

STEPWISE HYDROGEOLOGICAL CHARACTERISATION UTILISING A GEOSYNTHESIS METHODOLOGY – A CASE STUDY FROM THE MIZUNAMI UNDERGROUND RESEARCH LABORATORY PROJECT

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Abstract

The Mizunami Underground Research Laboratory (“MIU”) is now under construction by Japan Atomic Energy Agency (JAEA) in the Cretaceous Toki granite in the Tono area of central Japan. One of the main goals of the MIU project, which is a broad scientific study of the deep geological environment as a basis of research and development for geological disposal of nuclear wastes, is to establish comprehensive techniques for the investigation, analysis and assessment of the deep geological environment in fractured crystalline rock. For this purpose, a geosynthesis methodology has been developed and will be tested in a dry run to determine if it produces the data required for repository design and associated integrated safety assessment modelling.

Surface-based hydrogeological characterisation, intended to develop conceptual models of the deep geological environment based on an understanding of the undisturbed conditions before excavation of this URL, was carried out in a stepwise manner. This allows field investigations, construction of geological and hydrogeological models and interpretation of resultant groundwater flow simulations to develop in an iterative manner. Investigations have the goal of obtaining information on factors relevant to repository design, associated construction, operational and post-closure safety assessment, evaluation of the practicality of implementation and environmental impact assessment. Such factors include bulk hydraulic conductivity, the locations and properties of water conducting features, direct and indirect indicators of regional and local flow (e.g. based on chemistry or isotopes), etc.

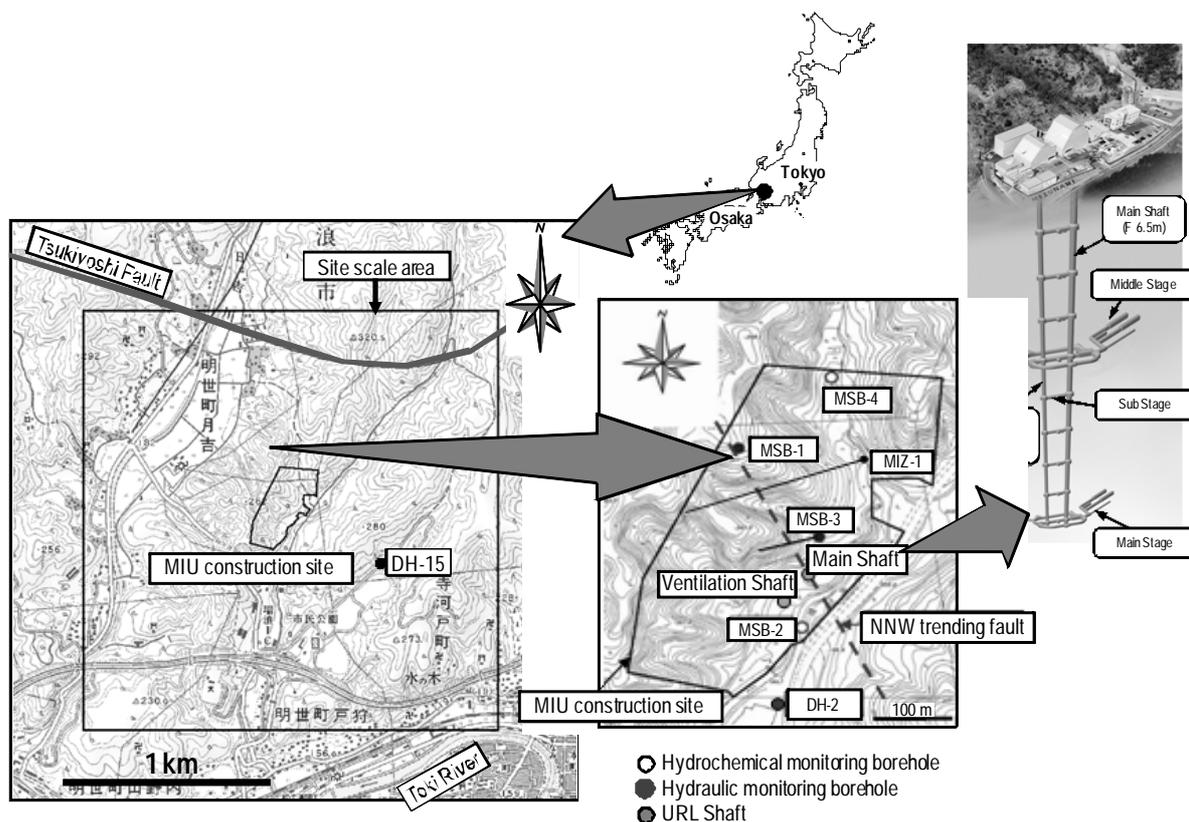
Following evaluation of pre-existing site information, field investigations began with fault mapping. This was followed by reflection seismic and vertical seismic profile surveys. In addition, a large programme of investigations was carried out in boreholes, including cross-hole tomography and hydraulic tests. Such input is utilised for the construction of hydrogeological models and groundwater flow simulations, which can be used to identify and prioritise key issues for further investigations. Results show that such an approach, focusing hydrogeological characterisations by a structured geosynthesis methodology, leads to an improved understanding of the deep hydrogeological environment and allows repository-relevant datasets to be produced in an efficient and traceable manner.

Introduction

The Mizunami Underground Laboratory (MIU)[1] is the location of a comprehensive research project investigating the deep underground environment within crystalline rock. It is conducted by the Japan Atomic Energy Agency in Mizunami City, Gifu Prefecture, central Japan and its role is defined in “Framework for Nuclear Energy Policy” [2] by the Japan Atomic Energy Commission. MIU is a

purpose-built generic underground research laboratory project that includes two 1 000 m circular cross section shafts and horizontal research galleries at depths of 500 m and 1 000 m (Figure 1)[3]. The project, which began in 1996, is implemented in three overlapping phases: Surface-based Investigation (Phase I), Construction (Phase II) and Operation (Phase III), with a total duration of 20 years.

Figure 1. Location of the MIU construction site, principal boreholes and the planned layout of the MIU facilities



MIU is a broad scientific study of the deep geological environment as a component of research and development supporting geological disposal of nuclear wastes. One of the main goals of the project is to establish techniques for comprehensive investigation, analysis and assessment of fractured crystalline rock. For this purpose, a geosynthesis methodology has been developed and is being tested to determine if it produces the data required for repository design and associated integrated safety assessment modelling.

In Phase I, a stepwise investigation was conducted by iterating investigation, interpretation, modelling and assessment in order to test applicability of the basic geosynthesis methodology and to modify it as required to optimise performance for this particular geological setting. This paper describes the results of this work, with a particular emphasis on hydrogeological characterisation.

Site geology

In the study area, Tertiary sedimentary rocks widely and unconformably overlay the Cretaceous Toki Granite, which was emplaced ca. 60-70 Ma ago [4]. The Tertiary sedimentary rocks are lithologically divided into the Mizunami Group (age ca. 15-20 Ma) and the Seto Group (1.5-12 Ma). The Mizunami Group is further sub-divided into the Toki Lignite-bearing Formation, the

Akeyo/Hongo Formation and the Oidawara Formation, in ascending order. The lower part of the Mizunami Group is mainly composed of tuff, silt/sandstone and conglomerate. The middle and upper parts of the Mizunami Group are mainly composed of mudstone and silt/sandstone alternating with shallow marine facies. The Seto Group consists of unconsolidated clay, sand and gravel.

The Toki Granite is typically felsic and is sub-classified by biotite content. The granite is also sub-divided into structural domains based on variations in fracture development (an upper highly fractured domain (UHFD) and a lower sparsely fractured domain (LSFD)). Below the unconformity with the Miocene sediments, the upper part of the Toki Granite has been intensely weathered. This weathered zone varies in extent across the study area, but is typically a few tens of metres thick.

The most significant structure in the area is the Tsukiyoshi fault, which has an E-W trend and a dip of 70-80° to the south. The Toki Granite and Mizunami Group are both cut by the fault, with approximately 30 metres of vertical displacement [5].

Geosynthesis methodology

Identification of specific aims

To determine specific aims for R&D activities in the MIU project, some key factors needing to be characterised and the resultant data requirements to support safety assessment, design and construction of underground facilities and environmental assessment have been identified. It is recognised that this list is not complete as, for example, long-term evolution of geological environment and biosphere assessment are not being considered at this time. The requirements for safety assessment have been assigned referring to the context provided by the generic H12 study [6] as well as the items and methods for investigation and evaluation considered for future preliminary investigations of potential HLW sites in Japan [7]. The extent to which such goals can be achieved will be examined in the MIU project.

Adopting of iterative approach

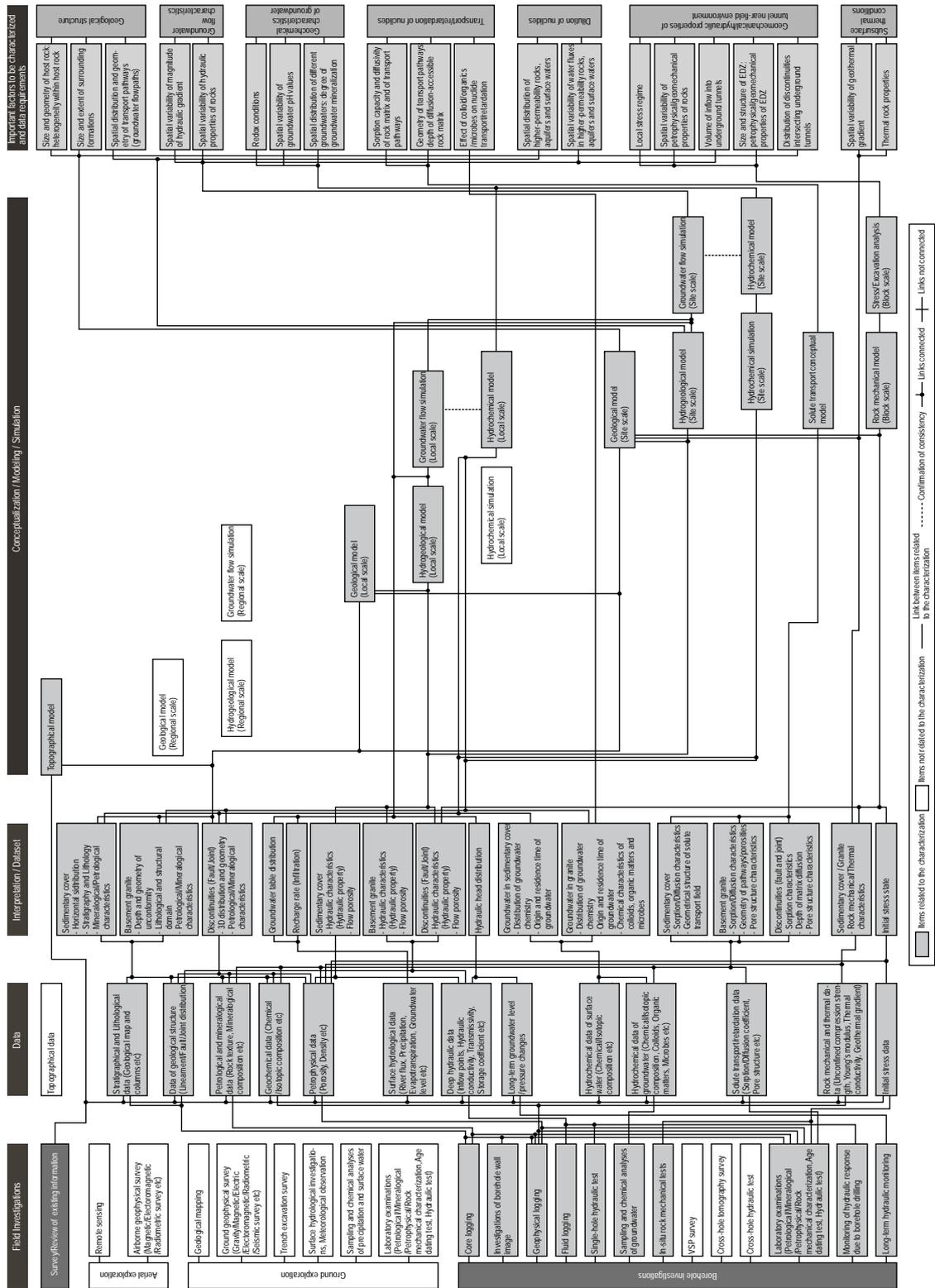
Various spatial and temporal as well as economic and socio-political constraints are likely to be encountered when characterising the geological environment at specific sites. For effective characterisation despite such limitations, it is important to evaluate the relationship between the information obtained during the investigations and that actually required to meet specific aims. This allows iterative assessment of the value of the characterisation output at each project stage, which leads to identification and prioritisation of key issues for further investigations [8,9].

Development and optimisation of the geosynthesis data flow diagram

For MIU site characterisation, investigations used an iterative approach based on a geosynthesis data flow diagram [8-10]. The geosynthesis data flow diagram illustrates, for specified aims, the data that need to be acquired and the subsequent process of interpretation and synthesis of information by different disciplines in order to derive output in the form desired by the end users.

The geosynthesis data flow diagram has been iteratively tested and optimised based on the technical knowledge accumulated during stepwise characterisation work. An example for step 3 (Figure 2) shows how the information from the studies carried out in new deep boreholes is combined with the background from the previous step in order to update and extend the models which produce the output data required by designers and performance assessors.

Figure 2: Example of a section of the geosynthesis data flow diagram focused on interpreting the data from boreholes produced during step 3



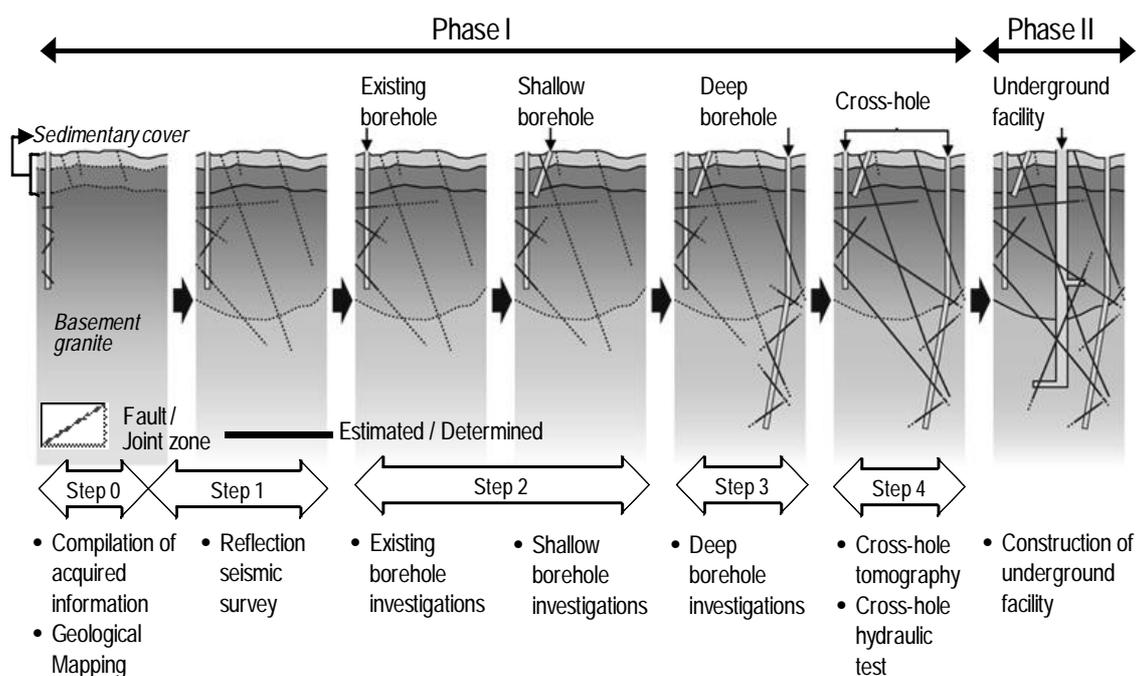
Application of the geosynthesis methodology for hydrogeological characterisation

Concept of the stepwise surface-based investigations

The five steps of site investigations (Step 0 to 4) have now been completed in Phase I of the MIU project (Figure 3). Following evaluation of relevant pre-existing information, field investigations began with fault mapping. This was followed by reflection seismic and vertical seismic profile surveys. In addition, a large programme of investigations was carried out in boreholes, ranging from 100 to 1,300 m deep, including *in situ* measurements during and after drilling and comprehensive analysis of carefully collected core and water samples. This was extended by subsequent cross-hole seismic and resistivity tomography, and hydraulic tests between the deep boreholes. Such input is utilised for the stepwise construction, testing and improvement of geological and hydrogeological models, hydrogeochemical evolution simulations and other quantitative representations of the properties of the geological environment (such an integrated model/database is termed by NUMO the “site descriptive model”).

Phase 2 excavation of shafts commenced in July 2003, and these had reached a depth of 230 m in March 2008. A range of geoscientific investigations is currently ongoing during shaft construction.

Figure 3. Concept of Phase I investigations



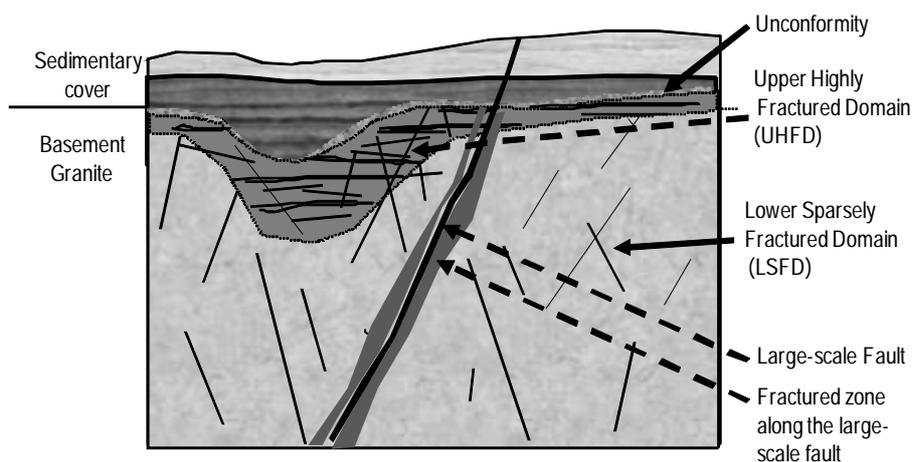
Hydrogeological characterisation

To illustrate application of the geosynthesis methodology in detail, this paper focuses on the hydrogeological characterisation carried out in the vicinity of the MIU construction site (“site scale” area; approximately 4 km²). This has the stated goals of developing understanding of groundwater flow characteristics, such as spatial variability of magnitude of hydraulic gradient and hydraulic properties of the various rocks and geological structures found at this location. As the groundwater flux has a great impact on design and groundwater flow scenarios are the main focus of post-closure performance assessment, resultant models are of great value for integrating investigation results. Evaluation of the impact of uncertainties in the hydrogeological model is also important, in order to identify and prioritise key issues for further investigations.

Hydrogeological characterisation in Step 0

Geoscientific studies at and around the nearby Tono mine have been carried out since 1987 [11-12]. Key hydrogeological information which had been accumulated prior to formal initiation of the MIU project, such as the hydraulic conductivity of the basement granite and of major fault zones such as the Tsukiyoshi fault, dominant groundwater flow directions and overall hydraulic gradient, was derived predominantly from the Regional Hydrogeological Study (RHS) [13]. The RHS project involved a broad scientific study of the deep hydrogeological environment at the scale of a complete flow system, from recharge to discharge (tens of km²; Local scale area). Remote sensing, airborne/ground geophysical surveys, surface-water/meteorological observations, deep borehole investigations, etc. were carried out over this area [13]. Based on the results of these investigations, a conceptual geological model for the site scale area was constructed (Figure 4) [8,9]. This describes significant geological/lithological elements that influence groundwater flow characteristics. The geological model shows the presence of joints and faults of varying scale within the basement granite. Large-scale faults, which have trace lengths over several hundred metres, may act as either as major conduits of water flow or as hydraulic barriers. An initial 3-D geological model [Figure 5(a)] of the site scale area was also constructed [8,9], which takes into account best estimates of the geometry of the main geological/lithological units and the major fault zone described in the 2-D model (Figure 4).

Figure 4. Geological conceptual model (see text for explanation)



This forms the basis for the first hydrogeological model, which allows groundwater flow simulations to be carried out [14] using hydraulic characteristics based on the data obtained in the RHS project. The conceptual groundwater flow model is illustrated in Figure 6. Although topographical gradients explain the general pattern of flow near the surface, it is clear that major fault zones have a dominant role in defining deeper flows – especially the hydraulic gradient downstream of the fault and sub-vertical components of such flow. This is particularly evident when they effectively form hydraulic barriers. Fluxes and flow velocities in the basement are related to the density of smaller water-conducting faults and fractures – either distributed throughout the rock mass or concentrated in damaged zones around major faults. A key goal of subsequent hydrogeological characterisation was thus to better define the role of larger faults on the site scale flow system.

Hydrogeological characterisation in Step 1

In Step 1, detailed geological mapping and reflection seismic surveys were carried out in order to improve the geological model of the MIU construction site [8-9]. Based on such information, complemented by lineament interpretations using aerial photographs, a revised geological model containing a representation of all large-scale faults was produced [Figure 5(b)] [15].

In Step 1, a 3-D hydrogeological model was also produced, which allowed groundwater flow simulations to be carried out, focusing on the uncertainties associated with hydraulic properties of the faults [14]. Since there was no additional information of hydraulic conductivity of geological formations, values assigned in the original hydrogeological model were not changed. In the new hydrogeological model, only faults with trace length over 1 000 metres were represented as discrete hydraulic features, since explicit representation of all observed faults would exceed computational capacity and lead to excessively long calculation times for groundwater flow simulations. Additionally, smaller faults in the vicinity of larger features with similar orientations were also excluded from the hydrogeological model, as they would not be expected to have a significant net hydraulic impact. Faults with unknown hydraulic characteristics were grouped based on their orientations and, as an initial simplifying assumption, were then assigned the same hydraulic conductivity. This process for screening of faults assigning hydraulic conductivity to groups of faults was also applied for the later site characterisation steps. Given the rapid rate of increase in computer capabilities, however, a more realistic and detailed representation of fracture properties may be feasible in later phases of work at the MIU construction site.

In Step 1, this process resulted in a total of 32 cases that were analysed. Examples of derived head distributions are shown in Figure 7(a). Note that Figure 7(a) [and later Figures 7(b), (c) and (d)], shows a horizontal slice at a depth of 1 000 m to illustrate the importance of the assumed hydraulic properties of large-scale faults on the groundwater flow characteristics at the horizon. In these figures, head distribution is illustrated; flow will generally occur from lighter to darker shaded areas. The model variants assume that either all [Figure 7(a)A] or particular sets [Figure 7(a)B and C] of the large-scale faults act as hydraulic barriers. Otherwise, faults are simply considered to be highly conductive. Areas identified by dashed circles in the figures are considered to be particularly sensitive to such model uncertainties; however, it is important that such a very simple model is not over-interpreted. For example, the investigations bias data improvement to the area of the construction site and hence the fault network outside this area is inevitably under-represented.

The results of these simulations vary widely. Visualisations of the 3-D head distribution indicate that the uncertainty in the hydraulic structure of the NNW and NE trending faults had the greatest impact on modeled heads, significantly reduced heads being produced when the NNW trending faults acted as flow barriers. Therefore, geological and hydrogeological characterisation of NNW and NE trending faults was identified as a focus for further steps of the site characterisation.

Hydrogeological characterisation in Step 2

Field investigations conducted in step 2 were based on the results of the geological models, hydrogeological models and groundwater flow simulations performed in Step 1. In Step 2, four shallow boreholes (MSB-1, MSB-2, MSB-3 and MSB-4, see Figure 1) were drilled to investigate the shallow geological and hydrogeological characteristics of the MIU construction site [16]. Specific studies included monitoring of groundwater pressure, and geological and hydrogeological characterisations of a NNW trending fault (shown by dashed line in Figure 1). The borehole MSB-3 was an inclined borehole, specifically designed to confirm the presence of this large-scale fault running through the center of the MIU construction site. Also, geological and hydrogeological investigations in an existing borehole (DH-2, see Figure 1) were carried out in order to characterise water conducting features (WCFs) and background fractured rock (BFR) from a depths of 168 m to 500 m in the Toki Granite [9]. Based on the conceptual geological and groundwater flow models, the following hydrogeological investigations were carried out using the boreholes.

- Fluid logging: to identify faults and WCFs.
- Hydraulic tests: to obtain hydraulic properties of the faults, WCFs and BFR.
- Installation of monitoring systems: to initiate monitoring of groundwater pressure in borehole sections containing faults, WCFs and BFR.

From the shallow borehole investigations, the geological, hydrogeological and hydrochemical features of sedimentary rocks were determined, with a special emphasis on the geometry and characteristics of the major NNW trending fault that cuts them. Also, from the DH-2 borehole investigations, such characterisation was extended into the UHFD; this includes a low angle fracture zone (LAFZ), which is a hydraulically significant feature, and NNW and EW trending faults that penetrate basement granite. Based on this input, a revised geological model was produced [Figure 5(c)] [15]. In particular, the interpretations of orientation, connectivity and continuity of some large-scale faults were significantly changed.

This input was, in turn, used to modify the hydrogeological model [17]; subsequent groundwater flow simulations focused again on systematic variation in the hydraulic property groups large-scale faults with similar orientations [Figure 7(b)]. The revised geological model resulted in the number of different fault groups being decreased, while the hydraulic conductivities of the faults hydraulically characterised in basement granite were now fixed – significantly decreasing the number of variants to a total of 12 cases that had to be analysed. Areas identified by dashed ellipses are considered to be significantly influenced by the uncertainties of the hydrogeological models – but here again the fundamental limitations of the model should be borne in mind, as should the limited support for the assumptions that hydraulic properties measured in an extensive fault near the surface can be extrapolated to greater depth and to all parts of a feature that may extend over several kilometers.

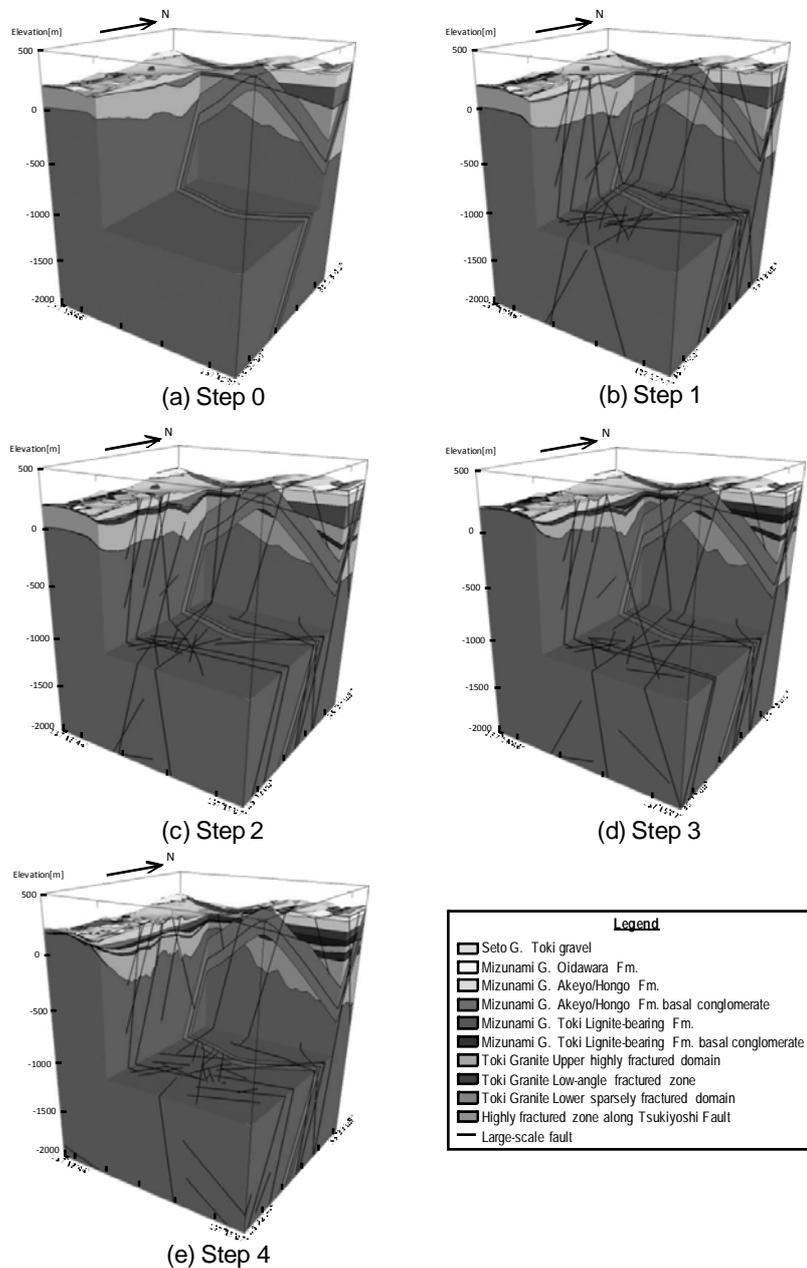
It was clearly shown from the sensitivity studies that the NNW, NW and EW trending faults in the basement granite had a significant influence on groundwater flow conditions at the reference –1 000 m horizon. Therefore, geological and hydrogeological characterisation of such faults within deeper parts of the Toki Granite was identified as a key focus of site characterisation activities in Step 3 [17].

Hydrogeological characterisation in Step 3

Field investigations conducted in Step 3 were also based on the results of geological models, hydrogeological models and groundwater flow simulations performed in Steps 1 and 2. In Step 3, a deviated deep borehole (MIZ-1, see Figure 1) was drilled with the main goal to characterise NNW, NW and EW trending faults. Geological, hydraulic and geochemical data were acquired from downhole measurements and analysis of core and water samples [18]. Also, geological, hydrogeological and hydrochemical investigations in a deep borehole (DH-15, see Figure 1), which was newly drilled to 1 000 m deep in basement granite, were carried out aimed at characterising an EW trending fault [19]. From these deep borehole investigations, properties of the NNW, NW and EW trending faults in the basement granite were directly characterised in some detail, and WCFs and BFR from the surface to over 1 000 m deep in granite were also investigated [9,20]. Based on a synthesis of such information, a revised geological model was produced [Figure 5(d)] [9].

The hydraulic properties of the faults were estimated based on the groundwater pressure responses observed at monitoring boreholes, MSB-1 to MSB-4 and DH-2, during activities in MIZ-1 and DH-15 that resulted in hydraulic signals, such as drilling fluid loss and pumping tests. Groundwater pressure responses were observed in the shallow boreholes, but not DH-2. Based on the results of such monitoring, most of NNW and EW trending faults can be classified as either being hydraulic barriers or not. Basically, any fault identified as lying between hydraulically connected boreholes was excluded as a potential barrier. In addition, since pressure responses were not observed in DH-2, which is relatively close to MIZ-1, it was concluded that the fault located between these boreholes acts as a hydraulic barrier.

Figure 5. Geological models constructed and revised based on the results from field investigations (Step 0 to 4)



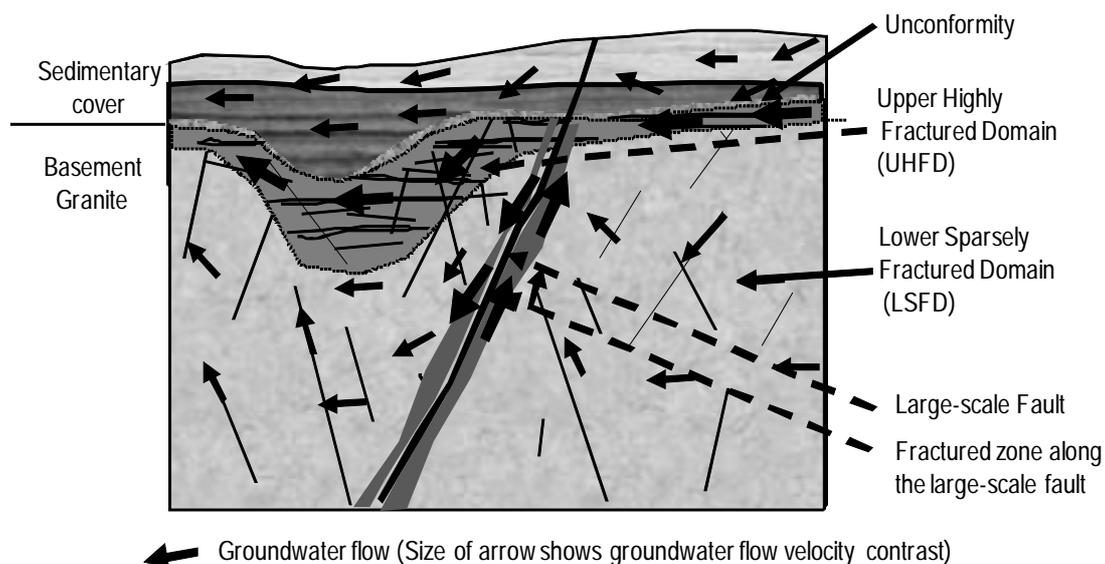
The hydrogeological model was updated on the principles discussed above which, based on the improved characterisation of fractures, required only 8 variant simulation cases to cover remaining uncertainties in the hydraulic characteristics of specific groups of fractures [Figure 7(c)] [21]. The resultant range of the simulated head distributions was noted to be less than in previous steps. The conceptual model of groundwater flow for the simulations was also examined by qualitative assessment of compatibility with a hydrochemical conceptual model [22] developed in Step 3. Overall, it is considered that groundwater pressure responses during deep borehole investigations significantly increased the understanding of the hydraulic properties of key groups of faults.

Hydrogeological characterisation in Step 4

In Step 4, cross-hole geophysical and hydrogeological tests were carried out in order to characterise geological/hydrogeological connectivity of large-scale faults and the UHFD, which were considered particularly important for hydrogeological characterisation at the MIU construction site. Cross-hole tests included seismic and resistivity tomography surveys between DH-2 and DH-15, multi-offset VSP surveys using MIZ-1 and DH-15 and reflection seismic surveys on two lines (NE through MIZ-1 and NNW through DH-15). From the results of these surveys, distribution of NW, NNW and EW trending faults, the UHFD and the LAFZ were interpreted with more confidence and in significantly more detail. Based on these investigations, the geological model was revised [Figure 5(e)] [9].

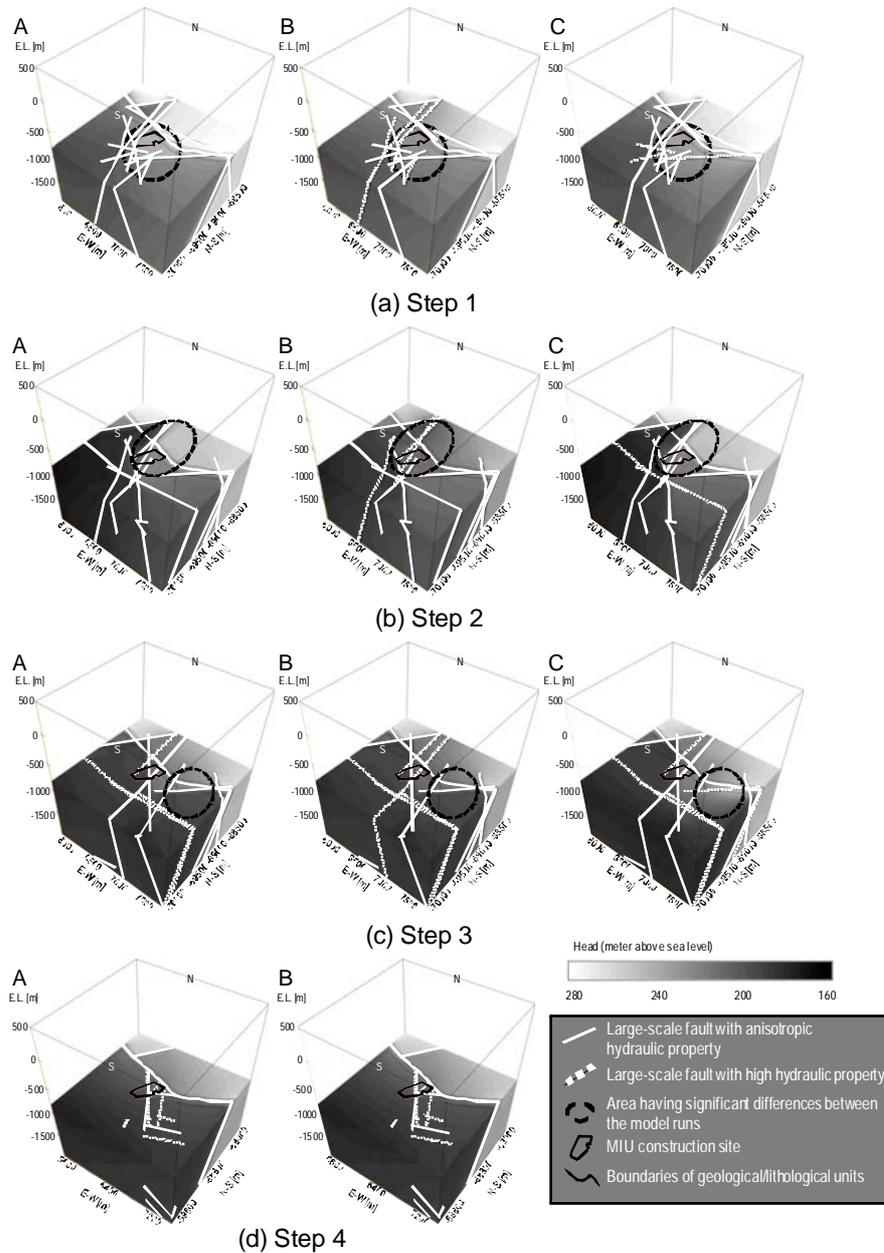
Cross-hole hydraulic tests were also carried to characterise the UHFD and the NNW trending fault intercepting MIZ-1. Two pumping tests in MIZ-1 were carried out; other boreholes with multiple packers were used to monitor groundwater pressure responses. In these tests, clear responses were observed in DH-15 during the pumping from two sections, whereas there was no response in DH-2, despite it being much closer to MIZ-1 than DH-15. Also, responses in deeper part of the Mizunami group at MSB-1 were observed, but no responses in the shallower part. Based on such observations, it was concluded that the NNW trending fault and the boundary between shallower and deeper parts of the Mizunami group act as hydraulic barriers; otherwise hydraulic responses during cross-hole tests were more typical of a porous medium [9].

Figure 6. Conceptual groundwater flow model



Using the data from the cross-hole hydraulic tests, the hydrogeological model was calibrated with emphasis on the hydraulic properties of the faults contained in the revised geological model [23]. In effect, the hydraulic properties of the faults in the area of the construction site are now constrained; the only uncertainty remaining is associated with minor faults outside the main area of interest and hence it is not surprising that very similar head distributions were derived from the 2 variants examined [Figure 7(d)]. These results are also consistent with additional site information sets, indicating that the synthesis is leading to convergence on a holistic site descriptive model.

Figure 7. Example of simulated head distributions

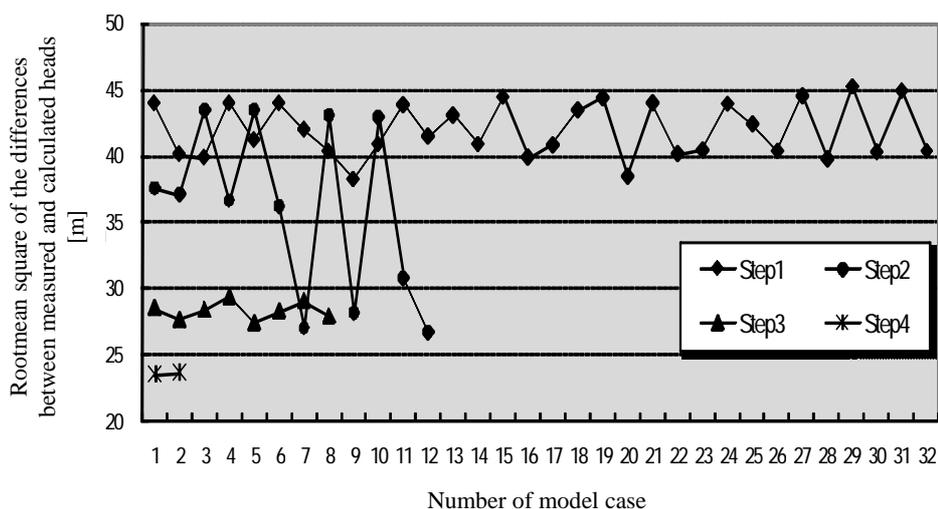


Improvement in understanding of hydrogeological environments

In order to evaluate and quantify the improvement in the hydrogeological models developed at each step of the hydrogeological characterisation programme, the result of all groundwater flow variants were compared to the best measured heads from 19 measuring intervals (in boreholes MSB-1, MSB-3 and DH-2) after the completion of Phase 1 investigations. These head values were selected in cases where reasonably stable groundwater pressures were observed during long term monitoring. This criterion excluded values from MIZ-1 and DH-15, since groundwater pressure fluctuated in these boreholes, possibly as response to the perturbation caused by installation of monitoring equipment and shaft sinking. However, it was considered that head values from DH-2 were able to represent the basement granite and be used for the comparison.

An integrated presentation of these comparisons is illustrated in Figure 8, which was developed by calculating the root mean square of differences between measured and calculated heads. Results show that this approach reduces the number of model cases that need to be analysed, the variation of results from sensitivity analyses and the discrepancy between measured and calculated heads as site characterisation proceeds. Further testing and modelling in phases 2 and 3 will extend these results and may confirm or disprove the models generated at the end of phase 1.

Figure 8. Quantitative evaluation of the convergence of hydrogeological models



Conclusion and future study

In this study, stepwise site characterisation was carried out utilising a geosynthesis methodology, involving iterative development of data flow diagrams. For the particular case of hydrogeological characterisation, it is concluded that this methodology leads to an improved understanding of the deep hydrogeological environment that allows repository-relevant datasets to be produced in an efficient and traceable manner. This stepwise approach focusing site characterisations on the basis of structured geosynthesis methodology will be continued in Phase II and Phase III of the MIU project.

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