Uncertainty Analysis of Multiple Canister Repository Model by Earth Simulator

Project Representative
Hiroshi Okuda Research into Artifacts, Center for Engineering, University of Tokyo

Authors
Keiichi Tsujimoto Mitsubishi Materials Corporation
Joonhong Ahn Department of Nuclear Engineering, University of California, Berkeley

An uncertainty analysis considering the heterogeneity of host rock has been made by using the multiple-canister radionuclide transport code, the VR code, for performance assessment for the high-level radioactive waste (HLW) repository. In the previous VR calculations, the number of connected canisters in the same water stream was determined arbitrary. In this study, the number of connected canisters in the same water-flow stream has been determined statistically by counting the number of canisters included in the same fracture network by using the FFDF code. The uncertainty resulting from fracture networks in host rock has been taken into account by applying the probability distribution function (PDF) of the numbers of connected canisters by a fracture cluster obtained by the FFDF code. The release rate of ^{237}Np from a hypothetical repository model containing 500 canisters has been evaluated by using the VR code with uncertainties associated with the ^{237}Np release rate resulting from variations of the number of connected canisters. The VR code and the FFDF code had been transplanted to the Earth Simulator by authors to perform large-scale computations. The Latin Hypercube Sampling has been utilized to reduce the number of samplings in Monte-Carlo calculation utilized in the VR code.

Keywords: uncertainty analysis, multiple canister repository model, high-level radioactive waste, fracture network, mass transport

1. Introduction

An uncertainty analysis considering heterogeneity of the host rock has been made by using the multiple-canister radionuclide transport code, the VR code [1][2], for performance assessment of the High-level radioactive waste (HLW) repository.

By deterministic studies with the VR code, it was found that, especially for a water-saturated repository where water flows in parallel to the repository plane, the effects of neighboring canisters on the release of radionuclides from the canister of interest are significant [1]. In the previous deterministic VR calculations, however, the number of connected canisters in the same water stream was determined arbitrary. The number of connected canisters in the same water-flow stream is an important parameter because the radionuclides are released from the only canisters in the water-flow stream, and transported via the groundwater flow, and could be determined statistically by counting the number of canisters included in the same fracture network.

Recently, the FFDF model, a Monte Carlo model for mass transport in fractured rock, was developed. [3] In the FFDF model, a two-dimensional circular model space considered as the repository in which a waste canister of interest is located at the center of the model space. The central waste canister is surrounded by the buffer and the host rock. In the host rock, fractures are generated based on statistical distribution functions. After a certain number of fractures are generated, inter-connection among the generated fractures is checked, and Flow-Bearing fracture Cluster (FBC), which connects the outer boundary of the circular model space and the outer boundary of the buffer in the central waste canister, is determined.

The FFDF code has been transplanted to the Earth Simulator [4] for a large-scale simulation of the fracture network in a circular domain with a radius of 60 m with more than a hundred thousand fractures. This scale of calculation has never been made in the previous calculations by PCs. The probabilistic distribution functions of the total numbers of connected canisters by the same fracture cluster are obtained by the code.

The release rate of ^{237}Np from a hypothetical repository containing 500 canisters has been evaluated by using the VR code as a surrogate measure for repository performance. Uncertainties associated with the release rate resulting from parameter variations including the number of connected canisters by a fracture network have been evaluated. In the uncertainty analysis, the PDF for the number of connected waste canisters by fracture network obtained by the FFDF code is used.

From the viewpoint of computational workload, we needed to solve the issue of a vast amount of calculation to obtain statistical convergence if a standard Monte Carlo approach is applied. To overcome this difficulty, Latin Hypercube Sampling [5] to reduce the number of samplings is applied.

2. Fracture Network Analysis by FFDF Code

In this study, the total number of fractures existing in the model space is estimated based on the geological survey data at JNC Horonobe site [6], where the linear frequency distribution of fractures is obtained.

As the FFDF code was originally developed for PC in C++ language, the code has been converted to Fortran-90 language.

Cases have been set for various total numbers of fractures in a circular model with a radius of 60m with 109 canisters. For each case, the number of connected canisters by FBC has been evaluated.

Figure 1 shows fracture networks for the total numbers of fractures of 20000. In the figure, the FBC are shown as blue lines, fractures not included in the FBC as gray lines, the canisters included in FBC as red circles, and the canisters not included in FBC as green circles.

The PDF of the total numbers of fractures connected by FBC is shown in Figure 2. As shown in Figure 2, each PDF has a bell-shape with its peak. The PDF strongly depends on the total number of fractures in the model space. As the total number of fractures increases, the distribution becomes narrower, and the median value for the number of canisters connected by the FBC increases.

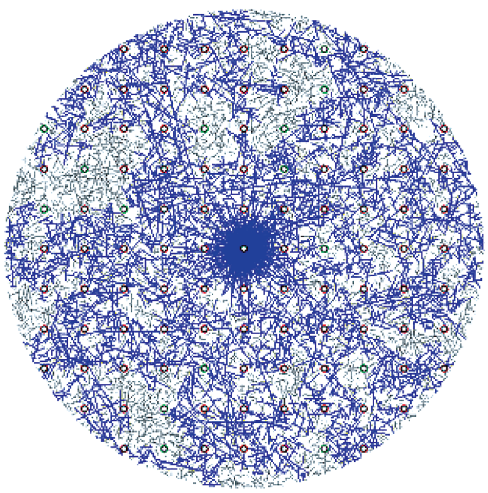

Fig. 1 FBC for 20000 fractures.

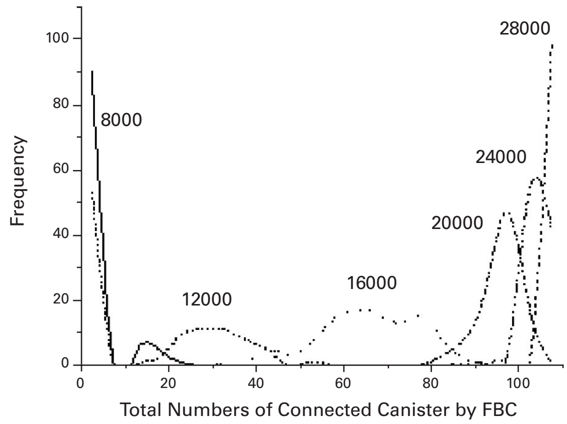

Fig. 2 The Frequency of Total Numbers of Canisters Connected by FBC for Various Number of Fractures in the Repository Model.

3. Uncertainty Analysis by VR code

Uncertainty analysis is performed by the VR code, a mass transport calculation code for multiple- canister repository model.

3.1 VR Model

In the VR model, the repository consist of multiple compartments, each containing a waste canister, the buffer that backfills the space between the waste canister and the disposal tunnel surface, and the near-field rock. The compartments are positioned in the direction of groundwater flow.

3.2 Uncertainty Analysis

The PDF for the maximum value of the ^{237}Np release rate to the far-field has been obtained by the uncertainty analysis. In this study, the ^{237}Np release rate to the far-field is used as a surrogate performance measure of the repository.

We assume that the following input parameters for the VR model are associated with uncertainties: the solubility, the sorption coefficients of the radionuclide, and the number of connected canisters in a row.

We consider that among the canisters in the repository only n canisters are included in the fracture cluster that is connected with the groundwater flow field in the region exterior to the repository, or the far-field. The probability for the event that a row of n compartments occurs is given by the PDF calculated by the FFDF code.

The VR code has been performed for each trial calculation, and the maximum value of the ^{237}Np release rate has been obtained and recorded to obtain the PDF for the release rate. The release rate to the far-field has been calculated by

$$F(t) = \sum_{j=1}^{N} P_j R_j(t), \qquad (1)$$

where $F(t)$ is the release rate from the repository to the far-field at time of t, P_j the probability for the number of connected canisters by a fracture cluster to be j, $R_j(t)$ the release rate from a row of j compartments at time of t obtained by the VR model, and N the total number of canisters in the repository model, set to be 500 in this study.

The PDF of the solubility for ^{237}Np reported in [7] has been utilized. The PDF of the sorption coefficient reported in [7] has also been utilized in the uncertainty analysis.

Figure 3 shows the ^{237}Np release rate with the PDF for the numbers of connected canister for 8000 and 18000 fractures. Thus, variations of the solubility and the sorption coefficient are also considered in the ^{237}Np release rate for 8000 and 18000 fractures. The primary interest is the peaks of the release rate. We observe that the peak value for 8000 is smaller than that for 18000. This is because with more fractures, more canisters are connected by the fracture cluster, so that greater mass of the radionuclide is released from the repository.

Based on these results, we have obtained the cumulative distribution function (CDF) for the maximum fractional release rate for various numbers of fractures. Figure 4 shows the results for various fracture numbers. The fractional release rate is obtained by dividing the release rate by the total mass of the radionuclide initially included in the n canisters in the repository.

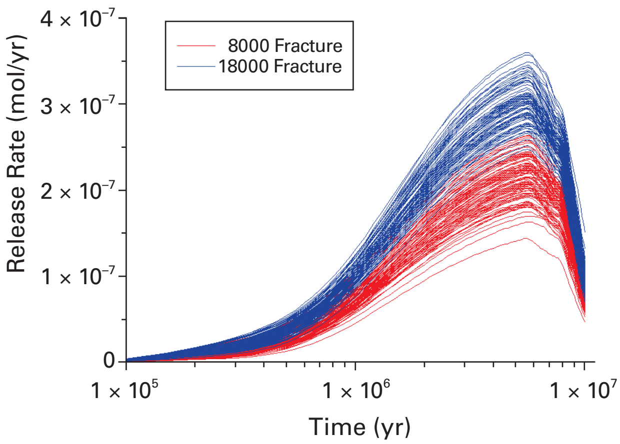

Fig. 3 ^{237}Np Release Rate with the PDF for the Number of Connected Canister for 8000 and 18000 Fractures in the Repository.

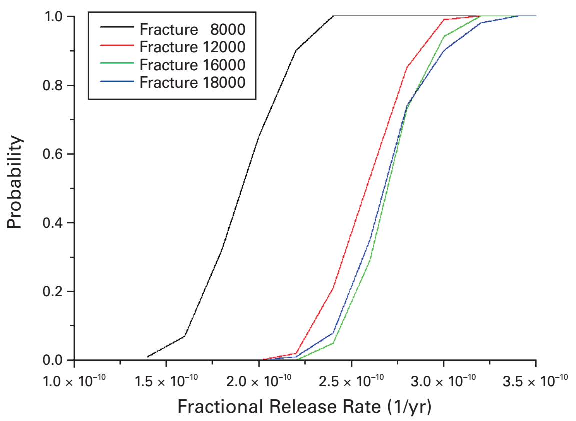

Fig. 4 The Cumulative Distribution Function for the Peak Fractional Release Rate of ^{237}Np.

From Figure 4, it is observed that with a fewer fractures, the fractional release rate tends to be smaller. With the fracture number 12000 or greater, the fractional release rate distributes around the same range.

4. Discussions

4.1 Computational performance of the FFDF code

We have measured the computational performance of the FFDF code with the repository model with a radius of 20 m containing 10 canisters. The CPU time and the amount of memory consumption for fracture calculation part of the code are measured by varying parameters of the numbers of fractures.

The measured computational performance is as followings:

The total numbers of fractures in the repository dominates the CPU time for fracture calculation. The CPU time is approximately proportional to the total numbers of fractures raised to the second power.

Since the total numbers of canisters in the HLW repository is 40,000, from the viewpoint of the numbers of fractures, the FFDF code with the present calculation models and the optimization condition can not calculate the fracture generation and interconnection judgment for the full-scale HLW repository model with more than 1.0E+6 fractures by using the Earth Simulator with full nodes.

To overcome this difficulty, the more efficient optimization of the FFDF code, the development of new fracture calculation algorithm, and the improvement of the calculation model of HLW repository are needed. For example, the development of the homogenization model of the canister and its surrounding materials is the promising method to improve the HLW repository calculation model to reduce the CPU time without severely decreasing the precision of the mass transport calculation. We should study further to decide which solutions is the most promising and has the highest priority to overcome the difficulty.

5. Conclusions

We have successfully transplanted the FFDF code, a fracture network generation, water flow, and mass transport code based on Monte-Carlo approach, on Earth Simulator and executed for a model space containing 109 waste canisters.

We have also successfully transplanted the VR code on Earth Simulator, and combined with the Latin-Hyper Cube sampling code for the uncertainty analysis.

With the codes we have made numerical exploration, and reached the following observations.

FFDF code

- Simulation of fracture networks in a circular model of a repository with a radius of 60 m with more than a hundred thousand fractures has been executed by Earth Simulator.

- The key parameter that determines the PDF of the total numbers of canisters connected by Flow Bearing Cluster is the total number of fractures in the model space. As the total number of fractures increases, the distribution becomes narrower, and the average value for the number of canisters included in the FBC increases.
- The present FFDF code can not handle the fracture calculation of the full-scale HLW repository model with more than 1.0E+6 fractures by using the Earth Simulator with full nodes. To overcome this difficulty is the future task.

VR code

- As the number of fractures included in the repository increases, the average for the peak release rate of the radionuclide increases. For sufficiently large number of fractures, the average peak release rate becomes unchanging, because in such a case most of the canisters in the repository are connected by the fracture cluster, and additional fractures does not change the number of connected canisters.

References

[1] J. AHN, D. KAWASAKI, and P.L.CHAMBRE, "Relationship Among Performance of Geological Repositories, Canister-array Configuration, and Radioactive Mass in Waste", *Nuclear Technology*, **140**, pp.94–112 (2002).

[2] K. TSUJIMOTO, and J. AHN, "Development of Object-Oriented Simulation Code for Repository Performance Assessment", *Trans. Am. Nucl. Soc.*, **81**, pp.54–55 (1999).

[3] D. Lim, "Mass Transport Analysis in the Near Field of Geologic Repository", University of California, UCB-NE–4238, (2003).

[4] K. TSUJIMOTO, and J. AHN," Large-Scale Simulation of Rock Fracture Network for Mass Transport in Geologic Repository by Earth Simulator", Proceedings of GLOBAL 2005, (2005).

[5] R. IMAN, and M. SHORTENCARIER, "A FORTRAN 77 Program and User's Guide For the Generation of Latin Hypercube and Random Samples for Use With Computer Models", SAND83–2365 (1984).

[6] Japan Nuclear Cycle Development Institute, "Horonobe Shin Tisou Kenkyu Keikaku H15 Tyousa Kenkyu Seika Houkoku [Horonobe Underground Research Project H15 Report]", JNC TN5400 2004–001, (2004).

[7] NAGRA," Project Opalinus Clay, Models Codes and Data for Safety Assessment", NTB02–06 (2002).

地球シミュレータによる複数廃棄体処分場モデルの不確実性解析

プロジェクト責任者
奥田　洋司　　東京大学人工物工学研究センター

著者
辻本　恵一　　三菱マテリアル株式会社
Joonhong AHN　　カリフォルニア大学バークレー校原子力工学科

高レベル放射性廃棄物処分場の母岩の不均質性を考慮した不確実性解析を、複数廃棄体の処分場モデルによる物質移行解析コードであるVRコードにより実施した。従来のVRコードによる解析では、地下水流れにより連結されている廃棄体数は根拠なしに決められていた。そこで本研究ではFFDFコードを利用して、亀裂ネットワークに含まれている廃棄体数を数えることにより、地下水流れにより連結されている廃棄体数を決定した。FFDFコードから得られた亀裂ネットワークによる連結廃棄体数の確率密度関数を適用して、母岩中の亀裂ネットワークに起因する不確実解析を実施した。廃棄体500体から構成される仮想処分場を想定して、連結廃棄体数の変化が仮想処分場から放出されるNp237の放出率に与える不確実性をVRコードにより評価した。VRコード及びFFDFコードが地球シミュレータに移植され、大規模計算が実施された。不確実性解析に適用されたモンテカルロ計算の莫大なサンプル数を低減するために、Latin Hypercubeサンプリングが適用された。

キーワード：不確実性解析, 複数廃棄体の処分場モデル, 高レベル放射性廃棄物, 亀裂ネットワーク, 物質移行