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Comparison of Groundwater Residence Time using Environmental Isotopes and Numerical Flow Model in Gneissic Terrain, Korea

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SUMMARY. For the purpose of a groundwater flow assessment in fractured rock mass, it would be more useful and credible using both the environmental isotope techniques and the discrete fracture network(DFN) modeling simultaneously. A deep borehole groundwater showing the meteoric water origin is lighter in ^{18}O and ^{2}H than other groundwaters. The recharge area of groundwater can be estimated as about 400m higher in elevation considering the altitude effect of isotopes in Korea. Tritium concentration of groundwater indicates that $Na\text{-}HCO_3$ groundwater were recharged prior to 1950s, whereas the groundwater flowing into the mine tunnel was estimated as the age from 4 to 18 years by the lumped-parameter model. And, the residence times of groundwater in selected flowpaths based on the DFN model were also estimated from 4.9 to 58.2 years, respectively. Thus, it is more desireable to combine these two technques in order to increase the reliability and reduce the uncertainty occurred from the result of the groundwater flow assessment in fractured rock mass.

1. INTRODUTION

Interpretation and prediction of groundwater flow affecting the behaviors of radionuclides are a important component of the performance assessment of subsurface radioactive waste disposal. Groundwater flow in fractured rock mass is controlled by fracture networks and its hydraulic properties. Furthermore the scale dependent and anisotropic properties of hydraulic parameters are resulted mainly from irregular patterns of fracture system, which are very complex to evaluate properly with the current techniques available.

The Samkwang Gold mine, being located about 50 km western part of Taejon city in mid of Korea, was chosen as the hydrogeological research site. The total length of mine tunnel is about 5.2km and has eight levels of adits. The geology of the gold mine were studied and well defined for scientific interest and prospecting gold veins(1, 2, 3), and preliminary structural, hydrogeological and geochemical studies has been performed(4, 5, 6, 7). This paper discusses the groundwater residence time controlling the basic hydrochemistry and physical hydraulic aspect of the groundwater system. The residence time and the origin of groundwaters are inferred from environmental isotope analyses of ^{2}H, ^{18}O and ^{3}H.

2. SITE CHARACTERISTISTICS

2.1. General geology and fractures

The Samkwang mine lies in the lower Kyeonggi gneiss complex and consists mainly of Pre-cambrian biotite-rich granitic gneiss showing banded structure and ptygmatic fold structures etc(Figure 1). It is unconformably underlain by Jurassic sedimentary rocks. The strike and dip of foliation of gneiss are N15 ~ 80W and 35 ~ 75NE, respectively(3). The fracture-filling minerals in the borehole cores are kaolinite of dominant constituent and, smectite and illite of minor minerals.

For the fracture characterization, the scanline mapping(8) and borehole acoustic scanning (BHTV)(9) were conducted from surface, mine tunnel and boreholes. And, about 4840 fractures over 50 cm in trace length had been surveyed for orientation, spacing, trace length(10), termination(10,11), probability of termination(12), fillings and seepage etc. And fracture aperture was also estimated by BHTV at boreholes(4, 5, 6). These all parameters had been processed according to the three sets of fracture orientation defined as 130 ~ 200/40 ~ 90(set 1), 210~280/50~90(set 2) and 010 ~ 060/60 ~ 90(set 3) in dip direction/ dip(Figure 2; Table 1).

Table 1. Representative values of fracture distribution characteristics by set.

Items	set1	set2	set3
orientation(mean)	164/60	044/66	283/08
spacing(m)	0.82	0.89	2.96
frequency	1.22	1.12	0.34
length(m)	2.97	2.16	3.19
aperture(mm)	5.52	4.49	4.79
interconnectivity (Ii)	6.82	5.44	2.22
termination probability(%)	21.22	26.3	9.88

2.2. Hydrogeology

The groundwater elevation measured from 8 boreholes ranged from 4 to 5 m in below ground. And groundwater pressure was also confirmed from horizontal boreholes located portal in mine tunnel level 0(EL.208 m) through rainy and dry seasons. The boreholes had been installed 100 m length perpendicular to the tunnel wall with single packer. The pressure head was stabilized within 10 days and recorded as about 60 m in head.

The constant pressure injection test and flow dimensional analysis had been conducted(13, 14). The hydraulic conductivity estimated are ranged as $1 \times 10^{-8} \sim 3.6 \times 10^{-6}$ m/s by transient flow analysis method(13). It was characterized that the upper regime of 30 ~ 40 m from surface has the hydraulic conductivity ranging as $2 \times 10^{-6} \sim 3 \times 10^{-6}$ m/s, significantly. In dimensional flow analysis, it was analyzed nearly radial to spherical flow in general. The sections of the assessed as spherical flow regime could be characterized as the fractures consisted of high dip angle from BHTV.

3. ISOTOPE CHARCTERISTICS

3.1. Sampling and analytical techniques

Water sampling and in-situ measurement had been carried out from 1990 to 1996. The samples of a borehole groundwater and the inflowed waters into the mine tunnel were collected(Figure 1). Groundwater samples from the borehole were sampled at different levels of 145 and 175 m below surface. Determination of $\delta^{18}O$ and δD in the water samples was carried out using with the VG SIRA II mass spectrometer. The relative errors wewe found to be within ± 0.1 ‰ for ^{18}O and 1.0 ‰ for ^{2}H. The tritium contents were measured by liquid scintillation counter from 600g to 20g and counted during 500 minutes with the precision of ± 1TU in common after electrolytical enrichment.

3.2. Environmental Isotopes

The chemistry of the collected waters in the study area shows quite different type such as inflowed waters of $Ca\text{-}HCO_3$ type and $Ca\text{-}SO_4$ type and a borehole groundwater of $Na\text{-}HCO_3$ type(7). The $Ca\text{-}SO_4$ type water are relatively higher in TDS (upto 760 mg /ℓ) than that of $Ca\text{-}HCO_3$ type.

The isotopic composition of the waters in the study area have $\delta^{18}O$ and δD values ranged from -9.5 to -8.7 ‰ and from -63.7 to -54.7 ‰ respectivel (Table 2), which are close to the Global Meteoric Water Line of Craig(15)(Figure 3). The $\delta^{18}O$ values show that the groundwaters from boreholes -9.5 ~ -9.3 ‰ are lighter than the other waters. These light groundwater supposedly indicate that the groundwaters had been recharged from the upper zone about 400 m higher in elevation than that of the mine tunnel considering the altitude effect of isotope (0.19 ‰ /100 m for $\delta^{18}O$) in Korea(16). The isotopic composition of inflowed water in deep levels of the mine($Ca\text{-}SO_4$ type) shows also the signature of recharged water from higher elevation than sampling points.

The tritium contents of inflowed water through the fracture zone of the horizontal mine tunnel had been monitored in twelve times from 1990 to 1996 at six sampling points(17). Tritium level indicates that the deep groundwater in the mine area can be grouped into older water recharged prior to 1950s and shallow groundwater recharged after 1950s. The tritium contents of mine tunnel show the tendency decreasing with time as 13.5 ~ 7.2 TU, 17.6 ~ 9.1 TU and 10.7 ~ 8.4 TU at the sampling points of A, E and P-1, respectively(Table 3). The values around point C analyzed 9.7 ~ 21.1 TU had been ranged higher than any other places. However, borehole groundwater and deep mine tunnel level 6 show tritium free or low(1.0 ~ 2.4 TU) and predicted as the old water recharged prior 1950s.

Table 2. Stable isotopic data of water samples from the Samkwang mine area (July, 1994).

Sample no.	Water type	$\delta^{18}O$ (‰)	δD (‰)	EL. (m)	EL. (surface)
S-1	surface	-8.9	-55.9	180	180
S-2	surface	-8.8	-54.2	180	180
A	drift	-8.7	-61.5	208	300
B	drift	-8.7	-55.8	208	278
C	drift	-8.7	-56.1	208	345
D	drift	-8.8	-55.1	208	335
E	drift	-8.7	-54.7	208	375
P-1	drift	-8.7	-55.3	208	385
G-1	borehole	-9.3	-61.7	30	175
G-2	borehole	-9.5	-63.7	0	175

Table 3. Tritium contents(TU) of the groundwater inflowing into the drift in the Samkwang mine area.

Data	Level 10						Level 6		Borehole	
	A	B	C	D	E	P-1	61	62	G-1	G-2
90.6	8.8	10.2	19.6	-	10.1	-	-	-	-	-
91.5	13.5	11.9	21.1	-	13.6	-	-	-	-	-
7	13.0	11.4	19.3	-	15.1	-	-	-	-	-
92.4	11.2	12.4	19.1	-	17.6	-	-	-	-	-
7	12.8	10.6	17.1	7.9	12.4	-	-	-	-	-
8	11.3	-	19.2	10.8	13.8	-	-	-	-	-
94.7	7.5	8.3	15.1	9.3	-	-	-	-	-	-
9	7.7	8.7	14.5	9.4	10.2	-	2.4	2.0	1.0	1.0
10	8.7	8.8	14.1	8.4	9.7	-	-	-	-	-
95.8	7.2	8.5	9.7	7.7	9.5	-	-	-	-	-
9	8.3	7.4	11.9	7.9	9.2	10.7	-	-	-	-
96.2	9.1	8.1	12.7	8.3	9.1	8.4	-	-	-	-

3.2. Residence time using tritium

Direct age estimation of groundwater using tritium is difficult due to the variable input of tritium and mixing behavior since the advent of thermonuclear testing in 1952. Supposed to match the tritium content at sampling points with that of the recharge at the inlet of a groundwater system, the distribution of residence time of each contribution can be estimated. The data of tritium contents are applied by the lumped-parameter model (MULTIS)(18) combined with the piston flow (PM)(19), the exponential (EM)(20) and dispersion concept (DM)(21). By this model, the tritium contents of the precipitation monitored monthly in Korea (1963 to 1976, 1982 to 1995) and Japan (1977 to 1981) were used as input parameter for dating of ground-water(22). Meanwhile, DM had not been considered due to the lack of existing parameters or in-situ test results.

The groundwater age estimated at point A is to 4 years, while the water at the point C is dated to 18 years(Table4; Figure 4b). Although the distance from surface to the point C is rather shorter than others, surface to point C shows the long pathway of groundwater flow or hydrological mixing of currently recharged water. The residence time of points B, D and E is estimated in the range of 6.5 to 8.5 years. The phenomenon of piston flow around point A, D, E and P-1would be more dominant than mixing phenomenon (Table 4; Figure 5a and c).

Table 4. Results of dating modeling of the groundwater inflowing into the drift in the Samkwang mine area(EL.208, tunnel).

Sampling points	A	B	C	D	E	P-1
Residence time (year)	4.0	8.0	18.0	6.5	8.5	8.5
Piston flow (%)	67	20	50	67	60	82
Mixing flow(%)	33	80	50	35	40	18
EL.(surface)	300	278	345	335	375	385

4. GROUNWATER FLOW BY DFN CONCEPT

The FracMan(Version 2.306) for fracture network and MAFIC(12) were used for assessment of groundwater flow. The concept of this modeling is forward approach method for natural condition of site specific characteristics through iterative execution. This model has been qualified as credible by the final assessment of validity on fracture flow modeling by the task force of OECD/NEA[23]. DFN models provide a means of explicitly representing flow path geometries in such case. In DFN model, the processes of flow and transport are assumed to take place primarily or entirely through networks of discrete fractures[26]. Thus, groundwater flow and solute transport in DFN are expected to occur mainly through networks of interconnected fractures.

4.1. DFN modeling

The fracture system using the FracSys of FracMan module was simulated based on the represent ative values which were investigated in-situ and reviewed from existing data(Table 1) as Table 5 and Figure 5.

The assessment model of conductive fractures was reprocessed and modified by the estimated fracture transmissivity(T_f) and conductive fracture intensity(P_{32c}) by each set. The former was simulated based on the mechanical aperture by BHTV and hydraulic aperture from Cubic law(24, 25) from the fixed-interval length injection test and flow dimensional analysis. The latter was simulated from conductive fracture frequency(f_c) of borehole(26) using FracWorks of FracMan module through iteration with best-fit to OxFilet simulation of FracMan as the Table 5.

Table 5. Input data for discrete fracture network modeling

Parameter	Set 1	Set 2	Set 3
orientation pole azimuth pole inclination dispersion	Fisher 344 30 12.28	Fisher 224 24 17.88	Fisher 58 82 2.61
fracture radius mean (m) standard deviation (m)	LogNormal 2.97 3.82	LogNormal 2.16 1.39	LogNormal 3.19 1.28
T_f mean($\times 10^{-7}$ m^2/s) standard deviation ($\times 10^{-4}$ m^2/s)	LogNormal 3.34 2.69	LogNormal 1.36 1.1	LogNormal 1.41 1.14
P_{32c}(m^2/m^3)	0.7819	0.4555	0.4059

For the purpose of model calibration, the fracture data which were selected from 100m borehole in the simulated model cube(100^3 m^3) had been compared with in-situ data. The representative values of P_{32c}, and cross-fracture transmissivity were suggested as 1.72, and 6.23×10^{-7} m^2/s, respectively(Table6).

Table 6. Statistics of discrete fracture network system.

No. of fracture	Simulated P_{32c}(m^2/m^3)	No. of fracture intersections	Simulated T_f ± SD(m^2/s)
3,080	1.72	83	6.23×10^{-7} $\pm 5.1\times10^{-4}$

For groundwater flow modeling, the input files had been specified by fracture network simulation program of Meshmaker module in FracMan and geometric model has been also completed. And, MAFIC which is a finite element flow model was used to simulate transient flow in a rock block with a discrete fracture network.

In this study, the geometry of model was designed as cubic of 100^3 m^3 and tunnel of $2\times2\times50$ m^3 considering for mine tunnel. The boundary conditions for the model were applied to all faces using H ($=H_{xx}+H_{yy}+H_{zz}+H_o$)(28). For modeling, outer boundary had been reviewed with the potential head and hydraulic gradients from the results of the dual porosity model TRAFRAP(27) in section 2.2. It was also defined that there are no hydraulic gradient in EW direction and adopted 60 m in head at south edge boundary and, zero in the inner boundary at mine tunnel considering continuous pumping condition(Table 7)(5).

Table 7. Coefficients for the outer and inner boundary conditions.

Boundary	Face	H_x	H_y	H_z	H_o
Outer Boundary	East	0.26	0	0.31	80
	West	0.26	0	0.31	80
	North	0.14	0	0.23	95
	South	0.35	0	0.13	60
	Top	0.28	0	0.35	45
	Bottom	0.23	0	0.27	114
Inner Boundary	(All)	0	0	1.0	0

The inflow rate into tunnel estimated from the model MAFIC was about 2.66 m^3/day, whereas the pumping water for mining operation was measured as 220 m^3/day. This value could be converted to about 2.11 m^3/day considering the total length of 5,200 m tunnel with an assumption no matrix inflow in steady-state and evaporation predicting up to 10% due to ventilation

4.2. Residence time using numerical flow model

For the assessment of groundwater residence time from surface to the mine tunnel, the media was considered as soil or weathered zone of 40 m thick and fractured rock mass in lower part. And, groundwater entered from the north edge of the model and discharged to the mine tunnel through fractured rock mass. The rock block was decided as the cube of 20^3 m^3 based on try-and-error for 10 steps of model size from 10^3~100^3 m^3, and the number of fracture were simulated as 942 for fratures and 153 for networks.

In this case, the shortest pathway is estimated as

9.50×10^2 m^2 in area, 1.048×10^{-8} m^2/s in conductance and 2.5×10^{-9} m^2/s in T_f. Total number of fractures are 10 in four kinds of fracture. Thus, total length are also estimated as about 41 m(C_e=T_f L_e)(28). This length is 2.9 times longer than that of TRAFRAP(5). The size of fracture in each set was estimated as 6.38 m (set 1), 5.94 m(set 2), 4.32 m(set 3).

The groundwater residence time was calculated as 7.8 years to point E from surface(Table 8). Darcy velocity and flow velocity are 2.5×10^{-8} m/s and 1.55×10^{-6} m/s respectively, and 1×10^{-7} m/s for hydraulic conductivity. The hydraulic conditions in this case of lower part had been considered as 0.25 for hydraulic gradient, 0.0161 for effective fracture porosity(29).

Table 8. Residence time estimated by DFN model in each point.

Location	A	B	C	D	E	P-1
Time (yr)	4.9 ~ 15.7	10.8 ~ 39.2	13.7 ~ 50.9	10.2 ~ 36.8	7.8 ~ 27.4	15.5 ~ 58.2

5. CONCLUSIONS

The inflowed water in the tunnel is estimated the age from 4 to 18 years by the lumped-parameter model withe tritium contents.

The residence times of groundwater in assumed flowpaths based on the discrete fracture network (DFN) model were also estimated from 4.9 to 58.2years, respectively. These residence times evaluated in the study area were much more reasonable comparing the result from the porous continuum model. And, one of the great advantages of DFN model is a forward modeling method to handle the qualitative data as well as quantitative ones.

It is more desirable to integrate numerical groundwater flow model and isotopic tracer techniques for the redution of the uncertainty for the groundwater flow assessment in fractured rock mass. The desired method for the evaluation of the groundwater flow in fractured rock mass must be based on the deep understanding of fracture processes and a simplified model representing the natural groundwater conditions.

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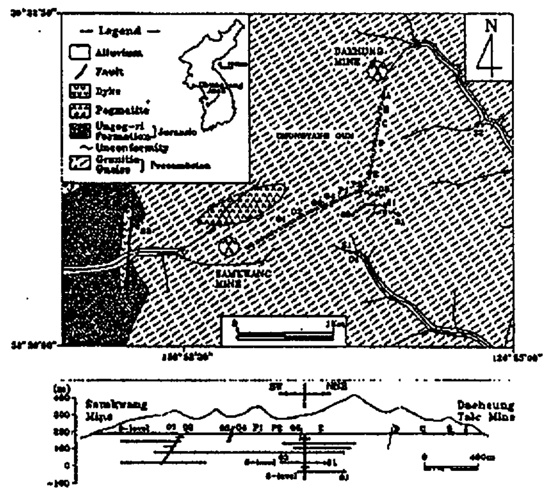

Figure 1. Geologic map of Samkwang mine area water sampling sites (Dashed lines are mine adits).

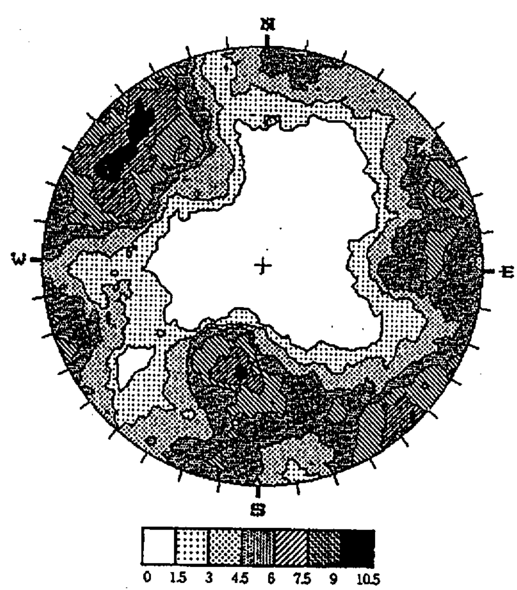

Figure 2. Stereographic plot of the poles of fractures measured from the surfaces, mine tunnel and boreholes(Lower hemisphere, equal angle)

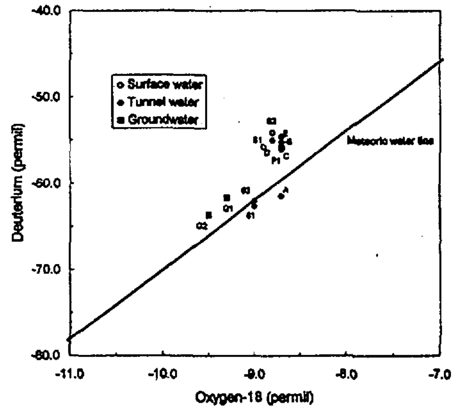

Fig. 3. Relation between δD and $\delta^{18}O$ values of the water samples from the Samkwang mine area with the meteoric water line.

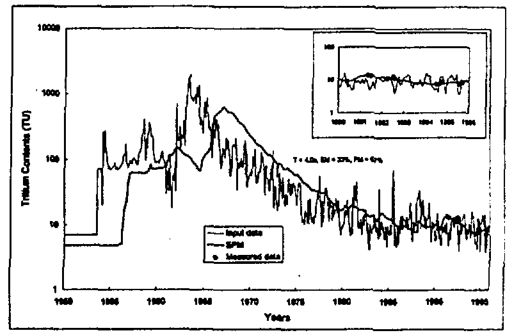

Fig. 4(a). Best fit of the tritium output curves for Point A in the Samkwang-mine area.

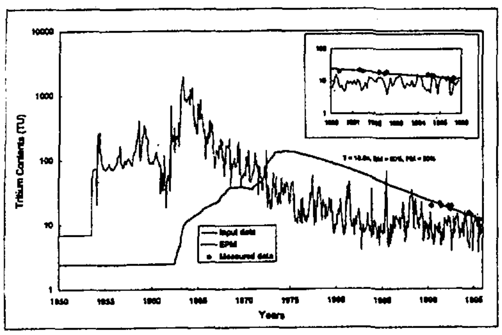

Fig. 4(b). Best fit of the tritium output curves for Point C in the Samkwang-mine area.

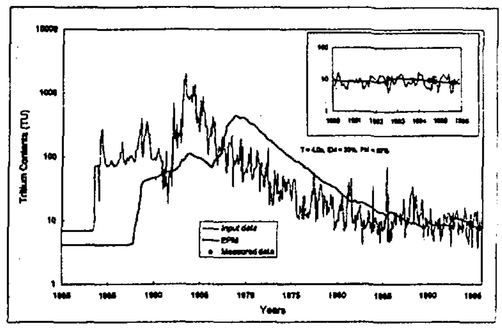

Fig. 4(c). Best fit of the tritium output curves for Point D in the Samkwang-mine area.

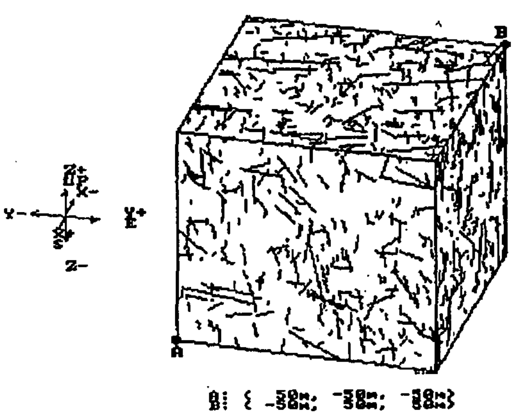

Figure 5. Fracture system model

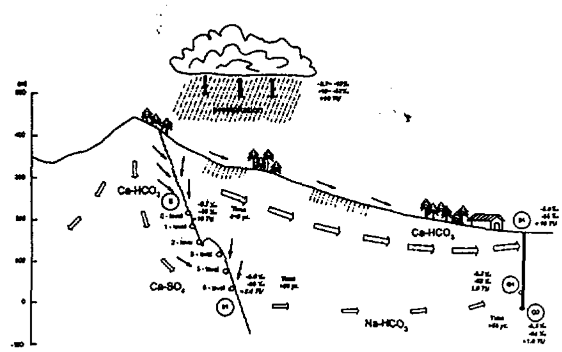

Figure 6. Conceptual illustration of ground-water flow around the drift from the Samkwang-mine area.