PROBABILISTIC TRANSPORT PATH ANALYSIS THROUGH THREE-DIMENSIONAL DISCRETE FRACTURE NETWORKS FOR UNDERGROUND RADIOACTIVE WASTE DISPOSAL FACILITIES

Doo-Hyun Lim

18300 NE Union Hill Road, Redmond, WA 98052, USA, Golder Associates Inc., dlim@golder.com

Probabilistic transport paths are estimated with a Monte-Carlo approach by identifying the shortest paths through the three-dimensional stochastic discrete fracture network (DFN) for a hypothetical geologic high-level radioactive waste repository. A numerical repository model consists of a disposition tunnel and a surrounding fracture rock represented by a stochastic DFN. The shortest path, identified for a given fracture rock system, is the most probable advective transport path providing the earliest arrival of radionuclides released from the repository to the environment. One hundred Monte-Carlo simulations of DFN are modeled for each of three different fracture intensity systems. Probabilistic density function (PDF) and complementary cumulative distribution functions (CCDF) of the shortest path lengths are obtained for each fracture system as results of the analysis. The current study for a hypothetical repository shows that the probability of the shortest transport path lengths longer than i) the minimum geometrical distance between a source and a target locations is 1.0 (CCDF=1.0), and ii) two times of the minimum distance between a source and a target locations is greater than 0.73 (CCDF=0.73) for the fracture intensity systems considered in this study. Results show that the minimum geometrical distance between the source and target location is not appropriate to be considered as the shortest flow and transport path length for the reference (or representative) case (CCDF=0.5) because those are too conservative (i.e., CCDF > 0.5).

I. INTRODUCTION

Radioactive wastes can be disposed either in a near-surface facility or in a deep geologic repository depending on the level of radioactivity of the wastes (Refs 1, 2). Disposal facilities or repositories for the intermediate and/or high-level radioactive wastes (HLW) are generally considered to be located in a deep underground low permeable rock. In these low permeable rock, nearly all the permeability is in the fractures. A fracture is any separation in a geologic formation, such as a joint or a fault that divides the rock into two or more pieces. In this study, the joints are considered as the fractures where those are characterized stochastically. A fractured rock can be represented by a stochastic DFN (Ref. 3). Groundwater and radionuclides can migrate mainly through the connected network of fractures. Estimation of paths for the groundwater flow and the radionuclide transport is one of the key factors in the safety assessment of geologic disposal of the radioactive wastes (Ref. 4).

A simplified numerical model is considered for a hypothetical geologic HLW repository. A disposition tunnel is located in a deep underground fractured rock. Groundwater and radionuclides can migrate mainly through the connected networks of fractures, and their transport paths through the fractured rock are highly heterogeneous and anisotropic (Refs 1, 3, 4). Potential transport paths of radionuclides are estimated with a Monte-Carlo approach by identifying the connected paths through the three-dimensional stochastic DFN between the disposition tunnel and the side boundary of the model. Among the potential transport paths through a three-dimensional stochastic DFN, the shortest transport path is one of the key parameters for the probabilistic safety assessment of the HLW repository because these identified shortest paths are the preferable migration paths providing the earliest arrivals of the released radionuclides from the geologic repository to the environment.

II. CONCEPTUAL MODEL

A hypothetical HLW repository is considered to be located in a deep underground (~500m depth) fractured rock. In the current study, a disposition tunnel (5m width x 15m height x 50m length) is located in the middle of the modeling volume (500m x 500m x 500m) as shown in Fig. 1 based on KBS-3V design concept (Ref. 5). A minimum geometrical distance between the tunnel and the side boundary of the model is 225m.

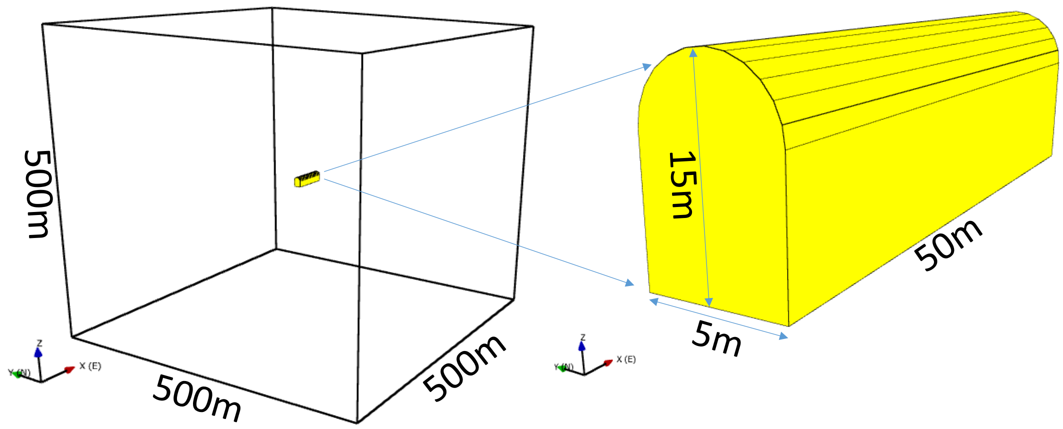


Fig. 1. Modeling area with a disposition tunnel for a hypothetical deep geologic HLW repository

The fractured rock surrounding the hypothetical repository (i.e., disposition tunnel) is represented by a stochastic DFN in the model volume of 500m scale. Fracture parameters (size, orientation, intensity) from JAEA Horonobe underground research laboratory (URL) are used in the current analysis (Refs 3, 4).

Orientation of the conductive fractures was determined by two orientation sets, i.e., Set 1 as Fisher distribution with a mean pole trend of 16.9, a mean pole plunge of 18, and Fisher constant of 3.84; Set 2 as Fisher distribution with a mean pole of 63.6, a mean pole plunge of 6.4, and Fisher constant of 8.4 (Ref. 4). Contributions of fracture intensity are 64% for Set 1 and 36% for Set 2.

The fracture size (equivalent radius) was determined as the power-law distribution by the tectonic continuum approach using data from the outcrops and faults (Ref. 3). Power-law distribution fit to this data has a slope of -1.5, corresponding to a power-law distribution parameter *D* of 3.5 with an assumed minimum size of 1.5m.

Volumetric fracture density P_{32} [m^2/m^3] is expressed as the total fracture area per unit volume. Three different fracture systems are considered with different fracture intensity values, i.e., P_{32} [m^2/m^3] =0.06, 0.05, and 0.04.

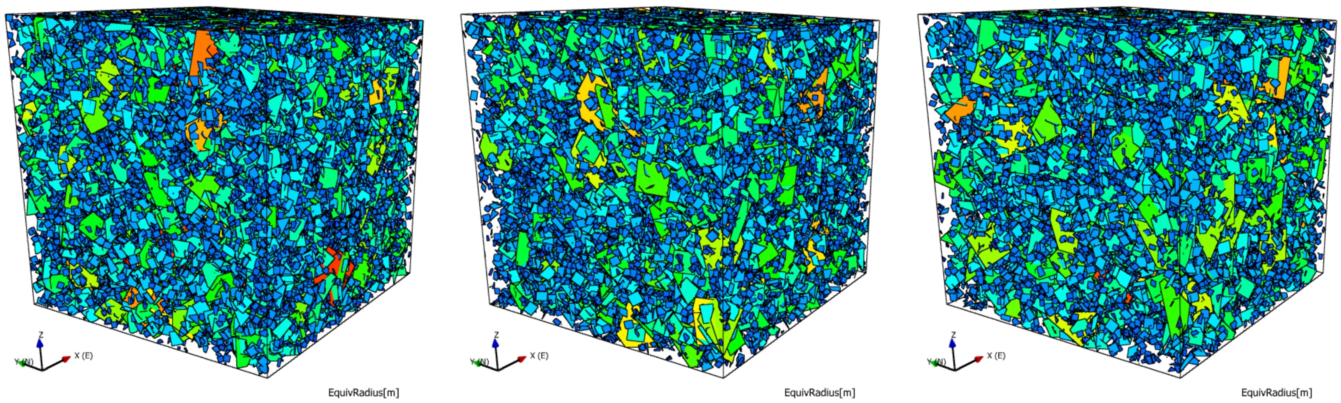
Radionuclides, escaped from the engineered barriers (i.e., canister, bentonite buffer, backfill), can migrate from the disposition tunnel into the environment through the surrounding fractured rock (Ref. 1). Without analyzing a flow field (e.g., finite element method) and a transport field (e.g., finite element method or particle tracking) numerically through the three-dimensional DFN, fractures connected between the disposition tunnel (i.e, source) and the side boundary of the model (i.e., target) are identified geometrically, and then the shortest connected path is determined for each of realized stochastic DFNs. Monte-Carlo approach is adopted to assess the probabilistic distributions of the shortest transport paths for three different fracture systems.

III. NUMERICAL SIMULATION & RESULTS

A hypothetical geologic repository for high-level radioactive waste is modeled numerically by FracMan® (Ref. 6). Three different fracture intensity systems are considered as given in Table I (Refs. 3, 4).

TABLE I. Three Cases of Fracture Systems

Case	**Fracture Intensity, P_{32} [m^2/m^3]**	**Fracture Orientation (Ref. 4)**	**Fracture Size (Equivalent Radius) (Ref. 3)**
A	0.06	Set 1: Fisher (16.9, 18), k=3.84 Set 2: Fisher (63.6, 6.4) k=8.4	Power Law Distribution (*D*=3.5 and r_0=1.5m) with generated equivalent radius between 5m and 50m.
B	0.05		
C	0.04		



(a) Case A: P_{32}=0.06 [m^2/m^3] (b) Case B: P_{32}=0.05 [m^2/m^3] (c) Case C: P_{32}=0.04 [m^2/m^3]

Fig. 2. A Particular Realization of Discrete Fracture Network for Three Fracture Systems

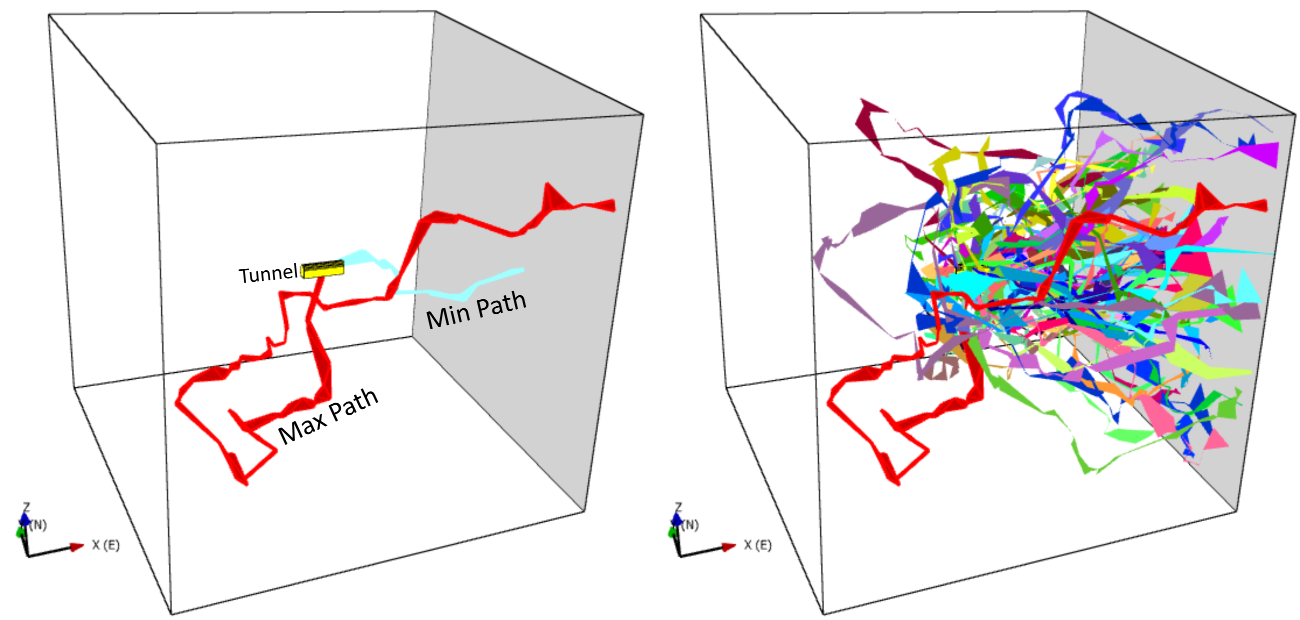
A particular realization of DFN for Cases A, B, and C is shown in Fig. 2. The number of generated fractures are 30450, 24729, and 19811 for Cases A, B, and C, respectively. Although it is very difficult to see the visual discrepancy among three cases, probability to have connected networks of fractures between the disposition tunnel and the side boundary is very different for three cases, such as 70% for Case A, 19% for Case B, and 0% for Case C.

For each realization of DFN for each case, the shortest path is identified among connected fractures between the disposition tunnel (i.e., source) and the side boundary of the model space (i.e., target). The shortest path for each DFN is the most probable advective transport path providing the earliest arrival of radionuclides released from the repository. If there is no connected networks of fractures for a particular DFN, the shortest path is not existed for that DFN. This (no connected network between the source and the target) implies that there is no advective transport path for this DFN, and thus transport lengths and travel time are generally greater due to the combination of advective and diffusive transports than the DFN with connected networks of fractures. 100 Monte-Carlo simulations of DFN are modeled for Cases A, B, and C. Note that the shortest path is identified as single path for each given DFN. Resulting statistics of the identified shortest path lengths for all cases are summarized in Table II.

For Case A (i.e., P_{32}=0.06 [m^2/m^3]), connected networks of fractures are available for 70 realized DFNs out of 100 realized DFNs. Fig. 3(a) shows the minimum shortest path of 308m and the maximum shortest path of 1481m among 100 realized DFNs. Fig. 3(b) shows the total of 70 identified shortest paths for 100 realized DFNs, while there is no connected network of fractures for other 30 DFNs. For Case B (i.e., P_{32}=0.05 [m^2/m^3]), only 19 DFNs have connected networks of fractures (i.e., 19 shortest paths) as shown in Fig. 4. For Case C (i.e., P_{32}=0.04 [m^2/m^3]), connected networks of fractures are not existed for all 100 realized DFNs mainly because the fracture intensity for Case C is below the percolation threshold (Ref. 7), where the number of fractures are not enough to make a connection between the source and the target locations. Thus, results related to the shortest paths for Case C are not available as shown in Table II.

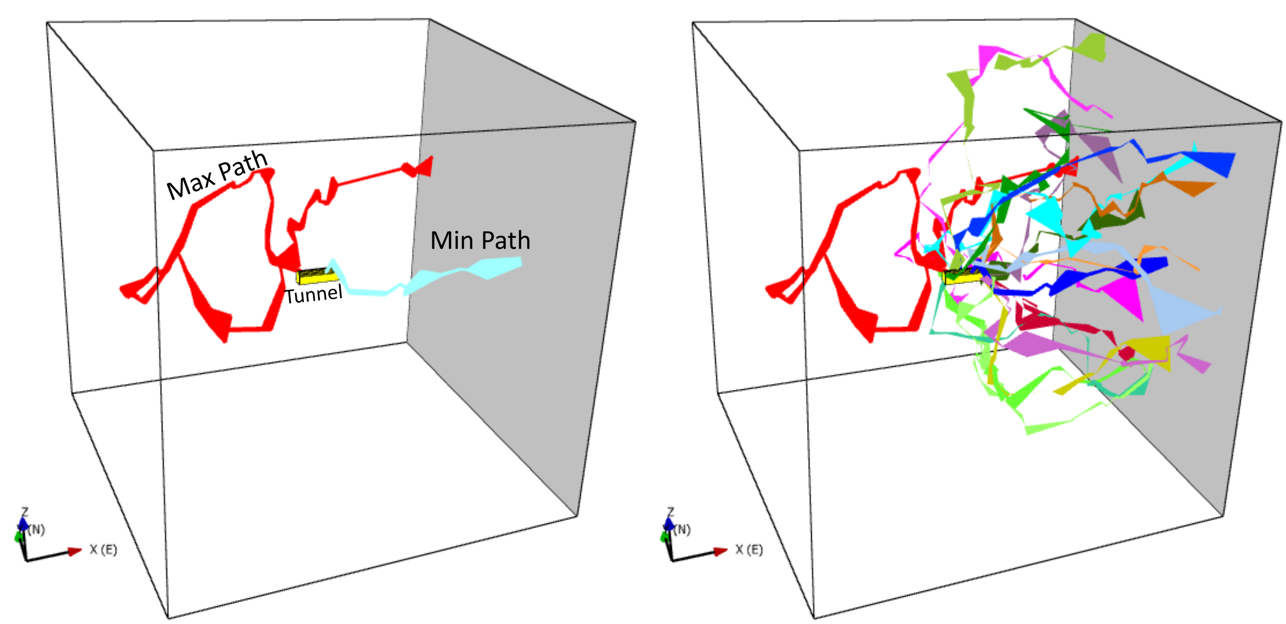
TABLE II. Statistics of Shortest Path Lengths

Parameters	**Case**		
	A	**B**	**C**
Fracture Intensity P_{32} [1/m]	0.06	0.05	0.04
Probability to connect between a tunnel and the east boundary	0.7	0.19	0
Min Shortest Path Length [m]	308	339	Not available
Mean Shortest Path Length [m]	549	587	Not available
Max Shortest Path Length [m]	1481	1268	Not available
Standard Deviation of Shortest Path Length [m]	199	222	Not available



(a) Min and Max Shortest Paths among 100 DFNs (b) Total of 70 Shortest Paths among 100 DFNs

Fig. 3. Shortest Paths for Case A



(a) Min and Max Shortest Paths among 100 DFNs (b) Total of 19 Shortest Paths among 100 DFNs

Fig. 4. Shortest Paths for Case B

Frequency of the shortest path lengths for Cases A and B are shown in Fig. 5. In the frequency graph (Fig. 5), bin size is 100m for Cases A and B. The 1st bin of Case A in Fig. 5 shows that there are 14 identified shortest paths ranging between 300m and 400m (i.e., average of 350m) over 100 realizations of DFNs for this case.

Probability density functions (PDFs) of the shortest path lengths for Case A and Case B are shown in Fig. 6. In Fig. 6, PDFs show that the probability of the shortest path length of 350m is 0.14 for Case A and is 0.03 for Case B. Complementary cumulative distribution functions (CCDFs) of the shortest path lengths are shown in Fig. 7. For Case A in Fig. 7, CCDF of 0.5 is corresponding to the shortest path length of 592m, and it is interpreted as a probability to get the shortest path length longer than 592m is 50% for Case A. Results in Fig. 7 show that the probability of the shortest path lengths greater than 1000m is 33% for Case A and 82% for Case B. Results show that the transport path lengths tend to increase as the fracture intensity decreases.

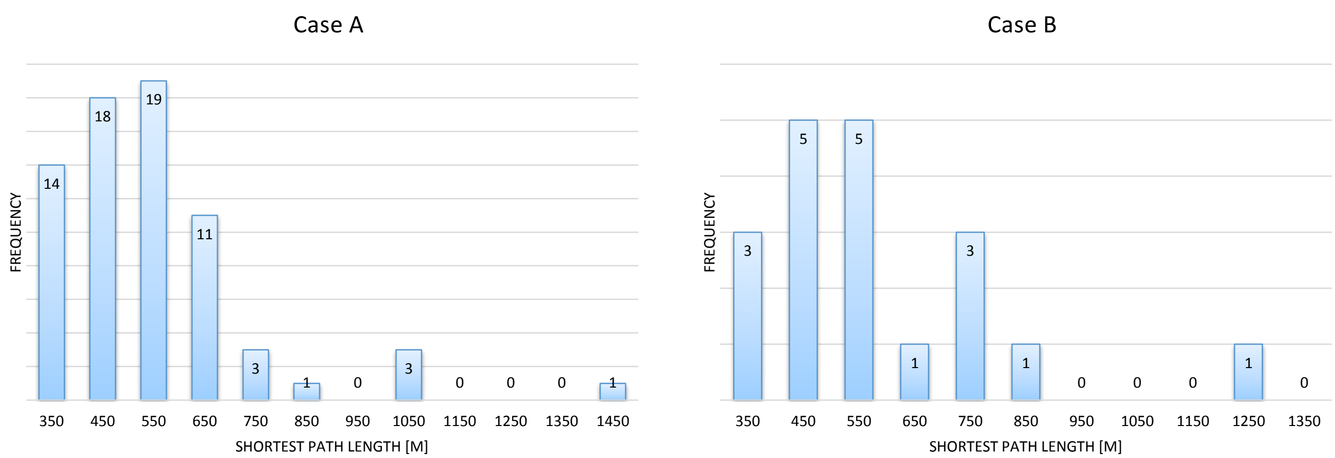


Fig. 5. Frequency of Shortest Path Lengths for Case A and Case B

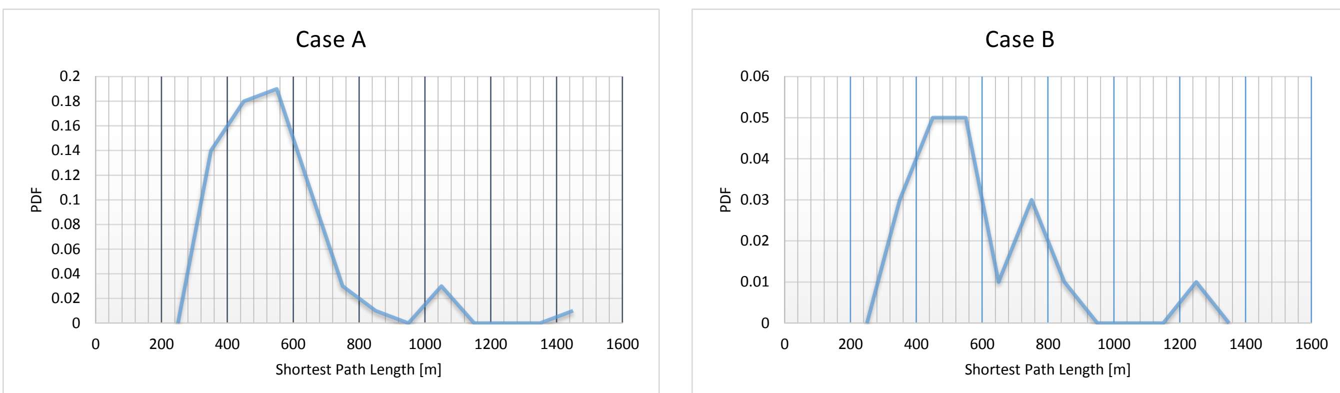


Fig. 6. Probability Density Function of Shortest Path Lengths for Case A and Case B

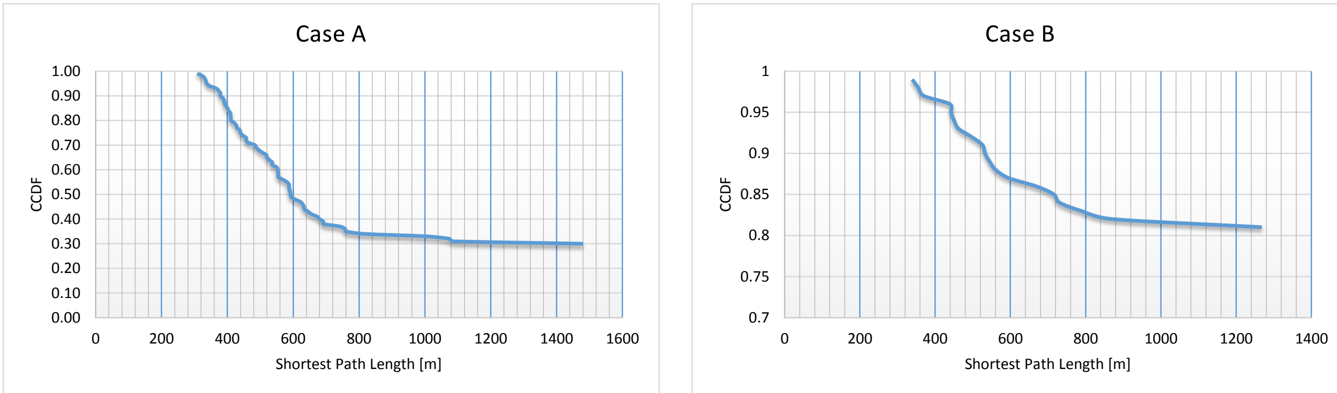


Fig. 7. Complementary Cumulative Distribution Function of Shortest Path Lengths for Case A and Case B

IV. DISCUSSION

Preferable location for the safe disposal of intermediate and/or high-level radioactive waste is considered to be in a deep underground low permeable fractured rock. In a deep geologic repository, radionuclides escaped from the waste packages or canisters migrate into the environment through the engineered barriers and the surrounding fractured rock. The connected networks of fractures are main conduits for groundwater flow and radionuclide transport in the fracture rock surrounding the repository.

The minimum geometrical distance (i.e., 225m in this study) between the source (i.e., disposition tunnel) and the target (i.e., side boundary) could be considered as the shortest travel length for a case of the worst case scenario for the repository safety assessment without incorporating the discrete natures of a fractured rock. For more reliable and realistic estimation of the shortest travel path and travel time through the fractured rock, a probabilistic transport path analysis taking into account the discrete fractures is essential.

The current study shows that the probability of the shortest path lengths longer than 225m (i.e., the minimum distance between the source and the target) is 1.0 for Cases A and B. Probability of the shortest path lengths longer than 450m (i.e., two times larger than the minimum distance of 225m) is 0.73 for Case A and 0.94 for Case B. Probability of the shortest path lengths larger than 1000m (i.e., 4.4 times larger than the minimum distance of 225m) is 0.33 for Case A and 0.82 for Case B. These results imply that i) the shortest path lengths are always (100% or CCDF=1.0) longer than 225m for all of 100 realizations both for Cases A and B, ii) 73% (CCDF=0.73) of 100 realizations have the shortest path lengths longer than 450m for Case A, and iii) 33% (CCDF=0.33) of 100 realizations have the shortest path lengths longer than 1000m for Case A. Thus, the current study shows that the minimum distance between the source and the target (i.e., 225m in this study, CCDF=1 for 225m) is not appropriate to be considered as the shortest flow and transport path length for the reference (or representative) case (e.g., CCDF=0.5) because those are too conservative (CCDF > 0.5) for the case considered in this study. Note that this interpretation is based on an assumption that the transport paths (and thus travel time) for a fractured rock without existing connected networks of fractures are greater than a fractured rock with the connected networks of fractures. This is a reasonable assumption because the diffusion is a dominant transport mechanism for such a fractured rock without connected networks of fractures in the vicinity of the repository (i.e., disposition tunnel in this study), and thus the transport paths and travel time by the diffusive transport (i.e., random Brownian motion) is generally much greater than those by the advective transport.

The current analysis enables to estimate the probabilistic distributions of the shortest transport paths for different fracture systems for a hypothetical HLW repository. Effects of fracture intensity (i.e., degree of fracturing) of the fracture system on evaluating of the transport paths are investigated, and the results of this study can be applied directly to the performance and safety assessment of the radioactive wastes disposal facilities and repositories.

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