ICEM2010-(00)*

DEVELOPMENT OF COMPREHENSIVE TECHNIQUES FOR COASTAL SITE CHARACTERISATION (1) STRATEGIC OVERVIEW

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ABSTRACT

Any assessment of long-term repository safety will require development of a set of analyses and arguments to demonstrate the persistence of the key safety functions of the geological environment up to several hundred thousand years into the future. However, likely future global climatic and sea-level fluctuations and uplift/subsidence would result in a dramatic change in the location of the current coastline with a subsequent significant change to hydraulic and hydrochemical conditions at coastal sites. It is thus of great importance in the Japanese disposal programme to establish comprehensive techniques for coastal site characterisation.

To this end, a systematic framework, which is known as a 'Geosynthesis Data Flow Diagram', has been formulated, which outlines a basic roadmap of the geosynthesis methodology for characterising temporal and spatial changes of various properties and processes at coastal sites, with particular focus on the palaeohydrogeology. A basic strategy for stepwise surface-based investigations has also been proposed, which incorporates the geosynthesis methodology in an effective manner. This technique has been introduced in an ongoing collaborative programme for characterising the coastal geological environment around Horonobe in northern Hokkaido, Japan, and now tested and optimised based on accumulated technical knowledge and experience during the progress of the investigations.

Key words: coastal site, site characterisation, geosynthesis methodology, Geosynthesis Data Flow Diagram, basic strategy, palaeohydrogeology, Horonobe

INTRODUCTION

The assurance of the long-term stability of the geological environment is *sine qua non* for deep geological disposal. The key safety functions to be served by the geological environment in a geological disposal system will include physically isolating the waste for a sufficiently long period of time, maintaining conditions favourable for the engineered barrier system (EBS), preventing or attenuating potential release of radioactivity and providing sufficient buffering against internal and external perturbations [1]. Consequently, any assessment of repository safety will require development of a set of analyses and arguments not only to define if these functions are currently adequate but also to demonstrate the persistence of the functions, despite external disruptive events and processes, up to several hundred thousand years into the future.

In Japan, natural events and processes that could take place over the next several hundred thousand years and affect a geological disposal system include earthquakes and fault movement, volcanic and hydrothermal activity, uplift/subsidence and climatic and sea-level changes. By applying the Siting Factors, which include criteria for exclusion of certain areas because of increased risk of disturbance of the repository, for the selection of Preliminary Investigation Areas established by the Nuclear Waste Management Organization of Japan (NUMO), significant impacts of earthquakes, fault movement and volcanic and hydrothermal activity could be precluded, thereby excluding areas that would clearly be unsuitable as a repository site [2]. However, in many cases, the potential

impacts of uplift/subsidence and climatic and sea-level changes will accumulate rather slowly, but constantly, over long time periods in a regional scale and these could not be precluded by siting. It is thus of great importance to develop a set of analyses and arguments for the reliance that can be placed on the key safety functions to assure the long-term stability of the geological environment.

A large number of nuclear facilities are situated in coastal areas: e.g. many nuclear power plants in Japan (Fig. 1) and repositories under construction or to be constructed in Finland, France, South Korea, Sweden and the UK. This is not coincidental; such locations offer ease of transport of bulky or radioactive materials by ship (thus avoiding the transport of hazardous materials by rail or road through densely populated areas) and effectively limitless supplies of cooling water. Such facilities may also be less intrusive in a coastal setting, especially in remote locations, which may have little alternative, e.g. islands/archipelagos with mountainous, tectonically unstable interiors like Japan. Nevertheless, it could be difficult to preclude a risk of some kind of dramatic perturbation at potential coastal sites [3]. Concern presently focusses on a sea-level rise caused by anthropogenic global warming [4] but, within a period of several tens of thousands of years, a return to glacial-period conditions is to be expected, inducing a sea-level fall. Based on previous glaciations, global sea-level could drop by up to 150±10 m [e.g. 5-7], although, during the Last Glacial Maximum, the Japan Sea is estimated to be 125-130 m lower than at present. Although unlikely, melting of the East Antarctic Ice Sheet would increase sea-levels by up to 60 m [8]. Such sea-level changes would result in an extremely dramatic change in the location of coastlines with a subsequent significant change to hydraulic and hydrochemical conditions at coastal repository sites [3, 9, 10].

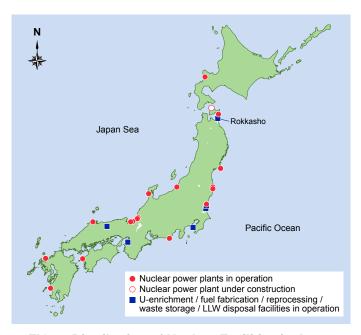
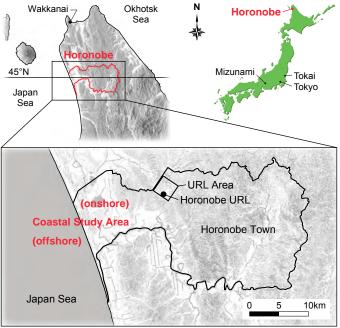


FIG. 1: Distribution of Nuclear Facilities in Japan

Although the importance of coastal sites in the context of geological disposal is commonly recognised in Japan, there is less practical experiences and technical knowledge, compared with inland areas, with characterising the coastal geological environment. As there exists a significant need to establish comprehensive techniques for coastal site characterisation, a research and development (R&D) task on this has been defined in Phase II (2006-2012) of the national "R&D Programme for the Geological Disposal of High-Level Radioactive Waste" [11]; the goal of the fundamental R&D in Phase II is to establish the technical basis for use in NUMO's preliminary investigations (PIs) before they begin in earnest. The main component of the task is demonstration of methodologies for characterising the actual coastal geological environment with focus on understanding the evolution of the hydrogeological and hydrochemical environment over geological time and the potential processes involved (e.g. movement of saline/fresh groundwater interface, density-driven flow).

To this end, Japan Atomic Energy Agency (JAEA) has commenced an R&D programme that involves surface-based investigations in a coastal zone of Horonobe in northern Hokkaido, Japan (Fig. 2), under collaboration with other research organisations [12]. At Horonobe, JAEA's underground research laboratory (URL) project is currently ongoing with the main aim of establishing and testing relevant techniques for future repository site characterisation in Japan. Throughout surface-based investigations in and around the URL area (i.e. inland), a vast amount of information on the properties and processes of the geological environment within a suite of sedimentary formations has been acquired and relevant investigation techniques developed [13]. These results can thus advantageously provide a basis for efficaciously implementing the new programme. Practical experiences and technical knowledge accumulated not only from the Horonobe URL project but also from the Mizunami URL project for crystalline rock [14] can also be fully utilised. In particular, these experiences indicate that a geosynthesis methodology, initially formalised in a site characterisation programme in Switzerland [15], has proved to be indeed effective throughout the surfacebased investigations in both URL projects [16, 17], should be applied.

Of particular importance for this – and the focus of this paper – is the formulation of the 'Geosynthesis Data Flow Diagram (GDFD)' that outlines a basic roadmap of the geosynthesis methodology for characterising the evolution of the coastal geological environment. Focus also concentrates on the establishment of a basic strategy, to effectively introduce the geosynthesis methodology in practice, for stepwise surface-based investigations at coastal sites. The applicability of this technique has now been tested during the progress of the surface-based investigations at the Horonobe coastal study area, which serves as a 'dry run' and generic test-bed of the PIs for any coastal site.



Shaded relief map (top-left) and base map (bottom) from part of the 1:50,000 topographical map (Wakasakanai, Toyotomi, Kamisarufutsu, Teshio, Onobunai, Pinneshiri) published by the Geographical Survey Institute, Japan

FIG. 2: Location of Coastal Study Area of Horonobe, northern Hokkaido, Japan

WHY GEOSYNTHESIS METHODOLOGY?

In the repository site characterisation programme, surface-based investigations in a variety of disciplines aim to derive a comprehensive and consistent overview of the geological environment at a site, as required for repository design (RD) and safety assessment (SA) [18, 19]. A global integration methodology, which clearly defines the goals of individual investigations and interprets and synthesises information from the wide diversity of investigations into a consistent site model, needs to be developed in advance and demonstrated. Once again, experience shows that, for enhancing interactions among different disciplines and ensuring the transparency and traceability of the production of the information needed by the end users, such a methodology is essential.

The geosynthesis methodology is defined as proceeding in the following five steps, which is represented in the GDFD:

- i) investigation and data acquisition;
- ii) data interpretation;
- iii) conceptual model development;
- iv) numerical modelling and simulation;
- v) clarification of the key properties of and processes ongoing in the geological environment.

Based on previous experiences accumulated both in Japan and Switzerland [13-18], it is clear that iteration of this process, gradually improving understanding of the geological environment in each phase of the stepwise surface-based investigations, can lead to building confidence in output of the geosynthesis. Importantly, the impact of limitations in

knowledge and uncertainties in data can be assessed by the end users to provide feedback to guide optimisation of investigations in the subsequent phases.

FORMULATION OF COASTAL GDFD

The key feature of the GDFD is a systematic framework that can guide efficaciously the surface-based investigations. The GDFD thus illustrates, in a systematic manner, data transformation from initial field-based 'Investigation' with 'Data' acquisition, through 'Interpretation/Dataset' and 'Conceptualisation/Modelling/Simulation' of the results from different disciplines, to final clarification of the 'Key Properties/Processes' of the geological environment [13, 14].

Identification of Key Properties and Processes

The geological environment in which a repository is constructed is expected to physically isolate the waste for a sufficiently long period of time, provide a suitable environment for installing the EBS and function as a natural barrier to constrain radionuclide migration [1, 20, 21]. A suitable geological environment is expected to have the following properties and functions:

- ➤ Demonstrated existence over an appropriate location and adequate depth with sufficient spatial extent.
- Relatively homogeneous stress conditions and low temperatures, to ensure operational safety and ease design, construction and maintenance of the EBS and other underground facilities.
- ➤ Low groundwater flux through the repository horizon, ideally with neutral to slightly alkaline chemistry and reducing conditions, which would serve to restrict erosion of the buffer material, corrosion of overpack, dissolution of the waste glass matrix and radionuclide migration.
- Slow groundwater movements and long flow paths between the repository and the accessible environment to reduce the rate of radionuclide migration.
- ➤ High dilution and dispersion during migration to the biosphere, resulting in reduction of radionuclide concentrations.

More importantly, the geological environment is required to be sufficiently buffered against natural perturbations, thereby maintaining such properties and functions for a long period of time [1].

To focus the surface-based investigations at coastal sites, the key properties of and processes ongoing in the geological environment to be investigated in relation to RD and SA have been identified, with reference to a variety of FEP (features, events and processes) lists [22-25] and a list of favourable factors and underlying key issues for the PIs [2], as shown in the left column of Table 1. Since characterisation of the overall site evolution over geological time is the focal point of the surface-based investigations at coastal sites, the temporal and spatial (or 4D) changes of various properties and processes are taken into account (see also discussion in [10]).

TABLE 1: Key Properties of and Processes Ongoing in the Geological Environment and Key Aspects of Geological, Hydrogeological and Hydrochemical Characterisation at Coastal Sites

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Key properties/processes		Key properties/processes	Key aspects of characterisation
Geology and geological structure • Spatial distribution and geometry of transport pathways • Size and extent of host rock • Heterogeneity within host rock • 4D geomorphological changes; 4D evolution of geological structure		Spatial distribution and geometry of transport pathways	✓ Spatial distribution, extent and geometry of discontinuities and sedimentary structures
		 Size and extent of host rock 	✓ Spatial distribution and structure of host rock✓ Stratigraphy, thickness and depth of host rock
Groundwater flow characteristics Groundwater flow field and process Spatial variability of groundwater fluxes Groundwater fluxes		Heterogeneity within host rock	 ✓ Spatial distribution of discontinuity within host rock ✓ Lithological variability within host rock
 4D evolution of groundwater flow field and process 4D evolution of groundwater flux distribution 		4D geomorphological changes; 4D evolution of geological structure	 ✓ Evolution of regional stress field (tectonics) ✓ Changes of style of crustal movement ✓ Evolution of geology and geological structure ✓ Evolution of petrophysical properties in response to uplift/subsidence and erosion/sedimentation ✓ Evolution of style of topographical changes ✓ Palaeo/present climate changes
Geochemical characteristics of groundwater Spatial distribution of saline/fresh groundwater (interface); degree of groundwater mineralisation Groundwater pH-Eh conditions 4D evolution of groundwater chemistry			
 Transport/retardation of nuclides Geometry of transport pathways; depth of diffusion-accessible matrix Sorption capacity and diffusivity of rock matrix and of transport 		Groundwater flow field and process	✓ Groundwater flow system and dominant process
athways ffect of colloid/organics/microbes on nuclide transport/retardation		 Spatial variability of groundwater fluxes 	 ✓ Spatial distribution of hydraulic properties of rock and discontinuities ✓ Spatial distribution of hydraulic head
Dilution of nuclides Spatial distribution of higher-permeability rocks, aquifers and surface waters; extent of marine environments Sorption capacity and diffusivity of rock matrix and of transport pathways		4D evolution of groundwater flow field and process/ groundwater flux	 ✓ Evolution of groundwater flow system and process ✓ Evolution of hydraulic properties of rock and discontinuities
Geomechanical/hydraulic properties of tunnel near-field environment		distribution	
 Regional and local stress regime Spatial variability of petrophysical/geomechanical properties of rocks Volume of inflow into underground tunnels; volume of gas emission from host rock Size and structure of EDZ; petrophysical/geomechanical properties of EDZ 		Spatial distribution of saline/fresh groundwater (interface); degree of groundwater mineralisation	 ✓ Spatial distribution of groundwater chemical and isotopic compositions ✓ Groundwater flow process
 Distribution of discontinuities intersecting underground tunnels 4D evolution of stress field at repository depth (NB this will change significantly with water depth above the repository) 4D evolution of petrophysical/geomechanical properties of rocks 		 Groundwater pH-Eh conditions 	√ Spatial distribution of groundwater chemical compositions
		4D evolution of groundwater chemistry	 ✓ Spatial distribution of groundwater isotopic compositions and ages ✓ Evolution of groundwater flow system and process ✓ Changes of groundwater evolution mechanisms
Subsurface thermal conditions • Spatial variability of geothermal gradient • Thermal rock properties • 4D evolution of thermal rock properties			

Visualisation of Systematic Framework

For the identified key properties of and processes ongoing in the coastal geological environment (Table 1), a range of key aspects to be addressed in the surface-based investigations at coastal sites has been specified in a comprehensive manner. As an example, key aspects – which are particularly sensitive to site uncertainties – to be addressed by geological, hydrogeological and hydrochemical characterisation are also listed in the right column of Table 1. This should serve as a basis for the formulation of the generic GDFD [12].

Based on the key aspects, a wide range of data to be obtained, which is relevant to each key aspect, has been explicitly identified. Then the processing of 'Data' into 'Interpretation/Dataset', i.e. comprehensively interpreting a range of acquired data and logically deriving the consistent dataset necessary for the key aspects, has been graphically visualised. Application of a palaeohydrogeological

methodology [e.g. 9, 26] is essential for performing this process because the relevance of a combination of data from different disciplines will be ensured and the data compiled in an appropriate manner so as to allow interpreting the evolution of the coastal geological environment.

Second, based on the key aspects of characterisation, types and combination of potentially useful investigation techniques to obtain necessary data have been selected and the correlation between 'Investigation' and 'Data' defined. Here the investigations involve the survey/review of pre-existing information, aerial, terrestrial and marine exploration and an extensive borehole programme. Finally, the sequence of activities for 'Conceptualisation/Modelling/Simulation' towards final production of relevant information on 'Key Properties/Processes' of the coastal geological environment has been illustrated, which involves:

- building up a conceptual model for the present site conditions and the overall site evolution, based on the relevant dataset;
- ii) numerically analysing the present characteristics and processes and their 4D changes, based on the conceptual model and the dataset;
- iii) checking the consistency of the simulation results, using data from observation or other disciplines (e.g. groundwater flow and salinity distribution).

The rationale behind the linkages illustrated in the GDFD is discussed in more detail in the underlying research report [12]. Figure 3 shows the section focussing particularly on the data flow for geological, hydrogeological and hydrochemical characterisation to be conducted during terrestrial and marine exploration, as an example of the GDFD for surface-based investigations at coastal sites. Of note is that the data flow for

'hydrochemical characterisation' is highlighted. Although impossible to read in detail, but as an example of the complexity of the problem, the entire GDFD is attached (see Annex A).

It is worth noting here that, when conducting exploration onshore or offshore, the potential approaches could be (almost) the same, although the practicalities of exploration and their methods are different. For example, superficial mapping offshore is difficult, but not impossible. Since Charles Darwin's first voyage on HMS Beagle in 1831 [27], sediment grabs and shallow 'stab' corers have allowed samples to be collected from the seabed [e.g. 28] and nowadays a diversity of advanced coring techniques and remote-controlled exploration systems enable more detailed sampling even in deep seas [e.g. 29]. The degree of coverage will, in effect, vary from method to method, depending on the recent advancement of technology and the financial and other constraints on the exploration.

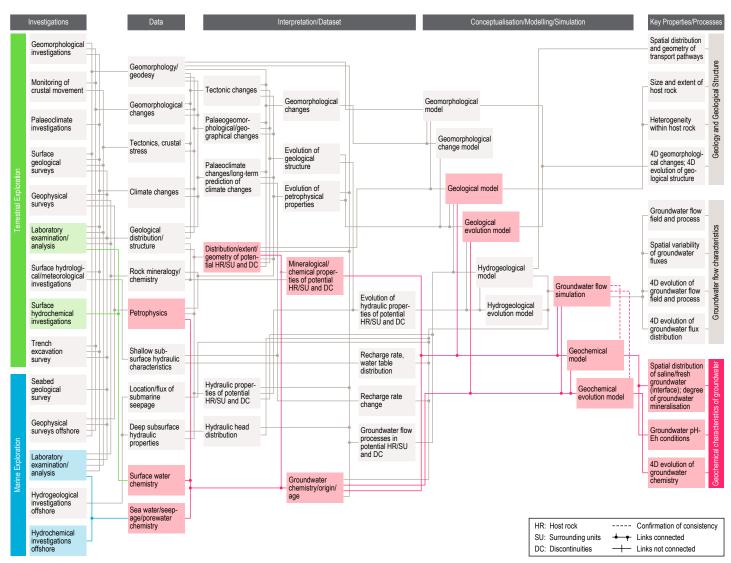


FIG. 3: Data Flow for Geological, Hydrogeological and Hydrochemical Characterisation on Terrestrial and Marine Exploration at Coastal Sites

ESTABLISHMENT OF BASIC STRATEGY

The stepwise surface-based investigations in which the geosynthesis methodology is incorporated in an effective manner will allow chiefly:

- addressing key issues that have remained or been newly identified in the previous investigations;
- ensuring the improvement of understanding of the key properties and processes of the geological environment, which is in many cases represented as the site model;
- identifying (the degree of) uncertainties in output of the geosynthesis;
- specifying and prioritising the investigation targets in the subsequent steps;
- improving techniques for characterising the geological environment by checking their applicability [13-18].

In addition, a stepwise programme is expected to provide flexibility to practically respond to the surprises that inevitably occur during investigations, which could allow enhancing the opportunity to adopt the investigations to the specific site conditions. Such a stepwise implementation approach is therefore widely accepted and will be planned in NUMO's site characterisation programme for the PI stage [18].

Based on NUMO's roadmap developed in a generic manner for implementing RD and SA with interaction with site characterisation during the PI stage [18], practical experience and technical knowledge developed in JAEA's URL projects [13, 14] and a wide diversity of investigation techniques presented in the generic GDFD, a basic strategy for the stepwise surface-based investigations at coastal sites has been proposed. A general workflow is outlined in Fig. 4, in which several work steps related to planning, geosynthesis and interaction with RD and SA activities are encompassed. In addition, investigation targets in each main step are identified (see the right column of Fig. 4) in the light of understanding the palaeohydrogeological site evolution, which is the focal point of the surface-based investigations at coastal sites.

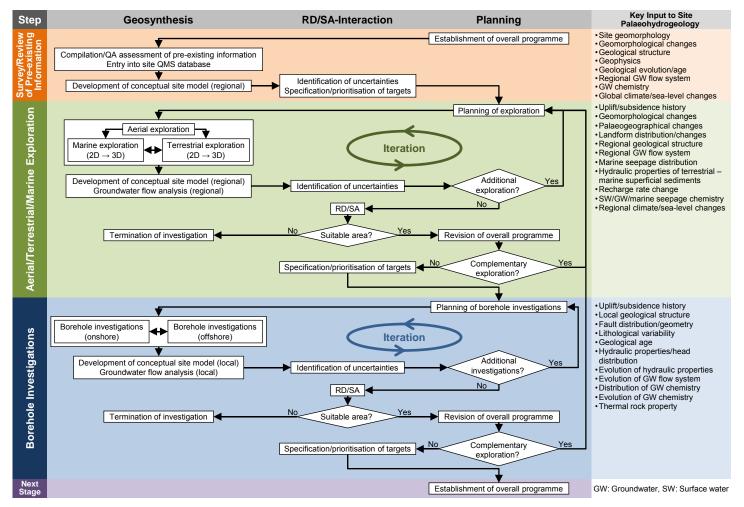


FIG. 4: Basic Strategy for Surface-Based Investigations at Coastal Sites, with Particular Focus on the Site Palaeohydrogeology

Note that it is implicit within the strategy that, within practical limits, effectively the same methods are applied both onshore and offshore.

Before looking at the various steps outlined in Fig. 4 in some detail, it is worth noting that, as there has been no choice of host rock or site to date in Japan, this strategy has been proposed in a generic manner; in each step, based on output of the geosynthesis in the preceding step, the investigation targets are to be specified and prioritised, then the investigations carried out iteratively following the GDFD and finally the investigation results assessed in the light of RD/SA for producing output. However, when the areas for the PIs are selected, this strategy needs to be optimised (e.g. defining more specific work steps, avoiding unnecessary repetition of work steps) with refinement of the GDFD, taking into account the known site-specific conditions and the temporal, financial and even societal constraints on the PI programme.

LESSONS LEARNT FROM HORONOBE CASE STUDY

The technique described above has been introduced in the ongoing collaborative programme for characterising the coastal geological environment at Horonobe and now tested and optimised based on practical experiences and technical knowledge developed during the progress of the investigations. Here some lessons learnt to date from the ongoing programme are discussed as are the basic concepts of investigations in each main step.

Survey/Review of Pre-Existing Information

Many of the activities involved in this step are already laid down in NUMO's roadmap [19] and this will be followed (with important additions, see below) here. The main aim of this step is to provide a conceptual overview of the area of interest, which should ideally identify the key properties/processes of the geological environment and, at least qualitatively, uncertainties. This will, in fact, serve as the basis for proceeding further with the surface-based investigations. It is thus necessary to compile all available information about the area and develop the database following re-assessment of the quality and reliability of the information.

In this step, the amount of information available will depend on many factors. For example, in the Horonobe area, a significant amount of oil and natural gas exploration has occurred, which means that some basic geological data are available for both onshore and offshore. However, some of the exploration goes back to 1925-1930 [30, 31]; the records are poor and of dubious quality. Even information from more recent work has to be re-assessed in the light of current quality management system (QMS) guidelines.

Because NUMO has currently been developing guidelines for such assessments, here JAEA's system is being followed and the quality of the pre-existing information evaluated before it is included in the 'Site QMS Database' (Fig. 4). Of note in this system is that not only are the data uncertainties taken into account, but also a whole range of additional factors (e.g. the existence or otherwise of a QMS in the original exploration programme) are evaluated to provide a measure of the 'value' of the pre-existing information. A final point to note here is that

the general workflow outlined in Fig. 4 implicitly includes temporal variations in the parameters studied where at all possible. This will be discussed further in the next section.

Aerial/Terrestrial/Marine Exploration

This step involves marine and terrestrial exploration by aerial means which is to be conducted based on the targets defined in the previous step, but concerns most likely surface mapping (2D) and geophysical investigations (preferably 3D). The main aims of this step are to check and revise the conceptual overview (or site model) – three-dimensionally where possible – and, based on this, to specify key aspects of characterisation and the degree of uncertainties so as to allow determining the targets and their priorities.

Of specific interest in the Horonobe area is that the availability of the pre-existing geophysical data means that temporal changes in some site parameters can also be assessed using true time-lapse (or 4D) imaging. Although this seismic methodology has been confined to oil exploration or CO_2 disposal studies to date [e.g. 32], it would seem the perfect tool to follow changes in the saline/fresh groundwater interface over the decades since the original survey lines have been shot during the period of hydrocarbons exploration.

For example, during the exploration of the coastal area for the construction of the Seikan Tunnel (the world's longest undersea tunnel) between Hokkaido and north-east Japan, onshore geophysical lines have been extended offshore by means of ships using towed arrays [33]. Some advances have recently been demonstrated in onshore – offshore integrated geophysical survey at the Horonobe coastal zone [34]; such technological advancement could allow more precise subsurface imaging in the onshore – offshore transition zone, becoming, no doubt, an essential technique for coastal site characterisation. However the survey offshore is more prone to disruption by bad weather or, as here, very strong tidal currents.

Borehole Investigations

Borehole investigations are likely to be more targeted, which would explore potential problematic areas as identified in the aerial survey and focus very much on particularly important issues specified after assessing the results of the previous step. After completion of this step, a more detailed site model is to be built up, updating the model in the previous step, and the degree of uncertainties quantified.

Of great importance in this step is borehole investigations offshore which should be combined with the geophysical survey in the previous step. Drilling offshore is, of course, extremely expensive compared with that onshore, particularly as water depth increases (although, as a rule, this is not a major problem for the near-coastal zone of the Japan Sea). However, modern controlled directional drilling technology — being developed worldwide and also in the Horonobe area [35, 36] — means that a significant volume of the sub-seabed can be explored from a drilling rig situated on the coast and drilling out to sea [e.g. 37].

CONCLUSIONS AND FUTURE PERSPECTIVES

JAEA's generic GDFD has been originally developed based on the surface-based investigation expertise both in Japan and Switzerland for inland areas. However, considering the likely attractiveness of coastal sites, it is now being reviewed and updated to address those features of site characterisation which are unique to coastal repositories. This update is based on the practical experiences and technical knowledge developed during the surface-based investigations in the Horonobe coastal study area. This attraction of coastal sites is not coincidental, especially in islands/archipelagos with mountainous, tectonically unstable interiors such as Japan. Such locations clearly offer ease of transport of bulky or radioactive materials by ship and effectively limitless supplies of cooling water. Such facilities may also be less intrusive in a coastal setting, especially in remote locations, e.g. the Drigg site in the UK, Rokkasho in Japan (Fig. 1).

Iteration of the geosynthesis methodology with the new GDFD for surface-based investigations at coastal sites will lead to the build-up of experiences and eventually establishing, in a systematic manner, comprehensive techniques characterising stepwise the coastal geological environment. The first phase of this process has been the development of site characterisation techniques [9] and palaeohydrogeological conceptualisation tools [10] based on the geological environment in the Horonobe coastal study area. The second phase of work will be to test the developed methodologies on other sites on Japan's western seaboard, to build confidence in their applicability to other coastal sites on the Japan Sea. This will enable rationales behind the update to be accumulated, reinforcing the knowledge base being developed in the Japanese national disposal programme. The third, and final, phase of work will see the methodologies being applied to other coastal sites, both in Japan and worldwide, eventually leading to a refined GDFD which is optimised for application to NUMO's future PIs.

This programme of transparent, rigorous testing, refining and polishing of JAEA's coastal GDFD will build confidence, not only within NUMO but also within the Japanese regulators and any volunteer communities, in the applicability of the procedure and should serve as a significant contribution to the safety case for assuring the long-term stability of the geological environment at a coastal site.

ACKNOWLEDGEMENTS

The authors would like to thank our numerous colleagues at JAEA Horonobe for their contribution to this programme.

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---- Confirmation of consistency

---- Links connected

Links not connected Geochemical charac-teristics of groundwater Dilution of nuclides Key Properties/Processes petrophysical gamechanical protection of the petrophysical gamechanical flows.

Quounteed inflow the under game makes the petrophysical game of Sase emisson from thest rock. Sase emisson from thest rock. Sase emisson from thest rock. Sase emisson for the petrophysical gamenchanical properties of EDZ.

Desthulton of discontinuities. Inflorescing undergound inflorescing undergound full season from the petrophysical gaments. Spatial distribution of saline/ fresh groundwater (inferface); degree of groundwater mineralisation 4D evolution of stress field at repository depth 4D evolution of petrophysical/ geomechanical properties of rocks Geometry of transport
pathways; cepth of diffusionaccessible matrix
Sorption capacity and
diffusivity of rock matrix and
of transport pathways
microbes on nuclide
transport/leardation Groundwater flow field and process
Spatial variability of groundwater fluxes
4D evolution of groundwater flow field and process Spatial variability of water fluxes in higher-permeability rocks, aquifers and surface waters Spatial variability of geothermal gradient
Thermal rock properties Regional and local stress regime Spatial variability of Geochemical model
Geochemical evolution model Crustal movement analysis Groundwater flow simulation (taking geological/hydro-geological/chemical evolution into account) Rock mechanical model Stress/excavation analysis Hydrogeological evolution model Solute transport conceptual model seomorphological model Transport processes in host rockdisconfinities; advection, diffusion, colloid-facilitated, two-phase Geometry of pathways/ porosities, sorpton/diffusion properties of host rock/ discontinuities Recharge rate, water table distribution
Recharge rate change
Evolution of hydraulic properties of rockdisconfinuities Groundwater flow processes in rock/discontinuities Groundwater chemistry in host rock; chemical/sobpic compositions, age Groundwater chemistry in surrounding units; chemical isotopic compositions, age Evidence of long-term solute transport in host rock and discontinuities Evolution of petrophysical properties (uplift/subsidence history) Geomorphological changes Palaeoclimate changes, long-term prediction of dimate changes Geological rock/fault formation Hydraulic properties of host rock Hydraulic head distribution Hydraulic properties of surrounding units
Hydraulic properties of discontinuities Shallow subsurface hydraulic characleristics; river flux, precipitation, evapotranspiration, vegetation etc Deep subsurface hydraulic properties; water pressure, K, De etc Long-term groundwater level/ pressure changes Sea water/seepage/pore water chemistry; chemical/ isotopic compositions etc ocation/flux of submarine Lab examina forvlanalysis; petrography, microfossil, porewater chemistry, sorption/ diffusion, rock mechanics etc Surface geological surveys; iithostratigraphy, fault etc Lab examination/analysis; petrography, microfossil, age, petrophysics/mechanics etc Geophysical surveys; gravity, Geophysical surveys; gravity, Hydraulic packer tests; single nole, cross-hole etc Borehole wall imaging Geophysical logging hydrochemistry; groundwate hemistryl/isotopes etc Fluid logging ieomorphology, geodesy; erial/satellite images etc Rock mechanics, thermal properties, stress etc ectonics, geology, eological structure etc Borehole Investigations Terrestrial Exploration Marine Exploration Survey/Review of Pre-existing Information

ANNEX A: Generic GDFD for Surface-Based Investigations at Coastal Sites