An Integrated Framework for Simulating Radionuclide Decay Transport of Low-level Radioactive Waste with Tunnel Disposal in Nearshore Environment

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Abstract

Tunnel disposal at nearshore environments was tentatively proposed as one of final disposal sites for low-level wastes in Taiwan. The disposal facilities was designed with several disposal tunnels and located at 50m~200m below ground surface. Safety functions adopted are containment and retardation provided by multiple engineered barriers and host rock to prevent leaching of radionuclides into biosphere. An integrated simulation framework was developed with three levels of finite element grids to simulate radionuclide decay transport with 3-D HYDROGEOCHEM5.6 numerical models. Steady flow and transient transport were performed in this study. The coarsest-level grids serve covers the far-field simulation domain. The middle-level grids described layouts of disposal tunnels serve as grids of near-field facilities. The finest-level grids were developed to investigate radionuclide migrations at selected tunnel sections. Total radioactive activities of source term and a total of 11 radionuclides (Pu-238, Am-241, Tc-99, Co-60, I-129, Cs-137, Ni-59, C-14, Sr-90, Y-90, Ni-63) with decay chains as given in the report of Taiwan Power Company were simulated in this study. Flow boundary conditions at finer-level grids were obtained from flow simulations of coarser-level grids. Release rates of radionuclides at coarser grids were obtained from simulations of radionuclide decay transports at finer grids. For the first 100 years, release rates of C-14, Tc-99, and I-129 are higher than the others. After 100 years, release rates of Ni-59, C-14, and Tc-99 are higher than the others. Owing to high sorption of Ni-59 onto bentonite barriers, long-lived Ni-59 with high initial concentration produced low release rates for the first 100 years. Low release rate of I-129 after 100 years was caused by low initial concentration of I-129. Results demonstrate complicated interactions among initial concentrations, half-life, decay chains, near-field processes, and far-field processes on radionuclide decay transport.

1. Introduction

The first nuclear power plant in Taiwan has been operated since 1978. To date, we have a total of four nuclear power plants with three in operations accounting for 13.5% of annual energy generations in 2016 (TPC web site). The highest percentage of nuclear power in annual energy generations was 52.4% in 1985 and has been gradually reduced to below 20% after 2005. More than 60% of today's energy is provided by thermal power generation with coal and gas. Although relatively less greenhouse gases were emitted by nuclear power generations, environmental concerns and debates on how the produced radioactive waste can be properly handled remains great channelings to waste management communities. As the government has been committed to phasing out nuclear power in Taiwan by 2025, the decommission project of the first new clear power plane will be deployed in 2019 and completed by the end of 2043. Two potential sites for final disposals of low-level wastes (LLW) were officially announced in 2012, one in the Daren Township located in southeast Taiwan and another one in the Wuciou Township located in an offshore island of Kinmen (Ministry of Economic Affairs, 2012). Although difficulties of having public votes for site approvals have been encountered for years, scientific and technical studies of feasibilities on building LLW final disposal facilities have never been suspended. To both the general public and experts, confidences and acceptances of waste final disposal repositories require demonstrations of long-term safety with comprehensive numerical simulations.

Near-surface or tunnel disposal is frequently adopted for intermediate and low-level wastes in many countries, such as UA, France, and USA. Tunnel disposal was tentatively designed for the LLW in Taiwan. In this study, we proposed an integrated simulation framework having three levels of finite element grids to simulate radionuclide decay transport with 3-D HYDROGEOCHEM5.6, a special version of 3-D HYDROGEOCHEM5.5 (Yeh et al., 2009) numerical model, for the LLW disposal at the Daren site. Steady flow and transient radionuclide transport of multiple decay chains in far-field and near-field were performed for 100,000 years. The objective is to investigate complicated interactions among initial concentrations, half-life, decay chains, near-field processes, and far-field processes on radionuclide decay transport.

2. Simulation Setup

The near-field multiple engineering barriers are designed to contain the release of radioactive waste after the closure of disposal facilities. In this study, we aim to simulate the migration of radioactive waste in nearby geosphere after failing of near-field engineering barriers. Several SKB reports for the SR-PSU site (SKB 2014a, 2014b) in Sweden were studied to inspire our design of simulation framework. The 3-D HYDROFEOCHE5.6 finite element numerical model was selected for having capabilities of resolving coupled flow, thermal, radioactive transport with decay chains. Our simulation flow chart was shown in Fig. 1. Far-field flow simulation was performed first to provide boundary conditions of near-field facilities. Subsequently, flow simulation of near-field facilities generates boundary conditions for simulations of near-field tunnels. For the transport part, we simulate radioactive decay transport of near-field tunnels to provide radionuclide release rates for radioactive transport simulations in near-field facilities. Finally, radioactive transport simulations in far-field are supported with radionuclide release rates simulated in near-field facilities. In this study, total radioactive activities of source term and a total of 11 radionuclides (Pu-238, Am-241, Tc-99, Co-60, I-129, Cs-137, Ni-59, C-14, Sr-90, Y-90, Ni-63) with decay chains are considered as shown in Table 1 (TPC, 2016).

The elevations of far-field simulation domain are from 475m above sea level at the west to -170 m below sea level at the east. The vertical depth of simulation domain is about 400 m and the top surface covers a region of 8,600 m times 3,800 m. The far-field domain, the coarsest-level grids, is discretized with 5,970 nodes and 4,749 elements as shown in Fig. 2 (left). The near-field facilities designed with five 828 m long, three 778 m long, and seven 352 m long disposal tunnels is discretized with 6,120 nodes and 4,720 elements in Fig. 2 (right). The near-field tunnel domain considers a single disposal tunnel section having eight kinds of engineering barriers and is discretized by a total of 873 nodes and 1,556 elements as shown in Fig. 3. Hydrogeological and transport parameters were modified from the TPC assessment report (TPC, 2016). Tables 2, 3 and 4 are parameters used for the far-field, near-field facilities, and near-field tunnel, respectively.

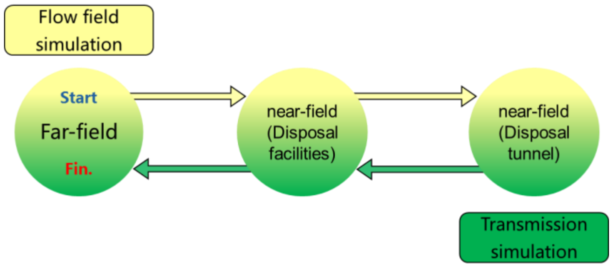

Figure 1 Simulation flow chart

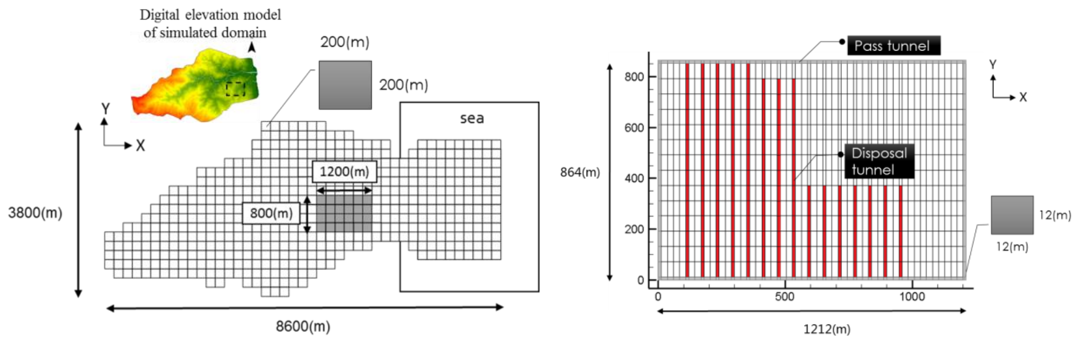

Figure 2 Elements and scales (plan-view) used in far-field (left) and near-field facilities (right)

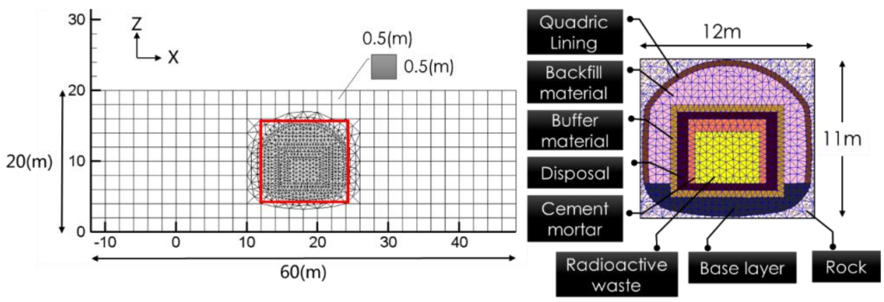

Figure 3 Elements and scales (side-view) used in near-field tunnels

Table 1 Source term concentrations

Radionuclide	^{242}Cm	^{241}Pu	^{238}Pu	^{137}Cs	^{129}I	^{99}Tc	^{90}Sr	^{63}Ni	^{60}Co	^{59}Ni	^{14}C
Concentration (TBq)	3x10^4	4x10^3	1x10^2	1x10^6	5x10^1	2x10^3	2x10^6	2x10^6	5x10^6	1x10^5	5x10^4

Table 2 Parameters for far-field grids

Flow parameters		layer1	layer2	layer3
	K_x=K_y	$3*10^{-2}$(m/day)	$3*10^{-3}$(m/day)	$3*10^{-5}$(m/day)
	K_z	$8.9*10^{-2}$ (m/day)	$8.9*10^{-3}$ (m/day)	$3*10^{-5}$ (m/day)
	Porosity		0.08	
Transport parameters	Longitudinal dispersivity		800(m)	
	Lateral dispersivity		200(m)	
	Diffusion coefficient		10^{-4}(m^2/day)	

Table 3 Parameters for near-field facilities grids

Flow parameters		Rock	Disposal tunnel
	K_x=K_y=K_z	$8.64*10^{-5}$ (m/day)	$5.16*10^{-5}$ (m/day)
	Porosity	0.25	0.28
Transport parameters	Longitudinal dispersivity	8(m)	
	Lateral dispersivity	2(m)	
	Diffusion coefficient	$1.73*10^{-4}$(m^2/day)	$4.89*10^{-5}$(m^2/day)

Table 4 Parameters for near-field tunnel grids

Material	Porosity (-)	K_x=K_y=K_z (m/day)	Diffusion coefficient (m^2/day)	Longitudinal dispersivity (m)	Lateral dispersivity (m)
Rock	0.25	$8.64*10^{-5}$	$1.73*10^{-4}$	8	2
Quadric Lining	0.25	$8.64*10^{-5}$	$1.73*10^{-4}$		
Base layer	0.2	$8.64*10^{-6}$	$8.64*10^{-8}$		
Buffer material	0.4	$8.64*10^{-8}$	$1.73*10^{-5}$		
Backfill material	0.3	$1.73*10^{-5}$	$8.64*10^{-6}$		
Disposal	0.2	$8.64*10^{-6}$	$8.64*10^{-8}$		
Cement mortar	0.3	$8.64*10^{-5}$	$3.46*10^{-5}$		
Radioactive waste	0.35	$1.73*10^{-4}$	$6.05*10^{-5}$		

3. Results and Discussions

Simulations of steady flow with steady transport or transient transport for up to 100,000 years were conducted this study. Figure 4(left) depicts flow field and total head distribution in far-field with a constant infiltration rate of 0.0003 m/day and a fixed sea level on the right. We do see some upward velocities due to terrain cavities. It is noted the regional flow velocities are small and such upward flow does not represent the occurrence of surface spring. Figure 4(right) gives flow field and total head distribution simulated for near-field facilities. Figure 5 shows cross-sectional view of flow field and total head distribution simulated with near-field tunnel grids. Overall the flow filed is eastward to the ocean. Owing to low hydraulic conductivities of engineering barriers, the flow velocities inside disposal tunnel are about 0.01% of those outside the tunnel. Figure 6 is the distribution of radionuclide concentrations simulated with steady transport. It is noted regions right above the disposal tunnel have relative high concentration compared to upward side of the tunnel due to dispersion.

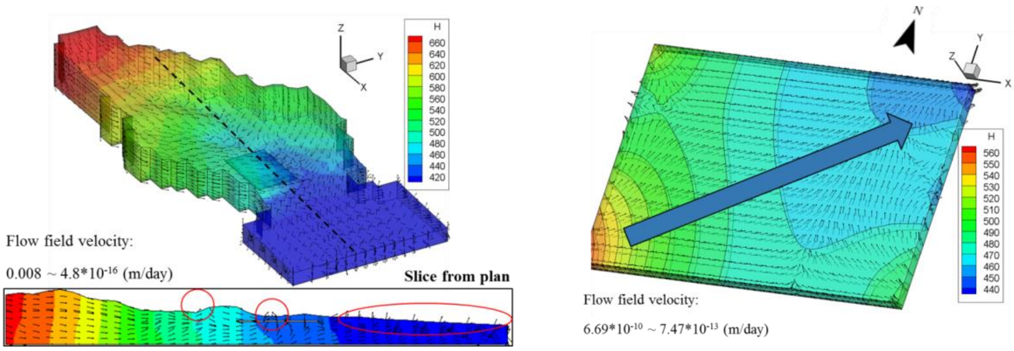

Figure 4 Flow field and total head distributions in far-filed (left) and near-filed facilities (right)

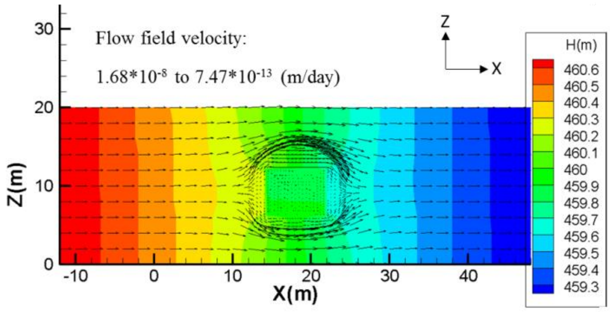

Figure 5 Flow field and total head distribution of near-field tunnel

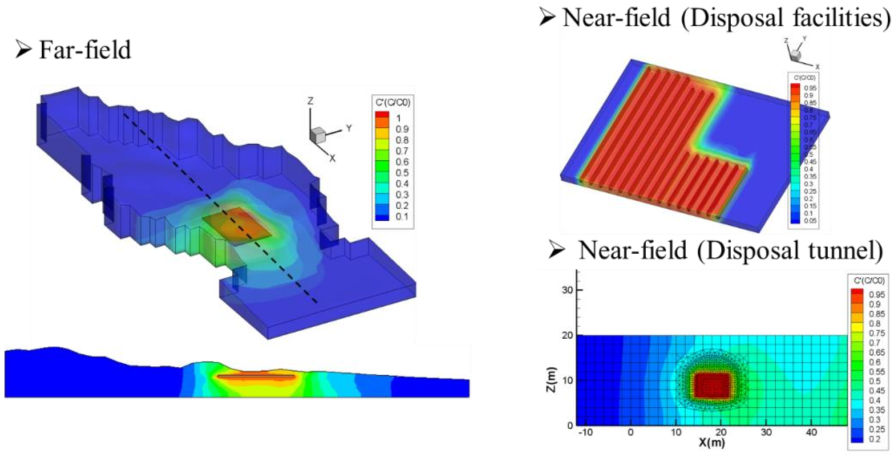

Figure 6 Relative concentration distributions of radionuclide with steady transport simulation

Source term concentrations given in Table 1 were used as initial concentrations for transient simulations of radionuclide decay transport with near-field tunnel grids, which will provide release rates of radionuclides out of tunnels to be simulated at the near-field facilities grids to further support simulations at far-filed grids. Figure 9 shows radionuclide concentrations in 100,000 years at 200 meters away from disposal facilities. For the first 100 years, release rates of C-14, Tc-99, and I-129 are higher than the others. After 100 years, release rates of Ni-59, C-14, and Tc-99 are higher than the others.

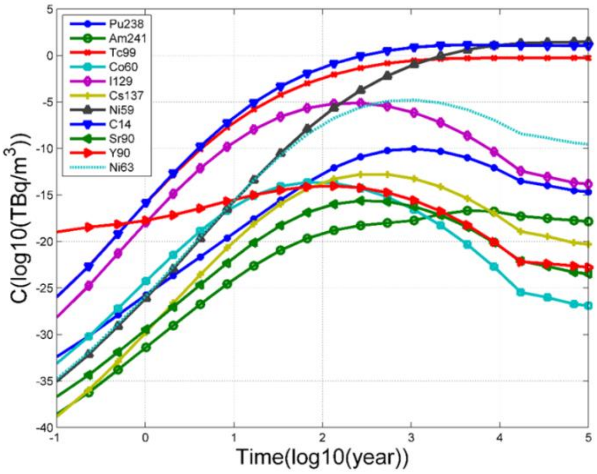

Figure 9 Radionuclide concentrations in far-field at 200 meters away from disposal facilities

4. Conclusions

For safety concerns of waste disposal, it is important to quantify the spatial and temporal distributions of released radionuclides. In this study a 3D numerical model was used to simulate the radionuclide migrations of low-level waste disposal site at nearshore environment tentatively selected by the Ministry of Economic Affairs in Taiwan. Based on current setting, flow velocities are 0.008 - $4.8x10^{-16}$ (m/day) in far-field, $6.7x10^{-10}$ - 7.5 x 10^{-13} (m/day) in near-field facilities, and $1.7x10^{-8}$ to $7.5x10^{-13}$ (m/day) on near-field tunnels observed from steady flow simulations. For the first 100 years, release rates of C-14, Tc-99, and I-129 are higher than the others. After 100 years, release rates of Ni-59, C-14, and Tc-99 are higher than the others. Owing to high sorption of Ni-59 onto bentonite barriers, long-lived Ni-59 with high initial concentration has a low release rate for the first 100 years. A low release rate of I-129 after 100 years is due to of having low initial concentration. Results demonstrate complicated interactions among initial concentration, half-life, decay chains, near-field processes, and far-field processes on radionuclide decay transport.

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