GROUNDWATER FLOW ANALYSIS FOR EVALUATING FACTORS ON WATER INFLOW TO THE FACILITY DURING THE OPERATION PERIOD

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Abstract

In order to ensure the long-term safety of geological disposal system for high level radioactive waste, it is necessary that each component of the disposal system should maintain its initial performance as required by the long-term safety assessment, taking into consideration disturbances caused by the construction and operation of the disposal facility. This research aims at developing an evaluation method to predict evolution of the state and/or performance of the engineered barrier system (EBS), focusing on disturbances during the construction and operation. For this evaluation, unsteady groundwater analysis is necessary for considering the hydraulic characteristics of the site and the staged shape transition of its disposal facility during the construction and operation. For this development purpose, a coastal site was investigated as a test case. First, numerical simulations of density-dependent groundwater flow were performed using a simple two-dimensional vertical model, taking the operation process into consideration, and major factors that may affect the underground hydraulic environment were summarized. Then, three-dimensional groundwater analysis on different regional scales was conducted to evaluate the influence of the operation procedure on water inflow to the facility. As a result, it was confirmed that the hydrostatic pressure of sea water was a dominant factor on water inflow to the facility. It was also possible to understand the trend of changes in water inflow to the disposal tunnel according to the operation process.

1. Introduction

We consider satisfying the following two requirements necessary to show the feasibility of the disposal system in the geological disposal of high level radioactive waste (Figure 1):

(a) Long-term safety after closure

(b) Prerequisite for long-term safety assessment after closure (initial performance of EBS at the time of facility closure).

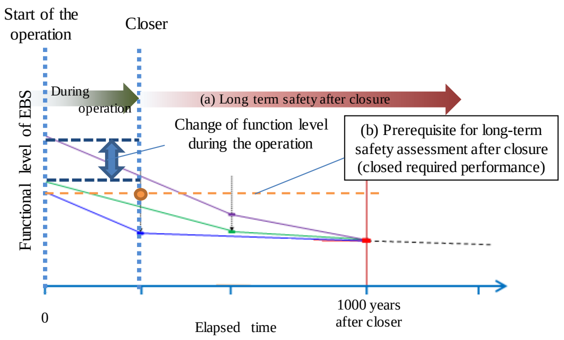


Figure 1 Feasibility of the disposal system handled within the engineering framework

The (a) has been researched as an approach to long-term safety assessment after closure, by the H12 report (H12 Project to Establish Technical Basis for HLW Disposal), etc., in Japan[1)]. But at the current stage, when a candidate site has not yet been materialized, (b) has not been researched sufficiently, including changes in EBS function due to disturbances during the construction and operation of the disposal facility.

Therefore, in this research we look at methods related to (b) regarding the feasibility of the disposal system under limited conditions. Through this research, we believe that it will be possible to promptly present its feasibility at when candidate sites and disposal concepts are materialized in the future.

In this research, we are advancing the development of methods, especially focusing on disturbance of hydraulic fields during the construction and operation periods, in conjunction with other research work[2)]. It is necessary to consider the hydraulic characteristics of the site and tunnel deployment of the disposal facility during the disturbances accompanying the construction and operation. Therefore, we will construct an analysis method for investigation, focusing on the water inflow at the disposal facility by unsteady groundwater flow analysis, with the coastal area as the test case, for the purpose of evaluating hydraulic fields during disturbances. The following three are set as concrete implementation items:

(i) To understand the specific influence of the coastal area on the underground hydraulic environment.

(ii) To grasp the influence of the operation procedure (disposal tunnel excavation) on the water inflow of the disposal tunnel.

(iii) To present engineering measures to mitigate influence (countermeasure against water inflow, etc.).

This paper is the result of studies in the first year of 3-year plan, and it is part of the result of making an analysis model and summarizing examination of (i) and (ii) above.

The analysis code used for this series of studies are the seepage flow/advection dispersion analysis program Dtransu 2D・EL and Dtransu 3D・EL based on the finite element method.

2. Specific influence of the coastal area on the underground hydraulic environment

We summarized the main factors that may affect the groundwater environment in the coastal area, to understand the influence on the disposal facility from the environment generally assumed for the coastal area of Japan. Based on the results, we analyzed the groundwater flow considering each factor, and studied the influence of each factor on the groundwater flow field around the disposal facility.

2.1 Influence of the operation procedure on the water inflow of the disposal tunnel

The study group on technical issues of geological disposal at the coastal seabed, etc. (hereinafter referred to as "Coastal Study Group"), reported that items to be considered in the coastal geological environment are sea level variation, seawater/freshwater interface, hydraulic fields and chemical fields[3)]. When selecting what seems to have a great influence on the water inflow of the disposal facility during the operation period, seawater/freshwater interface and hydraulic fields are notable.

The seawater/freshwater interface is supposed to have a shape protruding toward the sea side from near the shoreline because of the density difference between salt water and fresh water. The seawater/freshwater interface clearly separates the hydraulic field of fresh water and salt water, and a unique hydraulic field is formed near the seawater/freshwater interface. For this reason, the positional relationship between the disposal facility and the seawater/freshwater interface is an important factor in considering the influence of the hydraulic field around the disposal facility.

A small hydraulic gradient and the hydrostatic pressure of sea water in the hydraulic field can be considered as the unique environment of the coastal area. In Japan, due to large precipitation rate, the groundwater surface generally takes a shape conforming to the topography. The coastal area tends to have gentle slope, leading to a small hydraulic gradient and a slow groundwater flow velocity. In addition, the hydraulic gradient becomes small because the sea side has a constant water level. Thus, the hydraulic gradient is small in the coastal area both on the land side and the sea side, and the groundwater flow velocity in the area can be considered to be slow.

In addition, hydrostatic pressure equivalent to seawater (salt water density × seawater depth) always acts on the coastal seabed. The depth of the disposal facility is based on the depth from the seabed, and in general the depth of the seabed becomes greater going from the shoreline out to sea. In other words, it is considered that the water pressure on the facility increases as the location of the disposal facility goes toward the sea side.

These three items were considered as important factors that may affect the underground hydraulic environment, and their influences are evaluated by groundwater flow analysis as follows.

2.2 Groundwater flow analysis

Assuming a period from the construction of the disposal facility to its closure, we conducted groundwater flow analysis for multiple cases combining each factor, and evaluated the influence of each factor on the water inflow volume of the disposal facility.

(a) Setting-analysis-case

The specific factors (the seawater/freshwater interface, the small hydraulic gradient, and the hydrostatic pressure of the seawater) in the coastal area shown in 2.1 are inseparable from the geographical position of the disposal facility. This makes it necessary to consider the location of the disposal facility for each analysis case.

The land side being within 20 km from the coastline from a transportation point of view and the sea side area being within 15 km from the coastline from the viewpoint of engineering were used as guides for examination. Base on this, we set the location of the disposal facility as being 2.5 km/15 km away from the shoreline to both the land side and the sea side.

To consider the influence of salt density, we also investigated the influence by presence/absence of density-dependent flow. Moreover, since the influence of the local heterogeneity of the hydraulic geological structure is assumed around the disposal facility, a case where caprock was provided for each disposal facility position was also examined. Table 1 shows the list of analysis cases.

Table 1 List of Analysis cases

Influence factor		Case name			
Geographical location of the disposal facility		Land (U)		Sea (S)	
Horizontal distance from shoreline (km)		15.0	2.5	2.5	15.0
Scale of the initial dynamic water gradient near the facility		Large	Small	Very small	
Salt density	Caprock				
Consider	None	**U-2-1**	**U-1-1**	**S-1-1**	**S-2-1**
Not consider	None	**U-2-2**	**U-1-2**	**S-1-2**	**S-2-2**
Consider	Exist	**U-2-3**	**U-1-3**	**S-1-3**	**S-2-3**

(b) Hydraulic geological structure model

The hydrogeological structure was set to exclude influences peculiar to any particular area, due to the current situation in which a disposal candidate site is not yet specified in Japan. Specifically, the geological division was basically uniform, and a simple vertical two-dimensional model used. The terrain is roughly divided into terrestrial and oceanic areas, the sea side is divided into the continental slope of the coastal shelf and offshore areas, and the land side is divided into lowlands and plateaus, mountains and hills. The slope of the terrain was set using the median of the statistical data for each classification[4]. The caprock was set at 200m above the disposal facility, with a width of 3,000m and a thickness of 100m in order to make it large enough for blocking the groundwater flow towards the facility. Figure 2 shows the analysis mesh that was set up. The permeability coefficient set for the analytical model was set to 2.3E-8 (m/s) for host rock, and one of the caprock was set to 1/100 thereof.

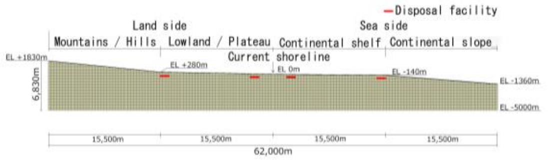


Figure 2 Analysis mesh diagram

(c) Analysis conditions

In case of not considering salt density, the initial conditions before the construction of the facility were set to the result of the seepage flow analysis in steady state. In case of considering salt density, the initial conditions were set to the results of the washout analysis, in which density-dependent flow analysis were used changing the sea level from the state where the top of the land to the current shoreline. The washout analyses were conducted for building the seawater/freshwater interface (salt distribution) for the initial conditions. Figure 3 shows the salt concentration distribution in case of considering salt density.

Next, we conducted groundwater flow analysis in unsteady state that maintained the open condition of the tunnel until 100 years after constructing the disposal facility. The boundary conditions set are shown in Figure 4.

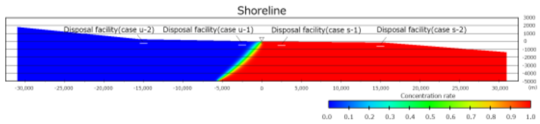
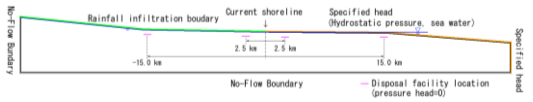
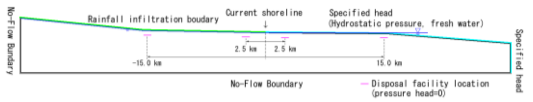


Figure 3 Salinity concentration distribution (initial condition)



(a) Considering density-dependent flow



(b) Not considering density-dependent flow

Figure 4 Boundary conditions

2.3 Results and discussion

Factors considered to influence the hydraulic environment around the facility in the coastal area were organized and the effects of each factor on the water inflow volume of the disposal facility were arranged based on groundwater flow analysis. Figure 5 compares the total amount of water inflow at the disposal facility in each analysis case, and Figure 6 shows the time course of the amount of water inflow with/without consideration of caprock, from the start of excavation of the disposal tunnel to 100 years later. Based on these results, the following conclusions were obtained.

(i) Hydraulic gradient (initial groundwater flow velocity)

In cases where disposal facilities were installed at 15 km on the sea side with a small hydraulic gradient, the amount of water inflow at the disposal facility was larger than in other cases. Therefore, it is considered that the influence of the hydraulic gradient is relatively small as compared with the hydrostatic pressure of the seawater. (Figure 5).

(ii) Seawater/freshwater interface

The difference in the amount of water inflow after tunnel excavation due to the positional relationship with the seawater/freshwater interface did not appear clearly. This is due to the stronger influence of other factors, and it is considered that the seawater/freshwater interface has little influence on water inflow volume in those cases where distance between the facility and the seawater/freshwater interface (shoreline) is about 2.5km (Figure 5).

(iii) Pressure of the seawater

If the disposal facility is set up in the sea side, the amount of the tunnel water inflow will be larger than that installed in the land side. This is considered to be due to the fact that the depth of the seabed becomes greater (water pressure becomes higher) as it goes further offshore. From the results of (i) and (ii), it is considered that the influence of seawater hydrostatic pressure on water inflow volume is relatively large compared with the influence of other factors.

(iv) Density-dependent flow

In the initial stage after excavation (about 1 to 10 years after excavation), the amount of water inflow at the disposal facility when not considering the density-dependent flow is slightly larger than that of considering the density-dependent flow. (Figure 5). This trend is the same regardless of the geographical position of the disposal facility. It is assumed that the difference in the amount of water inflow is due to the initial hydraulic gradient near the disposal facility and the difference in density between salt water and fresh water. In addition, the effect of the initial state on the amount of water inflow in the facility gradually decreases as the open condition of the tunnel maintained for a long time (about 10 to 100 years after excavation) after excavation, and it reaches to the value defined by the boundary condition of the top surface of the model. Especially, in the land side, almost the same amount of water inflow is obtained regardless of whether the density-dependent flow is considered or not, since the upper boundary condition is the rain penetration boundary. In the sea side, the upper boundary is the water pressure of the seabed, so in the case considering the density-dependent flow, the water inflow tends to increase slightly due to the difference in salt density.

(v) Caprock

When there is caprock above the facility, it will be less affected by the boundary conditions of the upper surface of the model than if it does not exist, so the tendency of the tunnel water inflow and its change does not depend on the geographical position of the disposal facility. (Figure 5,Figure 6). Also, as time goes by, the influence of flow inhibition by caprock appears and the amount of water inflow decreases. Afterwards, when the unsaturated zone is formed above the facility, the water inflow tends to decrease markedly (Figure 6).

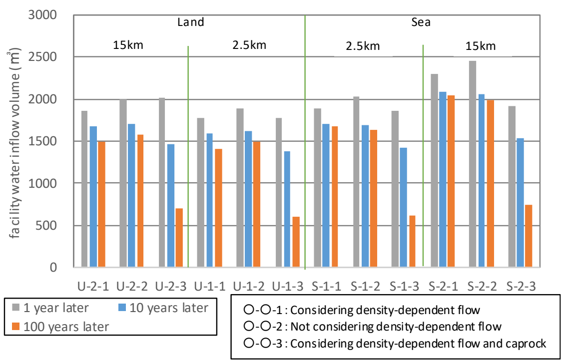


Figure 5 Comparison of the amount of water inflow at the disposal facility in each case

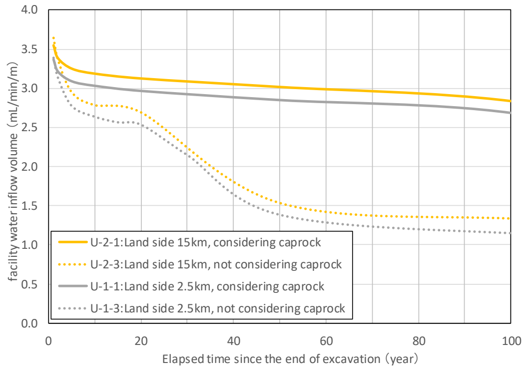


Figure 6 Change over time of the amount of water inflow at the disposal facility due to the caprock considered/not considered (in land)

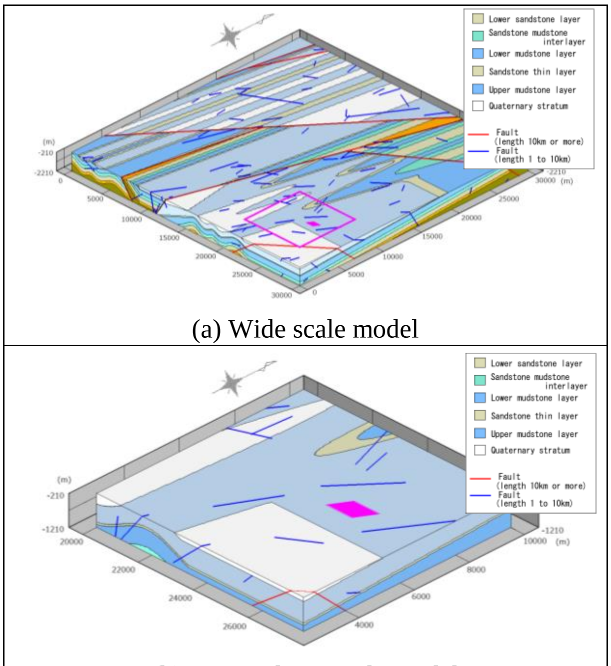
3. Influence of the operation procedure on the water inflow of the disposal tunnel

To grasp the influence on the water inflow condition of the disposal tunnel considering the difference in the operation procedure, a method of modeling the tunnel deployment according to the operation procedure was investigated, using three-dimensional groundwater flow analysis. From the results of the research in 2 above, the hydrostatic pressure of sea water which is shown to have a large influence as a factor specific to the coastal area was considered in this analysis.

3.1 Hydraulic geological structure model

As a prerequisite in this research, the target host rock is Neogene sedimentary rocks, the shape of the disposal pit is panel type, and the disposal concept is the vertical disposal method. Regarding the hydraulic geological structure model for the same rock, NUMO has already developed a geological environment model that considers the current generic stage[5]. Therefore, three-dimensional models in three different scale; the wide scale, the disposal site scale, and the near field scale respectively, were constructed in this study based on the hydraulic geological structure model developed by NUMO. We aimed to construct a hydrological analysis system based on the nesting method that enables evaluating groundwater flow field consistently in different scales.

The wide scale model and the disposal site scale model have been constructed so far. We modeled the hydraulic geological structure fractures and faults by substituting equivalent permeability coefficients considering their permeability. The disposal tunnel was not modeled in the wide scale model, but it was modeled in the disposal site scale model as a group of nodes given the pressure head of 0 m. The hydraulic geological structure model of each scale made is shown in Figure 7.



(a) Wide scale model

(b) Disposal site scale model

Figure 7 Hydraulic geological structure model of each scale (bird's eye view)

3.2 Groundwater flow analysis

Using both the wide scale and the disposal site scale described in 3.1, we analyzed groundwater flow considering the excavation order of the main tunnel and disposal tunnel in one panel, and evaluated the influence of the disposal facility on the water inflow volume. Steady flow analysis was carried out for the wide scale model, and unsteady flow analysis was carried out for the disposal site scale model, and as mentioned above, the latter boundary condition was handed over from the former analysis result. A list of analysis cases is shown in Table 2.

Table 2 List of analysis cases

Case set	Excavation procedure
Case 1	Excavate the entire main tunnel and disposal tunnel at once.
Case 2	① Excavate the main tunnel at once. ② Excavate the disposal tunnels at the same time 4 years after ①.
Case 3	① Excavate the main tunnel at once ② Excavate the disposal tunnel in three phases 4 years after ①.

3.3 Analysis condition

From the engineering point of view, the location of the disposal facility under the coastal seabed is said to be about 15 km from the shoreline. The location of the disposal facility has been obtained from the results of the research in 2 above, that the influence of the hydrostatic pressure of the seawater is greater toward the ocean. Therefore, the location of the disposal facility was set as a conservative setting at 15 km offshore from the shoreline. In this model, the seabed located 15 km offshore from the shoreline is E.L.-135m, and the disposal facility is installed at a depth of 500m (E.L.-635m) from the seabed. Also, in the land side the terrain has a slope of 1% of the terrain up to the 15 km from the shoreline. In the three-dimensional analysis, these settings are followed, and the boundary condition shown in Figure 8 is given to the wide scale model. Based on the result of the analysis in the wide scale model, the boundary conditions of the disposal site scale model were set to the outer peripheral surface of the model as fixed pressure heads.

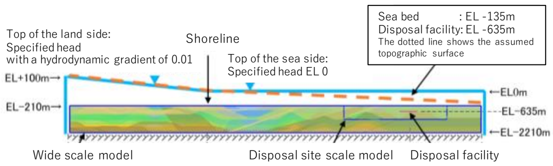


Figure 8 Boundary condition of the wide scale model

3.4 Results and Discussion

To grasp the influence of the operation procedure on the water inflow condition of the disposal tunnel, groundwater flow analysis was carried out in consideration of the excavation order of the main tunnel and disposal tunnel. The analysis results are shown in Figure 9 to Figure 12. From the results, the following conclusions were obtained on the influence of the disposal tunnel on water inflow volume.

- Assuming the emplacement of buffer material starts about 10 years after the main tunnel excavation, the amount of water inflow in the main tunnel and disposal tunnel at that time will be nearly the same value in any case, and it is not different regardless of the excavation process (Figure 9, Figure 10).
- Considering the excavation process, it is possible to evaluate a sudden change in the amount of water inflow immediately after excavation (Figure 9, Figure 10). However, this study is the result of excavation of multiple disposal tunnels at once, and we are to consider more detailed excavation process as a future subject.
- Comparing the total amount of water inflow from the early days of excavation, Cases 2 and 3 are fewer than Case 1. This is due to changes in the range in which water inflow is drawn as the excavation progresses. Accordingly, it is considered that more realistic water inflow can be evaluated by considering the excavation process in detail (Figure 11).
- The amount of water inflow at the disposal tunnel showed a tendency to increase as it was closer to the edge (rock) of the disposal facility (Figure 12). It is considered that this is because the rock side keeps higher water pressure than the tunnel side.

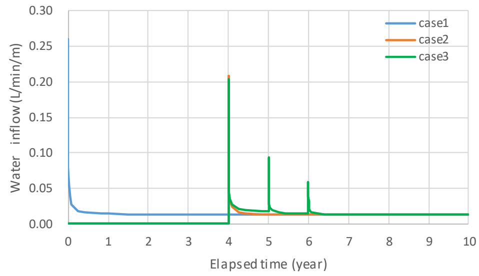


Figure 9 Changes in the amount of water inflow at the disposal tunnels

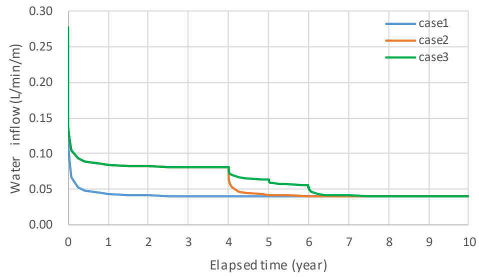


Figure 10 Changes in the amount of water inflow at the main tunnel

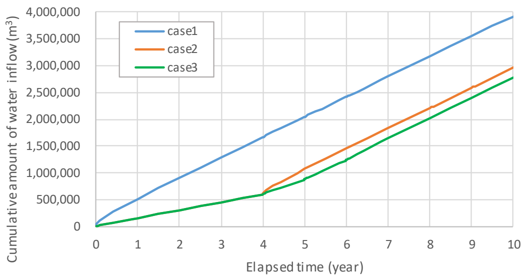


Figure 11 Changes in the total amount of water inflow at the disposal facility since the start of the construction

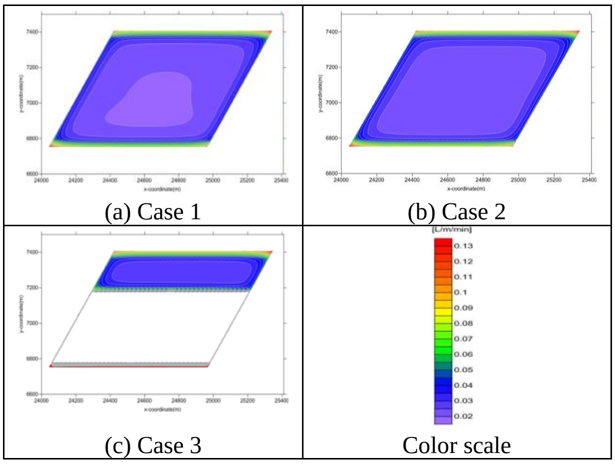


Figure 12 Comparison of disposal facilities water inflow volume due to differences in excavation process (5th year from excavation start)

4. Conclusion

In this research, we have been examining the amount of water inflow to the disposal facility focusing on the disturbance of the hydraulic field due to the construction and operation of the disposal facility, to evaluate the functional change of the EBS of the disposal system. This paper reported the results of the first year of the 3-year plan.

First, we clarified the influence of environment unique to the coastal area on the groundwater environment around the facility. As a result, it was concluded that the influence of the hydrostatic pressure of the seawater is relatively large as a factor affecting the amount of facility water inflow located in the coastal area. Next, taking that result into consideration, we have grasped the influence of the operation procedure on the water inflow at the disposal tunnel, and the change in the amount of water inflow at the disposal tunnel by tunnel excavation. In addition, through this series of studies, we advanced improvement of the analysis model and analysis method.

In the future, to evaluate the vicinity of the disposal tunnel, we will make a model (near field model) that precisely models the area around the disposal tunnel. Using the model, we will examine engineering methods (countermeasures against water leakage, etc.) and evaluate the behavior of the EBS in re-saturation conditions. We are to continue improving the analysis system through this study.

Acknowledgments

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References:

1) Japan Nuclear Cycle Development Institute: “Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan, H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Supporting Report 2 Repository Design and Engineering Technology”, JNC TN1410 2000-003, 2000.
2) Radioactive Waste Management Funding and Research Center: “Development of Advanced Technology for Engineering Components of HLW Disposal, Development of Coastal Disposal System”, 2016, (in Japanese).
3) The Japanese Ministry of Economy, Trade and Industry: “Study Group on Technical Issues Associated with Geological Disposal in Coastal Areas Compiled a Report”, 2016, (in Japanese).
4) Kazue Wakamatu et al.:” Topography and ground digital map of Japan”, Tokyo University Press, 2005, (in Japanese).
5) Nuclear Waste Management Organization of Japan, “External expert workshop on NUMO safety case”, 2016, (in Japanese).