Earth science in safety regulations of radioactive waste disposal

—Translation of scientific research to site selection criteria—

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AIST has been supporting scientific aspects of the Nuclear Regulatory Authority (NRA), mainly in regard to the regulation of site selection for radioactive waste disposal. NRA is constructing regulation criteria and examination guides for the disposal of intermediate level radioactive waste (ILW) at intermediate depth prior to the geological disposal of high-level radioactive wastes (HLW). This paper introduces some examples of utilizing AIST's R&D results for regulation of ILW disposal. This paper also presents examples of future tasks by analyzing the differences between the ILW and HLW disposal, and the differences between ILW regulation and criteria in the "Nationwide Map of Scientific Features for Geological Disposal" to categorize areas based on favorability for HLW disposal.

Keywords : Radioactive waste disposal, safety regulation, site selection, permission standards, geological event

1 Introduction

Regarding the safety regulation of deep underground disposal of high-level radioactive waste (hereinafter, will be called "geological disposal"), AIST started research to support safety regulation at the Research Center for Deep Geological Environments, since the establishment of AIST in 2001, by gathering scientific findings and by transferring such findings to regulatory agencies. The safety regulation of geological disposal was the responsibility of the Nuclear and Industrial Safety Agency that was also established in 2001. Although there were some changes in the organization of regulatory agencies, the support for research of radioactive waste disposal is being continued by the Research Institute of Earthquake and Volcano Geology, AIST. On the other hand, parts of the R&D for geological disposal project led by the Agency for Natural Resources and Energy are conducted by the Research Institute for Geo-Resources and Environment (GREEN), AIST.

The disposal of radioactive waste is supervised by the Nuclear Regulatory Authority (NRA) that was established in 2012. NRA works on the safety regulation for disposal of reactor components that were contaminated by long half-life radionuclides produced at nuclear power plants scheduled for decommissioning (hereinafter, these will be called intermediate-depth disposal to distinguish from geological disposal). Currently, the regulatory standards and examination guides are being organized by NRA.

The intermediate-depth disposal is similar to geological disposal in the point that it involves burial disposal of radioactive waste underground. Therefore, it was expected that the research results for volcanoes and faults that AIST had been engaging in could be used for geological disposal site location search, but in fact, fault activity results were never directly utilized.

The Designated Radioactive Waste Final Disposal Act (Final Disposal Law) and its enforcing body Nuclear Waste Management Organization of Japan (NUMO) were established in 2000. The cities, towns, and villages throughout Japan were called upon to participate in the literature survey that is the first stage of location search, and while this started in 2002, no actual literature survey has been initiated. Therefore, the government changed the basic policy for final disposal of designated radioactive waste, and decided to select the locations based on scientifically based evidence and to ask the local governments for cooperation to the survey (Cabinet decision May 22, 2015). The requirements and criteria for geological disposal were presented from the perspective of geological suitability, the features that should be considered when conducting geological disposal were extracted based on the existing geological data obtained throughout Japan, and the Nationwide Map of Scientific Features for Geological Disposal was published on July 28, 2017 to provide a general picture of the distribution throughout Japan of such possible locations.

In the future, the Geological Survey of Japan, AIST, conducting safety regulation support research must transfer the research results that can be used for regulatory standards and the review guides for geological disposal to NRA and the secretary

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of NRA that are the regulatory agencies. Therefore, in this paper, in addition to the summary of research results for intermediate-depth disposal, the Nationwide Map of Scientific Features (Scientific Feature Map) is referenced. By considering the common and different points of safety regulation for intermediate-depth and geological disposal, we shall propose how the research results can be transferred smoothly to the regulatory agencies so the research results can be reflected in the safety regulation for geological disposal in the future.

2 Categorization of radioactive waste disposals and involvement of regulation

2.1 Categorization of radioactive waste and disposal methods

The disposal of waste generated by nuclear power plants and fuel processing plants is categorized into Category I (high level) and Category II (medium to low level) radioactive waste disposal, according to the “standard set by law that categorize the radioactive materials according to the radioactivity concentration of the radioactive substance set by law, that may have major effect on human health,” under the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (Nuclear Reactor Regulation Law).

High-level radioactive waste (HLW) consists of spent nuclear fuels that undergo reprocessing in which radionuclides remaining after separation from uranium and plutonium are solidified into glass (vitrified waste). Medium-low level or intermediate level radioactive waste (ILW) includes materials with relatively high radioactivity concentration such as core internals and fuel cladding tubes of nuclear power plants, radioactive metal such as control rod and concrete structures, or radioactive waste that is generated at reprocessing plants and MOX fuel processing plants. Low level wastes include those with low radioactivity concentration such as ventilated air from buildings, washing waste liquid, used paper towels, and used work clothes and gloves.

The disposal methods of radioactive waste are categorized into the following: shallow disposal where waste is stored in trenches or pits dug near the ground surface; intermediate-depth disposal where tunnels are dug at depth of about 100 m that is deeper than the depth at which underground is utilized such as for traffic tunnels; and geological disposal where the waste is disposed in deep underground at depth of 300 m or more. Here, the waste disposed by geological disposal is HLW, as well as ILW or those that contain trans-uranium elements with very long half-life that are generated by MOX fuel processing plants. Intermediate-depth disposal may include ILW with relatively high radioactivity concentration such as core internals from nuclear power plants. The disposal methods are applied according to the half-life and concentration of radioactive materials. Figure 1 shows the schematic diagram of the disposal depth for each type of radioactive waste.[1]

2.2 Involvement of regulation in waste disposal projects

The radioactive waste disposal project is composed of the following phases: siting and design of disposal sites, safety assessment to evaluate future dose levels, construction of underground facilities, transport and burial of waste, closure of facilities, maintenance, and decommission of the project. Figure 2 shows the outline of the regulation at each project stage of the intermediate-depth disposal that is being

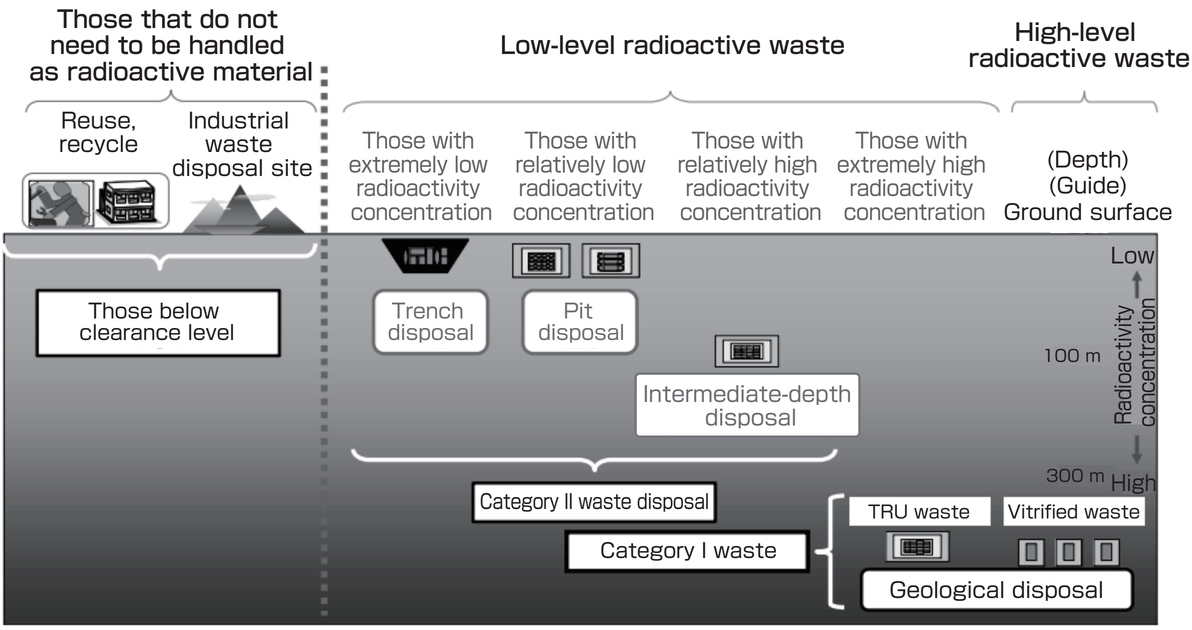

Fig. 1 Categories of radioactive waste and concept for their disposal
Category I and Category II are categorized according to radiation level.[1]

considered by the Nuclear Regulatory Agency.[2] In this system, the period during which the regulation is directly involved starts from the examination of the permit for basic plans submitted by the implementor, and ends at the final confirmation of decommission of the project. In the case of the intermediate-depth disposal, this period is expected to be about 300 to 400 years, and the implementor is expected to dissolve when the decommission procedure is completed and the regulation period ends.

The time course of radioactivity concentration of HLW in geological disposal and that of reactor materials that are objects for intermediate-depth disposal are shown in Fig. 3.[1] Both will decrease to 1/1000 of the initial radioactivity concentration in a few hundred years that is also the completion of the regulatory period. However, the time required for the initial radioactivity concentration to decrease to 1/1,000,000 is about ten million years for HLW and about a hundred thousand years for intermediate-depth disposal waste such as core internals. Therefore, the regulatory criteria of intermediate-depth and geological disposal must have regulations to guarantee there will be no radioactive damage (exposure) even after the completion of the regulatory period. Such regulations must be secured by the selection of the disposal site to avoid leakage of radionuclides due to the effects of volcanic or fault activities, by engineered barriers composed of buffer materials and disposal containers to contain radionuclides and to delay migration of radionuclides, and by site design including natural barriers such as surrounding bedrock.

Regarding intermediate-depth disposal, NRA and the secretary of NRA are preparing regulatory standards that indicate what the implementors must follow for each item, explanation of regulations that show examples that satisfy technological requirements, and an examination guide that provides specific case studies of survey and assessment methods to check compatibility to technological requirements, in order to check the adequacy of the survey and assessment results obtained by the companies. For

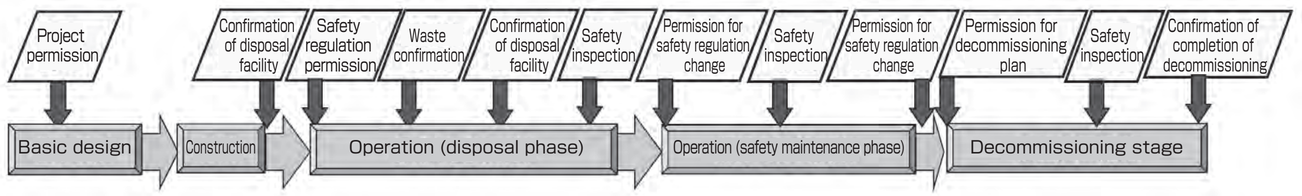

Fig. 2 Examples of procedures that must be taken in regulations of radioactive waste disposal project
Period to termination is assumed to be 300 to 400 years.[2]

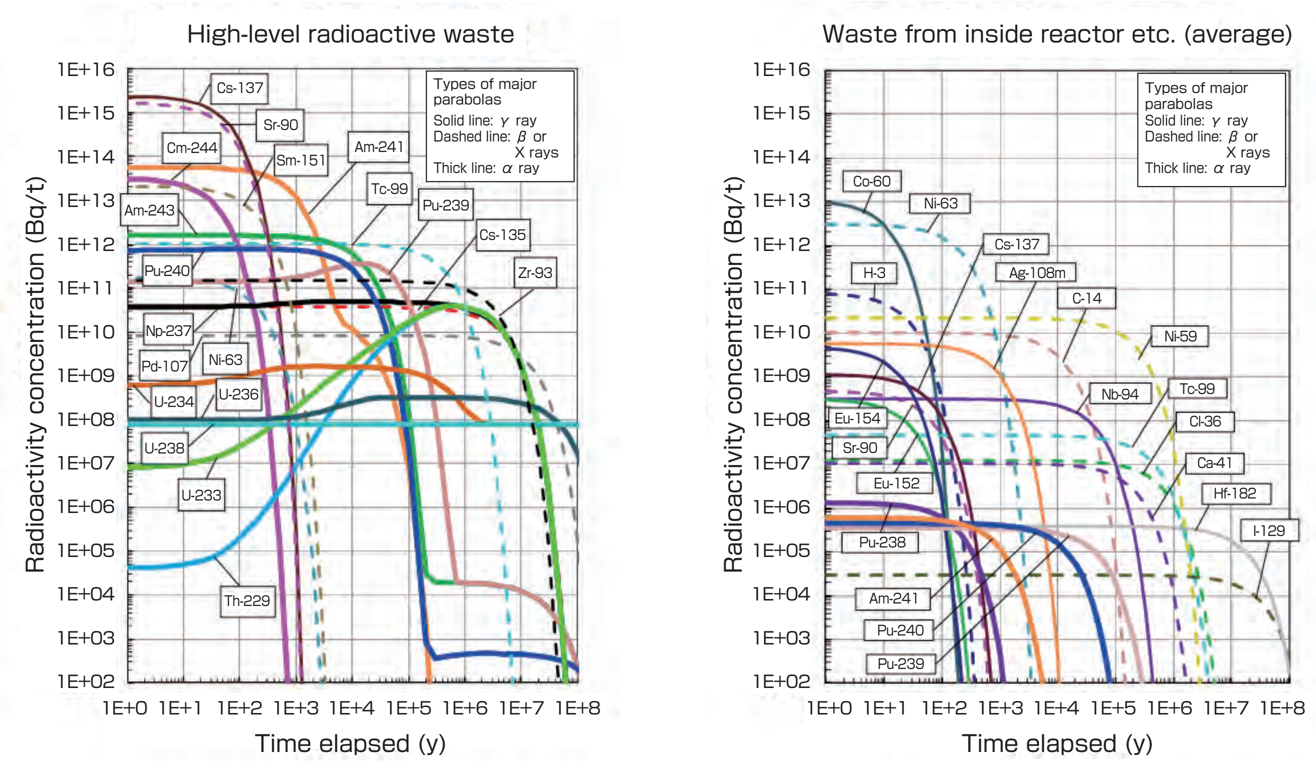

Fig. 3 Relationship between time and radioactivity concentration of radioactive waste, created by Nuclear Regulatory Agency (from [1])

example, in the proposed regulatory standard outline, volcanic activity, fault activity, achievement of depth, natural resources, and other events that must be considered are listed as categorical requirements for disposal site location. Taking one example for volcanic activity, it is stated as follows: “The waste disposal facilities must be set in an area where there will be no significant change in geology due to volcanic activities in the future.” According to the explanation, “future” means at least a hundred thousand years, and “there will be no significant change in geology” means that it is determined that no records of volcanic vents or dikes are found in the activity history in the Quaternary Period. It is also stated that the implementor must prove that there will be no expected volcanic activity in the future for at least a hundred thousand years.[3]

In the examination guide, survey and assessment methods are shown as cases of survey to negate the possibility of future volcanic activity based on scientific evidence, in addition to the literature survey, geomorphological survey, and geological survey through databases for areas in the range of 15 km from the disposal facilities.[4]

3 Existing research results and safety regulation for intermediate-depth disposal

3.1 Setting of period during which safety must be maintained after termination of regulatory period

As mentioned in the previous chapter, the concentration of radioactive materials in waste to be buried in intermediate-depth disposal does not decline for a long time. Yet on the other hand, the period in which the regulatory agency can directly be involved through periodical reviews, etc. is about 300 to 400 years or the period to the termination of the disposal project. In Japan, since there is high possibility that the waste materials may come into contact with groundwater over a long period, radionuclides that dissolve may reach the biosphere through groundwater flow over a long period, and this may expose residents to radiation in various ways such as through wells or agricultural products. The regulatory criteria require that the residents’ dose level must be at a certain level or lower even after a long period, but as a precondition, the location selected must not be subject to damage from direct hit by fault or volcano activities on the waste disposal site, or must not be subject to geological events in which waste materials are rapidly thrust up to the surface due to ground erosion. The period of at last a hundred thousand years is designated as the time during which such geological event will not occur, in the proposed regulatory standard outline.

In setting this time period, it is important that the predictability is assured for the changes in the radioactive properties of waste materials that will be disposed, the occurrence of volcano and fault activities in the future, and the tendency of uplift and erosion. For the radioactive properties of waste, many of the radionuclides decline to a sufficient level in about a hundred thousand years as shown in Fig. 3. On the other hand, prediction of geological events is difficult. In assessing erosion that directly affects and may change burial depth, in cases in which a hundred or more meter rise of sea level that can be observed in the past sea level change, geomorphic change occurs by lateral erosion and deposition in the horizontal direction in the coastal area, and therefore, it is difficult to predict how the erosion by sea level rise may spread during the next sea level cycle.[5] However, since behavior during the fall of the sea level is relatively predictable, the period of a hundred thousand years was set as the time until the next expected sea level rise would start.

3.2 Outline of regulatory requirements for each geological change events

3.2.1 Regulatory requirements for volcanic activities

For volcanic activities, it is required to check that there is no volcano that was active in the Quaternary Period (about 2.58 million years ago) within a 15 km range of the disposal site, to ensure that no deformation or damage of the waste disposal facilities will occur by the intrusion or ejection of magma in the next hundred thousand years.[3]

AIST analyzed the space-time distribution of past volcanic activities to present features of the fore-arc and back-arc volcanic activities, for example, in the Tohoku region.[5] For the Japanese islands, the “Database of quaternary volcanic and intrusive rock bodies in Japan” that combines survey data and existing data has been published.[6] In the examination guide for intermediate-depth disposal, it is clearly written that a survey utilizing these data must be conducted in the literature survey stage of location search.

3.2.2 Regulatory requirements for fault activities

For the examination guide of nuclear reactors for power generation, the definition of faults that may become active in the future is “those of which activities cannot be denied after the Late Pleistocene (120–130 thousand years ago to present).”[7] On the other hand, for intermediate-depth disposal, as mentioned in Subchapter 3.1, unlike the nuclear reactors for power generation which is expected to be in operation for 40 years in principle, it is necessary to maintain safety for a hundred thousand years into the future.

Looking at the examples of earthquakes in the past, there are cases like the 2003 Northern Miyagi Earthquake that occurred due to a fault which had no clear record of activity in the Quaternary Period,[8] and it was decided that there was too much uncertainty in terms of future prediction to consider the possibility of future activities from the latest activity history only. Therefore, in the examination guide for intermediate-depth disposal, unlike the nuclear reactors for power generation, the fault whose presence is determined in literature or on-site survey should be considered possibly becoming active in the future regardless of its activity history. It is required that the area where the waste material is buried within the disposal tunnel (waste disposal facilities) should be placed outside the fault and peripheral areas that may be affected. However, the lower limit of fault length that must be considered is set at 5 km or more, assuming that safety can be maintained by engineered barriers even if a slip occurs in one activity.

In a case in which a waste disposal facility is placed outside the area of influence of a fault of 5 km or more, i.e. it is compatible with the above-mentioned criteria, it is stated that "in a case where there is a fault near the waste disposal facility, the possibility of extension of the fault must be assessed, considering the form, scale, and activeness of the fault, and its effect on the waste disposal facility." However, a specific assessment method is not clearly stated in the current proposed examination guide outline.

AIST has engaged in regulation support research mainly for the assessment of reactivation possibility of low-activity faults, including developing methods of assessment using mineral and chemical properties of fault gouge (fracture zone composed of fault clay and fractured rock) in the granite region,[9] and developing methods to assess motion possibilities of faults using mechanical indices (slip tendency[Term 1]), that involves stress that act on 3D fault surfaces.[10] AIST applied this assessment method using mechanical indices to different tectonic blocks in Tohoku, Chubu, Kinki, and other areas.[11] As a result, as shown in Fig. 4, it was shown that the faults, for which the activity history had been confirmed in the Quaternary Period in the Tohoku region, could be extracted significantly by slip tendency in many cases. However, in the Chubu and Kinki regions, the slip tendency was distributed widely in varying scales for faults for which no activity history was recognized in the Quaternary Period. The reasons include the effects of pore water pressure in the fault surface and friction coefficients of faults, or the fact that assessment cannot be done accurately by geomorphological or geological methods, since the activity interval is long despite the presence of activity history during the Quaternary Period. With this in mind, it is concluded that some faults for which activity history is not recognized may become active in the future due to the current crustal stress state. Such analysis is only possible with the results of crustal stress that act on a certain area through observation of micro-earthquakes, in addition to the survey of 3D morphology, etc. of faults, and such research results are representative accomplishments of the Geological Survey of Japan which is capable of gathering and integrating such data.

However, in the examination guide, concerning faults that should be avoided in setting waste disposal facilities, the AIST results were not directly reflected since fault length was employed as the requirement rather than the activity history as mentioned above. This is because there exists conservative judgment about fault activity as mentioned above, there are not sufficient case studies of applying mechanical indices to assessments, and also because there remains uncertainty in setting the stress field and data parameters that are the limiting conditions.

3.2.3 Uplift and erosion

In the underground disposal of radioactive waste as in intermediate-depth and geological disposal, the reduction of burial depth may cause exposure by human intrusion such as boring for wells or underground space use such as for traffic tunnels, although it may not lead to waste material being exposed to the ground surface. Therefore, in the proposed regulatory standard outline for intermediate-depth disposal, the requirements pertaining to future erosion are set in the criteria for location of waste disposal facilities from the perspective of preventing human intrusion.

In the proposed regulatory standard outline, the requirement for depth is 70 meters for a waste disposal facilities for at

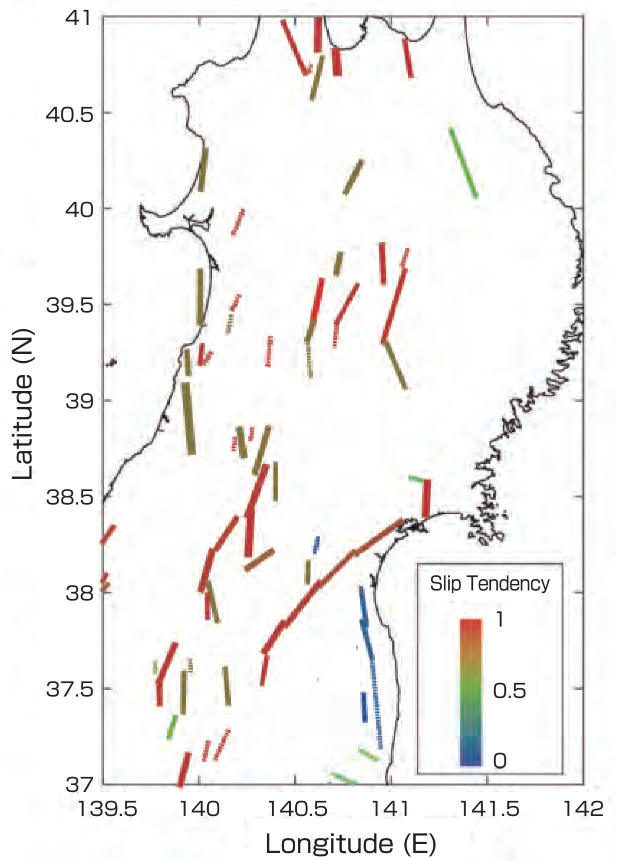

Fig. 4 Results of activity assessment by mechanical index for active faults in Tohoku region. Regional stress field was calculated from the earthquake data before the 2011 off the Pacific Coast of Tohoku Earthquake (East Japan Earthquake) ([10] was partially revised).

least a hundred thousand years into the future, based on experience of underground space use such as for traffic tunnels. Therefore, it is necessary to indicate the standard survey and assessment methods of erosion or uplift level in the past several hundred thousand years by extrapolating from the past, to determine the erosion or uplift quantity that may cause erosion in the next hundred thousand years. In the examination guide, chronology of the marine/river terrace that occurred by past erosion, or geochemical survey conducted as necessary are indicated as survey and assessment methods.

For the dating method that can be applied to the chronology of the index geomorphic surfaces such as marine terraces, AIST is working on the dating of sedimentation of shallow sea deposits by an optically stimulated luminescence method using potassium feldspar,[12] and the increased precision of uplift rate assessment of the past several hundred thousand years based on the determination of the sea level index by detailed analysis of the sedimentary facies.[5] On the other hand, for the method for directly assessing the rate of regional erosion in a several hundred thousand year time scale, we have conducted research on assessment using depth distribution of cosmogenic nuclides that were formed by the exposure of rocks near the ground surface to cosmic rays.[13]

For the former, in the chronology of index geomorphic surfaces, the general method is to detect wide-spread tephra[Term 2] for which dates are known from the terrace composition, and to indirectly estimate the stage of sea level change when the geomorphic surface was formed. However, there was a problem that in many cases, there was no tephra that might serve as the dating index in the old geomorphic surface that has undergone several cycles of sea level change. The research conducted by AIST allows assessment of the formation age of the geomorphic surface by directly assessing the sedimentation age of sediments, to enable application to such surfaces. The general luminescence method using quartz particles has a measurement limit of about a hundred thousand years,[5] and it was not possible to conduct sufficient assessment of the uplift and erosion for at least a hundred thousand years into the future. However, it became possible to expand the applicable limit to several hundred thousand years ago using the luminescence method by looking at the potassium feldspar particles. To precisely conduct prediction of future hundred thousand years by extrapolation from the past, it is necessary to precisely assess the uplift rate and the chronology of the geomorphic surface to at least several hundred thousand years in the past. This will increase the accuracy of the prediction for future hundred thousand years, and we have been able to provide results that may serve as scientific evidence for determining the adequacy of the method for selecting the actual disposal site location, in areas where the chronology by tephra is particularly difficult.

For the latter, measurement of cosmogenic nuclides is an assessment method independent from the sea level change. In the proposed examination guide outline, an example of a survey and assessment method that should be applied to check the adequacy of application filed by the implementors is shown, as a method that can directly assess the erosion rate and that is applicable even in cases where a clear index geomorphic surface cannot be observed. However, for the application to radioactive waste disposal, there are many issues that must be solved such as the investigation of space scale to which individual erosion assessment can be applied. Also, it is necessary to accumulate knowledge for the prediction of erosion in the horizontal direction in the next hundred thousand years by lateral erosion and river erosion in the coastal area accompanying sea level change, as these are difficult to assess with the current erosion assessment method.

3.2.4 Other geological events, etc.

In the proposed examination guide outline, large-scale mass movements[Term 3] and mud volcanoes[Term 4] are listed as events that may cause a site to be excluded as a disposal site location, other than the aforementioned geological events. Also, although not included in the exclusion conditions, the events for which impact assessment will be done considering the location condition include hydrothermal activities, crustal fluid flow, climate change, and sea level change, and individual safety assessment include THMC or the thermal, hydrological, mechanical, and chemical properties.

For such individual factors, AIST published a large-scale mass movement database[14] and a mud volcano database,[15] and is engaging in organizing the knowledge that may be used for the examination. For hydrothermal activities and crustal fluid flow, a database is made for the upwelling area of slab-derived aqueous fluids in the Japanese islands, and the origin and chemical properties of crustal fluids in the Japanese islands are categorized.[16] In the future, not only detecting the presence of crustal fluid upwelling but also developing an assessment method for the possibility of future upwelling of crustal fluids and the chemical properties when this occurs is necessary. Also, it is necessary to consider the accelerated dissolution of radionuclides into groundwater, or the possibility of the decreased function of engineered barriers such as bentonite to isolate or delay the dissolution of radionuclides, due to the relatively shallow disposal depth and the surrounding groundwater becoming an oxidizing environment.

On the other hand, technological summary and development of a method using drilling surveys and geophysical exploration of the so-called baseline survey before artificial disturbances occur due to construction of underground disposal facility have been done for the THMC properties.[5] Particularly, for hydrological properties, detailed investigation has been done for the assessment method of influence on abnormal pore water pressure, groundwater flow, and solute transport.[17] In the baseline assessment of such underground environment and long-term change prediction, research is being done on hydraulic and geochemical properties that may be a problem in safety assessment, and on the assessment method for predicting their long-term change. It is necessary to then organize the results so they will be reflected in the examination guide for survey and monitoring for which organization and revisions will be done in the future.

4 Ways of reflecting results to regulation of geological disposal

4.1 Common and different points in safety regulation compared to intermediate-depth disposal

The way of thinking about the regulation for geological disposal is characterized by the fact that the concentration of long-term half-life radionuclides in HLW is several digits higher compared to intermediate-depth disposal. Since the specific required depth and assessment period in geological disposal is considered different from those of intermediate-depth disposal, further technological investigation is necessary. However, as basic measures for protecting the living environment and the general public over a long period, the way of thinking about requesting measures to implementors concerning isolation and containment design is the same as the ones for intermediate-depth disposal.[1] Here, the differences in specific technological issues will be clarified between geological and intermediate-depth disposal, as we analyze the technological requirements of safety regulations for geological disposal and the issues in reflecting our research results in the regulations.

The “Nationwide Map of Scientific Features for Geological Disposal (Scientific Feature Map)”[18] published by the Agency for Natural Resources and Energy is a map to provide a general, bird’s-eye view on what scientific features must be considered when selecting sites for geological disposal, and how such possible sites are distributed throughout Japan. The requirements and criteria for undesirable ranges are shown, for example, for each topic such as volcanic, magmatic, and fault activities.[18] The Scientific Feature Map shows the overall geological feature distribution from existing data obtained at a national scale, as a preceding argument to the official selection of sites by the disposal companies. On the other hand, the regulatory criteria are criteria by which an implementor is examined after it conducts geological surveys for site selection and determines a disposal facility location, and the objectives of the two are greatly different. Therefore, simply arguing the differences for individual requirements by directly comparing the two criteria is not meaningful. However, comparing the requirements that must be considered when conducting geological disposal and the geological conditions for safety regulations of intermediate-depth disposal may be useful as reference when extracting the technological issues necessary to investigate the regulatory criteria for geological disposal in the future.

The requirements and criteria of the Scientific Feature Map and the regulatory criteria for intermediate-depth disposal are compared in Table 1. This will serve as the basis of discussion pertaining to the research issues that will be necessary in setting the regulatory criteria for geological disposal that will be organized in the future. As mentioned earlier, the two have different types of waste, and the Scientific Feature Map is presented from the standpoint of site selection that is determined from the available nationwide data at this point, while the regulatory criteria are used to determine the compatibility of the disposal site selected after the surveys are completed. It is necessary to notice the difference in the viewpoints as well as the stages in which the requirements and criteria are used.

For the time scale to be considered, in the report that summarizes the discussion for the Scientific Feature Map,[19] it is written, “The geological environment of disposal site scale must have features of a suitable locational environment where functions of engineered barriers can be maintained for a certain period, and natural barriers can prevent dissolving and transferring of radioactive materials. Moreover, such characteristics must remain within a tolerable range as they may change in a long time scale of several tens of thousands of years.” It is stated that no major change should occur in the delay characteristic of bedrock that will be the natural barrier for at least several tens of thousands of years. In the Scientific Feature Map, there is no clear result of the discussion on time scale because its objective is to provide an overview of scientific features to be considered and their distribution. However, a hundred thousand years is set as a time scale since the uplift volume of 300 m for a hundred thousand years is used as a criterion in uplift and erosion. On the other hand, for intermediate-depth disposal, as described in Subchapter 3.1, a hundred thousand years is considered from the perspective of predictability of depth reduction due mainly to erosion and the reduction of radioactivity concentration. Considering the characteristics of waste in geological and intermediate-depth disposal, for geological disposal, the time scale should be equivalent to or longer than that of intermediate-depth disposal.

Looking at the individual natural events in Table 1, for volcanic and magmatic activities and mineral resources, almost the same criteria are set for the two. On the other hand, in fault activity, the Scientific Feature Map assumes that “a fault that has repeatedly been active, has high possibility of being active in the future, that has large deformation must be avoided,[18]” and sets active faults and fracture zone widths (1/100 of length of fault on both sides) as undesirable areas that will be affected. However,

Table1. Comparison of requirements and criteria for individual geological events in the Nationwide Map of Scientific Features for Geological Disposal and the regulatory standards of intermediate-depth disposal

Precondition and assessment item	Conditions of undesirable range in the Nationwide Map of Scientific Features (categorization of features from the perspective of geological disposal)	Regulatory standard and examination guide for intermediate-depth disposal (NRA)
Objective and stage of use	Interactive activity to deepen understanding of general public in preliminary stage of official site location setting by the company	Safety examination for permit application by implementors
Base data	Literature data to fulfill the following conditions 1) Quality is established (perspective of trust) 2) Inter-regional data are objectively comparable through systematic organization at national scale (perspective of fairness among regions) 3) Generally available at this point (perspective of transparency and verifiability)	Survey and literature data after the implementor engages in actual location survey
Time scale of safety requirement	Delaying characteristic of natural barrier can be maintained for period of several 10,000 years; 100,000 years for uplift and erosion	At least 100,000 years
Volcanic and magmatic activities	・15 km from center of Quaternary volcano ・Range of caldera where the Quaternary volcanic activity range is over 15 km	・Region with record of Quaternary volcanic vents and dikes ・Region where volcanic activity may occur in the next 100,000 years based on time-space distribution of Quaternary volcanic activities
Fault activity	・Range with leeway of 1/100 of seismogenic fault length or active segment length	・Range subject to the effect of fault length of 5 km projected onto ground surface, or its mechanical effect (distance from subject fault is maximum 1/100 of the length of fault)
Uplift and erosion	・Region with more than 300 m erosion volume by uplift and sea level decrease in the next 100,000 years (perspective of rising of site to ground surface)	・Maintain depth of 70 m during the next 100,000 years ・Consider lateral erosion by sea level change (perspective of depth at which underground is used for traffic tunnels etc.)
Geothermal activity	・Geothermal gradient where the buffer material temperature cannot be kept below 100 °C at disposal depth	・Region in which geothermal resources that can be used for electric power generation are present ・Although heat characteristics are not exclusion conditions, effect must be assessed while considering the condition of location
Volcanic hydrothermal activity, deep groundwater flow	・For groundwater characteristic ranges, pH less than 4.8 or carbonate concentration 0.5 mol/L or higher	・Not an exclusion condition, but effect must be assessed while considering the condition of location
Nonconsolidated sediments	・Range to which strata after Middle Pleistocene are distributed at depth 300 m or deeper	・Not an exclusion condition, but effect must be assessed while considering the condition of location
Pyroclastic flow etc.	・Range at which Holocene pyroclastic flow sediment, volcanic rock, volcanic debris are distributed	・Range of distribution of Holocene pyroclastic sediments etc. for surface facilities ・Although not exclusive, item is important in assessing the performance of disposal system in actual geological survey
Mineral resources etc.	・Range at which mineral resources with large reserves, as designated by the Mining Laws, that can be technically mined are present in the literature data that was organized at a national scale	・Set in area where significant natural resources are not found ・Natural resources are resources that are currently used in society, or those that may be potentially used in the future

in intermediate-depth disposal, faults with length of 5 km or more and mechanically affected areas (1/100 of length of maximum fault surface on one side) are set as conditions to be avoided. In the difference in fault to be targeted, the criteria of Scientific Feature Map is based on the active fault database obtained on a nationwide scale at this point, while the criteria for intermediate-depth disposal is based on the way of thinking that a fault, which has a certain length or more, has the possibility of becoming active in the next hundred thousand years, after the 3D structure of a fault including its surrounding area has been revealed through an actual survey. For the range of effect of fault activity, the Scientific Feature Map assumes the width of the fracture zone from the fault length of the database and uses this as the criteria of undesirable factors for geological disposal, while the intermediate-depth disposal assumes the surrounding damage area as well as the fracture zone by survey, and employs this way of thinking that the maximum width of assumption is 1/100 of the length of the fault on one side.

For uplift and erosion, the values for standard erosion are different according to the depth of disposal. The Scientific Feature Map sets the criteria of an undesirable range area as having high possibility that erosion by lowered sea level and uplifting will surpass 300 m in the next hundred thousand years, while the intermediate-depth disposal sets as requirement to maintain the depth deeper than general underground use in the next hundred thousand years, as mentioned in Section 3.2.3. They are in common in the point that they require that the disposal facilities and waste materials do not rise close to the ground surface in the future.

In other items, for geothermal activity, hydrothermal activity, crustal fluid flow, unconsolidated sediments, and pyroclastic flow, specific criteria are shown in the Scientific Feature Map, while for the intermediate-depth disposal, there are no exclusion conditions, and these items are set as individual site features that must undergo safety assessment. However, particularly for hydrothermal activity and crustal fluid flow, problems remain in the assessment method of future activities and current water quality in the disposal depth, and in the setting method of geochemical properties for conducting safety assessment.

4.2 Requirements that must be considered for safety regulation of geological disposal

After the regulatory criteria and guide for intermediate-depth disposal are organized at the regulatory agencies, there is the possibility that the regulatory criteria on geological disposal will also be organized due to the social trend and demand as shown in Chapter 1. Since the geological events that must be considered for both intermediate-depth and geological disposal are similar, even in the case where the regulatory criteria of geological disposal are organized based on the standard of the intermediate-depth disposal, it is necessary to take notice of the following items.

4.2.1 Time scale to be considered

HLW requires a long period for the radioactivity concentration to decrease compared to waste materials of intermediate-depth disposal, and it is thought that the time scale to be considered for regulatory criteria should be equivalent or much longer than that of the intermediate-depth disposal. As an example, the Swiss Nuclear Regulatory Safety Inspectorate (Eidgenössisches Nuklearsicherheitsinspektorat = ENSI) states in the “Specific design principles for deep geological repositories and requirements for the safety case (ENSI-G03)” that the safety standards should be satisfied for at least one million years. In the Japanese islands, since there are regional characteristics in the predictability of geoscientific events pertaining to locational criteria, it may be necessary to clarify the predictable period for each event at a certain probability, and to present a methodology to assess safety in the future when uncertainty increases. When investigating the geological events at one million year scale, it is necessary to expand the range of investigation to the continuity and future changes of plate movements that are the basic driving force of geological phenomena for the entire Japanese Archipelago. An example of the existing research result by AIST for this issue is the research result of plate movement around the Japanese islands, changes of crustal movement, and future prediction.[20] Here, by reproducing the crustal and plate movements of the past 25 million years, the predictability of future plate movement is assessed, and it is shown that there is no active evidence that shows the possibility of crustal change due to plate movements for the next hundreds of thousands of years, and therefore, it is shown that at least in the next hundred thousand years, the current framework is likely to be maintained. The plate movement and the accompanying crustal movement are basic factors of natural events that must be considered in the regulatory criteria, and therefore, it is necessary to show the range of long-term uncertainly and the period of predictability for natural events that may affect the disposal site, under preconditions of future predictions.

4.2.2 Effect of depth difference

While the assumed disposal depth of intermediate-depth disposal is about 100 m, the geological disposal is assumed at a “stratum 300 m or more underground set by the ordinance” in the Final Disposal Act. While groundwater flow at depth of 100 m are circulation of water originating from meteoric water in many cases, when the depth increases, abnormal pore water pressure occurs in the sedimentary rock region, as mentioned in Section 3.2.4, and in many cases, it is not simple circulation of meteoric water. Depending on the cause of the abnormal pore water pressure, there may be cases where a conventional numerical analysis model cannot be applied to the groundwater flow and migration of radionuclides. It is necessary to assess the cause of abnormal pore water pressure when it is observed, and the knowledge must be gathered concerning the effects on groundwater flow and mass transfer, and these must be reflected in the examination guide.

In a case where there is no significant effect of heat and chemical fields on groundwater flow even with increased depth, the hydraulic gradient is relatively small compared to the ground surface, the hydraulic conductivity tends to be small, and the flow rate of groundwater tends to be slow.[19] In the intermediate-depth disposal, for the investigation of groundwater flow analysis results and the setting of the route of radionuclide transfer, it is required in the examination guide to provide explanation using the information for hydraulic head, water chemistry, and groundwater age, etc. as well as their analytical investigation. For geological disposal, longer time is required compared to the case of intermediate-depth disposal for the groundwater recharged from the ground surface to reach the required depth. Moreover, the groundwater at disposal depth may be a mixture of meteoric water, and water derived from multiple origins such as seawater and crustal fluids, and it is urgently necessary to conduct groundwater age assessment using multiple isotopes, and to build a method to organically integrate the results of numerical analysis and groundwater age assessment, as a result of change in underground environment through uplift, erosion, and sea level change.

5 Transferring to safety regulation frameworks

To have the research results of research institutions reflected in the regulatory standards and guides is primarily what the regulatory agencies do. On the other hand, the preparation of regulatory standards and examination guides for disposal site selection requires the knowledge of wide-ranging fields including geology, geomorphology, seismology, volcanology, quaternary studies, hydrogeology, geochemistry, and others. The regulatory agencies must collect the latest research results in those fields, organize them, and create the regulatory standards and examination guides. Therefore, the Geological Survey of Japan, the leading research institution for geosciences in Japan, must provide scientific support by delivering the results in response to the demands of regulatory agencies, and this is effective in raising the expertise of the regulatory agencies in the future. Here, topics on the regulation of geological disposal that must be organized in the future and must be addressed by a research institution, and ways of transferring scientific findings will be discussed and summarized.

The regulatory standards and examination guides, taking the example of intermediate-depth disposal, are composed of items to be examined and assessed (geological events and environments that are subjects of examination and safety assessment), examination criteria (period for assessment and exclusion standard for each event), and survey and assessment methods that must be conducted to verify compatibility. Here, the author extracts the investigation items to be added to the regulatory standards and examination guides for intermediate-depth disposal.

For examination and assessment items, as mentioned in Chapter 4, it is necessary to extract the detailed topics unique to geological disposal considering the difference between geological and intermediate-depth disposals, and present the assessment method for the geological events that must be considered in the regulatory criteria of intermediate-depth disposal. One example is the hydrothermal activity and crustal fluids that are shown in the Nationwide Map of Scientific Features. Although the final determination of whether to make an item an exclusion condition of disposal facility location will be done by the regulatory institutions, AIST must continue investigation on whether it is possible to set specific criteria for a long period surpassing a hundred thousand years into the future, or whether it is possible to do specific surveys and assessment during the site selection survey stage.

For the examination criteria, when regulatory agencies set the assessment period, first, it is important to understand the period that can be assessed for a geological event occurrence, as shown in Section 4.2.1. Next, as a discussion of possibility of occurrence during the assessable period for each event, the assessment will be done for future events through the assessment of time-space distribution of past activities. The research results of AIST include, for example, the database for volcanic activities as shown in Section 3.2.1, or cases in which time-space distribution of events that occurred in the past can be assessed. However, when conducting long-term prediction, it is necessary not only to simply extrapolate the events that occurred in the past into the future, but also to make assessments by understanding the mechanism by which the events occur and the history of structure development in the region.[21] Therefore, AIST must present a long-term prediction method for each natural event basing it on future predictions of crustal movements at a Japanese island scale, as shown in Section 4.2.1. The regulatory agencies will then show the period during which assessments should be made and the minimum criteria for exclusion (for example, depth that should be maintained during the assessment period considering the effect of erosion), and the judgment indices etc. during a long period when uncertainty will increase.

For example, the criteria of fault activities in geological disposal differ from volcanic activities[5] etc., for which it is thought there are regions where assessment of the next hundred thousand years is possible from past history, and there is a possibility that only fault length will be considered, as in intermediate-depth disposal, rather than activity history or possibility assessment of activity. In that case, it will be difficult for fault activity assessment by mechanical indices conducted by AIST to be applied directly to establishing the criteria. However, similar to the examination guide for intermediate-depth disposal, when the criteria are set for assessing the impact of fault activity near the waste disposal facilities, it is necessary to assess the activity of peripheral faults, extension, and the possibility of connection of plural faults. Currently, there are few cases in which such research has been done, not only at AIST, but also around the world, and this will be an important topic in supporting regulatory agencies. Therefore, it is necessary to develop the fault activity assessment method by mechanical indices, evaluate the relationship between fault activities and fault extension, investigate stress change that influences fault activities, and publish the results, so the methodologies of assessment and criteria pertaining to the effects of peripheral faults can be reflected in the examination guides etc.

For survey and assessment methods, as in the example shown in Chapter 3, some of the AIST results have been utilized in the examination guide for the current intermediate-depth disposal. A particularly important topic in geological disposal compared to intermediate-depth disposal is the assessment of slow groundwater flow at disposal depth. Particularly, the effect of factors such as uplift and erosion, sea level change, fault activities, etc. on survey results of hydraulic head, water chemistry, and groundwater age in deep underground must be extracted and organized from the results of hydrogeological surveys that AIST has conducted so far. By presenting the points to take notice in the survey and assessment corresponding to individual hydrogeological structures, it is necessary to have them reflected in the examination guide for site selection surveys and future groundwater monitoring.

While the subject is intermediate-depth disposal, after the start of investigation of specific regulatory criteria, transferring of AIST research results to regulatory agencies has been insufficient, even considering the difference in the regulatory criteria proposed for fault activities and the setting of research topics by AIST. The main reason is because the priority of regulation became temporarily unclear for radioactive waste disposal due to the change in the organization of the regulators, information exchange between regulatory agencies and AIST became insufficient, and quick response to organizing regulatory criteria became difficult. For example, for the criteria of intermediate-depth disposal location, the period from serious discussions with external experts to the publication of proposed regulatory standard outline is about three months at regulatory agencies. Since the direction is set in a relatively short period, quick response in a research project that is conducted on a fiscal year basis is difficult. For transferring research results of AIST, we are painfully aware of the need to deliver scientific findings that match the demand of the criteria and guide, as well as proposals of new research topics, through regular communication with regulatory institutions that utilize such research results. Also, through such information exchange, the author believes we can help train regulatory agency personnel who do not specialize in geology.

In the future, as groundwork for discussion with the regulatory agencies, we shall publish technological reference materials that summarize the current latest science and technology including the results of AIST, and provide materials that can be easily used by the regulatory agencies, like the databases that are continuously organized that visualize survey data. Personally, we wish to play the role of remodeling the scientific research results of AIST into knowledge that can be easily used in organizing and examining the regulatory criteria, and would like to propose and set topics that allow flexible response to the policy changes at the regulatory agencies.

Terminologies

Term 1. Slip tendency: Index calculated by the ratio of normal stress and shear stress that act on the fault surface calculated from the stress state, strike and dip of a fault, and pore water pressure acting on the fault plane.[22] In general, it is normalized by the friction coefficient, and is expressed as values 0 to 1. A fault that has large slip tendency is evaluated as likely to become active under the current stress state.

Term 2. Tephra: A general term for volcanic debris deposited on the ground surface after being released from a crater and traveling through air at the time of volcanic eruption. Tephra during a massive eruption may be observed as an independent stratum even in areas that are over several hundred to several thousand kilometers away from the supply source, and such stratum is used in dating as well as to compare ground surfaces.[23]

Term 3. Mass movement: A phenomenon in which rock mass that comprises a slope moves downward by gravity, as seen in landslides and collapse of volcanic edifices. This occurs when the shear force against the rock on the slope surpasses the shear force resistance. Large scale movements are known to have reached moving clod volume of 10 km3, moving distance of 10 km, and depth of sliding surface of 100 m.[5]

Term 4. Mud volcano: Mud volcano is a volcano-like structure that appears on the ground surface, as the underground mud with abnormally high pore fluid pressure pushes the above layers upward in a dome shape, and eventually erupts on the ground along with groundwater (thermal water), flammable gas, or, in some cases, oil. The deposit (convex) or depression (concave) geomorphologies may reach maximum height of several hundred m and diameter of several km.[5]

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Discussions with Reviewers

1 Overall

Comment (Chikao Kurimoto and Yoshio Watanabe, AIST)

This paper describes cases in which AIST's research results were utilized regarding intermediate-depth disposal regulation, and summarizes the challenges in using AIST results for future high-level radioactive waste disposal. The content is organized as an article whose purpose is to provide the trends and analyses for utilization of R&D results in society, and is worthy of publication in *Synthesiology.* It is also significant that there is a comparison with the "Nationwide Map of Scientific Features for Geological Disposal" published by the Agency of Natural Resources and Energy in July 2017.

2 Handling of regulatory criteria

Comment (Yoshio Watanabe)

When outlining the "intermediate-depth disposal" regulation, which precedes the national safety regulations, and comparing it to "geological disposal," it is essential to communicate to the readers that the requirements and criteria in the "Nationwide Map of Scientific Features" published by the Agency of Natural Resources and Energy cannot be handled in the same manner as the ones for "geological disposal" in the discussion of regulation itself. Please try to provide accurate and careful descriptions, as AIST conducts safety research for geological disposal of high level radioactive wastes. Please take care to use easily understandable sentence structures as well as accurate wording, vocabulary, and concept, so the original results described in this article can be conveyed smoothly to the readers.

Answer (Kazumasa Ito)

The two types of disposal compared in this article differ greatly in data volume and quality on which the discussion is based, as well as in objectives and stages of use. To clarify that the comparison cannot be made easily, I added descriptions on the objectives, stages, and comparison of basic data, and also added an explanation that although the two types of disposal cannot be simply compared, they are compared to point out the problems.

3 Research results of AIST

Comment (Chikao Kurimoto)

You describe cases of utilization of AIST's research results in the regulation of intermediate-depth disposal, and briefly summarize the challenges eyeing application to high-level radioactive waste disposal in the future. "3.2.2 Regulatory requirements for active faults" shows a case in which AIST's results were not employed, which is an important precept for future research, and it can be the main point of this article. You state that it is necessary to expand case studies of activity assessment by mechanical indices as well as to establish a rational setting method of parameters, but I think you should emphasize the progress of specific research on this topic, and the contribution and stance (forte) of AIST. I raise similar points for "3.2.3 Uplift and erosion."

Answer (Kazumasa Ito)

For fault activities, I added citations from latest papers on fault reactivation assessment conducted at AIST, and also added that the mechanical index of slip tendency is useful as an assessment method in the first stages of activity assessment of faults that exist near waste burial sites. Also, I added specific research topics that should be pursued so that AIST's method will be recognized as an actual survey and assessment method in the future. For uplift and erosion, I added the progress of research at AIST, as well as topics on erosion in the horizontal direction for which sufficient investigation has not been done, although it is an assessment method required in the current permission standard and examination guide.

4 Transfer of research

Comment (Chikao Kurimoto)

Based on your mentioning the academic level of AIST results and the specific explanation of existing research results in "3.2.2 Regulatory requirements for active faults" and "3.2.3 Uplift and erosion," please emphasize AIST's favorable position and its standpoint, and then discuss the future research policies and measures and plans in making proposals for the examination guide as a national standard.

Answer (Kazumasa Ito)

In Chapter 3, I added AIST's favorable position from the perspective of radioactive waste disposal, pertaining to the current research done by AIST. I also added in Chapter 5, particularly for fault activity, the description of the research policy about transferring results to the examination guide for standard compatibility of intermediate-depth disposal, which is thought to be carried over to the standard for geological disposal.