

STOCHASTIC CONTINUUM ANALYSIS OF GROUNDWATER FLOW PATHS FOR SAFETY ASSESSMENT OF A RADIOACTIVE WASTE DISPOSAL FACILITY

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ABSTRACT

A stochastic continuum (SC) modeling technique was developed to simulate the groundwater flow paths in fractured rocks. This model was formulated based on the discrete fracture network (DFN) model generated from field geometric and hydraulic data. The spatial distribution of permeability in the stochastic continuum model was defined by the probability distribution and variogram functions defined from the permeabilities of subdivided smaller blocks of the DFN model. The consistency of groundwater travel time between the DFN and SC models was found through the numerical experiment. It was also found that the stochastic continuum model was an appropriate way to provide the probability density distribution of groundwater velocity, which is required for the probabilistic safety assessment of a radioactive waste disposal facility.

INTRODUCTION

The radionuclides released from the repository would be mainly transported with the moving water through fractures in crystalline fractured rocks. Therefore, radionuclide transport in crystalline fractured rock is basically controlled by the connectivity of the fracture network and the hydraulic properties of the individual fracture [1,2]. Discrete fracture network (DFN) approach is one of the most efficient ways in predicting the advective groundwater flow paths through a fractured rock. This approach can provide statistical results on flow paths by the generation of a number of DFN models. It is more useful to predict the ranges of the flow velocities and travel times than the equivalent continuum modeling, which can only provide the deterministic results. The statistical results on the flow velocity and travel time can be used as an important input data for the probabilistic safety assessment of radioactive waste disposal facility.

However, it is well known that DFN approach is not an appropriate way for the regional scale modelling due to the computational limits. Therefore, there is a limitation on applying the local-scale DFN model to the larger-scale groundwater flow modeling. One possible way to overcome this problem is to represent the heterogeneity of the rock mass by using a stochastic continuum (SC) approach. The use of the stochastic continuum approach for the representation of a fractures medium was proposed by Neumann [3,4]. The approach is based on the assumption that the actual varying hydraulic properties of the rock mass can be represented in a model by a number of smaller volumes, having a defined size and varying hydraulic properties. The varying hydraulic properties of the blocks are defined based on probability distributions defining a set of stochastic variables.

The SC modeling technique that was used in this paper was to begin with the generation of a three-dimensional DFN model. The geometric input data for the DFN model were obtained from field

measurements [5]. Then the DFN model was divided into a number of blocks and the hydraulic conductivity was calculated for each block. After then the probability distribution and spatial distribution of permeabilities were derived. The SC model was also divided into the same number of blocks with DFN model, and each block was assigned the permeability according to the defined probability distribution and the variogram functions. Hence the permeability was considered to be a regional variable, which has a different value at different location. A SC approach implies generation of a number of realizations of heterogeneous material property fields. This means that the possible variation of groundwater travel time and velocity can be predicted through a number of realizations.

In this study, the consistency between the DFN and SC models was investigated by the parameter of flow travel time with the numerical experiment. Using SC model, it was also possible to provide the probability distribution of groundwater velocity, which is required for the probabilistic safety assessment of a radioactive waste disposal facility.

DESCRIPTION OF DFN MODEL

The input data for the DFN model were obtained from the field measurements: both scanline sampling and borehole inspections. Input data for the DFN model were achieved from Yeosu area located in southern Korea. The hydraulic input data for the transmissivity of each fracture set could be estimated from the single-hole packer tests, which was conducted with 5 m interval. Single hole packer test was conducted in the depth range of 20 to 100 m from the ground level in four different boreholes.

Table I summarized the statistical description of the fracture sets. The fractures could be divided into three major sets based on the distribution of fracture orientation. The fractures shorter than 1 m were disregarded. Therefore, the truncated power law was used to fit the distribution of fracture length. It is well known that not every fracture is water conductive. Furthermore, it is not computationally efficient to include all fractures. In this study, the fractures whose transmissivity is above 4×10^{-7} m²/sec were only included in the DFN model. The transmissivity distribution of fractures was defined to have a log-normal distribution.

Table I. Statistical description of fractures

		Set1	Set2	Set3
Density (m ⁻³)		0.01075	0.01563	0.00175
	Distribution	3-D Poisson Process		
Length (m)	Min.	1.0	1.0	1.0
	Max.	8.0	10.0	20.0
	Exponent	1.203	1.490	2.038
	Distribution	Truncated Power Law		
Transmissivity (m ²)	Mean	-12.68		
	S.D.	0.619		
	Distribution	Log-normal		
Dip & Dip Dir. (angle)	Mean of Dip Dir.	28.0	7.7	104.3
	Mean of Dip Angle	9.4	83.1	86.8
	Fisher Dispersion	16.58	10.63	30.64
	Distribution	Fisher		

The mean value of in-situ permeability was estimated to be $1.8 \times 10^{-15} \text{ m}^2$ from the single-hole packer tests. The arithmetic mean of permeability for x, y and z directions obtained from the modeling was calculated as follows.

$$\begin{bmatrix} 1.03 \\ 1.68 \\ 1.53 \end{bmatrix} \times 10^{-15} \text{ m}^2 \quad (\text{Eq. 1})$$

FORMULATION OF SC MODEL FROM DFM MODEL

To formulate a SC model, it is required to define the spatial distribution of permeability. First of all, the DFN model of 80 m cube block was constructed with seven different realizations of fracture network. This is the block size of REV scale. The 80 m cube block was divided into 8x8x8 smaller blocks so that the size of each smaller block was 10x10x10 m. The permeabilities were calculated for the smaller blocks and the probabilistic density function of X, Y and Z components of permeability was defined. It is also possible to define the spatial correlation of permeability using variogram models such as spherical and exponential models.

The SC model was also divided into 8x8x8 finite elements for the same dimension as DFN block. In this study, two kinds of SC model were constructed; SC-A and SC-B models. For SC-A model, the permeabilities of each finite element at a certain locations were obtained from those of subdivided small block at the same location in DFN model. The SC-B model was constructed on the basis of probability density function and variogram function. The variogram functions of X, Y and Z

components of permeability were defined for the eight vertical sections over seven realizations of DFN model. And the Probability density functions were defined for X, Y and Z components of permeability of the whole vertical sections over seven realizations of DFN model.

AN APPROACH TO IDENTIFY THE CONSISTENCY BETWEEN SC AND DFN MODELS

Many researchers have demonstrated that in describing water and transport through fractured rock, it is not always possible to represent the rock mass with simple continuum parameters[2,7]. This flow pattern can be simulated with the SC model. In this study, the consistency between the SC and DFN models was analyzed from the numerical experiments. The numerical experiments were conducted to estimate the groundwater travel times using the SC and DFN models. It is not easy to compare the groundwater velocity between DFN and SC models because the pathway is relatively more complex in the DFN model than the SC model.

Two kinds of boundary conditions were applied for the DFN and SC models. One was to apply the 1 MPa on Y plane so that the flow could occur along Y direction. The other is to apply 1 MPa on Z plane. For the two cases, the pressure of 0 Pa was applied to the opposite plane of pressure injection plane. And no-flux boundary condition was applied for the other four planes.

For the DFN model, 1,000 particles were distributed on the pressure injection plane. The transport calculations were carried out based upon a particle tracking algorithm by using Napsac[6]. It was assumed that particle transport was dominated by advection, and the major cause of dispersion is due to the existence of a number of different paths through the fracture network. Particles are tracked through the network from node to node, building up the path taken by each of the particles. For each fracture plane a representative number of pathlines between the intersections on the plane are calculated. Intersections are discretised by the transport nodes and pathlines are calculated from each transport node. The paths clearly demonstrate the heterogeneity in flow due to variations in network connectivity and fracture transmissivity.

For the SC model, the flow paths was allowed to start on 36 evenly spaced center points of each element on the pressure injection plane. The flow paths starting on the 28 elements directly adjacent to the model boundary were not included considering the influence of boundary. The permeability was zero where there is no fracture within the smaller blocks. To avoid numerical difficulties, the permeability of unfractured block was set to be $0.5 \times 10^{-16} \text{ m}^2$ in the SC model from the reference survey on the permeability of unfractured crystalline rock [8].

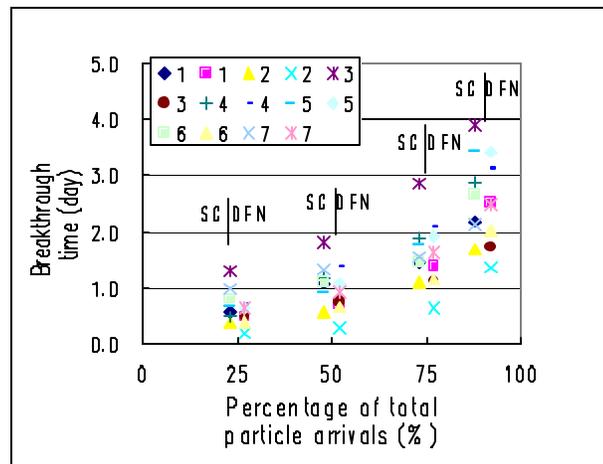
The groundwater travel time is also influenced by fracture porosity. Generally the range of the fracture porosity, which is defined as the fracture volume against model volume is between 0.01 to 1×10^{-5} [9]. The effective fracture porosity is even lower than the fracture porosity because the particles tend to follow the fastest channel in fracture network. In this study, the mean value of effective porosity of seven realizations was around 0.5×10^{-5} . And the effective porosity was assumed to be constant across the entire block of SC model.

RESULTS AND DISCUSSION

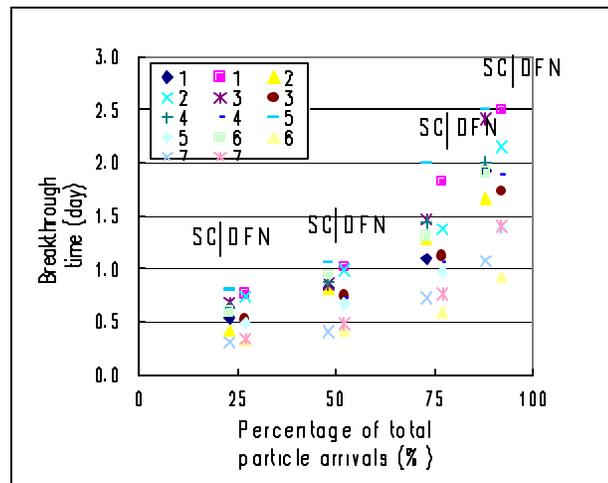
Consistency on travel time between DFN and SC-A models

As explained, the permeability at a certain location in the SC-A model correspond to that at the same location in the DFN model. The consistency on travel time of paths was investigated with 7 realizations of DFN and SC models. In this study, 25%, 50%, 75% and 90% breakthrough times of 1,000 particles along Y and Z direction were calculated from DFN models and then compared with the travel times of 36 paths from the SC model.

Fig.1 shows 25%, 50%, 75% and 90% breakthrough times from DFM model and the travel times of 36 paths from the SC model along Y and Z directions. The discrepancy was found for some realizations such as No.3 along Y direction and No.5, 6 along Z direction, For these, the travel times from the DFN model were faster than those from SC model. This might be due to that the highly conductive fractures or channels could not be accurately represented with the averaged permeability in the SC model. However the variation range on the 25%, 50%, 75% and 90% breakthrough times between two models was reasonably consistent between the SC and DFN models.



(a) Y direction



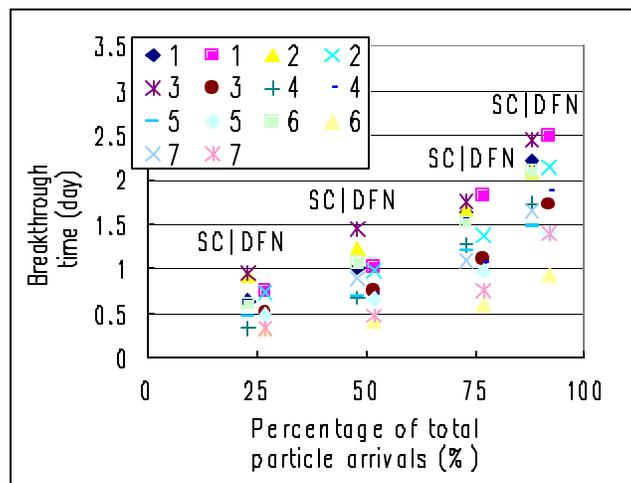
(b) Z direction

Fig.1 Comparison of 25, 50 75 & 90% breakthrough times between SC-A and DFN models

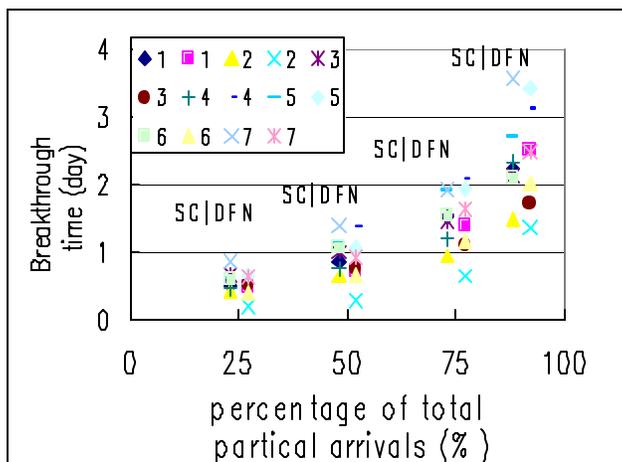
Consistency on travel time between DFN and SC-B models

The SC-B model was constructed from the probability density distributions and variogram functions of permeabilities obtained from the DFN model. Therefore, the permeabilities were randomly distributed across the entire block of SC model. For the SC-B model, the probability density function was defined for the 512 permeability values obtained from the whole smaller blocks within a DFN model. And variogram functions were defined for the eight vertical sections of a DFN model. A probability density function and eight variogram functions were defined for each DFN block.

Fig.2 shows the 25%, 50%, 75% and 90% breakthrough times of 1,000 particles and 36 paths from DFN and SC-B models. The results were summarized for the seven different realizations of DFN and SC-B models. As shown in this figure, the variation range of breakthrough time reasonably matches each other. Therefore it was found that the SC modeling is one of good approach for the analysis of groundwater flow paths in the fractured rock mass.



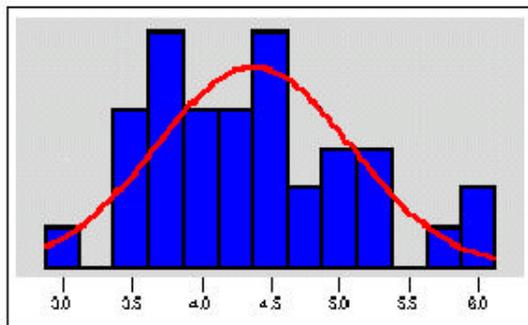
(a) Y direction



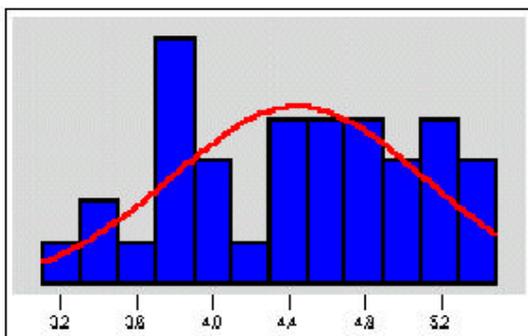
(b) Z direction

Fig.2 Comparison of 25, 50 75 & 90% breakthrough times between SC-B and DFN models

Fig.3 show the typical example of the distribution of groundwater velocity. This is necessarily required for the probabilistic safety assessment of radioactive waste disposal facility. Therefore the SC approach can provide useful input data for the probabilistic safety assessment of radioactive waste disposal facility.



(a) Realization No.3



(b) Realization No.4

Fig.3 Probability density distribution of groundwater flow velocity

CONCLUSIONS

The probabilistic safety assessment requires the probability distribution of groundwater velocity, travel time and path length. Though the DFN model can provide these results in heterogeneous distribution of permeability in fractured rock, this model has limitation on fracture number in the model domain. Therefore the SC model can be an alternative way if the heterogeneous characteristics of the fractured rock are effectively represented. In this study a SC model was formulated from the discrete fracture network (DFN) model based on field geometric and hydraulic data. The SC model was formulated from the probability distribution and variogram functions of permeability. To confirm that the SC model is reasonably consistent with the DFN model, the 25, 50, 75 and 90% breakthrough time from the DFN model were compared with travel times of 36 paths from the SC model through the simple numerical experiments. The 25%, 50%, 75% and 90% breakthrough times from DFN models was reasonably matches with those from the SC models for the most cases. And the variation range of breakthrough time was also similar. From this, the SC approach was turned out to be a good way to represent the heterogeneous distribution of permeability. And since the SC model can provide the probabilistic distribution of groundwater velocity, it would be effectively used for the probabilistic safety assessment of a radioactive waste disposal facility.

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