

## VALIDATION STUDY OF SAFETY ASSESSMENT ANALYSIS OF RADIOACTIVE WASTE DISPOSAL

Masahiro MUNAKATA<sup>1)</sup> and Kunio WATANABE<sup>2)</sup>

<sup>1)</sup>Nuclear Safety Research Center, Japan Atomic Energy Agency, <sup>2)</sup> Professor, Saitama University

### ABSTRACT

It is important for safety assessment of radioactive waste disposal facility to establish methodology for evaluation of groundwater flow and radionuclide migration in geologic media because of insufficient data based on field tests. In order to validate safety assessment codes for radionuclide migration, field tests used <sup>90</sup>Sr, <sup>237</sup>Np and <sup>238</sup>Pu were carried out in natural aquifer at 30m below ground surface of the field test site in China. Migration of radionuclides was evaluated by MIG2DF and the results obtained from field tests were compared to analyzed results. In order to validate safety assessment codes for groundwater flow, regional groundwater flow of Horonobe area was analyzed by modified 3D-SEEP. And then, analyzed results of total head and salt concentration were compared the data obtained from borehole researches. These results showed that the analyzed results of groundwater flow and radionuclide migration could explain the results obtained from field tests reasonably by MIG2DF and modified 3D-SEEP. In addition, regional groundwater flow with topographic change caused by climate change was analyzed to develop a method which evaluate changes of groundwater flow in future environment. The analyzed results of groundwater flow for Boso Peninsula in future environmental conditions showed that travel velocities change within a range of 10%.

**KEYWORDS:** Validation, Safety assessment, Radioactive Waste, Groundwater flow, Radionuclide migration

### 1. INTRODUCTION

In the nuclear fuel cycle policy of Japan, a safe disposal of radioactive waste to geological media is intended. In a safety assessment of radioactive waste facility, it is essential to evaluate enclosure and retardation function for radionuclides by using an artificial barrier as canister, bentonite and concrete materials and a natural barrier as geological media. However, it is difficult to avoid an uncertainty associated with safety assessment, because the assessment period is about 100,000 years or greater and scale to be considered in the safety assessment is about 10 km or greater.

One of key issues of the safety assessment of radioactive waste disposal facility is the validation of the safety assessment codes. The reason is that there is a few experimental data for radionuclide migration in a long-term period under the natural environment conditions, although simulation techniques are proposed by the laboratory experiments the radionuclides. And also, one of key issues in the safety assessment of geological disposal is establishment of analytical techniques to understand a regional groundwater flow. The radionuclide migration is strongly affected by the

groundwater flow so that the safety assessment codes for simulating regional groundwater flow are needed. In addition, it is necessary for the development of the analytical technique to evaluate influence on groundwater flow caused by changes of environmental conditions in future, like as topographical changes by uplift and erosion in long-term period to be evaluated in the safety assessment.

Firstly, in this study, in order to validate the safety assessment code for radionuclide migration, field migration experiments using radionuclides carried out in field facilities of the China Institute for Radiation Protection (CIRP). The experimental results of radionuclide migrations were analyzed by using MIG2DF (Kimura 1992). Secondary, to validate the safety assessment code for groundwater flow in geological disposal, regional groundwater flow of Horonobe area in Japan was analyzed. The 3D-SEEP (Kimura and Muraoka 1986) was modified and used for the analysis of regional groundwater flow. Simulated results are compared to the data obtained from research boreholes which were drilled to obtain data to validate. Finally, in order to estimate changes of

groundwater flow in future environment, an assessment method of the changes of groundwater flow was developed using topographical simulation and 3D-SEEP.

## 2. MATHEMATICAL EQUATIONS

MIG2DF is a two-dimensional, finite element code simulating saturated-unsaturated groundwater flow and radionuclide migration in geological media. 3D-SEEP is a three-dimensional, finite element code simulating saturated-unsaturated groundwater flow based on MIG2DF. These codes were developed by Japan Atomic Energy Agency (JAEA).

In the case of the disposal facility which constructed in coastal area in Japan, the safety assessment code for groundwater flow taking account of the effect of density of sea water is needed. In this study, 3D-SEEP is modified for this purpose and these codes can take account of the density dependent groundwater flow. In the modelling of groundwater flow and radionuclide transport, the basic equations are given by the continuity equation which expresses mass conservation of fluid, the Darcy's law for porous media which expresses momentum conservation and advection-dispersion equation which expresses mass conservation of solute.

The governing equation of density dependent groundwater flow is described as follows:

$$\rho\{C_s(\theta) + \beta S_s\} \frac{\partial h_p}{\partial t} + \rho_f \gamma \theta \frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i} \left\{ \rho K_{ij} K_r(\theta) \frac{\partial h_p}{\partial x_j} + \rho K_{i3} \rho_r \right\} \quad (1)$$

where  $h_p$  is pressure head (m),  $\theta$  is the volumetric water content,  $c$  is salt concentration normalized by the concentration of sea water,  $\rho$  is fluid density ( $\text{kg/m}^3$ ),  $\rho_f$  is fresh water density ( $\text{kg/m}^3$ ),  $\rho_r = \rho / \rho_f$  is the ratio of fluid density to fresh water density,  $C_s(\theta) = \partial \theta / \partial h_p$  is the specific moisture capacity (1/m),  $\beta$  is a constant for saturated or unsaturated domain,  $S_s$  is the specific storage (1/m),  $\gamma = (\rho_{sw} - \rho_f) / \rho_f$  is the ratio of the difference between the density of sea water and the density of fresh water to the density of fresh water,  $t$  is time (sec),  $K_{ij}$  is hydraulic conductivity tensor (m/sec) and  $K_r(\theta)$  is the ratio of unsaturated hydraulic conductivity to the saturated hydraulic conductivity.

The governing equation for radionuclide migration with decay is described as follows:

$$\nabla(\mathbf{D}\nabla C_k - \mathbf{u}C_k) = \frac{\partial}{\partial t}(\theta RC_k) + \lambda \theta RC_k \quad (2)$$

where  $C_k$  is concentration of radionuclide  $k$  in groundwater ( $\text{kg/m}^3$ ),  $\mathbf{D}$  is the hydrodynamic dispersion tensor ( $\text{m}^2/\text{sec}$ ),  $\mathbf{u}$  is the Darcy flow velocity (m/sec),  $R = 1 + \rho_s(1-n)K_d/\theta$  is the retardation factor and  $\lambda$  is the decay constant (1/sec). Equation (2) can be also applied for salt transport in groundwater by neglecting the distribution to geological media and by not taking account of decay.

The equation of groundwater is discretized by using the Galerkin finite element method and the equation for radionuclide migration is discretized by using the Bubnov-Galerkin finite element method. For a transient state analysis, the generalized Crank-Nicholson method is adopted for the discretization of time. The structure of MIG2DF is divided into parts of groundwater flow and radionuclide migration and also the structure of 3D-SEEP is divided into parts of groundwater, salt transport. The modified 3D-SEEP can solved density dependent groundwater flow in a coastal aquifer by weak coupling technique.

## 3. VALIDATION STUDY OF RADINUCLIDE MIGRATION

The field migration tests using radionuclide were carried out as a cooperative research project between Japan Atomic Energy Research Institute (JAERI) and CIRP from 1995 to 1998 (Ogawa et al. 2003). The objectives of research project were to develop and validate the safety assessment methodology for radionuclide migration in natural environment. The facility of CIRP for field tests was located in Tayuan, China, in the center of the Loess Plateau. The elevation of the facility was approximately 900m above sea level. The annual mean air temperature was about 10 degrees Celsius and the annual average precipitation was about 200-500mm so that the climate was cold and dry. The thickness of loess around the facility is approximately 270m and the groundwater table is 30m below from ground surface.

### 3.1 Radionuclide Migration Tests in Aquifer

The field migration tests using three radionuclides ( $^{90}\text{Sr}$ ,  $^{237}\text{Np}$  and  $^{238}\text{Pu}$ ) were carried out in natural aquifer under the CIRP's facility (Tanaka et al. 2003). Figure 1 shows summary of the facility.

The radionuclides with quartz sand were injected into the aquifer as point source. The groundwater was sampled from aquifer in downstream area and analyzed. The whole soils in test pit were excavated at the end of the migration tests for 3 years later and then the distributions of radionuclides were analyzed in detail.

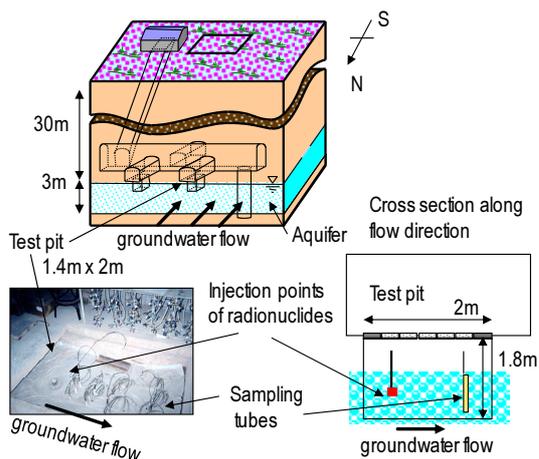


Fig. 1 Summary of test pit and facility

### 3.2 Analysis of Radionuclide Migration Tests in Aquifer

The results of migration tests for 3 years showed that the center of the distribution of  $^{90}\text{Sr}$  was moved several mm with advection and dispersion toward groundwater flow direction. On the other hand, the results of  $^{237}\text{Np}$  and  $^{238}\text{Pu}$  for 3 years later showed that the centers of the distribution of radionuclides not moved from initial injection points. Analysis of radionuclide migration was performed using parameters shown in Table 1. Figure 2 shows the obtained results for the distribution of concentration in a horizontal plane and the analyzed results. The groundwater flow and radionuclide migration in aquifer were analyzed in horizontal plane by MIG2DF. Parameters for analysis were obtained from laboratory column tests and batch tests (Mukai et al. 2003). It is also shown that the distributions of concentration along groundwater flow direction for 3 radionuclides in Fig. 3. These results show that the analyzed results of the distribution of concentration for  $^{90}\text{Sr}$ ,  $^{237}\text{Np}$  and  $^{238}\text{Pu}$  could explain observed results reasonably.

Table 1 Parameters used in the analysis for the radionuclide migration tests

Parameter	Loess	Quartz sand
Hydraulic conductivity (m/sec)	$3.0 \times 10^{-6}$	$1.0 \times 10^{-5}$
Density ( $\text{kg/m}^3$ )	1400	1600
Porosity	0.455	0.4
Distribution coefficient ( $\text{m}^3/\text{kg}$ )	$^{90}\text{Sr}$	0.04
	$^{237}\text{Np}$	0.2
	$^{239}\text{Pu}$	1.2
Diffusion coefficient ( $\text{m}^2/\text{sec}$ )	$^{90}\text{Sr}$	$5.8 \times 10^{-10}$
	$^{237}\text{Np}$	$5.8 \times 10^{-10}$
	$^{239}\text{Pu}$	$1.5 \times 10^{-11}$
Dispersion length (mm)	longitudinal	20
	transverse	2
Inventory (Bq)	$^{90}\text{Sr}$	$4.4 \times 10^6$
	$^{237}\text{Np}$	$3.5 \times 10^5$
	$^{239}\text{Pu}$	$3.2 \times 10^5$

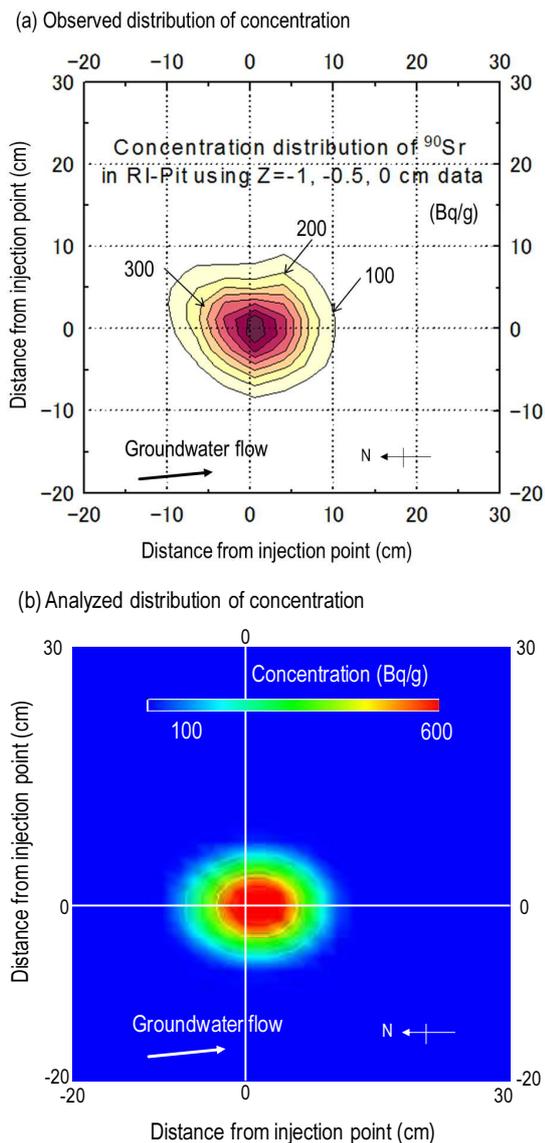


Fig. 2 Distribution of concentration of  $^{90}\text{Sr}$  at 1023 days later in radionuclide migration tests in aquifer

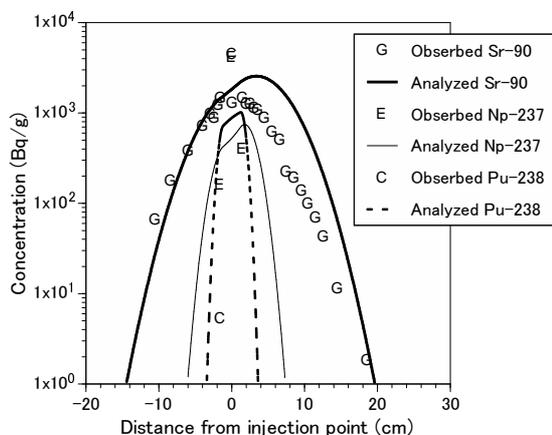


Fig. 3 Observed and analyzed distribution of concentration of radionuclides at 1023 days later in direction of groundwater flow

#### 4. VALIDATION STUDY OF REGIONAL GROUNDWATER FLOW

It is important to understand the regional groundwater flow system in the safety assessment for geological disposal of long-lived radioactive waste. In this study, regional groundwater flow of Horonobe area was analyzed by using 3D-SEEP.

##### 4.1 Hydrogeological Modelling for Horonobe Area

An analyzed domain in this study was a north part of Hokkaido and the area was 40km in East-West direction and 60km in North-South direction shown in Fig. 4. The modelled depth was approximately 5km. For the modelling, detailed geological data obtained from boring survey and aerial survey (Ota and Abe et al. 2007) was used. The hydraulic conductivity which have depth dependent characteristic was also used in analysis (Table 2). The number of finite elements was about 12 million (Fig. 5)

Horonobe is situated on the western coastal plain of Hokkaido where Quaternary alluvium and terrace deposits overlie Tertiary and Cretaceous sedimentary rock that were deposited in the Mesozoic Tenpoku Basin. The Tenpoku Basin is an on-shore basin that is elongated in the Horonobe area along a north-south axis. The Palaeogene rock are unconformably overlain by the marine sequences of the Miocene Masporo and Wakkanai Formations, the Miocene-Pliocene Koetoi Formation and the Pliocene-Pleistocene Yuchi and Sarabetsu Formations. The lower part of the Masporo Formation includes sandstones and conglomerates, which are overlain by a sequence of siliceous rocks that extend continuously into the overlying Wakkanai Formation. The Koetoi Formation is a soft diatomaceous mudstone and the Yuchi Formation is a sandy mudstone containing diatomaceous material.

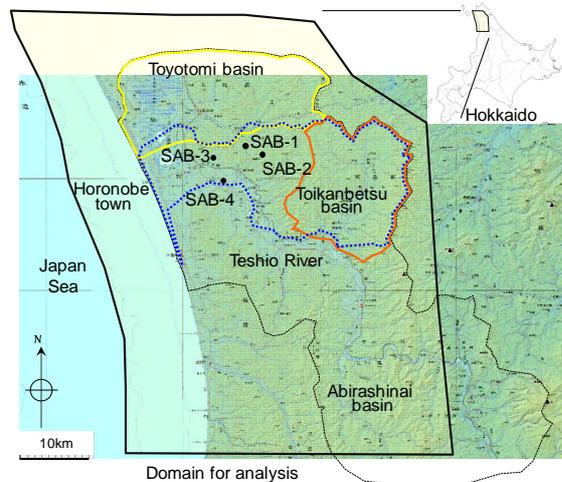


Fig. 4 Domain for analysis of regional groundwater flow

Table 2 Hydraulic conductivity and porosity setting for analysis

Formation	Hydraulic conductivity $k$ (m/sec), z: depth (m)	Porosity (-)
Surface layer	$1.0 \times 10^{-6}$	0.6
Alluvium	$1.0 \times 10^{-6}$	0.6
Sarabetsu	$\log_{10}k = -0.0034z - 8.3665$	0.6
	Upper limit: $1.0 \times 10^{-8}$ Lower limit: $1.0 \times 10^{-11}$	
Yuchi	$\log_{10}k = -0.0034z - 8.3665$	0.6
	Upper limit: $1.0 \times 10^{-8}$ Lower limit: $1.0 \times 10^{-11}$	
Koetoi	$\log_{10}k = -0.0039z - 7.5935$	0.6
	Upper limit: $1.0 \times 10^{-7}$ Lower limit: $1.0 \times 10^{-11}$	
Wakkanai	$\log_{10}k = -0.0061z - 5.5626$	0.4
	Upper limit: $1.0 \times 10^{-6}$ Lower limit: $1.0 \times 10^{-11}$	
Masuporo	$5.0 \times 10^{-10}$	0.3
Hakobuchi	$1.0 \times 10^{-11}$	0.2
Horonobe fault	$1.0 \times 10^{-8}$	0.5
Omagari fault	$1.0 \times 10^{-8}$	0.5

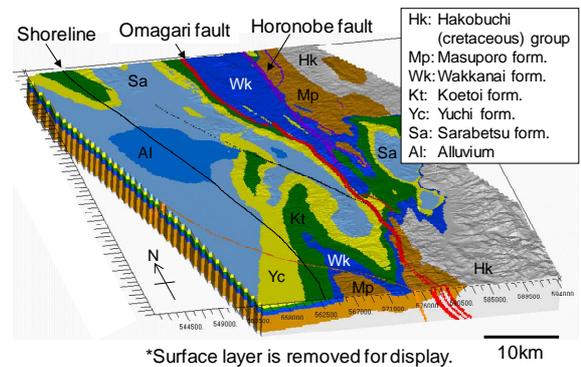


Fig. 5 Geological model for analysis of regional groundwater flow

The hydraulic conductivity of Neogene rocks in this area vary considerably from about  $10^{-5}$ - $10^{-12}$  m/sec but it seems to decrease with increasing depth, especially in fracture zone of the Wakkanai Formations. Fracture zones in the upper part of the Wakkanai Formations have locally higher hydraulic conductivities than the surrounding fractured rock. Therefore, depth-dependent hydraulic conductivity for Wakkanai, Koetoi, Yuchi and Sarabetsu Formations were used in the analysis.

In order to compare the results of analysis, 4 boreholes research were carried out. The locations of these boreholes were indicated in Fig. 4 as SAB-1 – SAB-4. The locations of these boreholes were determined by analysis. In the borehole researches, the total head and concentration of salt in groundwater were measured and the results were showed that the saline water was appeared at shallower depth in SAB-3 and 4 whereas the saline water was appeared deeper depth in SAB-2. It was suggested that SAB-2 was located in the recharge area and SAB-3 and 4 located in discharge area.

### 5.2 Analysis of Regional Groundwater Flow

Because the formations in the domain for analysis were consisted of marine deposit, saline water was found in deeper zone. The 3D-SEEP (Kimura and Muraoka 1986) was modified to be able to analyzed density driven flow in this study. Simulated results of total head and salt concentration were compared to the data obtained from research boreholes which were drilled to obtain data to validate. A wash-out analysis was carried out in order to simulate long-term unsteady groundwater flow. Therefore, initial condition was saturated concentration of sea water condition. Then, the groundwater including saline water is gradually washed out by fresh water of rain in long time. Analyzed result of total head shown in Fig. 6 indicates that groundwater flows from east mountains to sea generally. Figure 7 shows the detailed analyzed results of total head and salt concentration in vertical cross section through SAB-2 in West-East direction. In Fig. 7, geological structures like as faults and formations and boreholes locations are also indicated in the cross section. And also, Fig. 8 shows comparison between observed and analyzed vertical profiles for total head and salt concentration in SAB boreholes. In the figure, the concentration was normalized by concentration of sea water. The wash-out analysis was performed for 100,000 years after.

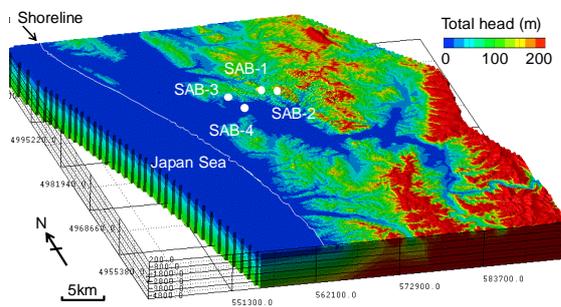


Fig. 6 Analyzed result of total head distribution (70,000 years after)

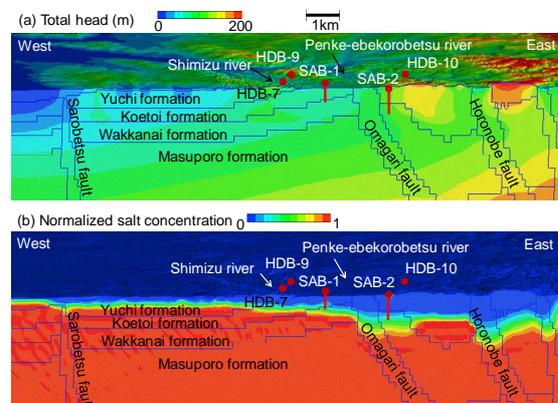


Fig. 7 Detailed distributions of total head and salt concentration in vertical cross-section through SAB-2 in west-east direction (70,000 years after)

In Fig. 8, it was shown that the analyzed total head in boreholes were good agreement with observed data. The analyzed result suggested that the total head for shallower than -500m in elevation was not changed after 10,000 years. It was also shown that the analyzed concentrations in boreholes were almost agreement with observed data at 100,000 years although there was the uncertainty associated with temporal change of environment. The results indicate that the 3D-SEEP could explain the regional groundwater flow in Horonobe area.

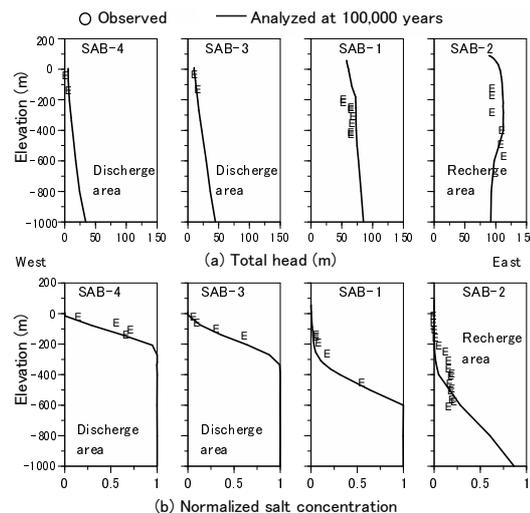


Fig. 8 Comparison between observed and analyzed vertical profiles for total head and salt concentration in SAB boreholes

### 5. SIMULATION OF GROUNDWATER FLOW IN FUTURE ENVIRONMENT

In the safety assessment for geological disposal of long-lived radioactive waste, it is important to estimate radionuclide migration to human environments through groundwater flow. In recent study, for example, JAEA has been developing a safety assessment code for nuclear regulation and studies regional groundwater flow systems in order to understand regional groundwater flow on a 10-100 km scale (Munakata et al. 2014).

It is necessary in the safety assessment to validate a conceptual representation of flow system for from the recharged area to discharged area compared with observed data. Therefore, regional groundwater flow system in a sedimentary rock area in Boso peninsula of Japan was investigated and conceptualized the regional flow model of this area using the observed data (flow rate, chemical composition of groundwater, and isotopic ratios of hydrogen and oxygen in water samples collected from wells, rivers and springs). In addition, the safety assessment of a high-level radioactive waste repository in Japan may require evaluating influences of tectonic movement and climate

change for long time period. Especially, groundwater flow may vary with changes of infiltration and landform caused by climate change for long time period but not much study for them has been conducted so far. In this study, the groundwater flow in present steady conditions was analyzed and the result was compared to observed data. Then, the groundwater flow in a future environment was analyzed by using estimated future conditions (rainfall and topographic changes caused by climate change in 80,000 years) and the result was compared to the modelled present conditions, in order to quantify the uncertainties of estimation of groundwater flow rate involved in the safety assessment.

### 5.1 Hydrogeological Modelling for Boso Peninsula

Boso Peninsula is located southeast of Tokyo. Yoro River flows in the central part of Boso Peninsula towards the northwest from the southeast and flows out to Tokyo bay with flow length about 50 km. Figure 9 shows the elevation map of the area and position of main rivers and observation wells. The main geological feature of this area consists of alternating sandstone and mudstone, and the layers dip in the northwest direction slightly. Chemical composition and isotopic data indicate the boundary of Ca-HCO<sub>3</sub> type groundwater and Na-HCO<sub>3</sub> type groundwater and also suggests that the groundwater flow to the surface and the groundwater flow to a deep formation which are restricted by alternation (Sakai et al. 2008). In addition, the above results are supported by the observed data that relatively new dating of groundwater appears in sandstone formation with high permeability and old dating of groundwater appears in mudstone formation with low permeability. Table 3 shows the hydraulic parameters for groundwater analysis based on data from the geologic researches.

### 5.2 Analysis of Regional Groundwater Flow with Topographic Change

In order to quantify uncertainty included in the result of safety assessment of geological disposal, it is important to evaluate groundwater flow under environmental conditions in a future with climate change. From the viewpoint of evaluation of groundwater flow velocity in the future, two factors caused by climate change was focused on in this study. One was a change of precipitation with the climate change. The other was a topographic change caused by uplift and erosion. The 3D-SEEP for groundwater analysis was modified to take account temporal change of landform caused by climate change, uplift and erosion in future environment. The domain for evaluation had dimensions of 50km in West-East direction, 50km in North-South direction and 3km in depth, and

was modeled using 2 million finite elements shown in Fig. 9.

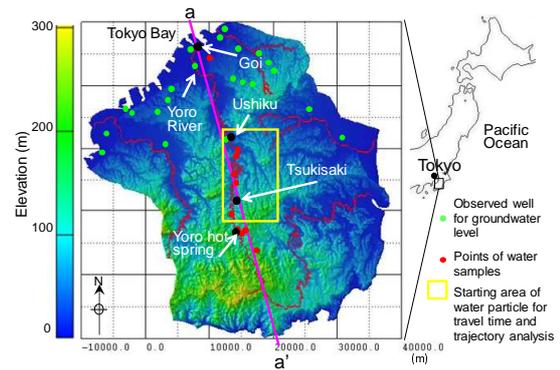


Fig. 8 Modelled domain and elevation of the Boso Peninsula

Table 3 Hydraulic Parameters for Groundwater Analysis of Boso Peninsula

Formation	Facies	Hydraulic conductivity (m/sec)	porosity
Shimousa Group	Sandstone	$3 \times 10^{-5}$	0.5
Kasamori	Mudstone	$1 \times 10^{-7}$	0.5
Matano-Kakinokidai	Sandstone - Sandy Mudstone	$4 \times 10^{-5}$	0.46
Kokumoto	Mudstone	$1 \times 10^{-7}$	0.47
Umegase	Sandstone	$1 \times 10^{-5}$	0.4
Kiwada, Ohtadai	Mudstone	$5 \times 10^{-7}$	0.45
Miura Group	Sandstone, Mudstone, Conglomerate	$3 \times 10^{-7}$	0.4

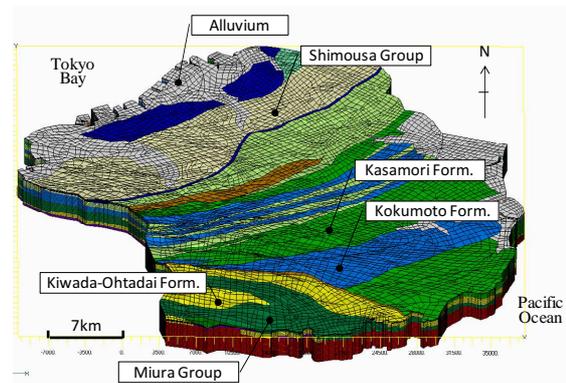


Fig. 9 Numerical mesh for groundwater flow analysis

In the simulation of groundwater flow in future environment, it was assumed that the temperature fell 8 degrees Celsius from the current temperature and infiltration was reduced 30% in 80,000 years (Fig. 10(a)). Also, a change of topography in 80,000 years was estimated by using data of uplift and erosion in Boso peninsula using topography simulation (Sanga and Yasue 2008). Fig. 10(b) shows the estimated landform in 80,000 years along the cross-section (a-a') in Fig. 8. Future

topography in 80,000 years was estimated from differences between uplift data of Fig. 10(c) and erosion data of Fig. 10(d) for 500 m square grids.

The simulations were performed from current environmental condition (0 years; case 1) to the estimated conditions in 80,000 years (case 2). The simulation of case 1 uses infiltration of 100 mm/year and the current landform of surface layer and the simulation of case 2 uses infiltration of 70 mm/year and the estimated landform in 80,000 years. Temporal changes of infiltration and landform was considered in this simulation. Sea level change caused by climate change was not considered because of difficulties of definitions for domain in these simulations and also the positions

of the rivers in that future environment may not change. The boundary conditions for the analysis were assumed that the bottom of the domain at depth of 3 km was a no flow condition and the pressure head in the rivers on the surface was zero, and the infiltration rate (100 or 70 mm/year) was applied to the other area on the surface. In addition, no flow was assumed to cross the boundary of north-eastern and south-western side. The boundaries that face Tokyo bay and Pacific Ocean were set as the current sea water level.

Figure 11(a) show the results of total head distribution for the current environmental conditions (case 1: 0 year) and Figure 11(b) show

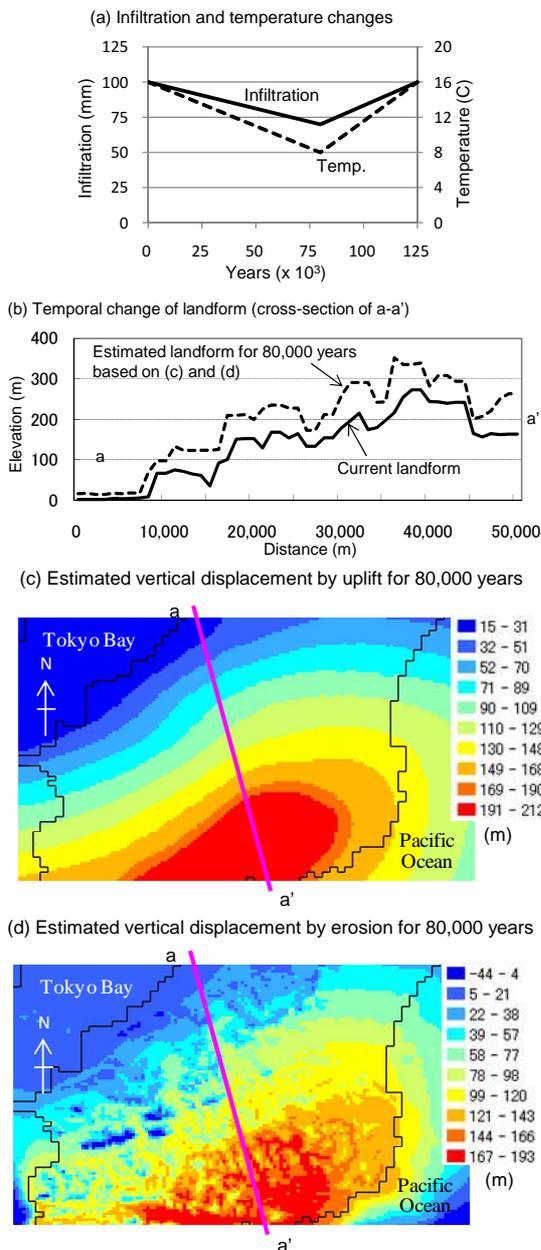


Fig. 10 Parameter setting for temporal change of infiltration and temperature and simulation results for topography change

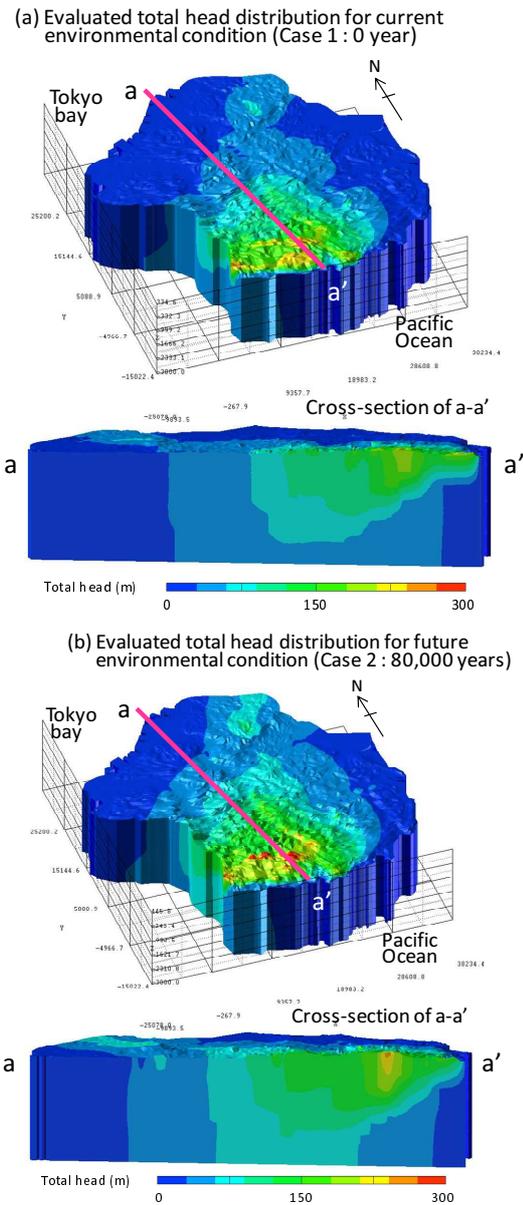


Fig. 11 Total head distributions of the results of (a) case 1 and (b) case 2 (upper figure shows outlook from south western direction and lower figure shows the cross-section along the a-a')

the future environmental conditions (case 2; 80,000 years after). The analyzed results in current steady conditions (case 1) show that the groundwater flows mainly from south-eastern area to north-western area in the direction of dip in the stratum. The distributions of total head appear almost the same between case 1 and case 2, however, the results of case 2 indicate an increased hydraulic gradient caused by topographic changes on the domain.

The analyzed results for current environmental conditions showed that groundwater flows mainly from south-eastern area to north-western area in the direction of dip in the formations. The analyzed results of groundwater flow in future environmental conditions showed that the mean values of travel velocity of water particles change within a range of 10%. It was indicated that variance of groundwater flow caused by changes of infiltration and landform with climate changes was small in this study. Also, it was suggested that uncertainties in the estimation of groundwater flow rate in the future was able to quantify for the safety assessment of HLW facilities in Japan.

## 6. CONCLUSION

This paper reports the results of validation study for groundwater flow and radionuclide migration. In order to validate safety assessment codes for radionuclide migration, field tests used  $^{90}\text{Sr}$ ,  $^{237}\text{Np}$  and  $^{238}\text{Pu}$  were carried out in natural aquifer at 30m below ground surface of the field test site in China. Migration of radionuclides was evaluated by MIG2DF and the results obtained from field tests were compared to analyzed results. It was confirmed that the migration behavior of radionuclides could be evaluated by MIG2DF reasonably.

In order to validate safety assessment codes for groundwater flow, regional groundwater flow of Horonobe area was analyzed by modified 3D-SEEP. The analyzed results of total head and salt concentration were compared the data obtained from borehole researches. The results showed that the analyzed results of groundwater flow and salt concentration could explain the results obtained from borehole researches reasonably by 3D-SEEP.

Furthermore, by using 3D-SEEP, regional groundwater flows with topographic change caused by climate change was analyzed to develop the method which evaluate changes of groundwater flow in future environment. The analyzed results of groundwater flow for Boso Peninsula in future environmental conditions showed that travel velocities change within a range of 10%.

In future work, it is needed for safety assessment that the technical issues associated with long-term evolution for natural and geological environment are identified to archive reasonable evaluation.

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