LAYOUT DESIGN OF UNDERGROUND FACILITIES TAILORED TO SDM IN THE NUMO SAFETY CASE

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Abstract

NUMO has developed a generic safety case for geological disposal in Japan. This safety case provides the multiple lines of arguments and evidence to demonstrate the feasibility and safety of geological disposal, which will encourage stakeholder confidence in the safe implementation of geological disposal and will provide the basic structure for a safety case which will be applicable to any potential site. This paper provides the outline of trial underground repository layout designs tailored to the site descriptive models (SDMs) in this safety case. Suitable emplacement areas were first selected in the repository-scale SDMs based on the Layout Determining Features (LDFs) defined by the geological features such as faults and permeable rocks. Next, geometry of repository panels was determined. Regarding the high level radioactive waste, both through type and dead-end type were applied for the vertical and horizontal emplacement concepts. Then, layout of the repository panel was designed in the suitable emplacement area considering the Emplacement Determining Features (EDFs) defined by the features such as water inflow from minor faults and fractures in the disposal tunnels, ensuring the space for the reserved areas. As a result of comparison among the above design options, the dead-end type geometry with the horizontal emplacement concept could be identified as a relatively efficient and economical approach which has more flexibility to the geological structures.

1. Introduction

NUMO has developed a generic Safety Case on geological disposal of high-level vitrified waste (HLW) and various types of radioactive waste generated from the reprocessing of spent nuclear fuel and mixed-oxide fuel fabrication (termed "TRU waste" in Japan)[1, 2]. The siting process of a Deep Geological Repository (DGR) in Japan is based on volunteerism and no specific site and geological environments have yet been identified. This safety case will present technical evidence to support the feasibility and safety of geological disposal, which will encourage stakeholder confidence on the safe implementation of geological disposal and to provide the basic structure of a safety case that will be applicable to any potential site. In order to demonstrate the feasibility and long-term safety of the geological disposal system, the DGR design and the safety assessment tailored to site descriptive models (SDMs) developed in this safety case.

This paper provides the outline of trial repository designs and specific design examples of underground facilities tailored to illustrative SDMs in this safety case and focuses on the layout design of the underground repository.

2. Design premises

2.1. Waste characteristics

In this paper, a DGR would be designed to dispose HLW and TRU waste. HLW is mixed high-level radioactive liquid generated from the reprocessing of spent fuel and glass into stainless steel cylindrical canister. The amount of HLW was assumed 40,000 containers based on Final Disposal Plan in Japan (2008) .

TRU waste is low-level radioactive waste generated by the operation and decommissioning of reprocessing and MOX (mixed oxide) fuel fabrication plants, containing long-lived nuclides above specific concentrations. Table 1 shows grouping, total generation volume and heat production of each TRU group divided by containment and heat production.

2.2. Site descriptive model

The DGR design would be performed as model case tailored to SDMs of Plutonic rocks, Neogene sedimentary rocks and Pre-Neogene sedimentary rocks extracted based on studies of the geological environment in Japan. Although, Pre-Neogene sedimentary rocks are divided into the coherent faces and melange face, the case of coherent faces is treated in this study. The features of SDMs are summarized in Table 2.

Table 1. Volume and heat production of TRU waste[3]

Group	Key waste type	Total volume (m^3)	Heat production*1 (W/waste)
1	Cemented iodine absorbent	319	<1
2	Compressed hulls and ends pieces, Returned waste	5792	19
3	Bituminized low-level concentrate, Mortar, etc.	5228	3
4	Cemented combustible, poorly combustible, incombustible waste.	L: 5436*2 H: 1309*3	3 60

*1: After 25years for the period from manufacturing until the commencement of the disposal, *2: Waste of low heat generation, *3: Waste of high heat generation

Table 2. Three types of SDMs and their features

SDM	Thermal features	Hydraulic features	Mechanical features	Chemical features
Plutonic rocks	Thermal gradient 3°C/100 m	Fractured media	Hard rock	Fresh Reducing condition Weakly alkaline
Neogene sedimentary rocks		Porous media with low density of fractures	Soft rock	Saline Reducing condition Neutral
Pre-Neogene sedimentary rocks		Fractured media with high density of fractures	Hard rock	Saline Reducing condition Neutral

2.3. Repository concept

The DGR design shall be based on the tunnel disposal method, from the viewpoints of the applicability to the geological disposal of heat generating waste such as vitrified waste, reliability of transportation and emplacement techniques to underground and ease of quality control. The tunnel disposal method can be divided into dispersed emplacement in the tunnel and accumulated emplacement in the tunnel according to the way the waste is emplaced. Application of these concepts depends on the heat generation characteristics of the radioactive waste. In order to control the temperature rise in a repository, the former concept is applied to vitrified waste which has a higher heat generation. On the other hand, the concept of accumulated emplacement in the tunnel is applied to TRU waste with less heat generation relatively.

In current design study, concept options of the vertical pit emplacement and the horizontal PEM emplacement have been selected for the HLW disposal, whereas vault emplacement has been for the TRU waste disposal that was developed in a past study[4] as starting points for structured review of concepts. These concepts of EBSs are summarized in Fig. 1.

3. Repository layout demonstration

3.1. Procedure to determine layout

Fig. 2 shows the procedure to determine layout of underground facilities and requirements. First, the suitable emplacement area is selected for the SDM in repository scale with considering the Layout Determining Features (LDFs). Next, shape and size of a disposal panel is determined according to the suitable emplacement area. Through type and dead-end type are applied for the disposal panel options. Then, the layout of the disposal panel is conducted in the suitable emplacement area with considering the Emplacement Determining Features (EDFs), and connecting tunnels and access tunnels are installed so that construction, operation and closure will be carried out efficiently. In addition, it is considered to ensure the reserved area in the suitable emplacement area for some difficult cases of waste emplacement. Juxtaposition of the DGR for HLW and the DGR for TRU waste is assumed in this layout demonstration.

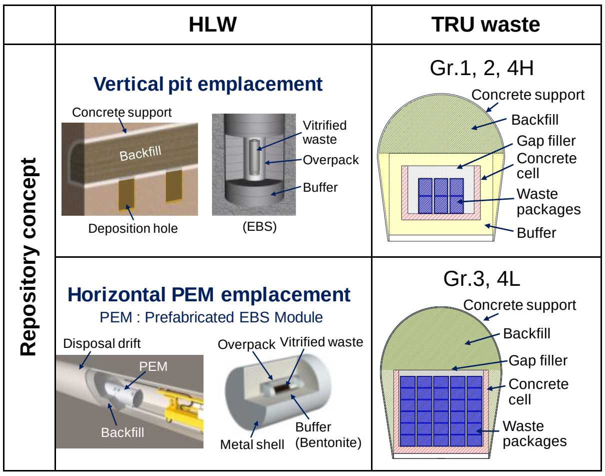


Fig. 1. Repository concepts

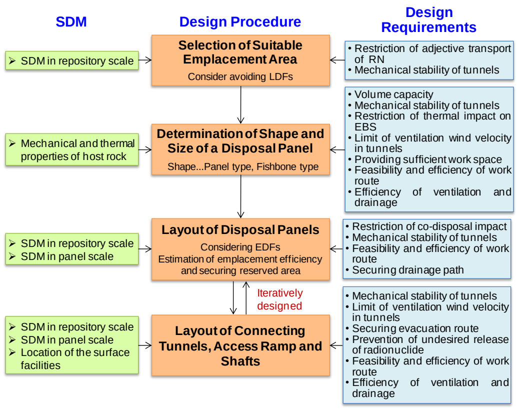


Fig. 2. Procedure to determine layout and requirements

3.2. Suitable emplacement area

The suitable emplacement area shall be selected considering the arrangement of disposal tunnels in the repository scale SDM. The index to assess the suitable area for disposal has been defined as LDF. Examples of LDFs are shown in Table 3. LDF is defined as the geological features such as fault fracture zones and permeable host rock which have potential risk for emplacement. LDF would be identified by surface based investigation, and the suitable emplacement area would be selecting by precluding LDFs. Handling in the underground repository layout design for LDFs on faults and factures is shown in Table 4.

Table 3. Geological features serving as LDF

Categories	Risks	LDFs
Assumed risks during construction	Collapse of the tunnel face	Fault, fracture Local soft areas (such as serpentine)
	Sudden water inflow	Fault, fracture, etc.
Assumed risks during operation	Increased volume of groundwater to be treated (drainage volume) during operation	Fault, fracture Formations with high transmissivity (such as conglomerate layer)
Possible risks related to the post-closure safety	Fast groundwater flows Shear deformation of the EBS	Fault, fracture Permeable host rock

Table 4. Handling for LDF on fault and fracture

Categories of faults and fractures	Handling in the development of SDM	Handling in the underground facility design
Active fault (e.g. trace length of 10 km or longer)	Define the repository-scale SDM not to be included in the possible repository site.	Not subject to the layout study due to the reason shown in left column.
Large-scale fault with unknown activity (e.g. trace length of 10 km or longer)	Define the repository-scale SDM not to be included in the possible repository site.	Not subject to the layout study due to the reason shown in left column.
Major fault (e.g. trace length of 1 – 10 km)	A fault listed in the repository-scale SDM	Categorized as a LDF considering the possibility of causing difficulties during the excavation, such as abnormal flooding. Disposal tunnels should not be constructed in a fault and fractures and in the range of its impact.
Small-scale unconsolidated fault (e.g. trace length of less than 1km)	A fault which is not listed in the repository-scale SDM but listed in the SDM as the panel-scale	A disposal tunnel excavated but no waste nor EBS is emplaced if it is likely to cause difficulties with respect to spring water in the excavation of disposal tunnels or deposition holes (handled as an EDF).
Consolidated fault and fractures (without a fracture zone)	Listed in the SDM as panel scale	Waste and EBS emplaced if there are no difficulties in the excavation of disposal tunnels and cavities (handled as an EDF).

In addition to the fault and fractures, the transmissivity of the host rock and travel time of groundwater can also be a LDF. Disposal tunnels shall be arranged in a way that the waste is emplaced preferentially in the area where the groundwater flow is considered to be relatively slow at repository-scale. It is better that the groundwater flow velocity of the host rock around the area is as slow as possible for the disposal. Thus, disposal tunnels are arranged preferentially in the area with a lower groundwater flow velocity and a relatively long travel time. Travel time estimated by using Darcy velocity field is used here as an indicator determined as travel time per unit travel path length assuming the travel path length of particles on the host rock to be 500 m.

Groundwater flow analyses have been performed with consideration of faults and fractures for each SDM in repository scale. The suitable emplacement area selected for Plutonic rocks is shown on the distribution of travel time in Fig. 3. The faults described on the disposal site scale are characteristic as the hydrological geological structure of the host rock, there is a tendency that travel time becomes relatively short around the faults. Therefore, the disposal panel shall be installed preferentially in the suitable emplacement area excluding around the faults.

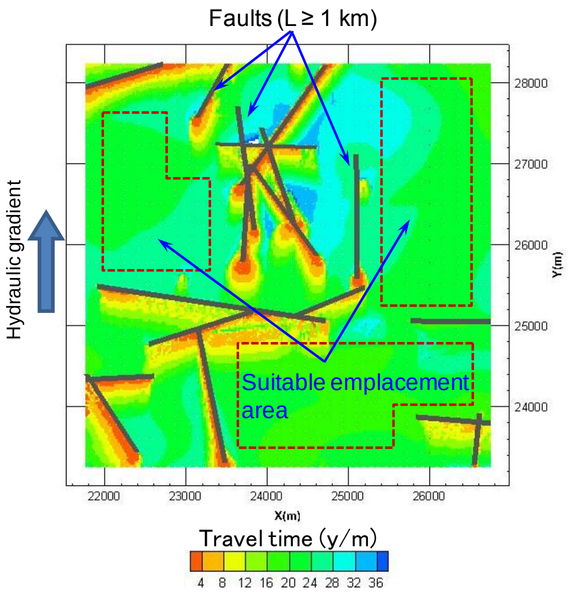


Fig. 3. Distribution of travel time based on Darcy velocity and suitable emplacement area (A plane view at the depth of 1,000 m for Plutonic rocks)

3.3. Disposal panel

3.3.1. DGR for HLW

Through type and dead-end type are applied as the disposal panel option of the DGR for HLW. A through type panel has been employed as the DGR concept in a previous generic safety case in Japan[5]. In order to connect a number of disposal tunnels in the same direction at regular intervals, appropriate spacing is set between them in a way as not to affect each other with respect to thermal impact of waste and the mechanical stability of tunnels.

The number of disposal panels is examined as 6 to 8 areas considering the volume capacity (40,000 containers of vitrified waste will be accommodated), the limited ventilation wind velocity (≤ 7.5 m/s) and the limited temperature (≤ 37 °C) in the tunnels. The length per disposal tunnel and the number of disposal tunnels shall be set, so that it can be accommodated in the suitable emplacement area. Here, the length and number of disposal tunnels are determined so that the same amount of waste can be emplaced for each disposal panel.

As an example, detailed plan views of a disposal panel for the through type and the dead-end type in the case of Plutonic rocks are shown in Fig. 4 and Fig. 5, respectively.

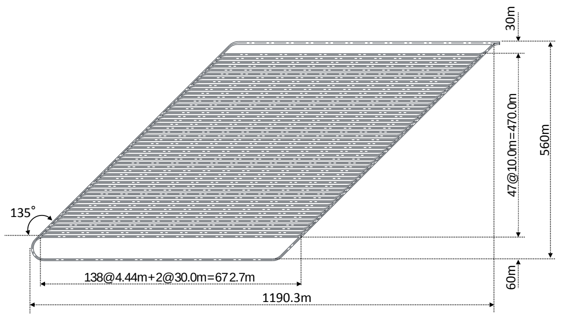


Fig. 4. Disposal panel of through type (Vertical pit concept, Plutonic rocks)

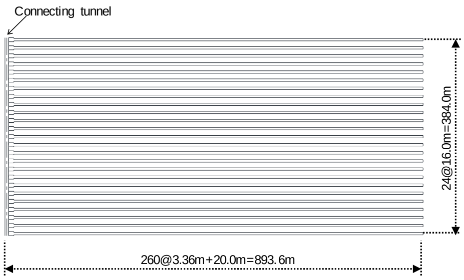


Fig. 5. Disposal panel of dead-end type (Horizontal PEM concept, Plutonic rocks)

3.3.2. DGR for TRU waste

A detailed plan view of the underground facilities for TRU waste in the cases of Plutonic rocks and Pre-Neogene sedimentary rocks is shown in Fig. 6. The groundwater is assumed to flow from bottom to top of the figure. In this case, to ensure the migration distance as much as possible, waste group 1 and 2, whose contribution to the evaluation results of the radionuclide migration are large, are arranged in the upstream side of the groundwater flow, i.e., the lower side in the zone on the left side. Group 3 is arranged in the downstream side of the groundwater on the right side so as to minimize the impact of nitrates contained in group 3 on other waste groups.

3.4. Emplacement efficiency and reserved area

EDF is used for the suitability judgment for the waste emplacement in the panel scale of the SDM. Based on EDF, the reserved area shall be set to be used for disposing waste that cannot be emplaced in the pre-specified disposal panels. EDF would be defined as the geological features such as flowing water from fracture zones which have potential risk for emplacement of the bentonite buffer and excavation. EDF would be identified in detail investigation in the underground investigation facility or construction phase, and the suitable emplacement area should be selected by precluding EDFs.

Water inflow into the deposition hole or the disposal tunnel is used as an indicator for the suitability judgment of the waste emplacement, as shown in Table 5. In the case of the vertical pit emplacement for the HLW disposal (HLW-V), if the water inflow rate into a deposition hole is higher than the following criteria, the deposition hole is judged unsuitable for the emplacement, and more space is assigned in the reserved area.

- Allowance of the water inflow rate determined from eroded mass of bentonite buffer due to piping
- Allowance of the water inflow rate determined from the feasibility of emplacement of bentonite block in the deposition hole

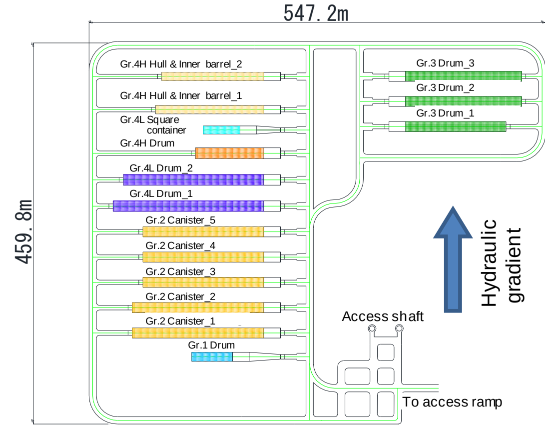


Fig. 6. Plane view of underground facilities for TRU waste (Plutonic rocks & Pre-Neogene sedimentary rocks)

Table 5. Criteria for EDFs

Disposal Concept	Risks due to EDZ	Criteria
HLW-V	Erosion of buffer due to piping	< 0.78 L/min *1 < 0.83 L/min *2 < 0.51 L/min *3
	Feasibility of EBS emplacement	< 0.63 L/min
HLW-H (PEM)	Difficulty of excavation due to water inflow from tunnel face	300 L/(min m)
TRU waste		

*1: Plutonic rocks, *2: Neogene sedimentary rocks, *3: Pre-Neogene sedimentary rocks

In the case of the PEM concept, the buffer is protected by the metal shell so that it is not likely to be affected by piping and erosion. Further, there is the prospect that the volume of water inflow during the operation period can be restricted by taking water inflow measures such as grouting and a reverse surface drainage[6,7]. Thus, based on results of actual construction of tunnels, the criterion of EDF in the case of horizontal emplacement for the HLW disposal (HLW-H) is determined to be less than 300 L/min of water inflow considering difficulty to the excavation at the tunnel face. The criterion of EDF for the TRU waste is determined considering difficulty to the excavation of disposal tunnels same as the HLW-H.

In the construction and operation of the repository, it is expected that the waste emplacement efficiency will increase or decrease against the prospect at the repository design. Preparing the reserved area with sufficient margin so that the underground facility can be expanded, it is possible to tailor flexibly to unexpected situations.

In the case of the HLW-V, in order to determine the required reserved area for the deposition hole which is not suitable for emplacement of EBS, the water inflow rate into the deposition hole has been calculated by 3D groundwater flow analysis. The groundwater flow analysis has been performed with 100 realizations of the distribution model of fractures around disposal tunnels by using the stochastic SDM in the panel scale. The cumulative probability of water inflow into the deposition hole by the analysis is shown in Fig. 7 as an example of the case of Plutonic rocks. In this case, allowance of the water inflow rate is applied to the EDF criterion, and deposition holes with the water inflow rate exceeding this criterion shall be deemed unsuitable for the waste emplacement.

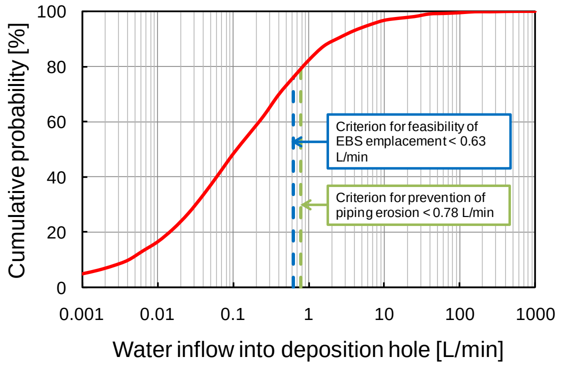


Fig. 7. Cumulative probability of water inflow into deposition hole (HLW-V, Plutonic rocks)

Table 6 shows the estimating results of the waste emplacement efficiency and required reserved area for each disposal concept and SDM. In the HLW-V, the reserved area is not required since the waste emplacement efficiency for Neogene sedimentary rocks is 100%. On the other hand, in the case of Plutonic rocks and Pre-Neogene sedimentary rocks, it is necessary to ensure the reserved area corresponding to 24% and 11% per disposal area, respectively. It means that the reserved area possible to dispose 9,600 and 4,400 containers of vitrified waste in Plutonic rocks and Pre-Neogene sedimentary rocks, respectively, will be needed as the total number of waste in the DGR for HLW to be 40,000.

Similar analyses have been also performed for the disposal tunnels of the HLW-H concept and the TRU waste. The sections of water inflow ratio exceeding the criterion of EDF were very small.

3.5. Repository layout

Layout examples of the underground facilities for the co-disposal concept of the HLW and the TRU waste in plutonic rocks are shown in Fig. 8. The contours in the background of these figures represent the distribution of Darcy travel time ratio.

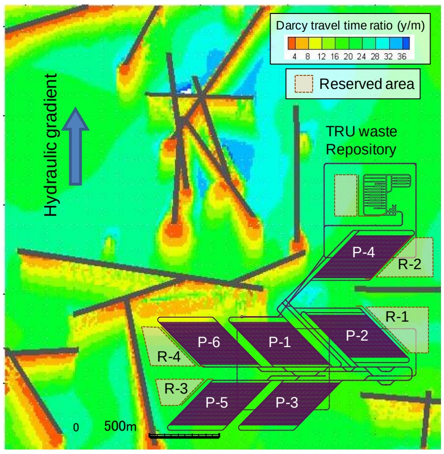
Table 6. Estimating results for reserved area

Disposal concepts	SDM	Waste emplacement efficiency(%)	Required reserve area (m^2)
HLW-V	Plutonic rocks	76.0	430,000 (9,600 HLWs)
	Neogene sedimentary rocks	100	0
	Pre-Neogene sedimentary rocks	88.7	310,000 (4,400 HLWs)
HLW-H (PEM)	Plutonic rocks	99.7	6,500 (120 HLWs)
	Neogene sedimentary rocks	100	0
	Pre-Neogene sedimentary rocks	100	0
TRU waste	Plutonic rocks	99.5	130
	Neogene sedimentary rocks	100	0
	Pre-Neogene sedimentary rocks	100	0

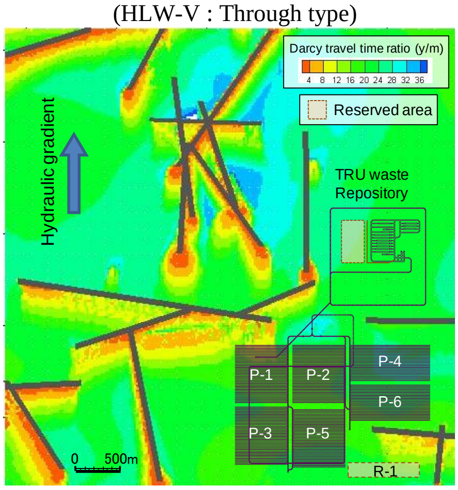
As for the capacity of the repository tailored to 3 types of SDMs, it was possible to arrange the disposal panels which is the predetermined amount and the reserved area which is over the required amount in the suitable emplacement area after considering the distribution of faults in each SDM. For example, in the case of the HLW-V and the through type in Plutonic rocks represented in Fig. 8, the reserved area equivalent to 9,900 vitrified waste emplacements (440,000 m^2) could be ensured by expanding two reserved areas (R-1, R-2) adjacent to the disposal panels on the right side (P-2, P-4) against required area (430,000 m^2) equivalent to 9,600 vitrified waste emplacements based on estimating the waste emplacement efficiency. Furthermore, it will be possible to ensure two reserved areas (R-3, R-4) where 6,000 vitrified wastes (270,000 m^2) can be accommodated by expanding adjacent to the disposal panels on the left side (P-5, P-6). In this case for the TRU waste repository, the reserved area secured adjacent to the TRU waste disposal area has an area of 117,000 m^2 (260 m × 450 m), which has enough margin for 130 m^2 required from the estimation of the waste emplacement efficiency.

The excavation volume estimated from the layout of HLW underground facilities for each SDM is shown in Table 7. The size and the excavation volume of the HLW underground facilities are larger in the case of the HLW-V concept than the HLW-H concept for every SDM. The size of the underground facilities is remarkably large in the case of Neogene sedimentary rocks, because the host rock has a lower strength and the center-to-center spacing of disposal tunnels is more required. It is found that the concept of the horizontal emplacement and the dead-end type is able to reduce the excavation volume to approximately 1/2 compared to the concept of the vertical emplacement and the through type. For the HLW-V concept, the through type in case of Plutonic rocks and the dead-end type in case of Pre-Neogene sedimentary rocks are examined, however it can be seen that there is no big difference between the excavation volumes of both. Then, among dead-end type, horizontal concept is economically preferable to vertical concept.

As a result of comparison among these design options, the underground facilities combined with the horizontal emplacement concept and the dead-end type panel can be identified as a relatively efficient and economical approach which is flexibly applicable to the geological structure.



(HLW-V : Through type)



(HLW-H : Dead-end type)

Fig. 8. Plane view of underground facilities (Co-disposal concept of HLW & TRU waste in plutonic rocks)

Table 7. Excavation volume of DGR for HLW

Type	Disposal concept	SDM	Excavation volume ($\times 10^3$ m^3)
Through type	HLW-V	Plutonic rocks	7,050
		Neogene sedimentary rocks	9,030
Dead-end type		Pre-Neogene sedimentary rocks	6,060
	HLW-H	Plutonic rocks	3,680
		Neogene sedimentary rocks	4,040
		Pre-Neogene sedimentary rocks	3,670

4. Conclusions

In this paper, specific design examples of underground facilities tailored to illustrative SDMs in NUMO safety case and focuses on the layout design of the underground facilities for HLW and TRU waste were provided.

The layout of underground facilities was designed taking into consideration discontinuous geological structures such as faults and the groundwater flow. Regarding the shapes of the disposal panel for HLW, the through type and the dead-end type were adapted for the vertical emplacement concept and for the horizontal emplacement concept, respectively. The layouts of the underground facilities were provided for each emplacement concept.

As a result of comparison among these design options, the underground facility combined with the horizontal emplacement concept and the dead-end type panel was identified as a relatively efficient and economical approach which is flexibly applicable to the geological structure.

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