MODELING THE HYDRAULIC CHARACTERISTICS OF A FRACTURED ROCK MASS WITH CORRELATED FRACTURE LENGTH AND APERTURE: APPLICATION IN THE UNDERGROUND RESEARCH TUNNEL AT KAERI

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A three-dimensional discrete fracture network model was developed in order to simulate the hydraulic characteristics of a granitic rock mass at Korea Atomic Energy Research Institute (KAERI) Underground Research Tunnel (KURT). The model used a three-dimensional discrete fracture network (DFN), assuming a correlation between the length and aperture of the fractures, and a trapezoid flow path in the fractures. These assumptions that previous studies have not considered could make the developed model more practical and reasonable. The geologic and hydraulic data of the fractures were obtained in the rock mass at the KURT. Then, these data were applied to the developed fracture discrete network model. The model was applied in estimating the representative elementary volume (REV), the equivalent hydraulic conductivity tensors, and the amount of groundwater inflow into the tunnel. The developed discrete fracture network model can determine the REV size for the rock mass with respect to the hydraulic behavior and estimate the groundwater flow into the tunnel at the KURT. Therefore, the assumptions that the fracture length is correlated to the fracture aperture and the flow in a fracture occurs in a trapezoid shape appear to be effective in the DFN analysis used to estimate the hydraulic behavior of the fractured rock mass.

KEYWORDS : Discrete Fracture Network, Correlation between Fracture Length and Aperture, Equivalent Hydraulic Conductivity, Representative Elementary Volume, Groundwater Inflow, KURT.

1. INTRODUCTION

In order to access the performance of a disposal facility of high-level radioactive waste, it is necessary to first investigate the geological, mechanical, chemical, thermal, and hydraulic characteristics and solute transport of the deep rock mass, preferably with real scale data obtained from an underground research laboratory. Many countries have constructed underground research laboratories in order to investigate the disposal of high-level nuclear waste and have conducted testing for the disposal of such waste in deep rock masses, including the Korea Atomic Energy Research Institute (KAERI), which has constructed an underground research tunnel (KURT).

The three-dimensional hydraulic characteristics of a rock mass are generally simulated using either the equivalent porous medium (EPM) model or the discrete fracture network (DFN) model. The EPM approach is based on the assumption that groundwater flows through a geological

continuum; however, this may have limited applicability when the geological medium is dominated by a fracture system with well defined fracture sets, as commonly observed in crystalline rock masses. This difficulty arises because crystalline rock masses have negligible permeability within the rock matrix, meaning that the flow through and permeability of the rock mass is largely controlled by the fracture system.

The DFN model is widely used to simulate the hydraulic characteristics of fractured crystalline rock masses. The DFN approach relies on stochastic realizations of the fracture systems using Monte Carlo simulations in order to improve the reliability of the DFN models, thereby providing improved evaluations of the effects of the size of the sampling domain, the existence of a representative elementary volume (REV), and the overall hydraulic properties [1].

Fracture systems in rock masses are geometrically complex. In the DFN approach, each hydraulic and geometric property of the fractures (e.g. aperture, shape, location, length, orientation) is assumed to be statistically distributed. Although most previous studies that have employed a DFN model assumed no correlation between the fracture aperture and length [1-7], other studies have demonstrated that such a correlation exists [8, 9]. Because faults and large fractures usually have higher values of hydraulic transmissivity than smaller fractures, thereby controlling the flow within and the permeability of the rock mass, it is reasonable to assume that a correlation exists between the fracture aperture and length.

It has been suggested that the fluid flow in a fracture may occur through one or many channels [10]. Thus, it is reasonable to use equivalent one-dimensional (1D) pipes to conceptually represent the flow in a two-dimensional (2D) fracture in order to simplify and minimize the complexity of the flow. In a three-dimensional (3D) DFN, the fractures are generated as equivalent circular discs, and the intersection lines are determined between the fractures. Most previous 3D DFN studies have assumed that the flow in a fracture occurs through a rectangular pipe placed between the center of the fracture disc and the midpoint of the intersection line. Thus, the length of the pipe is the distance between the center of the fracture disc and the midpoint of the intersection line, and the width is assumed to be proportional to the pipe length [10]. However, it is also reasonable to consider the flow between any two intersecting fractures as a 2D trapezoid [3].

The objective of this paper is to develop a 3D DFN model that can simulate the hydraulic characteristics of a fractured rock mass, considering the correlation between the distribution functions of the fracture aperture and length, and assuming that the flow occurs through 2D trapezoidal channels in order to create a more practical and reasonable model. This model is then applied to an analysis of the KURT constructed by KAERI.

2. HYDRAULIC AND GEOMETRIC PARAMETERS AND ASSUMPTIONS FOR THE 3D DFN MODEL

2.1 Hydraulic and Geometric Characteristics of Fractures

Disc-shaped fractures are assumed in the 3D DFN model in this study due to their advantages in formulating mathematical expressions. In order to describe a fracture, it is necessary to determine its diameter (d), center position (x, y, z), direction vector (l, m, n), and aperture (a). The spatial positions of fractures are assumed to follow a Poisson distribution; i.e. the centers of the fractures are located randomly in a three-dimensional space. This assumption requires that the rock mass does not contain bedding planes, fracture zones, or geological structures [11-13].

Fracture orientations are assumed to follow Fisher's distribution. If the rock mass contains asymmetric features in the orientation distribution, the Fisher's distribution cannot be correctly assumed. If θ is the angle of deviation from the mean orientation angle, then

$$\theta = \cos^{-1} \left[\frac{\ln \{e^k - F(e^k - e^{-k})\}}{K} \right] \quad (1)$$

where F is a random number uniformly distributed in the range $0 \leq F \leq 1$ and K is the Fisher constant [14]. The Monte Carlo method is then used to generate the fracture orientations based on Eq. (1).

The fracture aperture is generally assumed to follow a log-normal distribution [15, 16]. The probability density function (PDF) for the log-normal distribution of fracture apertures (h) can be written, in a general form, as

$$f_A(h) = \frac{1}{h\sigma\sqrt{2\pi}} e^{-\frac{(\ln h - \mu)^2}{2\sigma^2}} \quad (2)$$

where μ and σ are the mean and standard deviation of the natural logarithm of the fracture aperture, respectively. (By definition, the logarithm of the fracture aperture is normally distributed.) The cumulative distribution function (CDF) for the log-normal distribution of fracture apertures is given by:

$$F_A(h) = \frac{1}{2} + \frac{1}{2} \operatorname{erf} \left[\frac{\ln h - \mu}{\sigma\sqrt{2}} \right] \quad (3)$$

where erf is the error function, which can be written by:

$$\operatorname{erf}(h) = \frac{2}{\sqrt{\pi}} \int_0^h e^{-t^2} dt \quad (4)$$

A log-normal distribution of fracture apertures is characterized by a long tail of large aperture values. Because the measurement technique has upper and lower detection limits, the distribution function commonly has a sampling bias known as a truncation threshold. In numerical modeling using data on a mapped fracture system, the use of the truncated distributions of fracture apertures and lengths cannot be avoided because these distributions are a direct consequence of the *in situ* fracture mapping. Then, the truncated probability density function (TPDF) for the log-normal distribution of fracture apertures is given by:

$$f_{TA}(h) = \frac{f_A(h)}{\int_{h_a}^{h_b} f_A(t) dt}, \quad h_a \leq h \leq h_b \quad (5)$$

where h_a and h_b are the lower and upper aperture limits, respectively.

The truncated cumulative distribution function (TCDF) for a log-normal distribution is given by:

$$F_{TA}(h) = \int_{h_a}^h f_{TA}(t)dt = \frac{\int_{h_a}^h f_A(t)dt}{\int_{h_a}^{h_b} f_A(t)dt} = \frac{F_A(h) - F_A(h_a)}{F_A(h_b) - F_A(h_a)}, \quad h_a \leq h \leq h_b \quad (6)$$

In this study, based on the results of the field mapping at KURT, the fracture lengths follow a negative exponential distribution. The PDF and CDF for the negative exponential distribution of the lengths (l) can be written, in a general form, as:

$$f_L(l) = \lambda e^{-\lambda l} \quad (7)$$

$$F_L(l) = 1 - e^{-\lambda l} \quad (8)$$

where λ is a parameter of the distribution, often called the “rate parameter”, and $1/\lambda$ is the mean fracture length. The negative exponential distribution of the fracture lengths, as well as the log-normal distribution, is characterized by a long tail of large aperture values. The TPDF and TCDF for negative exponential distributions of fracture lengths are then given by:

$$f_{TL}(l) = \frac{f_L(l)}{\int_{l_a}^{l_b} f_L(l)dl}, \quad l_a \leq l \leq l_b \quad (9)$$

$$F_{TL}(l) = \int_{l_a}^l f_{TL}(t)dt = \frac{\int_{l_a}^l f_L(t)dt}{\int_{l_a}^{l_b} f_L(t)dt} \quad (10)$$

$$= \frac{F_L(l) - F_L(l_a)}{F_L(l_b) - F_L(l_a)} = \frac{e^{-\lambda l_a} - e^{-\lambda l}}{e^{-\lambda l_a} - e^{-\lambda l_b}}.$$

The fracture diameters were derived using a negative exponential distribution function based on the results of the field mapping at KURT.

2.2 Correlation between Fracture Aperture and Length

Observations of fracture properties based on the results of field mapping have led researchers to propose a relationship between the fracture trace length and aperture [17-20]. It was reported that the relation between the length and width (aperture) must be considered probabilistically [17]. Furthermore, it was found that the clustering of vein trace lengths reflects a greater frequency of smaller fractures and is typically a consequence of the power-law size distribution [18]. In the study by Dreuzy *et al.* [19], through studies of the relationship between the measured fracture length and maximum opening displacement of fracture populations in the Kelduhverfi and Myvatn areas in Iceland, it was found that the correlation between the fracture length and aperture follows a power law with different values of proportionality constants and exponents. Furthermore, it

was found that the correlation relationship between the fracture length and aperture followed a power law:

$$L = kT^\alpha \quad (11)$$

where L and T are the trace length and thickness (aperture), respectively, and k and α are scaling constants [20].

The most comprehensive study on the correlation between the fracture aperture and length on field mapping results was reported by reference [21]. The study of the scaling properties of tensile fractures in the Krafla fissure swarm in northern Iceland demonstrated that there is a distinct break in the slope in the aperture-length scaling relationship. In the study, a multi-scale log-linear curve was fitted to the data using a least squares method in order to quantify the results:

$$W = s_1(L - L_0) + W_0, \quad L \leq L_0$$

$$W = s_2(L - L_0) + W_0, \quad L \geq L_0 \quad (12)$$

where W is the log-maximum aperture, L is the log fracture length, and s_1 and s_2 are the scaling exponents. The subscripts indicate the fracture length and aperture corresponding to the break in slope. This break in the slope was qualitatively interpreted as an indicator of a non-universal, scale-dependent growth mechanism.

The above studies illustrated certain correlations between the fracture length and aperture; nevertheless, the studies proposed quite different relationships and a general relationship for the correlation between the fracture aperture and length remains to be elucidated. However, it is evident from the available measurement data and observations that the aperture and length of the fractures are indeed correlated, even though a universally valid correlation function may not exist with the power law relationship appearing to be the dominating type of such correlations.

In this study, it is assumed that the TCDF for the log-normal distribution of fracture apertures (h) has random numbers that are the same as those of the TCDF for the negative exponential distribution of the fracture length l . Using this concept, the fracture lengths generated in the 3D DFN model have a power law relationship to the fracture apertures. Based on this, Eq. (13) can be written as follows:

$$\frac{F_A(h) - F_A(h_a)}{F_A(h_b) - F_A(h_a)} = \frac{e^{-\lambda l_a} - e^{-\lambda l}}{e^{-\lambda l_a} - e^{-\lambda l_b}} \quad (13)$$

Eq. (13) leads to a relationship between the fracture length and aperture in the form of Eq. (14):

$$l = -\frac{1}{\lambda} \ln \left[e^{-\lambda l_a} - (e^{-\lambda l_a} - e^{-\lambda l_b}) \times \frac{F_A(h) - F_A(h_a)}{F_A(h_b) - F_A(h_a)} \right] \quad (14)$$

Fig. 1 shows the correlation between the fracture aperture and length plotted using these relations and the input data from KURT.

Fig. 1. The Correlation between the Fracture Aperture and Length Plotted using the Input Data of KURT

2.3 Flow Analysis in Trapezoidal Channels

Fig. 2 shows the intersection lines and nodes of six fractures in a discrete fracture network. Each fracture in the network that contributes to the groundwater flow should intersect at either at least two other fractures or at least one fracture and a boundary. The flow region from the center of a fracture to the center of an intersection line, or vice versa, can be considered as a trapezoid, as shown in Fig. 2, in which b_c is the width at one end of the flow path where it crosses the diameter of the fracture and b_L is the width at the other end of the flow path, equal to the length of the intersection line between the fracture and another fracture or the fracture and a boundary. The width b_c may be approximated using the following Eq. (15) [3]:

$$b_c = 2D \times b_L / \sum_{i=1}^{N_L} b_L \quad (15)$$

where D is the diameter of the fracture, and N_L is the total number of intersections between the fracture and the other fractures or boundaries. N_L should exceed 2 in order to ensure that the flow occurs in the fracture. $b_L / \sum_{i=1}^{N_L} b_L$ is a weighting factor that is calculated assuming that b_c is

proportional to b_L . According to Eq. (15), even if a fracture intersects numerous other fractures, the sum of the b_L values in the fracture must be double that of the fracture diameter.

If a case as presented in Fig. 2 is assumed, the flow paths between fracture F_b and F_c are the trapezoid 1256 and 2345. If the water head of the fracture F_b is larger than that of fracture F_c , the flow occurs from fracture F_b to fracture F_c through trapezoid 1256 and 2345, and vice versa. In this case, the N_L of fracture F_b and F_c are 2 and 4, respectively. Furthermore, the b_c of fracture F_b equals the diameter of fracture F_b (D) because the length of the intersection line between fractures F_a and F_b equals that between fractures F_b and F_c . If it is assumed that the b_L values of the length of the intersection lines between fractures F_c and F_b , F_c and F_d , F_c and F_e , and F_c and F_f are 6, 2, 3 and 1, respectively, the width b_c that is one end of the trapezoidal flow path 2345 can be calculated as the length of the diameter of fracture F_c (D). Then, the sum of the four b_L values in fracture F_c is double that of the diameter of fracture F_c .

According to Darcy's law, the flow rate Q (L^3/t) of

(a) Intersection lines and nodes of the six fractures

(b) Flow in fractures F_b and F_c

Fig. 2. Example of the Intersection Lines and Nodes of the Six Fractures and Flow in a Fracture Network: R_{bc1} and R_{bc2} are the Length of the Trapezoidal Flow Path 1256 and 2345, and C_b and C_c are the Center of the Fracture F_b and F_c

the trapezoidal flow path can be written using Eq. (16) [3], as follows:

$$Q = \frac{Km(b_L - b_C) \frac{H_C - H_L}{R}}{\ln\left(\frac{b_L}{b_C}\right)} \quad (16)$$

where K is the hydraulic conductivity (L/t), m is the fracture aperture (L), H_C is the hydraulic head at the side of the trapezoidal flow region with the width b_C , H_L is the hydraulic head at the side of the trapezoidal flow region with the width b_L , and R is the distance between the two ends of the trapezoidal flow path. Thus, $(b_L - b_C)/\ln(b_L/b_C)$ is the width of the rectangular flow path that has an equivalent flow rate to the trapezoidal flow path.

3. APPLICATION OF THE MODEL TO KURT AT KAERI

3.1 Development and Validation of the DFN Model

Using the above assumptions, a program that can generate 2D and 3D DFNs, analyze the connectivity of the generated fractures, and then estimate the equivalent hydraulic conductivity tensors was developed (Fig. 3). The equivalent linear pipe fluid flow DFN model adopted in this study may be applicable when the fracture system contains numerous fractures of relatively small but uniform sizes. However, when the fracture sizes are not small but vary over a significant range, this DFN model may not be valid. Therefore, validation of the model must be undertaken before application in the KURT at KAERI because the KURT has large fracture lengths.

Fig. 3. Screen Capture of the DFN Program Developed in this Study

Table 1. Information of the Fracture Sets used by Park *et al.* [22]

Fracture Set		1	2	3
Orientation	Dip / Dip direction (°)	89.3 / 158.6	87.2 / 251.4	15.6 / 067.8
	Fisher K	9.95	7.46	7.17
Density (1/m ³)		0.1260	0.0476	0.0226
Aperture	Mean (mm)	2.78	3.01	3.90
	Standard deviation (mm)	3.49	3.49	4.57
Mean length (m)		2.74	2.45	2.91

Field mapping was undertaken at Yeosu in Korea and the equivalent hydraulic conductivity was estimated for a domain size of $50 \times 50 \times 50 \text{ m}^3$ using a commercial code NAPSAC [22]. The fracture geometry used by Park *et al.* [22] is summarized in Table 1 and the mean fracture lengths were not small and are similar to those of KURT. Thus, using the fracture data in Table 1, the equivalent hydraulic conductivities were estimated and compared with the results presented by Park *et al.* [22]. In order to avoid boundary effects, sufficiently large ‘parent’ DFN models of $200 \times 200 \times 200 \text{ m}^3$ in size were first generated based on the characterization parameters of the fracture system. From each of the ten large parent network models, smaller DFN models of $50 \times 50 \times 50 \text{ m}^3$ were extracted and the equivalent hydraulic conductivities were calculated. Then, the mean values of the equivalent hydraulic conductivities were compared with the results of Park *et al.*

[22] (Table 2 and Fig. 4). Table 2 and Fig. 4 illustrate that the results of this study are very similar to those of Park *et al.* [22]. Therefore, it was decided that the DFN model of an equivalent pipe fluid flow could be applied to the KURT at KAERI because it has similar mean fracture lengths to those of Park *et al.* [22].

3.2 Geology of KURT

An underground research tunnel, KURT, has been constructed beneath a steep slope of a mountainous area near Korea Atomic Energy Research Institute (KAERI). Various *in situ* validation experiments were planned in order to access the performance of the disposal system for high-level radioactive waste (Fig. 5). Vertical and inclined boreholes were drilled in order to obtain the geological, mechanical, hydraulic, and geotechnical

Fig. 4. Comparison of the Equivalent Hydraulic Conductivities Calculated in this Study with Those Presented by Park *et al.* [22]

Table 2. Comparison of the Results of this Study with the Results of Park *et al.* [22]

Unit: 1 × 10 ⁻⁹ m/s)		
Hydraulic conductivities	This study	Park et al. [22]
K _{xx}	4.76	3.92
K _{yy}	3.86	4.76
K _{zz}	5.37	7.79
K _{xy}	0.23	0.17
K _{yz}	0.25	0.19
K _{zx}	0.77	0.18

Fig. 5. Layout of KURT at KAERI

Table 3. Summary Details of the Fracture Sets within the Granite Rock Mass into which KURT was Constructed

Fracture Set		1	2	3
Orientation	Dip / Dip direction (°)	86 / 184	60 / 300	78 / 079
	Fisher K	7.85	5.02	3.28
Density (1/m ³)		0.390	0.241	0.072
Aperture	Mean (mm)	7.976		
	Standard deviation (mm)	0.079		
Mean length (m)		3.10	2.92	2.20

characteristics of the rock mass at the site. KURT, which has a maximum depth of 80 m from the surface, length of 255 m (access tunnel, 180 m; research modules, 75 m), and dimensions of 6 × 6 m in a U shape, was excavated

in a rock mass consisting of gneissic granite and granitite rock. Fifteen boreholes at the site provide the geologic and hydraulic data that are collected via a televiwer and packer tests. Table 3 lists the geometrical characteristics

of the three fracture sets identified at the site. The three fracture sets are identified and the orientations of the three sets follow the Fisher distributions. Also, the lengths and apertures of the fracture sets follow the negative exponential and the log-normal distributions. The fracture data set demonstrated high fracture densities and highly dispersed fracture patterns characterized by low Fisher constants.

3.3 Estimation of the Representative Elementary Volume of KURT

In order to apply an equivalent continuum approach for a rock mass, the REV should be investigated for the hydraulic behaviour of the rock mass. The REV for the hydraulic behaviour is defined as the size beyond which the hydraulic conductivity of the rock mass remains the same. For sizes larger than or equal to the REV size, the equivalent continuum approach can be applied for the rock mass [3].

In order to avoid boundary effects, sufficiently large 'parent' DFN models of $200 \times 200 \times 200$ m in size were first generated based on the characterization parameters of the fracture system. From each of the large parent network models (parent domains), smaller DFN models (analysis domains) were extracted with sizes varying from $5 \times 5 \times 5$ m to $50 \times 50 \times 50$ m for the REV studies (Fig. 6). Then, the minimum, maximum, mean, and coefficient of variation (CV) were calculated for the hydraulic conductivity of 10 DFN realizations of different sizes.

The obtained results of the hydraulic conductivity K_{xx} , K_{yy} , K_{zz} , K_{xy} , K_{yz} , and K_{zx} were plotted as a function

of the DFN model size, including the minimum, maximum, mean, and CV values (Fig. 7). With an increasing DFN side length, the difference between the minimum and maximum values of the hydraulic conductivity K_{xx} , K_{yy} , and K_{zz} , and the corresponding CV value, decreases. It was reported that the model size at a CV value of 20% or less can be approximated as a REV value [8]. However, in this study, the changes in the hydraulic conductivity K_{xx} were sufficiently large when the CV value was approximately 20%. For DFN side lengths greater than 17.5 m, the hydraulic conductivity K_{xx} demonstrated a slight change and the CV fell below 15%. In this study, it was assumed that the REV value is the DFN side length when the CV value is below 15%. Therefore, the REV value was 17.5 m for KURT.

3.4 Determination of 3D Hydraulic Conductivity Tensor at KURT

In order to determine the hydraulic conductivity tensor at KURT, a DFN cube of 20 m in size was extracted from the center of a cube with a size of 200 m because it is larger than the REV size at KURT. The DFN cube was extracted in a number of different orientations in order to calculate the directional hydraulic conductivity. The first block was selected in order that six boundaries of the cube were perpendicular to the north (Y) direction, the east (X) direction, and the vertical direction (Z). Then, by rotating the block at 30° increments around the vertical axis, east axis, and north axis, the directional hydraulic conductivities were calculated at every 30° increment. In this manner, the directional hydraulic conductivity was

Fig. 6. Example of a Parent Domain and an Analysis Domain

Fig. 7. Minimum, Maximum, Mean, and Coefficient of Variation of the Calculated Hydraulic Conductivities for the DFN Models with Different Sizes

calculated in a total of 62 directions covering the 3D space. Fig. 8 and Fig. 9 show the variation of the directional hydraulic conductivity on the 2D planes and in the 3D space; they also illustrate that the hydraulic conductivity at KURT is significantly anisotropic forming a sub-vertical ellipsoid because all fracture sets are vertical or sub-vertical.

Table 4 provides the principal directions for the hydraulic conductivity tensor at KURT calculated using the least squared error method when the polyhedron in Fig. 9 was assumed as the ellipsoid. Note that two of these directions (K_2 , K_3) are sub-horizontal and the third direction (K_1) is sub-vertical. Also, note that all fracture sets of KURT are

Fig. 8. Variation of the Directional Hydraulic Conductivity (in 10^{-8} m/s) in 2D Planes: (a) on the Horizontal Plane, (b) on the Vertical Plane Striking NS, and (c) on the Vertical Plane Striking EW.

Fig. 9. Variation of the Directional Hydraulic Conductivity in a 3D Space: (a) View along the Direction with a 190° Trend and 15° Downward Plunge, and (b) View along the Direction with a 230° Trend and 15° Downward Plunge.

Table 4. Directions of the Principal Hydraulic Conductivities of the KURT

Trend of K_1	Downward plunge of K_1	Trend of K_2	Downward plunge of K_2	Trend of K_3	Downward plunge of K_3
85	86	281	4	191	1

sub-vertical. It could be concluded that the fracture system at KURT causes the direction of the major principal hydraulic conductivity. Furthermore, the ratio between the major principal hydraulic conductivity (K_1) and the minor principal hydraulic conductivity (K_3) was approximately 2.4.

3.5 Groundwater Flow into KURT

The groundwater flow was monitored in KURT at 177 m away from the tunnel entrance (Fig. 10). The observation data were used to validate the numerical simulations. In order to estimate the amount of groundwater flow into KURT, a DFN model was created with a

cube with a side length of 200 m and a tunnel with the same dimensions as KURT. Cubic samples with sizes of 16, 21, 26, 31, 36, 41, 46, 66, and 86 m were selected from the center of the cube in order to investigate the effect of the DFN side length on the estimates of the groundwater flow into the tunnel. For the above cube sizes, the distances from the tunnel side to the side boundary were 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, 20.0, 30.0, and 40.0 m, respectively. It was necessary to conduct this investigation in order to determine the region of influence of the effective region of the fracture length. For each sample, the tunnel was placed horizontally at the center of the cube (Fig. 11).

Fig.10. Observations of the Groundwater Flow into the Tunnel at 177 Meters from the Tunnel Entrance of the KURT.

Fig.11. The Cubic Sample used to Simulate the Groundwater Inflow into the Tunnel

In order to implement the conceptual and numerical model, a custom computer program was used to obtain all necessary information, including the intersections between fractures, between fractures and boundaries, between fractures and the tunnel, and the groundwater flow into the tunnel. A constant head boundary condition was applied to boundaries B5 and B6, and a trapezoid head boundary condition was applied to boundaries B1 to B4. For each cube size, 20 DFN analyses were simulated. Fig. 12 shows variations of the predicted groundwater flow into the tunnel at each model size. With an increasing DFN side length, the difference between the minimum and maximum groundwater flow into the tunnel decreased. For the DFN side lengths greater than 41.0 m, the groundwater flow showed little variation. The average amounts of groundwater flow into the tunnel were 21.96, 22.08, 21.73, and 22.02 m³/day when the DFN side lengths were 41.0, 46.0, 66.0, and 86.0 m. Furthermore, as seen in Fig. 10, the average amount of groundwater flow into the tunnel observed by the flowmeters was 21.11 m³/day. Therefore, these average values of groundwater flow into the tunnel estimated using the DFN model are similar to that observed by the flowmeters.

It was noted that the REV value of the equivalent hydraulic conductivities was 17.5 m for KURT. Furthermore, a DFN side length of 41.0 m indicated that the distance between the tunnel side and side boundary was 17.5 m. Therefore, the REV values of the hydraulic conductivities and groundwater inflows into the tunnel were almost identical. Accordingly, the boundaries must be placed at a distance from the tunnel side and crown that exceeds the REV size.

4. DISCUSSIONS AND CONCLUSIONS

A numerical model was developed to simulate the hydraulic behaviour of KURT; it was based on a three-dimensional discrete fracture network assuming a correlation between the fracture length and aperture, as well as a trapezoidal flow path in the fractures in order to produce more effective flow simulations in a fractured rock mass. The DFN model that assumes the equivalent linear pipe fluid flow is capable of representing the characteristics of the fluid flow in a fractured rock mass as a result of the model simplicity through the application of hydraulic and geometric parameters. Furthermore, the model requires fewer computer resources and can solve field problems in larger scales.

Meanwhile, in many studies it has been reported that the lengths and apertures of fractures are correlated. Attempts have been made to find relationships between the fracture length and aperture using positive linear correlations or power-law correlations [17-21]. When the fracture length and aperture are correlated, the few larger fractures with higher apertures dominate the fluid flow in a fracture system [8]. This means that the DFN model that is applied to the correlation between the fracture length and aperture requires fewer computer resources and can solve field problems in larger scales through the elimination of smaller fractures.

Via a televiwer and packer tests of fifteen boreholes at the site, the geologic and hydraulic data of fractures in the rock mass at the KURT were obtained. These data were applied to the developed fracture discrete network model. A block with a size of 17.5 m was determined as

Fig.12. Variations of the Predicted Groundwater Inflow into the Tunnel at Each Model Boundary

the REV value that can represent the hydraulic behaviour of the rock mass at the KURT. The amount of groundwater flow into the tunnel was estimated to be approximately 22 ton/day, which is very similar to the in-situ data monitored by the flowmeters at the KURT. Furthermore, the distance between the tunnel side and side boundary at the REV size of the groundwater flow into the tunnel was determined to be 17.5 m, which is the same as the REV size of the equivalent hydraulic conductivities. This indicates that the tunnel walls become boundaries. Thus, when several boundaries except the basic six boundaries of the DFN model exist, such as two tunnels in a rock mass, the minimum distance between the boundaries must be greater than the REV size.

The developed discrete fracture network model has the capability of determining the REV size for a rock mass with respect to the hydraulic behaviour and estimating the groundwater flow into the tunnel at the KURT. Furthermore, the assumptions that the fracture length is correlated to the fracture aperture and the flow in a fracture occurs in a trapezoidal shape appear to be effective in the DFN analysis estimating the hydraulic behaviour of the fractured rock mass. The validity of the conclusion drawn in this study is restricted to the assumptions that the fracture lengths are negatively exponentially distributed and the apertures of fractures are log-normally distributed. Thus, the impact of other possible distributions of fracture lengths and apertures, such as the power law and gamma distributions, are not examined. Moreover, depending on the site specific conditions, the assumption that the fracture length and aperture are not correlated can be more able to estimate the hydraulic characteristics of a rock mass. Further study is planned for these cases in the future.

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