characteristics under varying magnitudes of vertical and horizontal principal stresses and related the results to the orientation and size of the fracture sets. According to the face mapping data, four fracture sets are distributed across the KURT site, as shown in Figure 5.

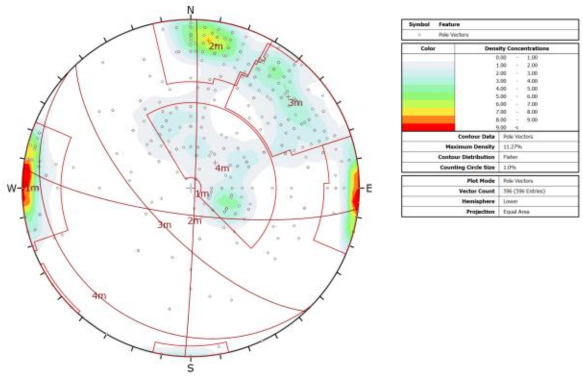

Fig. 5. Fracture set distribution around the KURT site

4. Concluding remarks

This study presents a block-scale KURT site model, serving as fundamental research for the prospective development of an equivalent porous media (EPM) model via equivalent properties. Consequently, it is anticipated to make significant contributions by constructing a site descriptive model for KURT and developing a coupled hydro-mechanical model for demonstration at a generic underground research laboratory (URL).

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