Journal of Rock Mechanics and Geotechnical Engineering 10 (2018) 411–435

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection, site characterization and in situ tests

Ju Wang*, Liang Chen, Rui Su, Xingguang Zhao

CNNC Key Laboratory on Geological Disposal of High-level Radioactive Waste, Beijing Research Institute of Uranium Geology, Beijing, 100029, China

ARTICLE INFO

Article history:
Received 15 January 2018
Received in revised form
5 March 2018
Accepted 8 March 2018
Available online 22 April 2018

Keywords:
Beishan
Xinchang site
Granite
Underground research laboratory (URL)
High-level radioactive waste (HLW)
Geological disposal

ABSTRACT

With the rapid development of nuclear power in China, the disposal of high-level radioactive waste (HLW) has become an important issue for nuclear safety and environmental protection. Deep geological disposal is internationally accepted as a feasible and safe way to dispose of HLW, and underground research laboratories (URLs) play an important and multi-faceted role in the development of HLW repositories. This paper introduces the overall planning and the latest progress for China's URL. On the basis of the proposed strategy to build an area-specific URL in combination with a comprehensive evaluation of the site selection results obtained during the last 33 years, the Xinchang site in the Beishan area, located in Gansu Province of northwestern China, has been selected as the final site for China's first URL built in granite. In the process of characterizing the Xinchang URL site, a series of investigations, including borehole drilling, geological mapping, geophysical surveying, hydraulic testing and in situ stress measurements, has been conducted. The investigation results indicate that the geological, hydrogeological, engineering geological and geochemical conditions of the Xinchang site are very suitable for URL construction. Meanwhile, to validate and develop construction technologies for the Beishan URL, the Beishan exploration tunnel (BET), which is a 50-m-deep facility in the Jiujing sub-area, has been constructed and several in situ tests, such as drill-and-blast tests, characterization of the excavation damaged zone (EDZ), and long-term deformation monitoring of surrounding rocks, have been performed in the BET. The methodologies and technologies established in the BET will serve for URL construction. According to the achievements of the characterization of the URL site, a preliminary design of the URL with a maximum depth of 560 m is proposed and necessary in situ tests in the URL are planned.

1. Introduction

Safe disposal of high-level radioactive waste (HLW) is a challenging task for the sustainable development of nuclear energy and environmental protection. Geological disposal is considered to be a feasible and safe option for the long-term management of HLW worldwide, and many countries have considered building deep geological repositories (DGRs) in which to dispose of spent fuel or vitrified HLW. In order to investigate the suitability of geological rock formations such as crystalline, clay and salt rocks for hosting DGRs, to develop and test disposal concepts and technologies, to gain knowledge about thermo-hydro-mechanical-chemical-biological-radiological (THMCBR) processes in geological and engineered barriers, and finally to assess and demonstrate the long-term performance and safety of DGRs, a number of underground research laboratories (URLs) have been constructed around the world (Kickmaier and McKinley, 1997; Nuclear Energy Agency (NEA), 2001; Zhang et al., 2006; Wang, 2007).

URLs can generally be divided into generic URLs and site-specific URLs. Generic URLs are facilities developed for research and testing purposes at a site that will not be used for waste disposal, while site-specific URLs are facilities developed as a potential site for waste disposal and a precursor to the development of a repository at the site (Nuclear Energy Agency (NEA), 2001; Ahn and Apted, 2010). Over the past few decades, generic URLs have been developed within pre-existing underground excavations, such as mines and tunnels, e.g. the Grimsel test site and Mont Terri road tunnel in

* Corresponding author.
E-mail address: wangju9818@163.com (J. Wang).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2018.03.002

Switzerland and the Tournemire facility in France. There are also purpose-built generic URLs in specific rock types, such as the Äspö Hard Rock Laboratory in granite in Sweden and the Whiteshell URL in granite in Canada. The site-specific URL may be constructed either adjacent to or within the proposed repository location. Site-specific URLs include the ONKALO URL in granite in Finland, the Meuse/Haute Marne URL in claystone in France (Delay et al., 2010), the Gorleben URL in salt in Germany, and the ESF in volcanic tuff in the United States (Nuclear Energy Agency (NEA), 2001).

In 2014, the concept of the area-specific URL was firstly proposed by Wang (2014). An area-specific URL is a facility at a site within an area under consideration for a HLW repository, or located near a future repository site, and may be a precursor to the development of a repository at the site. The area-specific URL acts as both generic URL and site-specific URL to some extent. It aims to investigate host rock suitability, conduct general research and development (R&D), guide the layout of disposal tunnels and the design of the repository, and demonstrate technological operations. When a general area has been identified as the first top priority area for a repository, but a specific site has not been selected, an area-specific URL can be built as long as the site has similar geological, hydrogeological, engineering geological conditions and environments to those of a future in-depth repository site. The area-specific URL has a potentially important role, i.e. if the site characterization and experiments conducted in the URL demonstrate that the site is suitable for a repository, the process of selecting and confirming the site will be accelerated (Wang, 2014). Meanwhile, all experience and investigation results obtained from such a URL can be transferred directly to the future DGR in the selected area.

The development of URLs is one of the most important stages in national geological disposal programs. With the rapid development of nuclear energy in China, challenges with respect to the safe disposal of HLW are increasing. To meet these challenges, China plans to build a URL for the geological disposal of HLW around 2020. This paper introduces the overall planning, site selection, site characterization and in situ test plan for China's first URL.

2. Overall planning for China's URL development

The Chinese government has decided that the installed capacity of nuclear power plants (NPPs) will reach 58 GW by 2020, with an additional 30 GW under construction (The State Council of China, 2012). The spent fuel generated from those NPPs will reach 83,000 tons by 2050. The Chinese policy for HLW disposal is that the spent fuel from light-water reactors should be first reprocessed, then vitrified, and finally geologically disposed. The preliminary repository concept proposed is a shaft-tunnel model located in saturated zones of granite (Wang, 2010; Chen et al., 2012; Liu et al., 2014; Zhao et al., 2014a). The Chinese strategy for HLW disposal can be characterized by three typical stages: (1) laboratory studies and site selection for the HLW repository (2006–2020), (2) underground in situ testing (2021–2040), and (3) repository construction (2041–2050). One of the major milestones is to complete the URL construction by 2020 (China Atomic Energy Authority (CAEA), 2006).

The 13th Five-year Plan for the National Economy and Social Development of China (2016–2020) determined that "*the construction of China's URL should start before 2020*", while the completion of the URL construction will be around 2024. The successful construction of the URL relies on the overall planning including a definition of the strategy, a technical road map, functions of the URL, a plan for in situ tests, and technical preparations.

2.1. URL strategy

As introduced above, URL types include generic URLs, site-specific URLs and area-specific URLs. It is presently not necessary for China to build a generic URL. If we plan to build a site-specific URL, the site for the future repository has to be selected. However, it is difficult to have a repository site right now because of the long approval process. The most suitable option is thus to build an area-specific URL (Wang, 2014). With this basic understanding, the major considerations of the URL strategy are as follows:

(1) To build an area-specific URL in a representative granite formation within the area that has been identified as having the greatest potential for a geological repository in China.
(2) The URL will be a large-scale facility with full functionality.
(3) The URL will be about 500 m deep, similar to the depth of the future repository.
(4) The URL should be expandable.
(5) The URL will serve for technology development and demonstration, site characterization, and public acceptance.
(6) The URL will be open to domestic and international cooperation in the R&D of HLW repositories in granite.

2.2. Technical road map

On the basis of a nationwide comparison and intensive consultation, the China Atomic Energy Authority (CAEA) and the Ministry of Environment Protection (MoEP) decided in July 2011 that the Beishan area in Gansu Province can be regarded as the first priority area for China's HLW repository. This important decision has provided a sound basis for URL site selection. The technical road map for the construction of the "Beishan URL" is divided into four stages:

(1) Site selection and characterization for the URL;
(2) A feasibility study for the URL;
(3) Preliminary design and detailed design for the URL; and
(4) Construction of the URL.

In stage 1, site selection and characterization for the URL was mainly conducted in the Beishan area during 2016–2017. Candidate sites from Xinjiang and Inner Mongolia regions were also considered for a comprehensive comparison.

During the feasibility study stage, the site will be confirmed, preliminary approval from the local government of Gansu Province and the MoEP will be obtained, data needed for design will be acquired, and other specific reports, such as an environment impact assessment report and a safety assessment report, will be prepared. Design criteria for the URL will also be determined.

2.3. Functions of the Beishan URL

The following functions are planned for the Beishan URL:

(1) To characterize the deep environment of the representative Xinchang granite site, including geological, hydrogeological, geochemical and geomechanical conditions;
(2) To develop and demonstrate disposal concepts by conducting full-scale experiments;
(3) To develop technologies and equipment for excavation and construction of the repository, emplacement of HLW canisters, backfilling and sealing of boreholes, tunnels and shafts, and to evaluate the cost of repository construction;

(4) To provide in situ data of the site for validation and verification of scientific tools used in predicting the long-term performance and assessing the safety of the repository;
(5) To provide a platform for the public to understand the disposal technology and the safety of the disposal system, and to build confidence in geological disposal; and
(6) To provide a platform for domestic and international exchange and personnel training, and to provide logistics for in situ tests and staff.

2.4. Technical preparations

To construct the Beishan URL in line with the plan, technical preparations began in 2013 with regard to site selection, development of excavation technology, and preliminary design of the URL. The CAEA approved two important projects. The first project is "Studies on Construction and Safety Technologies for URL", while the second is "Site Selection and Preliminary Design for URL". The Beijing Research Institute of Uranium Geology (BRIUG) is currently leading these two projects. In the first project, a tunnel called the Beishan exploration tunnel (BET) has been under construction since June 2015. The tunnel is a 50-m-deep facility for developing technologies associated with safe construction and operation of the URL. This paper presents most of the achievements of the two projects.

3. Site selection for China's URL

As China will build an area-specific URL, the site selection for the URL is connected with the site selection activities for the future repository. This means that a suitable area for the URL should be firstly selected according to the results obtained in the repository site selection process, and the URL site will then be determined within that area by considering the specific requirements and by using the siting criteria for the URL. This is the overall technical procedure for the site selection of the area-specific URL.

3.1. Siting criteria for the URL

The siting criteria for the URL comprise basic considerations, excluding criteria and specific criteria. The basic considerations for the URL are as follows:

(1) The URL should be located within a preferred area for the HLW repository.
(2) The URL should be constructed in a representative rock formation.
(3) The URL should provide conditions for various underground in situ tests.
(4) The URL should be approved by local government and local citizens.
(5) The URL should follow the national laws and regulations for engineering construction and environmental protection.

The excluding criteria are that the URL should not be in:

(1) Areas where the effects of neo-tectonic processes, seismic activities, volcanism, folding, diapirism or other geological process are not acceptable;
(2) Areas of severe sea-level change, corrosion/subsidence, glaciation, severe change in the surface water level and groundwater level, severe uplifting and subsidence or potential geo-hazards;
(3) Areas of potential mineral resources, oil/gas resources, or water resources;
(4) Areas of existing underground engineering projects that could provide channels for radionuclide migration;
(5) Areas that could be flooded by existing or future reservoirs;
(6) Environmentally sensitive areas; and
(7) Areas unacceptable to the public or stakeholders or that have social impacts.

The specific criteria include geological, future natural changes, hydrogeological, geochemical, engineering and construction criteria and land-use, socioeconomic and human conditions.

3.2. Siting process for the URL

Site selection for China's HLW repository started in 1985. The overall siting process was divided into four stages (Wang et al., 2004, 2006; Wang, 2010): nationwide screening, regional screening, area screening and site confirmation. Since 1986, the following activities have been conducted for site selection:

(1) Nationwide screening (1985–1986). Six regions were selected as potential regions: southwestern China region, eastern China region, Inner Mongolia Region, southern China region, northwestern China region, and Xinjiang region.
(2) Regional screening (1986–1989). From the results obtained in the previous stage, further investigation was conducted and 21 candidate areas were selected. In the northwestern China region, the Beishan area in Gansu Province is considered as the most potential area.
(3) Area screening (1990–present). Since 1990, major efforts have been concentrated on the Beishan area. However, since 2011, the drilling of granite intrusions in Xinjiang and Inner Mongolia has also been conducted to find suitable sites for the purpose of comparison with the Beishan site.

The siting process for China's first URL in granite, beginning in 2015, is based on the achievements mentioned above for repository site selection. The process includes the following considerations:

(1) To determine siting criteria for the URL;
(2) To select candidate URL sites from the Beishan preselected region, Xinjiang preselected region, and Inner Mongolia preselected region for the HLW repository;
(3) To preliminarily select a preferred candidate URL site and a back-up URL site in a review meeting attended by senior experts and organized by BRIUG; and
(4) To decide the preferred URL site and the back-up site in a review meeting attended by senior experts and organized by CAEA.

A total of nine candidate sites (see Fig. 1) have been chosen for comparison and selection. These sites are:

(1) Jiujing, Xinchang, Shazaoyuan, and Suanjingzi sites in the Beishan preselected region;
(2) Aqishan, Tianhu, and Yamansu sites in the Xinjiang preselected region; and
(3) Tamusu and Nuorigong sites in the Inner Mongolia preselected region.

Comprehensive geological, hydrogeological and geophysical investigations based on surface mapping and drilling of deep boreholes have been conducted in parallel at these candidate sites, providing a sound basis for comparison. The final results were that

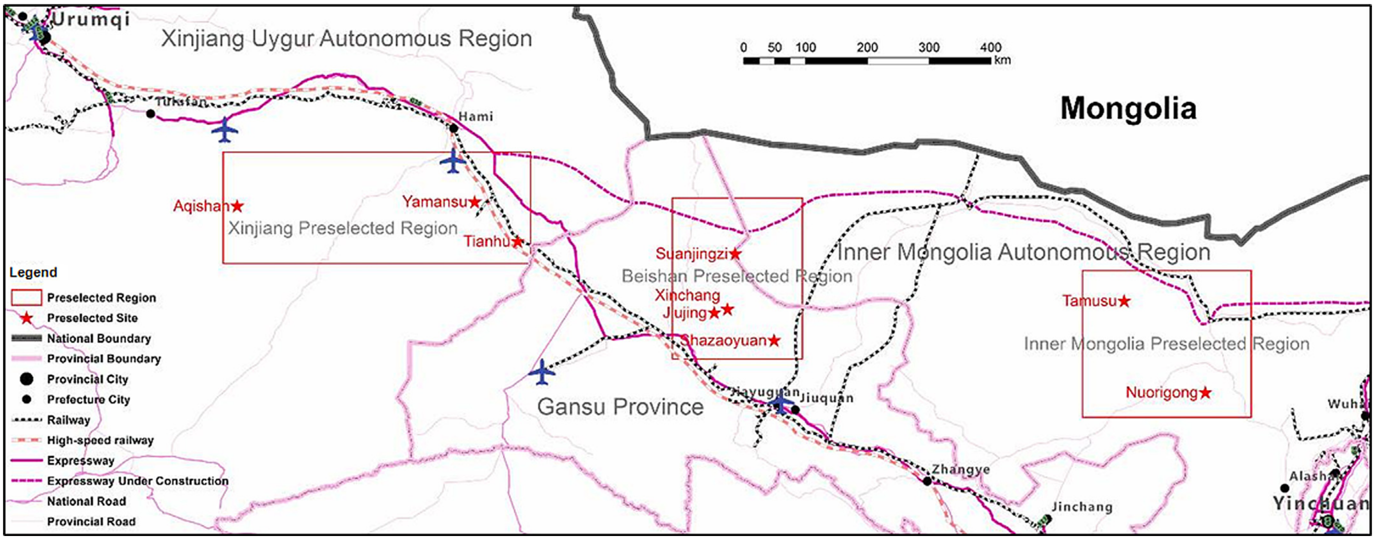


Fig. 1. Distribution of the nine candidate URL sites in northwestern China.

the Xinchang site in the Beishan region was selected as China's first URL site while the Shazaoyuan site was selected as the back-up site. Consequently, China's first URL is named the Beishan Underground Research Laboratory or Beishan URL.

3.3. Comparison among the candidate URL sites

According to the established siting criteria for the URL, a step-wise site selection was made in 2015.

3.3.1. Comprehensive comparison of the nine candidate sites

As mentioned above, a systematical comparison was carried out among the nine candidate sites in the Beishan, Xinjiang, and Inner Mongolia preselected regions:

(1) Geological conditions. All nine sites are located in the pre-selected regions for the HLW repository, while the main host rock type is granite with adequate volume and depth. The geological conditions satisfy the requirements of safe construction and operation. In terms of rock quality and the engineering suitability index Q_{HLW} (see Section 3.4), the Xinchang, Shazaoyuan, Suanjingzi, Yamansu, Aqishan and Nuorigong sites have greater potential.
(2) Future natural changes. All nine sites meet requirements.
(3) Hydrogeological conditions. All nine sites are characterized by low permeability, slow groundwater seepage, long flow paths and favorable geochemical conditions. The Shazaoyuan site is closer to a discharge area, at a distance of only about 20 km.
(4) Construction and engineering conditions. All nine sites are favorable in terms of the in situ stress, rock strength and topography for construction. However, the Suanjingzi and Aqishan sites are too far from towns, being more than 200 km away, resulting in difficulties in water and electricity supply and other logistics.
(5) Human activities. No important mineral resource mining activity is being conducted at any of the nine sites. However, there are quarries or granite (as a building material) mining activities at the Aqishan and Nuorigong sites.
(6) Land use. All nine sites are located in remote areas of the Gobi Desert without farming lands.
(7) Environment protection. None of the nine sites are environmentally sensitive.
(8) Transportation conditions. Xinchang, Jiujing, Shazaoyuan and Yamansu sites are closer to current railway and expressway networks.
(9) Social economical and human conditions. All nine sites are located in remote areas with limited economic prospects. However, the Aqishan and Nuorigong sites have economic potential in terms of granite mining. In terms of the attitude of local government, the Gansu Provincial Government has officially expressed welcome to host the URL facility, while no positive reply was received from the other local governments.

3.3.2. Sites recommended in the review meeting of senior experts organized by the BRIUG

On the basis of the systematical comparison among the nine sites mentioned above, the BRIUG organized a review meeting of senior experts in January 2016, which resulted in the recommendation of four candidate sites.

In the Xinjiang Uygur Autonomous Region, considering that there are many quarries at the Aqishan site and many granite mining companies are operating there, the Aqishan site was not recommended, while the Yamansu site was recommended for further comparison.

In the Inner Mongolia Autonomous Region, considering that the Tamusu site has poor rock quality and a low engineering suitability index (Q_{HLW}) and is about 240 km from the nearest town, the site was not recommended, while the Nuorigong site was recommended for further comparison.

In the Beishan region, considering that the Suanjingzi site is about 200 km from the nearest town, it was not recommended, while the Xinchang and Shazaoyuan sites were recommended for further comparison.

Four sites were thus finally recommended for further consideration: Xinchang, Shazaoyuan, Yamansu and Nuorigong sites.

3.3.3. Preferred site determined in the review meeting of senior experts organized by the CAEA

On the basis of the recommendations of the BRIUG in the early 2016, the government authority (the CAEA) organized a review meeting of senior experts in March 2016 and determined the preferred site and the back-up site.

At this stage, the major concern was the attitude of local government and public acceptance. Considering that the Gansu Provincial Government had officially expressed interest in hosting the URL facility, while no official interest was received from Xinjiang or Inner Mongolia, the group decided to recommend the two sites (i.e. Xinchang and Shazaoyuan sites) in the Beishan region of Gansu Province in their final decision.

Considering that the Xinchang site has better rock quality, higher Q_{HLW} index, greater potential to host a future repository, and is farther from towns, it was finally recommended as the preferred site for the URL, while the Shazaoyuan site was selected as the back-up site.

The successful selection of the URL site has laid a sound foundation for further activities, such as detailed site characterization and URL design. Since April 2016, a systematical site evaluation has been carried out at the Xinchang site, while the URL has been preliminarily designed according to site data and other design guidelines, leading to the high possibility of building China's first URL in granite around 2020.

3.4. Suitability index Q_{HLW} of the candidate URL sites

In general underground engineering, the suitability of the host rock can be evaluated employing conventional rock mass classification methods, which are mainly concerned with constructability (Barton et al., 1974; Bieniawski, 1989). In addition to constructability, long-term safety is an important issue in evaluating the host rock suitability for a deep geological disposal facility of HLW. In particular, the near-field of the repository is subjected to a hazardous multi-field coupling condition, which will deteriorate the properties of host rock, thus affecting the long-term safety of the repository (Äikäs and Riekkola, 2000). Thereby, in light of the host rock characteristics in the potential disposal areas in China, a new quantitative rock mass classification system Q_{HLW} was proposed (Chen et al., 2015a) to evaluate the suitability of the site for disposal purposes. The Q_{HLW} system has two evaluation scales, namely the repository and tunnel scales, for the quantitative evaluation of the suitability of host rock at different development stages of the HLW geological disposal program. The application of the Q_{HLW} system at repository scale (Q^{R}_{HLW}) to URL site selection is presented in this paper.

3.4.1. Q_{HLW} system

Overall, the Q_{HLW} system (Chen et al., 2015a) was developed on the basis of the Q classification method (Barton et al., 1974). Besides constructability, five other factors affecting the long-term safety of the repository, namely the fracture zone, groundwater chemistry, thermal effect, hydraulic conductivity and strength/stress ratio, are taken into account to comprehensively evaluate the suitability of host rock. According to the Q_{HLW} system, the host rock formation to be classified should firstly fulfill four basic assumptions:

(1) The host rock is of sufficiently large scale and depth for the final disposal repository.
(2) The host rock formation is located in a stable geological environment, and the host rock has a sufficient distance to large faults.
(3) There are relatively low seismic and tectonic activities.
(4) There is little oxidizing groundwater over the rock volume planned for disposal.

(1) Evaluation equation

The classification procedure at repository scale consists of two steps. The first step is to identify a potential site according to the strategy of avoiding fracture zones. The second step is to evaluate the suitability of the rock mass according to

$$Q^{R}_{HLW} = C^{R}_{chm} C^{R}_{T} Q' \frac{J^{R}_{w,HLW}}{SRF^{R}_{HLW}} \tag{1}$$

where C^{R}_{chm} is the groundwater chemistry index, C^{R}_{T} is the thermal effect index, Q' is the constructability index from the Q system, $J^{R}_{w,HLW}$ is the hydraulic conductivity index, and SRF^{R}_{HLW} is the strength/stress ratio index.

(2) Definition of evaluation parameters and rating criteria

(i) Fracture zone effect

Considering the effect of seismicity events on geological disposal, fracture zones are classified into Classes A, B and C according to the zone size. Class A with the largest size is prohibited from intersecting with any part of the repository. Class B is permitted only within the ramp. Class C comprises fracture zones that are permitted to intersect with disposal tunnels but are not permitted to intersect with disposal holes. The effects of even smaller fractures on the constructability and long-term safety of the repository are considered to be negligible.

According to the research based on the KBS-3 disposal concept (Swedish Nuclear Fuel and Waste Management Co. (SKB) 1999), Class A is defined as fracture zones longer than 10 km, Class B as fracture zones with length ranging from 3 km to 10 km, and Class C as fracture zones with length ranging from 0.1 km to 3 km.

(ii) Groundwater chemistry index C^{R}_{chm}

The chemical environment of groundwater may affect the long-term performance of the waste canister and the buffer backfill material. Relevant studies have shown that the groundwater chemistry index C^{R}_{chm} can be determined by the pH value, total dissolved solid (TDS) and Cl^{-} content, as shown in Table 1.

(iii) Thermal effect index C^{R}_{T}

The thermal effect due to radioactive nuclide disintegration is one of the main characteristics of geological disposal. According to experimental results, the thermal effect index C^{R}_{T} is defined as the ratio of the crack damage strength at the maximum temperature on canister exterior surface σ^{Tmax}_{cd} to the value at room temperature σ_{cd}:

$$C^{R}_{T} = \frac{\sigma^{Tmax}_{cd}}{\sigma_{cd}} \tag{2}$$

(iv) Constructability index Q'

The Q' index reflecting the rock mass constructability in the Q system is adopted in the Q_{HLW} classification system as an independent index:

$$Q' = \frac{RQD}{J_n} \frac{J_r}{J_a} \tag{3}$$

where RQD is the rock quality designation, J_n is the joint set number, J_r is the joint roughness number, and J_a is the joint alteration number. The determination criteria of these four parameters are the same as those in the Q system.

(v) Hydraulic conductivity index $J^{R}_{w,HLW}$

In safety assessments carried out by Swedish Nuclear Fuel and Waste Management Co. (SKB) (1999), host rock with hydraulic

Table 1
Definition of groundwater chemistry index C^{R}_{chm}.

Chemical environment of groundwater	C^{R}_{chm}
6 < pH < 10, TDS < 50 g/L, Cl^- < 20 g/L	1
One of the conditions (6 < pH < 10, TDS < 50 g/L, Cl^- < 20 g/L) is not satisfied	0.8
Two or more of the conditions (6 < pH < 10, TDS < 50 g/L, Cl^- < 20 g/L) are not satisfied	0.1

conductivity lower than 10^{-8} m/s is considered acceptable for HLW disposal. The safety analysis of HLW disposal carried out by National Cooperative for the Disposal of Radioactive Waste (Nagra) (1994) indicated that hydraulic conductivity lower than 10^{-9} m/s in the neighborhood of the repository greatly reduces the degree of erosion to engineered barriers, resulting in favorable performance. In light of the significance of the performance of an engineered barrier to long-term safety, hydraulic conductivity of 10^{-9} m/s is chosen as the critical conductivity K_r in this study. The rating of the hydraulic conductivity index is determined according to the percentage of the rock mass with a hydraulic conductivity lower than the critical value K_r:

$$J^{R}_{w,HLW} = \begin{cases} 1 & (Per(K < 10^{-9}\ \mathrm{m/s}) \geq 90\%) \\ 0.66 & (70\% \leq Per(K < 10^{-9}\ \mathrm{m/s}) < 90\%) \\ 0.33 & (50\% \leq Per(K < 10^{-9}\ \mathrm{m/s}) < 70\%) \\ 0.1 & (Per(K < 10^{-9}\ \mathrm{m/s}) < 50\%) \end{cases} \quad (4)$$

where $Per(K < 10^{-9}$ m/s) is the percentage of hydraulic conductivity data smaller than 10^{-9} m/s among all measurements within the scope of the potential site.

(vi) Strength/stress ratio index SRF^{R}_{HLW}

According to the constructability classification of Barton et al. (1974) and Grimstad and Barton (1993), the rating criterion is defined as

$$SRF^{R}_{w,HLW} = \begin{cases} 0.5 & (Per(\sigma_c/\sigma_1 > 5) \geq 90\%) \\ 1 & (70\% \leq Per(\sigma_c/\sigma_1 > 5) < 90\%) \\ 5 & (50\% \leq Per(\sigma_c/\sigma_1 > 5) < 70\%) \\ 20 & (Per(\sigma_c/\sigma_1 > 5) < 50\%) \end{cases} \quad (5)$$

where σ_c is the uniaxial compressive strength (UCS), σ_1 is the maximum in situ stress, and $Per(\sigma_c/\sigma_1 > 5)$ is the percentage of the strength/stress ratio data that meet the condition among all test data.

(3) Suitability classes

Suitability at the repository scale is classified into three classes in the Q_{HLW} system, namely high suitability (class I), moderate suitability (class II) and low suitability (class III), as shown in Table 2.

Table 2
Suitability classification for candidate sites based on the index Q^{R}_{HLW}.

Q^{R}_{HLW} range	Class	Suitability	Related suggestions
(100, 1000]	I	High suitability	The stability and safety of the project can be ensured without a number of measures
(40, 100]	II	Moderate suitability	More in-depth researches are necessary to determine the engineering measures in design and construction of the project to ensure its stability and safety
(0, 40]	III	Low suitability	The evaluated rock volume should be avoided in the construction of a repository

3.4.2. Suitability evaluation of URL candidate sites

The Q_{HLW} system was used to evaluate the engineering suitability of the nine URL candidate sites mentioned in Section 3.2.

(1) Parameter identification

(i) Fracture zone effect

In the determination of the candidate sites, all nine candidate sites are at least 500 m far from Class A fracture zones and 100 m from Class B fracture zones. Therefore, according to criteria of the Q_{HLW} system, the candidate sites meet the requirement of being a safe distance from fracture zones.

(ii) Groundwater chemistry index C^{R}_{chm}

According to the Cl^- content, TDS and pH value of groundwater at each candidate site and Table 1, the groundwater chemical environment is favorable for geological disposal at all candidate sites and the groundwater chemistry index is thereby taken as 1.

(iii) Thermal effect index C^{R}_{T}

According to the test data and Eq. (2), thermal effect indices C^{R}_{T} of the Jiujing and Xinchang sites are respectively 0.9 and 0.83. Although high-temperature mechanical tests of the drilling cores at other sites have not been carried out, considering that the lithology is similar among sites, the thermal effect indices C^{R}_{T} of all the other candidate sites are conservatively taken as 0.83.

(iv) Constructability index Q'

According to geological survey results obtained by borehole drilling, the constructability indices of the nine URL candidate sites are listed in Table 3.

(v) Hydraulic conductivity index $J^{R}_{w,HLW}$

Hydraulic conductivity conditions at the Xinchang, Yamansu and Suanjingzi sites are found to be favorable and the hydraulic conductivity index $J^{R}_{w,HLW}$ is taken as 1. The hydraulic conductivity index $J^{R}_{w,HLW}$ of the Shazaoyuan, Aqishan and Nuorigong sites is taken as 0.66 according to the results of field tests, while the hydraulic conductivity index $J^{R}_{w,HLW}$ of the Tianhu site is 0.33.

(vi) Strength/stress ratio index SRF^{R}_{HLW}

Overall, the in situ stresses are relatively low while the granite at the candidate sites has relatively high strength. The in situ stress level of a candidate site is slightly higher in Xinjiang and

Table 3
Constructability index Q' for each candidate site.

Preselected region	Candidate site	Sampling borehole	RQD	J_n	J_r	J_a	Q'
Beishan	Jiujing	BS03	76.7	3	3.3	1.6	52.7
	Xinchang	BS06	97.6	3	3.8	0.79	156.5
	Shazaoyuan	BS24	96.5	2	3.9	0.85	221.4
	Suanjingzi	BS22	80.4	3	3.9	0.88	118.8
Xinjiang	Yamansu	YM01 YM02	95.2	3	4	0.95	133.6
	Tianhu	TH02	79.9	3	4	1.27	83.9
	Aqishan	AQ01	98.4	3	3.7	1.03	117.8
Inner Mongolia	Tamusu	TMS02	89.6	3	4	0.75	159.3
	Nuorigong	NRG01	94.1	3	4	0.75	167.3

Inner Mongolia areas than that in the Beishan area. According to Eq. (5), the strength/stress ratio index SRF^{R}_{HLW} for the Yamansu site is 1. The strength/stress ratios for all the other sites are greater than 5 and the strength/stress ratio index SRF^{R}_{HLW} is taken as 0.5.

(2) Suitability evaluation of URL candidate sites

According to the above analyses, classification results for the nine URL candidate sites are shown in Fig. 2. According to the values of Q^{R}_{HLW}, Xinchang, Shazaoyuan, Suanjingzi, Yamansu, Aqishan and Nuorigong are considered to be suitable sites of the URL for HLW disposal. Furthermore, the Xinchang site is most suitable owing to its high rock mass integrity, low permeability and high strength/stress ratio.

3.5. Final site for the URL

With suitable geological conditions and especially with the support of government authorities (i.e. the CAEA and the National Nuclear Safety Authority) and local government (i.e. the Gansu Provincial Government), the Xinchang site in the Beishan area was finally selected as the site for China's first URL in granite. This decision has laid a sound foundation for detailed characterization of the site and preliminary design of the planned URL.

4. Characterization of the URL site

4.1. Introduction to the Xinchang site

The Xinchang URL site is located in the middle of the Beishan area (Fig. 3) at a distance of about 135 km from Jiayuguan City. The topography of the site is characterized by small flat hills (Fig. 4) with elevation ranging between 1670 m and 1730 m above sea level. The height variation is usually less than 30 m, which provides favorable conditions for the construction of surface facilities. More specifically, the Xinchang URL site is located within the Xinchang granite intrusion (Fig. 5), which is a potential sub-area for the HLW repository. The Xinchang granite intrusion is a 22-km-long and 7-km-wide rock block. The major rock types include gneissic biotite monzonitic granite and biotite granodiorite with an age of around 260 million years.

4.2. Site characterization plan

The objectives of site characterization are to investigate the rock types, geological structures (i.e. faults and fracture systems) and hydrogeological, geochemical and engineering geological conditions of the Xinchang site, to establish a three-dimensional (3D) geological model, and finally to provide necessary data for URL design, excavation, construction and future in situ tests in the URL. Comprehensive activities, such as surface geological mapping, hydrogeological investigation, geophysical surveying, borehole drilling and borehole testing, have been planned at the Xinchang site.

The surface geological mapping includes investigations at 1:10,000 scale, with focus on investigating the rock types, faults, fracture distribution and rock integrity. Such investigations provide data with which to identify locations of exploration boreholes and shafts.

During a geophysical survey, the audio-frequency magnetotelluric (AMT) method has been used to identify the locations, bearings and extensions of faults and to understand the distribution of granite intrusions. In total, eleven AMT profiles with a total length of 55 km have been measured.

Borehole drilling is the most important method for investigating underground geological conditions. In total, one 1000-m-deep borehole, fourteen 600-m-deep boreholes (three vertical and eleven inclined) and eighteen 100-m-deep inclined boreholes have been drilled. The distribution of these boreholes is shown in Fig. 6.

The borehole design was as follows:

(1) Vertical deep boreholes were planned for exploration of geological conditions around the main shaft of the URL, e.g. boreholes BS28, BS32 and BS33. The depths of these boreholes are about 600 m.
(2) Inclined boreholes were planned to investigate faults around the site, e.g. boreholes BS35, BS36, BS38 and BS39.
(3) For faults, shallow inclined boreholes (to a depth of about 100 m) and deep inclined boreholes (to a depth of about 600 m) were planned, e.g. BSQ05 and BS35 for fault F31.
(4) For the same fault, boreholes were planned at different sections of the fault, e.g. BSQ05 and BS35 in the northern section of fault F31 and BSQ04 and BS36 in the southern section of fault F31.

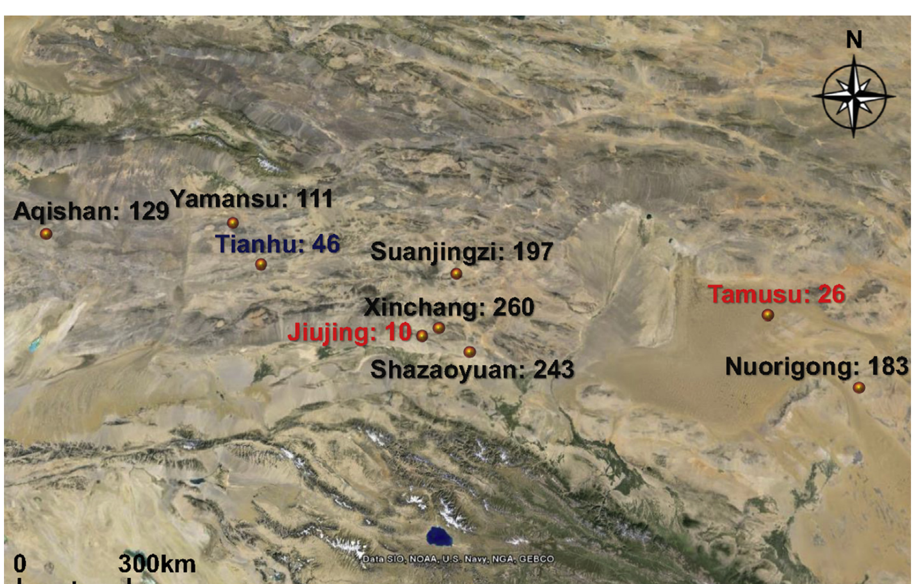
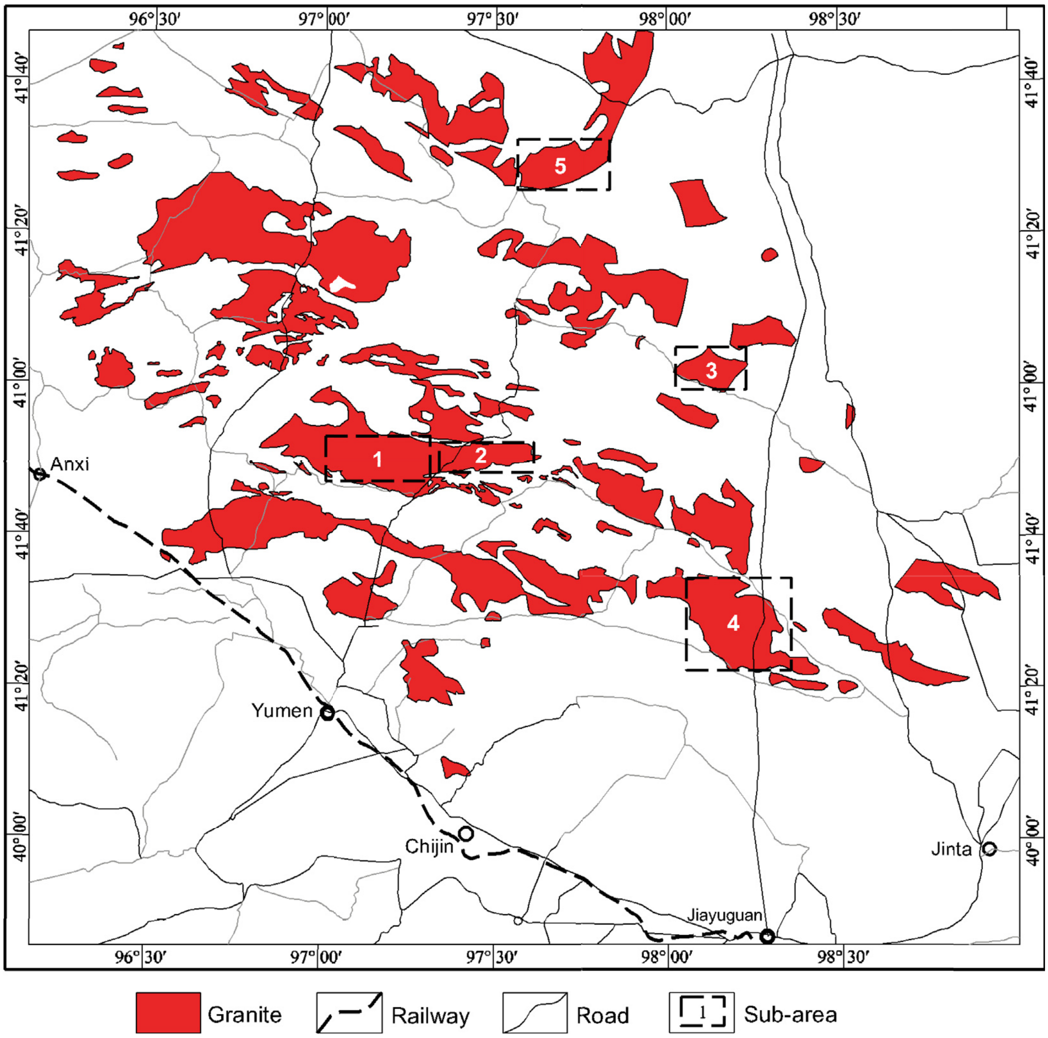


Fig. 2. Q^{R}_{HLW} values for the nine URL candidate sites.



1 – Jiujing sub-area; 2 – Xinchang sub-area; 3 – Yemaquan sub-area; 4 – Shazaoyuan sub-area; 5 – Suanjingzi sub-area

Fig. 3. Location of the Xinchang URL site in the Beishan area.

Measurements of drilling fluid loss were made during the drilling of boreholes. Additionally, sodium fluorescein was added to the drilling fluid as a tracer. The borehole cores were comprehensively logged in terms of lithology, structure and degrees of weathering and fracturing, and the RQD index was determined.

Systematical in situ borehole logging and tests were conducted. The tests included standard single-point electrical resistance and resistivity tests, electrical potential tests, gamma–gamma density tests, natural gamma and magnetic susceptibility tests, neutron scattering tests, seismic P-wave velocity tests, caliper tests, in situ stress measurements and hydrogeological tests.

4.3. Site characterization results

4.3.1. Geology

Good outcrops of rock in the area have allowed detailed surface geological mapping and the convenient identification of rock types and faults. The surface mapping shows that the bedrock just crops out in the area, with few weathering layers.

Surface geological mapping and borehole drilling have identified that the major rock types at the Xinchang URL site are biotite monzonitic granite and biotite granodiorite. Results also show that the rock mass is of high integrity and has low fracture density.

Fig. 7 shows the geological profile of the URL site. The major faults include F31 and F34 in the west and F32 and F33 in the east. The lengths of these faults range between 3 km and 6 km, while the thicknesses of the faults are between 0.8 m and 2 m. The depths of F31 and F34 are less than 500 m, while F32 and F33 are about 800 m deep. Investigations have shown that they are extension faults or

Fig. 4. Typical topography of the Xinchang site.

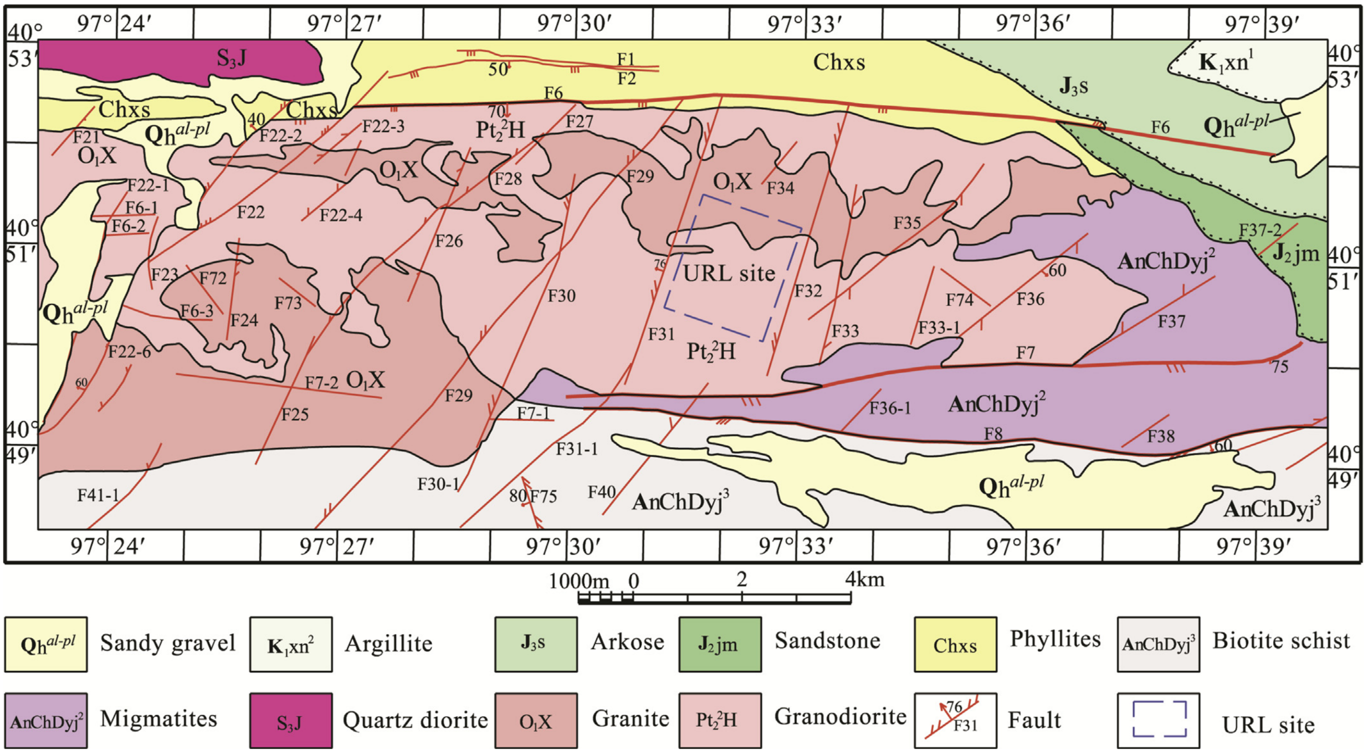


Fig. 5. Geological map of the Xinchang site.

extension slip faults with well-consolidated breccia. The highly integrated granite mass at the site provides excellent conditions for URL construction and underground space stability, while faults at the site make it possible to conduct various in situ underground tests, such as hydraulic tests, radionuclide migration tests along the faults and grouting tests.

A surface electromagnetic survey and high-resolution magnetic survey were conducted and shown to be effective in identifying discontinuities and rock mass integrity. Fig. 8 presents an electromagnetic profile across the Xinchang URL site, clearly showing that the rock mass has a good integrity with a depth of about 2 km. Meanwhile, the major faults, F31 and F34, are distributed at a shallow depth while F32 is located at greater depth.

According to a comprehensive integration and interpretation of the geological and geophysical data obtained from site characterization, a 3D geological model of the Xinchang site has been established, as presented in Fig. 9. The 3D model visually presents the characteristics of the deep geological environment of the Xinchang site, and is an efficient tool for optimizing the URL design, guiding the construction and planning of in situ tests (Luo et al., 2017).

4.3.2. Hydrogeology

In characterization of the Xinchang URL site, the groundwater levels of all the boreholes were monitored and the results are listed in Table 4. It is seen that that the water levels in the boreholes range from 3.8 m to 47.79 m below the ground surface and the groundwater heads above sea level in shallow boreholes are generally higher than those in deep boreholes.

Another important hydrogeological investigation focused on hydraulic tests in eight deep boreholes, including three vertical boreholes (BS28, BS32 and BS33) and five inclined boreholes (BS35–BS39) (see Fig. 6). Constant-head injection tests were carried out in these boreholes using a double packer test system. The aim of injection tests was to characterize the hydraulic properties of rock formations and faults intersected by the boreholes (Su et al., 2007; Ji et al., 2018). The major parameter to be determined was the hydraulic conductivity. Test intervals with a length of 12 m were used for obtaining the hydraulic conductivity along the boreholes.

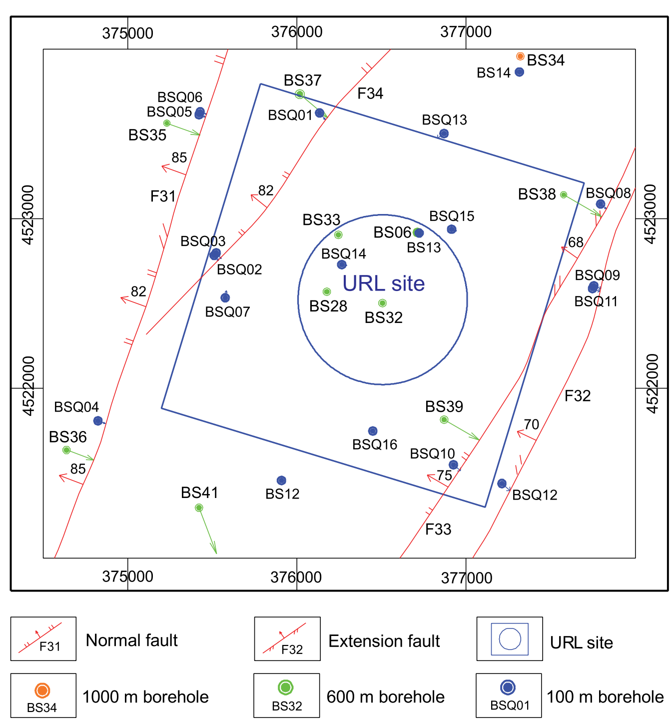


Fig. 6. Locations of boreholes at the Xinchang URL site.

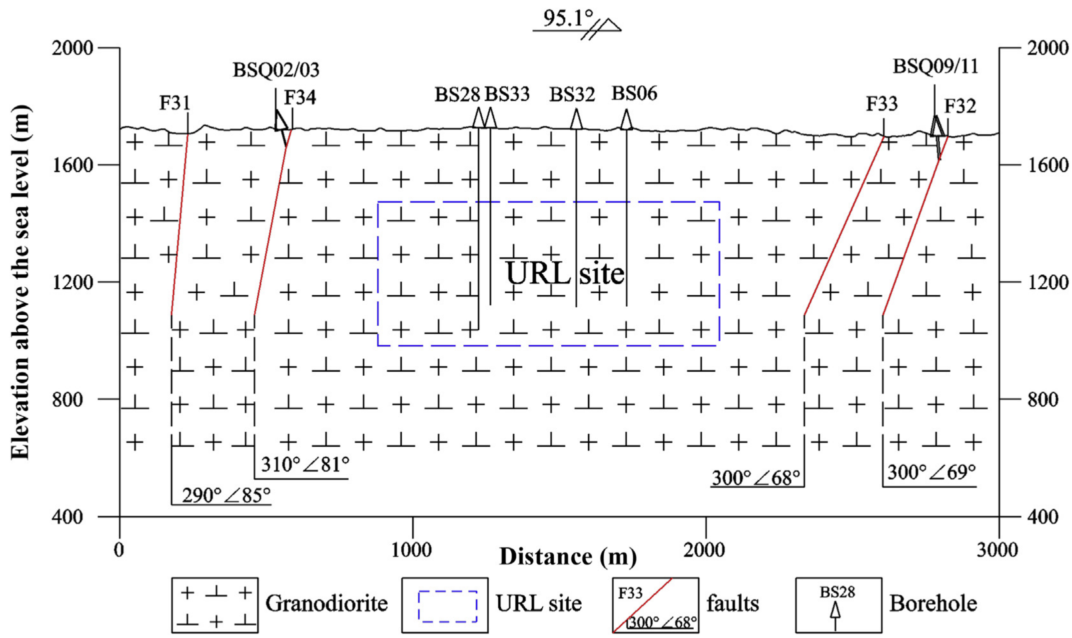


Fig. 7. Geological profile of the Xinchang URL site.

Fig. 10 presents the hydraulic conductivity distributions in the eight boreholes. The data show that for most test intervals within intact rocks or fracture zones, the hydraulic conductivity was low, generally less than 10^{-8} m/s, mainly between 10^{-12} m/s and 10^{-10} m/s, indicating that the rock masses of the site have extremely low permeability.

Further statistical results of hydraulic conductivities in vertical boreholes BS28, BS32 and BS33 revealed that the hydraulic conductivities of 90% of the test intervals were lower than 10^{-8} m/s, and the values mainly ranged from 10^{-12} m/s to 10^{-10} m/s (Fig. 11a). In addition, analysis of the statistical results gained from inclined boreholes BS35–BS39 showed that the hydraulic conductivities of 98% of the test intervals were lower than 10^{-8} m/s, and the values mostly ranged between 10^{-12} m/s and 10^{-10} m/s (Fig. 11b). According to the hydraulic conductivities measured for 127 test intervals in vertical boreholes and 236 test intervals in inclined boreholes at the Xinchang URL site, the basic statistical estimators (minimum, median and maximum values) were calculated. The hydraulic conductivities at the Xinchang site were generally lower than those at three granite URL sites in Sweden, Finland and Switzerland (Mejías et al., 2009) (see Table 5).

4.3.3. Engineering geology

To evaluate the quality of rock masses at the Xinchang URL site, RQD (Deere, 1968) data were obtained from drilled cores of four vertical boreholes (i.e. BS06, BS28, BS32 and BS33 in Fig. 6). These drilled cores have a cumulative length of 2505 m. Statistical analyses indicate that RQD values between 75% and 90% (indicating good rock quality) and larger than 90% (indicating excellent rock quality) respectively account for 7.2% and 86.2% of the total borehole cores (see Fig. 12a), showing very good rock integrity at the URL site. A photograph of intact drilled cores from borehole BS32 is presented in Fig. 12b, showing the extremely high quality of the rock mass. It is noted that crystalline rocks inevitably contain fractures. Fractures in the four vertical boreholes were investigated through borehole televiewer (BHTV) measurements and borehole logging. The location, orientation and dip angle of a fracture that intersects the borehole can be determined from images of the borehole wall and drilled cores. A typical BHTV image is presented

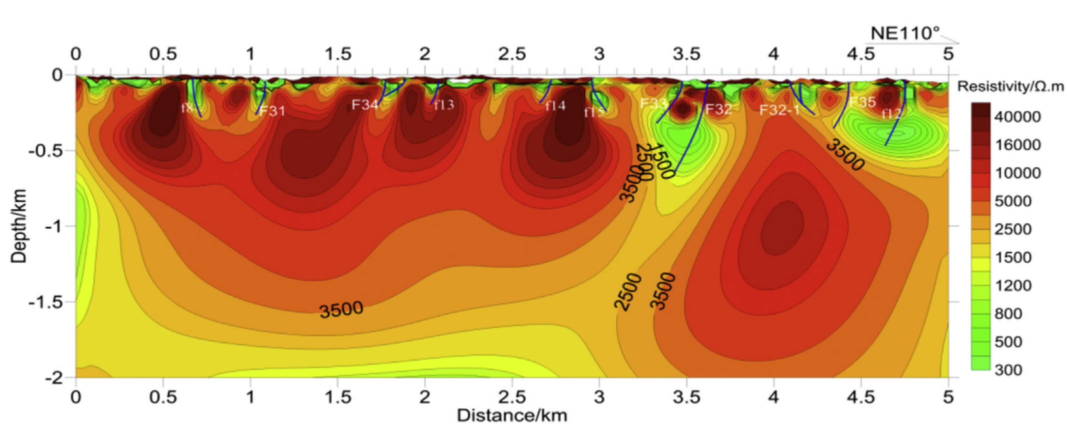


Fig. 8. An electromagnetic profile of the Xinchang URL site.

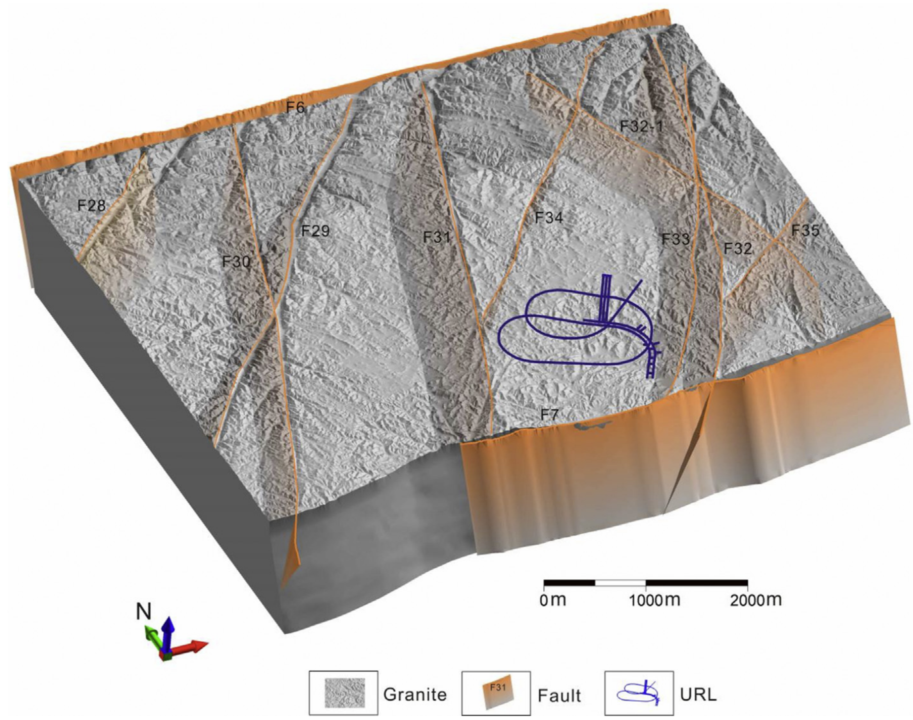


Fig. 9. Established 3D geological model of the Xinchang URL site.

in Fig. 13. Statistical results indicate that fractures in the four boreholes are dominantly in the northeast direction (Fig. 14a), and the maximum Fisher concentration is 3.2% (Fig. 14b). In addition, four fracture sets were identified. The results are listed in Table 6.

The mechanical characteristics of Beishan granitic rocks have been widely investigated (Chen et al., 2014, 2015b, 2017a; Zhao et al., 2013a, 2014b, 2016). To clarify the basic mechanical properties of the drilled cores, uniaxial compression tests and Brazilian tests were conducted using cylindrical samples collected from five boreholes within the site. A total of 237 rock samples, with a diameter of approximately 50 mm, were prepared in accordance with the specifications recommended by the International Society for Rock Mechanics (ISRM) (Fairhurst and Hudson, 1999). Fig. 15 shows the strength distributions of the core samples taken from different depths along these boreholes. It shows that the UCS of the rock samples ranges between 110 MPa and 235 MPa and has an average value of 173 MPa (Fig. 15a), while the tensile strength values are between 6 MPa and 15 MPa and have an average value of 11 MPa (Fig. 15b).

Rocks at depth are subjected to stresses resulting mainly from the weight of the overlying strata and stresses of tectonic origin (Hoek, 2007). The in situ stress state at a URL site should be known with sufficient confidence to provide stress boundary conditions for underground excavation design and long-term stability evaluation. In addition to the magnitudes of the in situ stress components, the orientation of the maximum principal stress should be identified accurately because it directly affects the layout of the URL (Zhao et al., 2015). Hence, in the process of site characterization, 80 hydraulic fracturing (HF) in situ stress measurements were made in four vertical boreholes (i.e. BS06, BS28, BS32 and BS33 in Fig. 6) at depths ranging from 23 m to 579 m below the ground surface. The HF method is a two-dimensional (2D) stress measurement approach applicable to the determination of the maximum horizontal stress (σ_H) and the minimum principal stress (σ_h) (Haimson, 1978). The vertical stress (σ_v) can be estimated from the overburden weight. Fig. 16 presents the variation of the principal stresses with depth at the URL site. It is seen that the in situ stress components tend to increase with depth and the magnitudes of measured σ_H and σ_h are respectively less than 20 MPa and 13 MPa within the measurement depth range. Compared with the UCS values of the core samples (see Fig. 15a), the magnitude of the in situ stresses at the site is at a low level based on the empirical classification approach (Hoek et al., 1995). Moreover, among all test points, 78% of

Table 4
Groundwater head data recorded for boreholes at the Xinchang URL site.

Borehole type	Borehole No.	Depth (m)	Elevation (m)	Water level (m)	Groundwater head above sea level (m)
Vertical	BS12	100.17	1681.91	4.58	1677.33
	BS14	100.33	1723.2	43.27	1679.92
	BS06	602.61	1716.76	45.99	1670.77
	BS28	690.67	1725.40	47.79	1677.61
	BS32	607.98	1718.57	38.44	1680.13
	BS33	605.55	1719.2	41.34	1677.86
Inclined	BSQ01	126.27	1704.21	16.64	1687.57
	BSQ02	78.97	1719.02	23.10	1695.92
	BSQ03	75.54	1719.73	22.31	1697.42
	BSQ04	145.3	1723	17.18	1705.82
	BSQ05	120.01	1696.29	4.56	1691.73
	BSQ06	99.63	1695.58	3.8	1691.78
	BSQ07	94.69	1716.83	27.35	1689.49
	BSQ08	86.07	1692.13	26.16	1665.97
	BSQ09	83.25	1696.41	32.38	1664.03
	BSQ10	120.41	1678.01	14.63	1663.38
	BSQ11	80.4	1698.23	32.97	1665.25
	BSQ12	99.85	1681.12	30.57	1650.56
	BSQ13	120.08	1709.98	44.47	1665.51
	BSQ14	79.19	1723.2	43.27	1679.92
	BSQ15	101.54	1710.26	27.65	1682.61
	BSQ16	125	1702.59	23.69	1678.9
	BS35	628.47	1701.86	18.4	1683.47
	BS38	491.15	1704.93	39.86	1665.08
	BS41	612.13	1691.12	15.53	1675.59

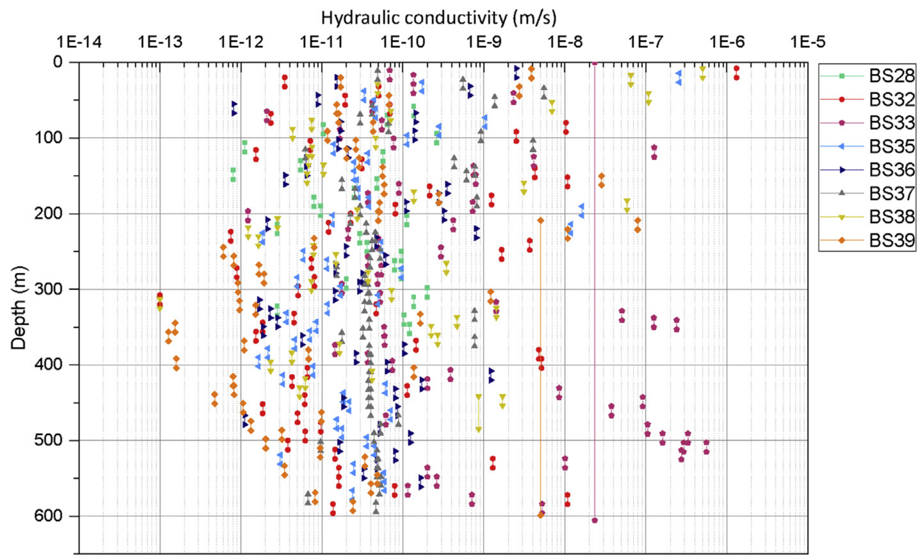


Fig. 10. Variation of hydraulic conductivity with depth in eight deep boreholes at the Xinchang URL site.

σ_H values are larger than σ_v values, indicating that the in situ stress field is dominated by tectonic horizontal stress rather than by the overburden load. Linear relationships between σ_H and σ_h and depth (H) are established by fitting the data employing a least-squares approach (see Fig. 16). It is seen that within the measurement depth range, the stress field at the URL site is characterized by $\sigma_H > \sigma_v > \sigma_h$.

After the fracturing tests, a total of 27 fracture impression measurements were performed to determine the orientation of the hydraulic fractures (i.e. orientation of σ_H). Field observations indicated that all mapped hydraulic fractures were sub-vertical. A typical impression packer image is presented in Fig. 17a. The fracture impression results show that all orientations of σ_H at the URL site are in NE–SW direction. A further statistical analysis of all fracture impression data indicates that the dominant orientations of σ_H range from N50°E to N70°E and have an average value of N55°E (see Fig. 17b). It is thus concluded that the in situ stress field at the URL site is affected by the NEE-SWW tectonic stress. The current measurement results are in good agreement with those obtained by the previous in situ stress measurement program conducted in the Beishan area (Zhao et al., 2013b).

4.3.4. Geochemistry

The evaluation of a site for construction of URL requires an understanding of to-date geochemical environments and processes (Tian et al., 2014), i.e. how the geochemical environments have changed in the past and will change in the future. To understand these processes associated with radionuclide migration to the accessible environment, geochemical characteristics of the Xinchang site have been investigated. The information obtained includes mineralogical and chemical compositions of the host rocks and their geochemical properties.

The bedrock of the Xinchang site is mainly Hercynian crystalline rock with an age ranging from 235 to 296 million years, mainly consisting of granite and granodiorite on the basis of visual, microscopic and lithogeochemical investigations. The main minerals of the granite and granodiorite are potassium feldspar, quartz and plagioclase, with smaller proportions of biotite and hornblende. The main compositions of the rocks are uniform, with 65% or more SiO_2, 12%–15% Al_2O_3 and small amounts of natrium, iron, magnesium and calcium. Typical fracture minerals found at the Xinchang site are calcite, quartz, chlorite and clay minerals (see Fig. 18). The C, O and Sr isotopic compositions of calcites indicate

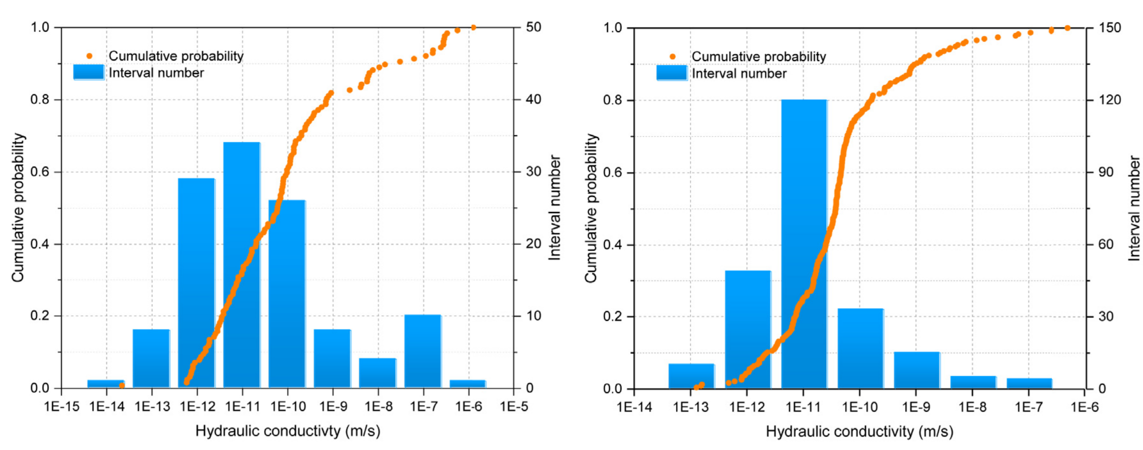


Fig. 11. Cumulative distribution of hydraulic conductivities obtained from (a) vertical boreholes (BS28, BS32 and BS33) and (b) inclined boreholes (BS35–BS39) at the Xinchang site in the Beishan area.

Table 5
Comparison of hydraulic conductivities at the Xinchang URL site with those at granite URL sites in Sweden, Finland and Switzerland.

Test site	Hydraulic conductivity (m/s)		
	Minimum	Median	Maximum
Xinchang site, China	2.18×10^{-14}	6.17×10^{-11}	1.32×10^{-6}
Faults around the Xinchang site, China	1.28×10^{-13}	4.18×10^{-11}	3.22×10^{-6}
Äspö Hard Rock Laboratory, Sweden	3×10^{-10}		10^{-8}
Olkiluoto research site, Finland	10^{-9}		10^{-8}
Grimsel test site, Switzerland	10^{-13}	10^{-9}	4×10^{-4}

that they have been formed from meteoric water or basin brines, which have undergone various degrees of water/rock interaction. The alteration of the wall rock adjacent to the fractures has been observed to be related to K-metasomatism, illitization and chloritization, which have very little effect on redox buffering capacities. The redox condition of the Xinchang site has been studied using mineralogical (redox-sensitive minerals), geochemical (redox-sensitive elements) and U-series disequilibrium investigations of mineral coatings along fractures, as well as Eh measurements of groundwater in boreholes. The results show a reducing condition at a depth ranging from 520 m to 600 m at the URL site. In consideration of the above features, it is concluded that geochemical environments of the Xinchang site are suitable for the construction of a URL for geological disposal studies.

4.3.5. Summary

The major findings of site characterization associated with the geology, hydrogeology, engineering geology and geochemistry are as follows:

(1) The dominant rock types at the Xinchang URL site are biotite monzonitic granite and biotite granodiorite. The rock masses at the site have good integrity, providing excellent geological conditions for the construction of the URL.
(2) Hydraulic conductivities along different boreholes at the URL site mainly range between 10^{-12} m/s and 10^{-10} m/s, reflecting that the rock masses have extremely low permeability. The low permeability not only means good rock quality at the site, but also provides a favorable condition for the construction of the URL and for the permanent isolation of HLW in the geological formation.
(3) The in situ stress field at the URL site is dominated by the horizontal tectonic stress, and the measured σ_H values are all less than 20 MPa. Compared with the strength of the core samples, the magnitudes of the in situ stresses at the site are relatively low. Meanwhile, the stress σ_H is mainly oriented in NEE direction. The obtained in situ stress state is favorable for the stability of surrounding rocks (Zhao et al., 2010) due to the low stress magnitudes and stress differences among the three principal stresses.
(4) The reducing condition was demonstrated at a depth ranging from 520 m to 600 m at the URL site. The geochemical conditions at the depth of the site are favorable for conducting in situ tests in the URL and hosting a DGR.

5. Technical preparations for construction of the Beishan URL

5.1. Beishan exploration tunnel

As a small pilot underground facility for the proposed URL, the BET was constructed at the Jiujing site, which is about 30 km from the Xinchang URL site. Fig. 19 shows the photographs of the BET. The main purpose of the BET is to provide a field experimental platform for developing and testing technologies of underground excavation and safe operation, which will be used for the construction of the proposed URL. Another objective is to establish management systems for field experiments and engineering operations. During construction of the BET, mine-by R&D experiments were performed by the BRIUG, in conjunction with the Fourth Research and Design Engineering Corporation of the China National Nuclear Corporation (CNNC), Sichuan University, China University of Mining and Technology (Beijing), Engineering University of People's Liberation Army of China, and Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

5.2. Location and layout of the BET

The BET is located in the vicinity of the Shiyuejing fault, which is one of the typical faults in the Beishan area. The BET is mainly composed of a ramp (having a length of 146 m, inclination of 20°, and cross-sectional area of 6.8 m^2), horizontal tunnels (having a total length of 126 m and cross-sectional area of 6.8–12.2 m^2), experimental tunnels (having a total length of 90 m and cross-sectional area of 7.2–11 m^2), a water chamber and a ventilation

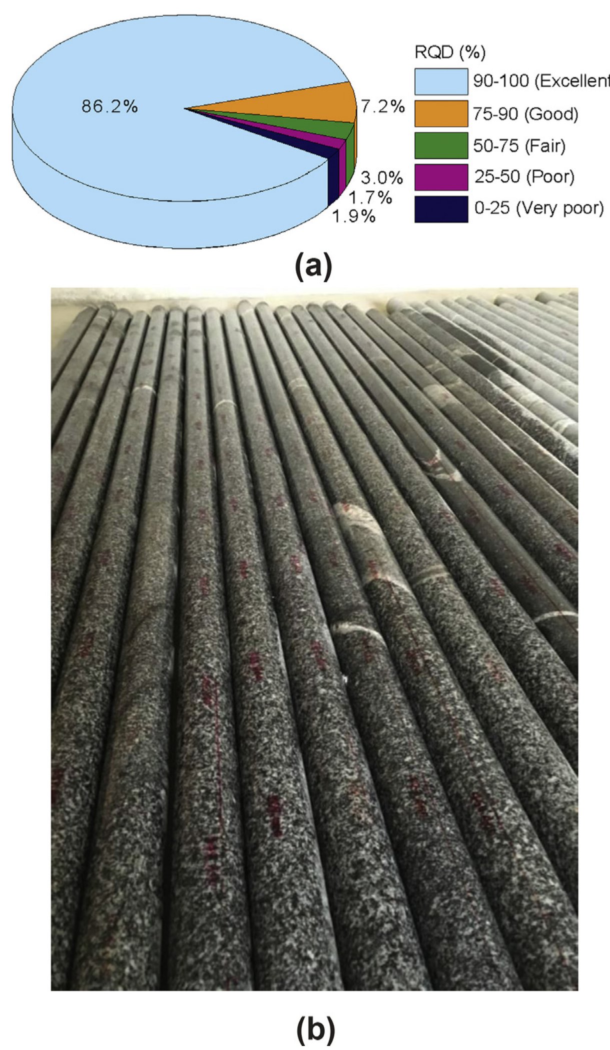


Fig. 12. (a) RQD classification showing the proportion of different rock mass qualities for four vertical boreholes (BS06, BS28, BS32 and BS33) at the Xinchang URL site; and (b) Intact 63-mm-diameter drilled cores extracted from borehole BS32.

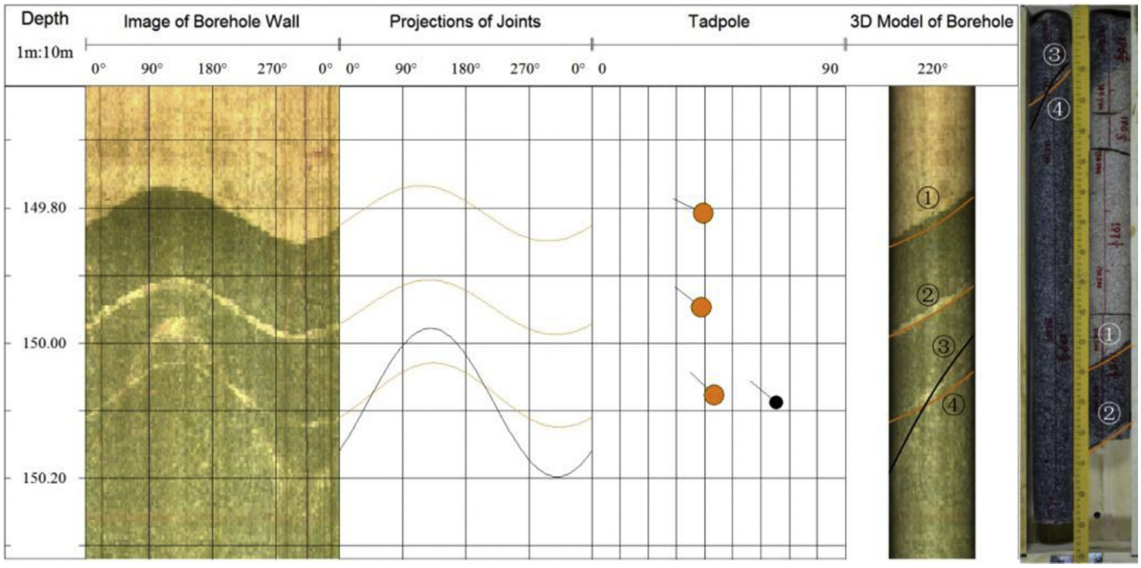


Fig. 13. Typical BHTV image of a borehole wall and interpretations of several joints in borehole BS32.

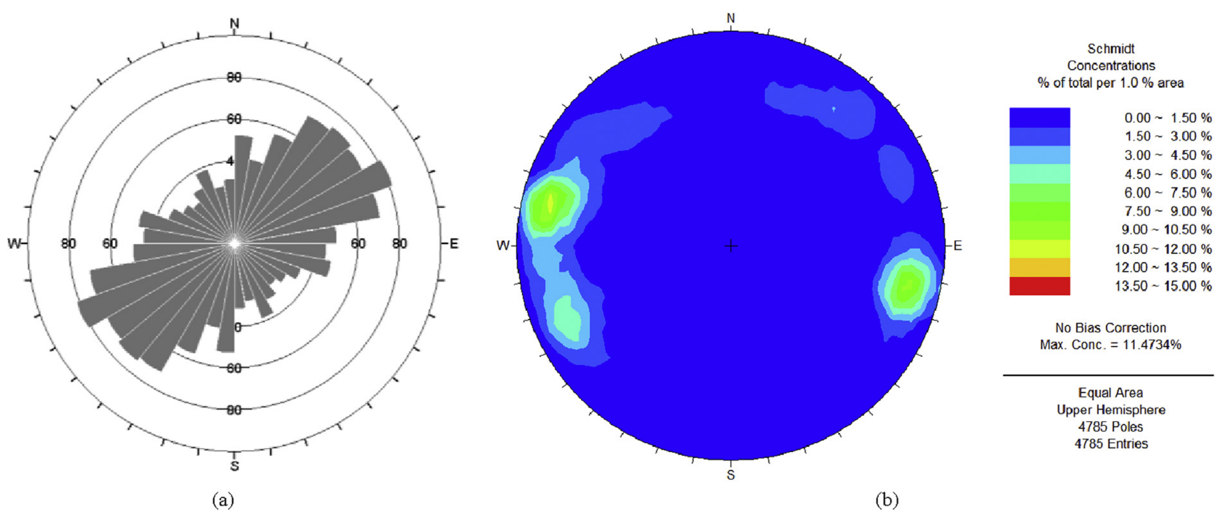


Fig. 14. (a) Strike rosette plot and (b) stereographic contours of fractures (upper hemisphere) in four boreholes (BS06, BS28, BS28 and BS33) at the Xinchang URL site.

borehole (see Fig. 20). It took 18 months (i.e. from June 26, 2015 to December 20, 2016) to complete the excavation of this facility and all in situ experiments.

5.3. R&D achievements

As listed in Table 7, different in situ tests have been conducted in the BET. This section presents the main achievements of drill-and-blast tests, characterization of the excavation damaged zone (EDZ), advanced detection of unfavorable geological conditions, deformation monitoring of the surrounding rocks and 3D fracture mapping and modeling.

5.3.1. Drill-and-blast test

Drill-and-blast tests were conducted to investigate the effect of blasting excavation on the surrounding rock and to optimize the blasting parameters. The results will be used for the construction of the Beishan URL. This testing used different surrounding hole spacings and cutting patterns during excavation of a passing bay with a cross-sectional area of 12.15 m^2.

Fig. 21 presents the distribution of the energy percent when using different cutting patterns. It is seen that the parallel hole cutting method attenuates the energy distribution from low to high frequency. However, the double wedge cutting method generates lower vibration energy with small differences among various frequency sections, which can be beneficial to blasting

Table 6
Fracture orientation parameters for four boreholes (BS06, BS28, BS28 and BS33).

Set No.	Data percent (%)	Fracture orientation	
		Dip direction (°)	dip (°)
1	24.2	305.1	67.1
2	14.8	350.3	24.8
3	52.7	158.8	46.5
4	8.3	91.3	79.8

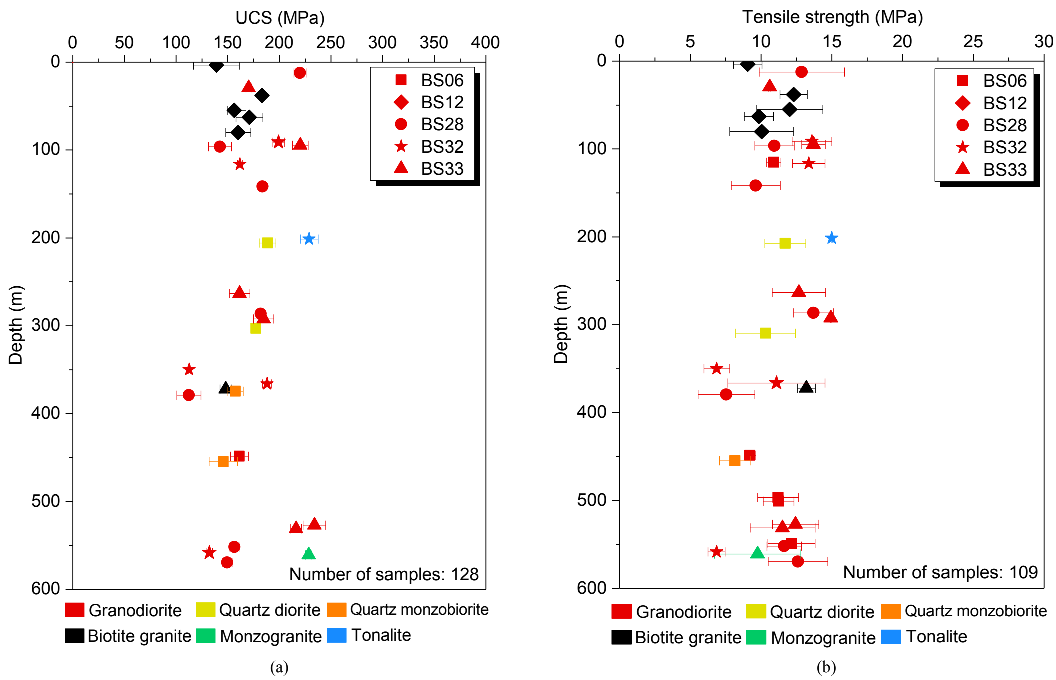


Fig. 15. Variations of (a) the average UCS and (b) tensile strength with depth in the five boreholes at the Xinchang URL site. Error bars indicate the standard deviation of the UCS and tensile strength.

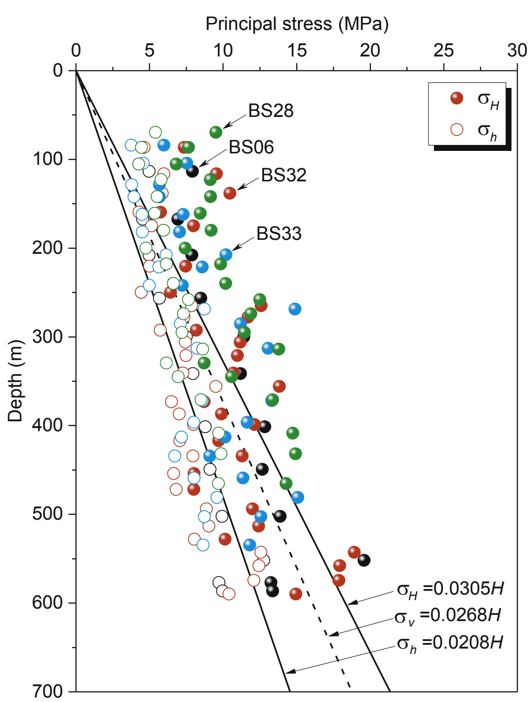


Fig. 16. Variations of the horizontal and vertical principal stresses with depth at the Xinchang URL site.

excavation. In addition, according to quantitative analysis of the blasting vibration signal from blasting delay identification, it is better to select multi-series millisecond-delay detonators and to avoid detonators with longer segments of delay intervals. The blasting parameters recommended for the construction of the URL are shown in Table 8.

5.3.2. EDZ characterization

During the drill-and-blast tests, EDZ characterization was carried out to evaluate the suitability of different EDZ monitoring methods in granite, and finally to propose a systematical EDZ evaluation technology. A series of field testing systems, such as acoustic emission (AE) monitoring system, microseismic monitoring (MS) system, ultrasonic wave testing system, ground penetrating radar (GPR), borehole radar and borehole televiewer, has been employed to characterize the EDZ distribution around the test tunnel. The sensors were installed in 21 monitoring boreholes before excavation, as shown in Fig. 22a.

For GPR investigation with a high-frequency (1.5 GHz) antenna, a strong reflection response was observed within 0.1–0.25 m of the wall surface, which is defined as the damage zone (Fig. 22b). GPR, especially high-frequency GPR, was demonstrated as a promising technique in EDZ assessment owing to its nondestructive property and good performance in delineation of the EDZ. Fig. 22c shows the P-wave velocity measurement results before and after blasting. The P-wave velocity was observed to decrease significantly within 0.2 m of the tunnel wall, and that within 0.2–0.5 m was slightly lower than the results before excavation. Fig. 22d presents the AE monitoring results obtained in blasting excavation. Locations of AE sources were mainly clustered within 0.6 m of the wall surface. According to the above-mentioned results, GPR and ultrasonic testing combined with a borehole televiewer are recommended for identification of the EDZ in the rocks surrounding the URL, while AE monitoring technique is useful for understanding the evolution of the EDZ.

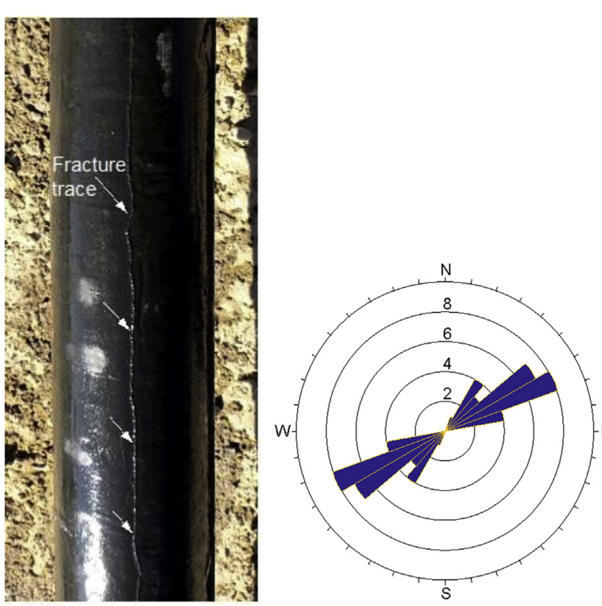
5.3.3. Advanced detection test

To verify the applicability of geophysical survey methods and to establish a high-precision advanced detection technology for finding water-conducting fracture zones and small faults, an in situ detection test was conducted in the BET. Different technologies were used in this test, including multi-frequency GPR detection, transient electromagnetic analysis and seismic-infrared detection.

The detection results obtained with the GPR at a frequency of 50 MHz are shown in Fig. 23. Within the range of near 150 m along the inlet of the ramp towards the passing bay, the fault suddenly shrinks within the section of 75–95 m mileage in the ramp, and the distance to the ramp changes from 33 m to 39 m (Fig. 23a, red dashed line in the black box). This increase in distance was confirmed in the detection test and borehole drilling carried out in detection area 2 (Fig. 23b). Two fissure zones vertical to the inclined ramp nearby 30 m and 90 m were observed and two fissure zones were located at the horizontal level of the BET (Fig. 23, dark-blue dashed lines). These fissure zones match the crushing of surrounding rocks in the ramp and the severely broken rocks with yellow mud intrusions. According to the test results, an advanced detection system mainly based on GPR technology was developed for the URL.

5.3.4. Deformation monitoring of surrounding rocks

Deformation monitoring of surrounding rocks was carried out at the passing bay and fault zone in the BET. The variation in the displacement of surrounding rocks throughout tunnel excavation was obtained, as shown in Fig. 24. Results show that the internal displacement of surrounding rocks throughout blasting excavation experiences three stages, namely an initial displacement growth stage, rapid displacement growth stage and stable convergence stage. The temporal curve of internal displacement of surrounding rocks near the monitoring section shows stepwise characteristics, which are similar to the morphological characteristics of the creep curve of rock in a stepped loading test. The spatial effects of the excavation face and the loss displacement were calculated with three typical longitudinal deformation profile curve equations (i.e. the Lee equation, Hoek equation and V-D equation). It is noted that the loss displacement calculated using the Hoek equation best fits the measurement. The displacement monitoring results indicate that the loss displacement is at least 50% of the total displacement when the measuring section was set 2 m from the excavation face. Furthermore, a new tunnel profile monitoring system was proposed according to the deformation monitoring results of the surrounding rocks.



(a) (b)

Fig. 17. (a) A typical fracture trace impressed on the packer in the test interval at a depth of 345 m in borehole BS28; and (b) A statistical analysis showing the dominant orientations of σ_H at the Xinchang URL site.

5.3.5. 3D fracture mapping and modeling

Joints in granite are important factors affecting the local stability of an underground tunnel and the joint network might form potential pathways of groundwater and radionuclides (Liu et al., 2015). During construction of the BET, outcrop survey and tunnel mapping were carried out to study the joint network of the surrounding rocks. A total of 2571 joints at 48 outcrops were recorded employing the synthetic scan-line method and three dominant occurrences were identified as 282° ∠76° (Set-1), 172° ∠71° (Set-2) and 49° ∠37° (Set-3). A total of 865 joints in the BET were mapped employing the updated tunnel mapping method and 3D laser scanning, and a 3D model of joint traces was established (see Fig. 25).

To generate the 3D joint network in the surrounding rocks, a new method for joint occurrence cluster was proposed and thus the subjective judgments in the conventional methods were avoided. A new method of estimating the distribution of joint diameters was established and the truncation effect in the outcrop survey was successfully evaluated with the proposed method. Using the corrected occurrence and trace-length data, a new method of identifying the homogeneous structural domain was proposed by generating a 2D matrix of the weighted correlation coefficients for different outcrops. Finally, with the improved statistical parameters obtained using the above methods, a discrete joint network model of the surrounding rocks for the BET was generated (see Fig. 26). In the 3D fracture network model, the fractures of Set-3 are scarce, but some are so large that they cut through the entire modeling domain. According to stability analysis based on the fracture network model, the movable blocks in the surrounding rocks of the BET are formed mainly by the intersection between these large fractures of Set-3 with low dip angle and the fractures of Set-1 with large dip angle. Furthermore, water seepage was found in several fractures of Set-3 during in situ mapping. This indicates that these large fractures of Set-3 might generate groundwater pathways. Therefore, when the local stability and hydrological condition are evaluated for the rock mass in the vicinity of a fault similar to the Shiyuejing fault, more emphasis should be placed on the factures of Set-3. However, more in situ investigation is needed to verify this conclusion.

6. Preliminary design of the Beishan URL and in situ test planning

6.1. Preliminary design of the Beishan URL

6.1.1. Design principles

The design considerations of the Beishan URL include the development strategy of China's URL, URL type (i.e. an area-specific URL), URL functions, preliminary in situ test plan, operational safety and technical feasibility. The main design principles for the Beishan URL are as follows:

(1) The URL should enable detailed underground characterization of the host rock.
(2) The URL should enable a wide variety of R&D of concepts and technologies for the disposal of HLW in granite.
(3) The URL should be designed and constructed in a way that allows it become part of the potential repository. It should also preserve the flexibility in terms of the design, construction and operation of the potential repository. The experimental levels should be expandable, regarding future needs for area, logistics and ventilation.
(4) The URL should not have any negative effect on site conditions that are considered favorable for the disposal of HLW, and disturbances to the target host rock should be minimized.

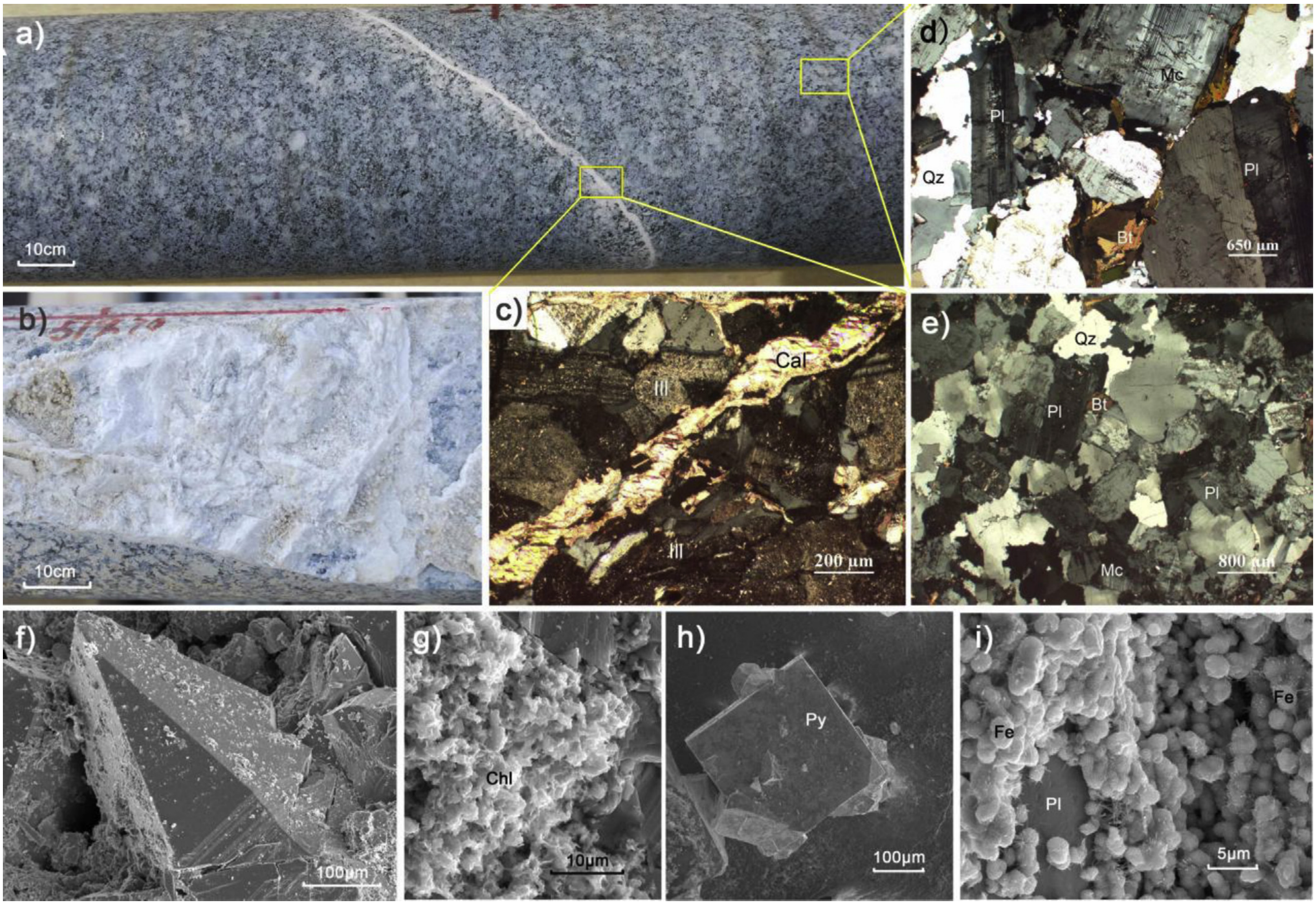


Fig. 18. (a, b) Photographs of drilled cores (c–e) transmissive micrographs, and (f–i) back-scattered scanning electron microscopy images. (a) The drilled core with a calcite-dominated fracture, from borehole BS33 at a depth of 271.2 m at the Xinchang site. (b) Calcite coating on a fracture surface in the drilled core from BS26 at a depth of 519.7 m. (c) A closed fracture filled with calcite ("Cal"), and slightly alteration of illitization ("Ill") close to the fracture and a thin section from the sample in photograph (a). (d) Medium-grained granodiorite with plagioclase ("Pl"), quartz ("Qz"), microcline ("Mc") and biotite ("Bt") occurring as major minerals, and a thin section from the sample in photograph (a). (e) Fine-grained granite, in a sample from borehole BS33 at a depth of 487.2 m. (f) Scalenohedral calcite in an open fracture and a spot of clays on the crystal surface at a depth of 368.5 m (borehole BS28). (g) Chlorite ("Chl") that has replaced biotite close to and at the fracture surface at a depth of 553.7 m (borehole BS06). (h) Cubic pyrite ("Py") crystal on the surface of a fracture at a depth of 527.1 m (borehole BS06). (i) Needle-shaped Fe-oxyhydroxide ("Fe") crystals on an open fracture surface at a depth of 462.2 m (borehole BS25).

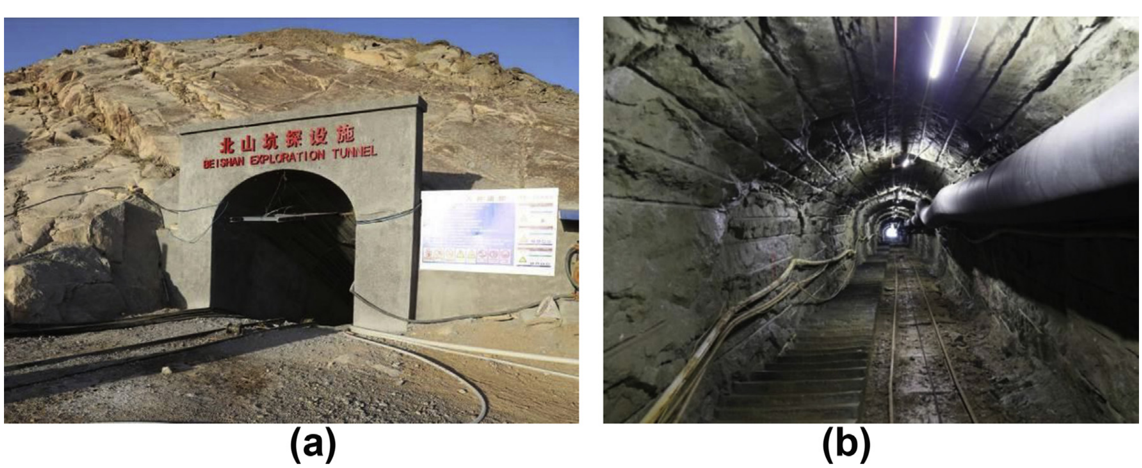


Fig. 19. Photographs of the BET showing (a) the entrance and (b) the ramp.

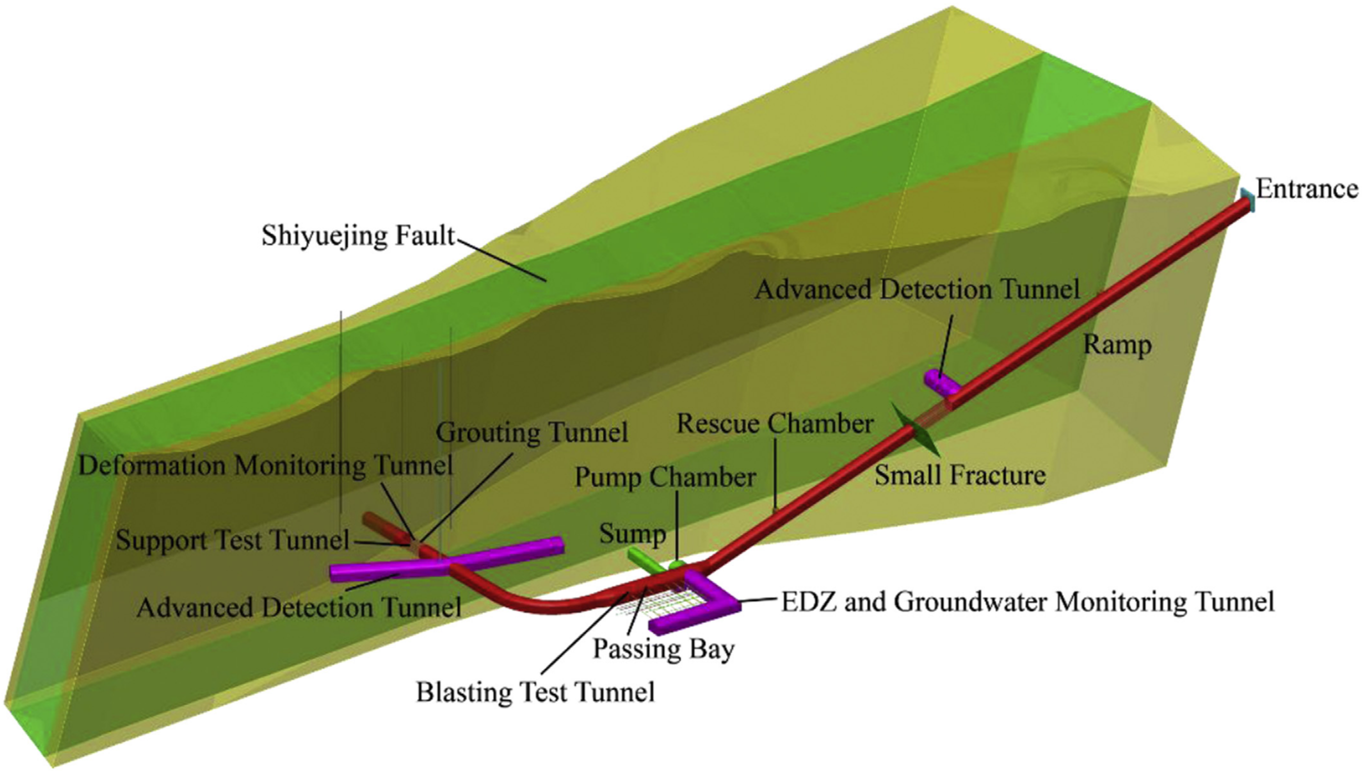


Fig. 20. Layout of in situ tests in the BET.

(5) Underground facilities must have at least two safety exits to the ground surface.
(6) The use of the URL for communication purposes should also be considered.

6.1.2. Preliminary design

According to the design principles and the experiences of URLs built in other countries and the specific engineering conditions at the Beishan site, three schemes of the underground structure for the Beishan URL were proposed, namely multi-shaft + multi-level tunnels, spiral ramp + multi-shaft + multi-level tunnels, and double ramps + single-level tunnels. More detailed investigations suggested that the second scheme mostly meets the key requirements for the URL. Therefore, the Beishan URL is preliminarily designed with one access ramp for material transport, three shafts for personnel transport and ventilation, and two-level tunnels for in situ experiments, as shown in Fig. 27.

The maximum depth of the Beishan URL is designed at −560 m. The access ramp will be 7970 m in length, with a cross-sectional diameter of 7 m, maximum inclination of 1:10 and maximum curve diameter of 400 m. Among the three shafts, one shaft with a diameter of 6 m is used for personnel transport and the other two with identical diameter of 3 m are for ventilation. From the shafts, horizontal tunnels will be constructed at two levels for in situ experiments, i.e. the main level at −560 m and the auxiliary level at −240 m.

The construction of the Beishan URL is expected to be completed within 6 years. The use of a tunnel boring machine (TBM) is proposed for the ramp excavation as it will less disturb the rock mass

Table 7
Research organizations and durations of in situ tests performed in the BET.

In situ test	Institution
3D fracture mapping and modeling	Beijing Research Institute of Uranium Geology (BRIUG)
In situ detection test of the unfavorable geological condition	China University of Mining and Technology (Beijing)
EDZ characterization and groundwater monitoring test	Institute of Rock and Soil Mechanics, Chinese Academy of Sciences
Deformation monitoring test of surrounding rocks	Engineering University of People's Liberation Army of China
Dynamic disaster monitoring	Sichuan University, and China University of Mining and Technology (Beijing)
Drill-and-blast test	Beijing Research Institute of Uranium Geology (BRIUG)
Grouting in BET	The Fourth Research and Design Engineering Corporation of CNNC
Advanced support in Shiyuejing fault	Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

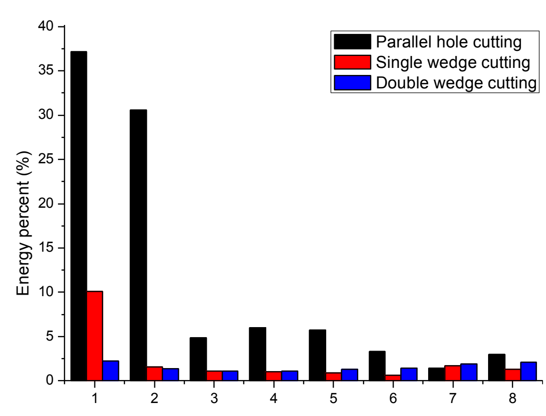


Fig. 21. Energy percent distribution diagram of different cutting patterns. 1: 0–31.25 Hz, 2: 31.25–62.5 Hz, 3: 62.5–93.75 Hz, 4: 93.75–125 Hz, 5: 125–156.25 Hz, 6: 156.25–187.5 Hz, 7: 187.5–218.75 Hz, and 8: 218.75–250 Hz.

Table 8
Recommended blasting parameters for the construction of the URL.

Parameter	Recommended value
Designed footage driving cycle	2 m
Charge structure	2 kg/m^3
Cutting pattern	Double wedge cutting
Surrounding hole distance	30 cm
Detonator type	Millisecond detonator
Detonator connection pattern	Series-parallel detonator connection
Surrounding hole pattern	Slit charge cartridge

and be faster and safer than traditional drill-and-blast excavation. Moreover, the use of TBM technology has been demonstrated to be feasible for excavation of the Beishan URL because adverse ground conditions (Ma et al., 2015, 2016), such as highly fractured zones, large inflow, mixed face ground and high in situ stresses, will hardly be encountered at the Xinchang site. The personnel shaft will be excavated using the drill-and-blast method, followed by the two ventilation shafts using the raise boring method.

6.2. R&D program in the Beishan URL

The technical R&D plan in the URL provides a basic guidance for URL construction and operation and plays an important role in implementation of the geological disposal program. The R&D plan of the Beishan URL is based on the national geological disposal program, the experience and lessons gained from other URLs in operation, the research requirements proposed by more than 20 relevant research organizations in China and extensive consultation with international experts. It is noted that the R&D plan will be periodically updated as research progresses.

6.2.1. Stages of the R&D program

As for some representative URLs, such as Äspö in Sweden, Meuse/Haute Marne in France and ONKALO in Finland, the research program is implemented in stages, with the main stages being pre-investigation stage before URL construction, URL construction stage and URL operation stage. According to the development of HLW disposal in China, activities in each research field will be implemented step by step, and the whole R&D program in the Beishan URL is divided into five stages:

(1) Stage 0: Baseline monitoring stage;
(2) Stage I: URL construction stage;
(3) Stage II: Short-term operation stage, 0–5 years after the completion of the URL construction;
(4) Stage III: Medium- and long-term operation stage, 5–20 years after the completion of the URL construction; and

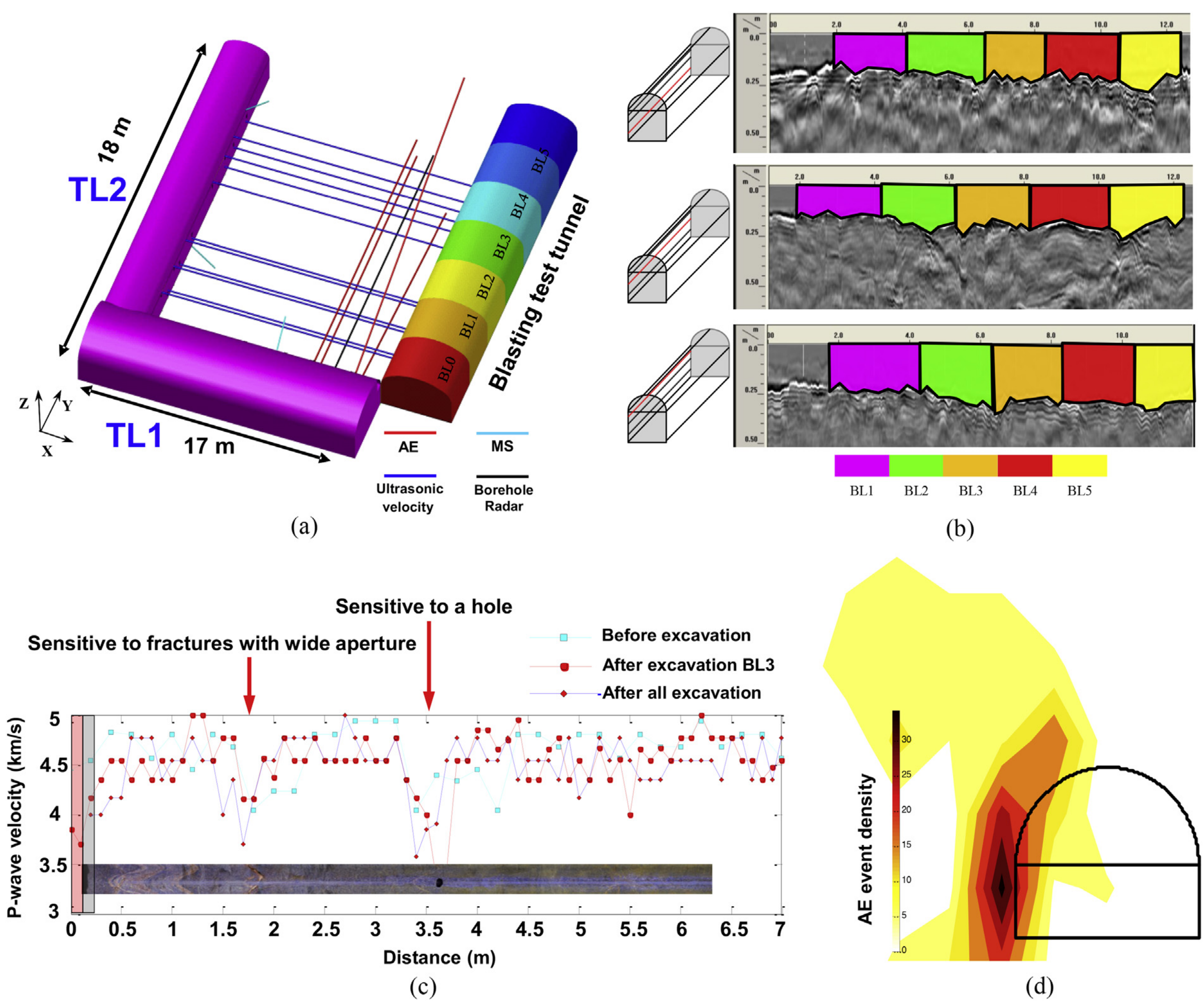


Fig. 22. In situ tests for EDZ characterization: (a) Distribution of monitoring boreholes, (b) GPR measurement, (c) P-wave velocity measurement, and (d) AE monitoring results (Chen et al., 2017b; Wang et al., 2017).

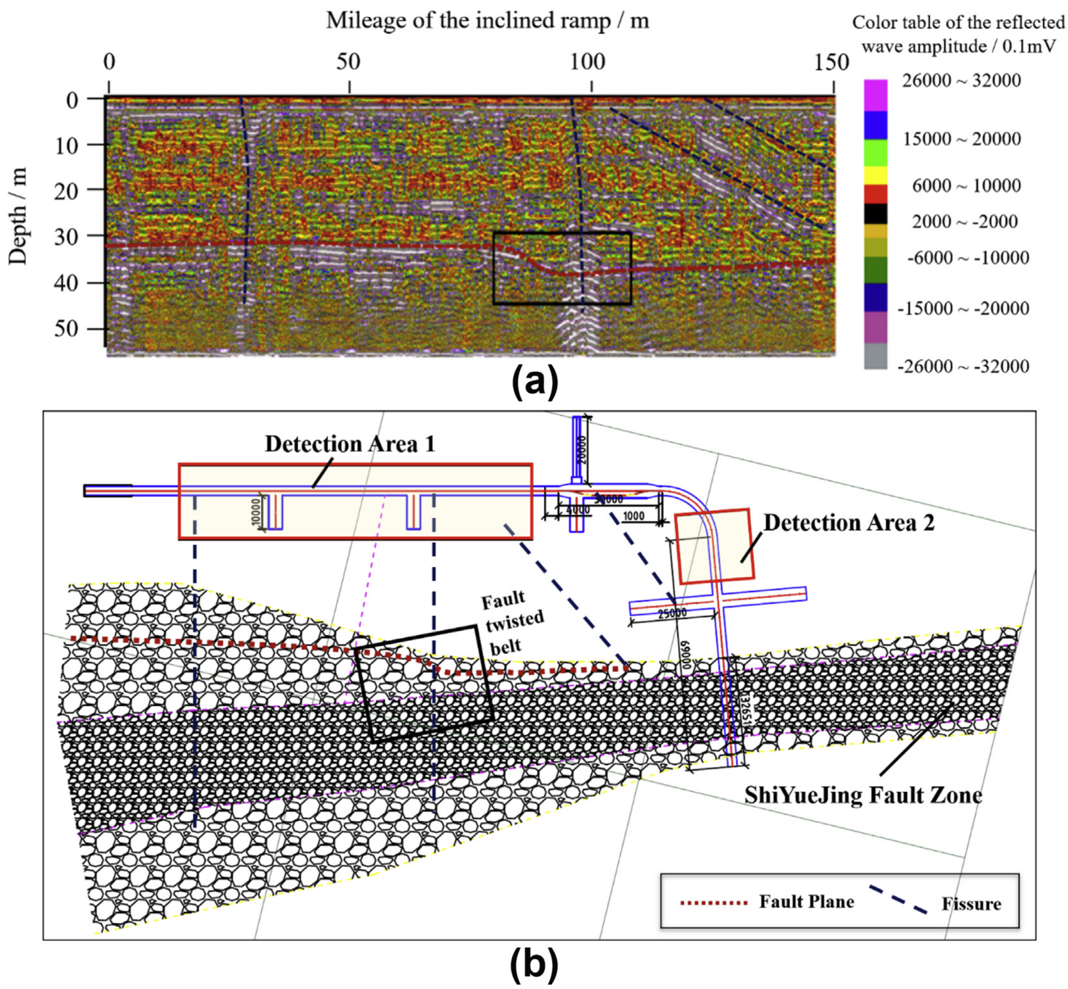


Fig. 23. Schematic diagram of fault detection on the inclined ramp: (a) Radar detection profile and geological interpretation results, and (b) An overview of the detection results.

(5) Stage IV: Forward operation stage, 20 years after the completion of URL construction.

6.2.2. Stage 0: Baseline monitoring

The main objectives of Stage 0 are to obtain the baseline data (e.g. initial geological, hydrological and ecological data), to establish the long-term monitoring system for the URL site and its surrounding environment, and to establish a rock suitability criterion system that will serve for repository design and construction. The rock suitability criterion system will be implemented, verified and optimized during URL construction and operation.

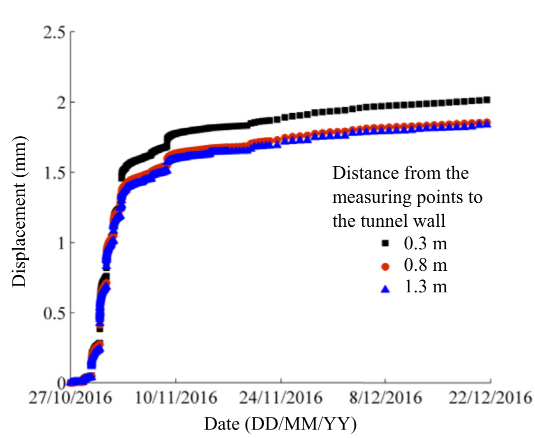


Fig. 24. Displacement of surrounding rocks after tunnel excavation.

6.2.3. Stage I: URL construction

The construction stage of the URL is important for site characterization with respect to investigation of hydromechanical responses of rock to excavation of the ramp and shafts. Additionally, it offers us a chance to verify construction technology, following the same rules that will be used in repository construction. The main objectives of Stage I are to perform site characterization, to develop and verify the methods of characterizing the deep geological environment, and to develop suitable construction technology for deep rock engineering.

In accordance with the research objectives, many tests focusing on site characterization and engineering technology will be performed during URL construction, as shown in Table 9. The test locations at the main experimental level of −560 m and along the ramp are respectively presented in Figs. 28 and 29. Site characterization activities, such as geological mapping, 3D laser scanning, geophysical exploration and rock mass quality evaluation, will continue along with ramp excavation. Activities related to engineering construction technology, such as TBM penetration test, in situ stress measurement, hydraulic test and EDZ evaluation, will be conducted along the ramp and at the level of −560 m. In parallel with the above activities, equipment to be used in Stage II will be

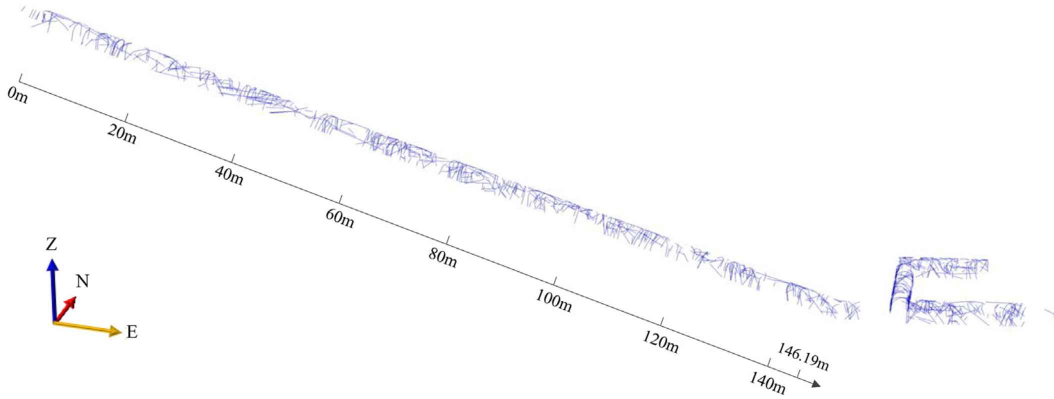


Fig. 25. 3D model of joint traces identified in the BET.

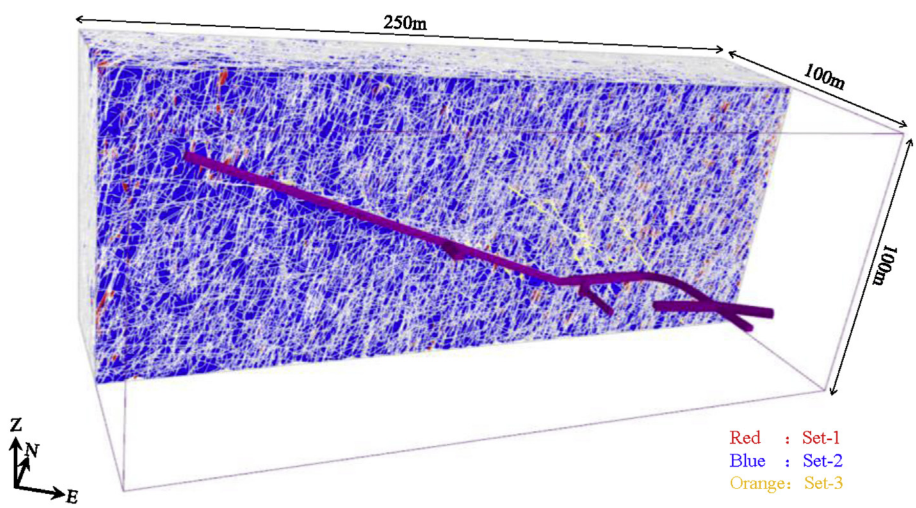


Fig. 26. 3D model of the joint network for the surrounding rock mass of the BET.

developed in surface laboratories and then tested in the URL, e.g. excavation equipment for the deposition hole, installation equipment for the buffer material, and equipment for radionuclide migration testing.

6.2.4. Stage II: Short-term operation

The main objectives of Stage II are to better understand the site with the aim to evaluate the site suitability for a repository, to understand the evolution mechanism of the long-term performance of a multi-barrier system step by step, and then to verify and optimize the conceptual model for HLW disposal and repository design.

The main test program in this stage will focus on detailed site characterization, different kinds of in situ tests for monitoring and understanding the long-term performance of multi-barrier (especially interactions between the engineering materials), demonstration of different excavation equipment for disposition holes and small-scale testing of key radionuclide migration. Activities of site confirmation for large-scale tests to be conducted in the next stage will also be performed according to the detailed site information. The main tests to be conducted in Stage II are listed in Table 10.

6.2.5. Stage III: Medium- and long-term operation

The main objectives of Stage III are to obtain the long-term performance parameters of multi-barrier systems for different waste types, to obtain radionuclide migration characteristics and reliable data for performance assessment, to develop and demonstrate disposal process technologies, and to establish an industrialized technology system for repository construction.

Most activities in this stage will focus on the full-scale tests of long-term performance of the engineered barrier system under

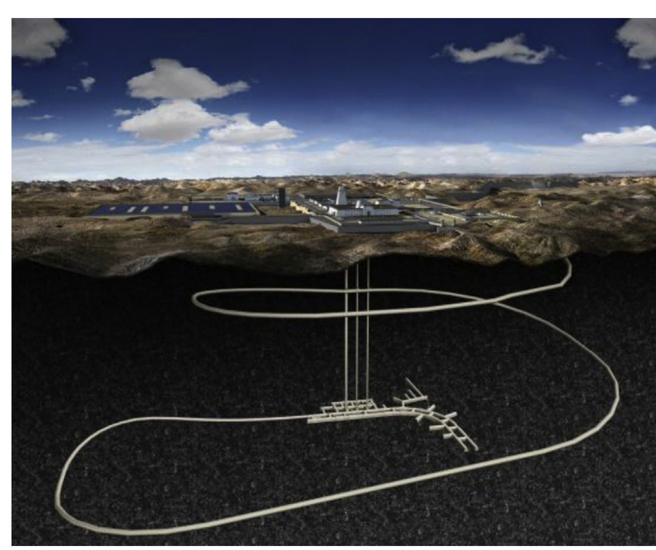


Fig. 27. Preliminary design of the Beishan URL with one access ramp, three shafts and experimental tunnels.

Table 9
Test program in Stage I.

Research field		Test program
Site characterization		(1) Geological mapping (2) Borehole hydraulic test in EDZ (3) Hydraulic test in faults and fractured zone (4) Geochemical properties in deep rock mass (5) Comprehensive geophysical exploration (6) 3D in situ stress measurement in deep rock mass (7) Detailed investigation of fracture in the rock mass of URL (8) Long-term monitoring of environment in the URL site
Engineering technology	Engineering construction	(1) Drill-and-blast test (2) TBM penetration test (3) EDZ evaluation test (4) Advanced detection technology test (5) In situ test of grouting technology (6) In situ test of rockburst tendency evaluation (7) Monitoring of long-term deformation of surrounding rock, and key parameters of supporting facilities
	Engineering barrier	Test of installation technology of buffer material
	Disposal process	Development of excavation equipment for deposition hole
Geological disposal chemical behavior		Technology verification for radionuclide migration test

thermo-hydro-mechanical-chemical (THMC) coupling conditions, large-scale tests of radionuclide migration and retardation studies under repository conditions that further clarify the mechanisms and support performance assessment models, and disposal process tests that demonstrate the engineering feasibility of the operation and closure of the repository, such as backfill and plug testing, canister retrieval testing and prototype repository demonstration testing. The main tests to be conducted in Stage III are listed in Table 11.

6.2.6. Stage IV: Forward operation

With comprehensive tests and verifications during the previous stages, the technologies developed for repository design and construction are supposed to fulfill the requirements. Hence, the demand for URL activities in Stage IV will decrease. The main activities in this stage will be of further investigations on the long-term performance of multi-barrier systems for different types of waste, prototype testing of final disposal, and long-term environment monitoring. Research activities provoked during repository construction will also be conducted in Stage IV.

7. Conclusions

(1) To ensure the sustainable development of nuclear energy in China, a three-phase long-term plan has been published to guide R&D for the geological disposal of HLW, with major

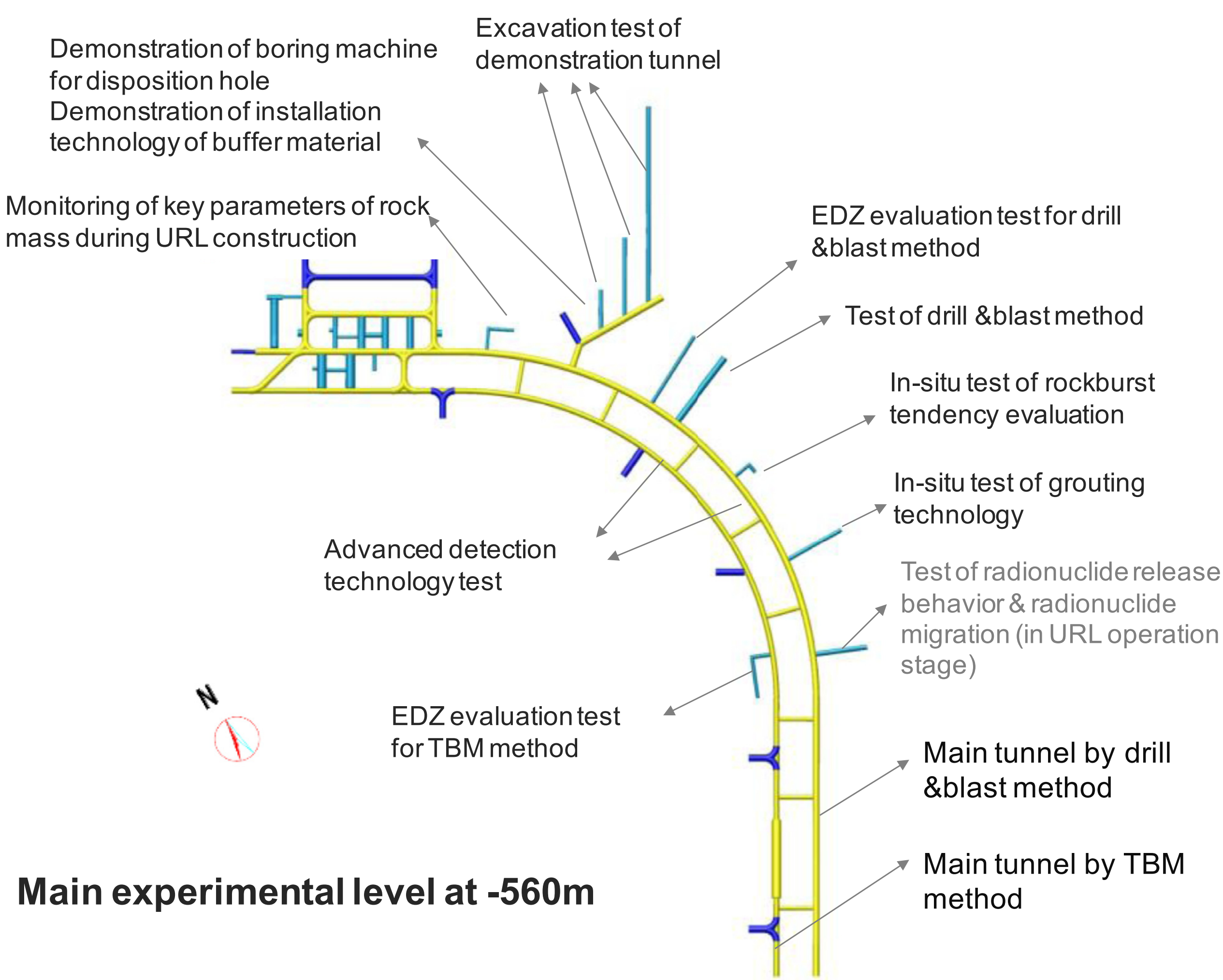


Fig. 28. Preliminary design of in situ tests to be conducted at the main experimental level of −560 m during URL construction.

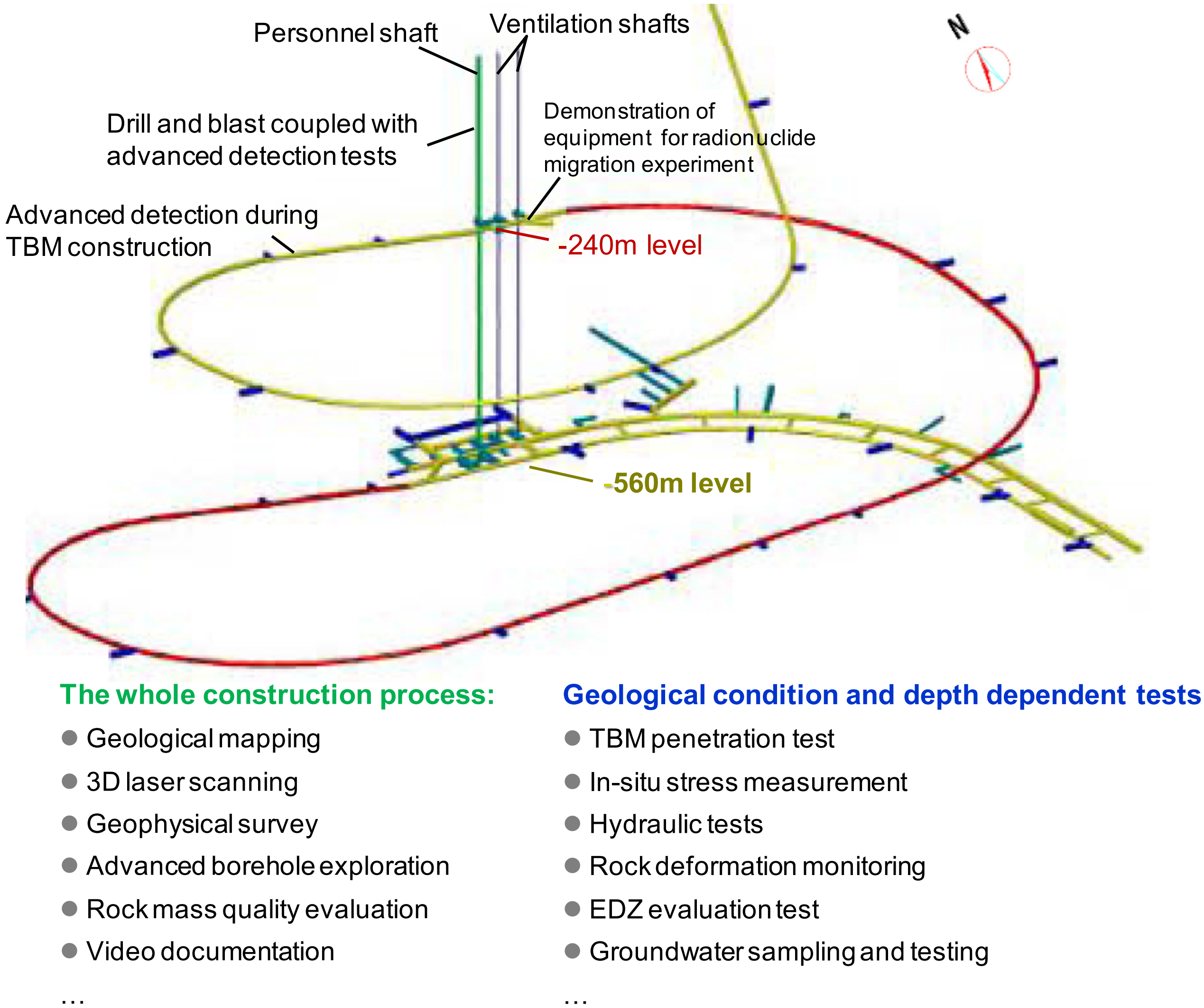


Fig. 29. Preliminary design of in situ tests to be conducted along the access ramp during URL construction.

milestones being to build a URL by 2020 and a national geological repository by 2050.

(2) A strategy and technical road map to develop China's URL have been proposed. The strategy is to build an area-specific URL in a representative granite formation within an area that has been identified as having the greatest potential for a geological repository in China. It will be a large-scale facility with full functionality, and will be about 560 m deep, similar to the future repository depth. The URL will serve for technology development and demonstration, site characterization and public acceptance, and will be open to domestic and international cooperation.

(3) Siting criteria for the URL have been proposed with basic considerations, excluding criteria and specific criteria. With the guidance of siting criteria and according to the achievements in site selection for the HLW repository in China, site selection for the URL has been successfully conducted since 2015. Nine candidate sites from the Beishan, Xinjiang and Inner Mongolia regions were selected for a comprehensive comparison. Finally, the Xinchang site in the Beishan region was recommended as the preferred site for the URL, while the Shazaoyuan site is considered as the back-up site. Hence, the first URL to be built in China is called the Beishan URL.

(4) Systematical site characterizations, including surface mapping, borehole drilling and tests, have been conducted at the Xinchang URL site since 2015. The objectives are to investigate rock types, faults, the fracture distribution and hydrogeological, geochemical and engineering geological conditions of the site, to establish a 3D geological model, and finally to provide necessary data for URL design, excavation, construction and future in situ tests in the URL. The results have identified that the major rock types at the Xinchang URL site are biotite monzonitic granite and biotite granodiorite, while the rock mass has high integrity, low fracture density, very low permeability and relatively low in situ stress. The geological, hydrogeological, geochemical and engineering conditions at depth have shown that the Xinchang site is favorable for the construction of a URL.

(5) To validate and develop construction and safety technologies for the Beishan URL, a small pilot underground facility called the BET has been built. The BET is a 50-m-deep facility, where different in situ tests, such as drill-and-blast tests, EDZ characterization, advanced detection of unfavorable geological conditions, deformation monitoring of surrounding rocks and 3D fracture mapping and modeling, have been conducted. The technology developed in the BET and the

Table 10
Test program in Stage II.

Research field		Test program
Site characterization		(1) Detailed investigation of site characteristics (geology, hydrogeology, geochemistry, etc.) (2) Long-term performance test of host rock under thermo-hydro-mechanical (THM) coupling condition (3) Monitoring of key parameters of host rock mass (4) Long-term monitoring of environment surrounding URL site
Engineering technology	Engineering construction	(1) EDZ study (EDZ damage and evolution characterization, sealing technology test) (2) Pillar stability test (3) Excavation test of deposition tunnel
	Engineered barrier	(1) Long-term performance test of buffer/backfill material (2) Long-term performance test of canister (3) THM coupling test of buffer material (4) Test of interaction between buffer material and canister
	Disposal process	(1) Development and demonstration of disposal equipment (excavation, drilling, installation, etc.) (2) Small-scale vertical/horizontal disposal tests
Geological disposal chemical behavior		(1) Radionuclide release behavior under simulated repository conditions (2) Small-scale test of key radionuclide migration

Table 11
Test program in Stage III.

Research field		Test program
Site characterization		(1) Two-phase flow test (2) Gas migration test (3) Long-term monitoring of key water-conducting fracture zone (4) Long-term monitoring of environment
Engineering technology	Engineering construction	(1) Test and demonstration of excavation technology of repository chambers (2) Test of remote monitoring technology of repository
	Engineering barrier	(1) Full-scale test of engineering barrier for HLW repository (2) Full-scale test of multi-barrier system under THMC conditions (3) Effects of microbiological, gas and organic substances on the long-term performance of buffer/backfill materials (4) Long-term performance test of multi-barrier system with different waste types
	Disposal process	(1) Horizontal disposal test (2) Backfill test (3) Plug test (4) Prototype test of final disposal (5) Canister retrieval test
Geological disposal chemical behavior		(1) Radionuclide release behavior test under repository condition (2) Large-scale test of radionuclide migration (3) Large-scale test of radionuclide retardation (4) Colloid and radionuclide retardation (5) Colloid formation and migration

experiences accumulated have provided technical preparations for the future Beishan URL.

(6) A design of one access ramp + three shafts + two-level tunnels has been proposed as the preliminary layout of the Beishan URL. The access ramp, which will be excavated by a TBM, has a length of 7970 m, a diameter of 7 m, a maximum inclination of 1:10 and a maximum curve diameter of 400 m. Among the three shafts, the one with a diameter of 6 m is used for personnel transport and the other two with the same diameter of 3 m are for ventilation. Furthermore, the URL contains two levels of tunnels, i.e. the main experimental level at −560 m and the auxiliary experimental level at −240 m. R&D programs during the construction and operation of the URL have been proposed.

All the efforts made in the past 33 years, all the achievements of site selection and site characterization at the Xinchang site, and all the developed and prepared technologies have laid a sound foundation for the development of China's first URL for the geological disposal of HLW, i.e. the Beishan URL. It is anticipated that the construction of the Beishan URL will soon begin, while the technologies and experience to be obtained from the URL will contribute greatly to the future success of a HLW geological repository in China and similar facilities around the world.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

The authors wish to thank the support from the China Atomic Energy Authority (CAEA) for China's URL Development Program and the Geological Disposal Program. The International Atomic Energy Agency is specially thanked for its support for China's geological disposal program through its Technical Cooperation Projects. Contributions from our colleagues from Beijing Research Institute of Uranium Geology, Drs. Honggang Zhao, Hongsu Ma, Jian Liu, Hui Luo, Ruili Ji, Ming Zhang, Zhichao Zhou, Ke Man and Hanping Wan, are highly appreciated.

References

Äikäs K, Riekkola R. Locating of the high level waste repository. Report YJT-95–19. Helsinki, Finland: Nuclear Waste Commission of Finnish Power Companies; 2000.

Ahn J, Apted MJ. Geological repository systems for safe disposal of spent nuclear fuels and radioactive waste. Cambridge, UK: Woodhead Publishing Limited; 2010.

Barton N, Lien R, Lunde J. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics 1974;6(4):189–236.

Bieniawski ZT. Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil and petroleum engineering. John Wiley & Sons, Inc; 1989.

China Atomic Energy Authority (CAEA). R&D guidelines for the geological disposal of high-level radioactive waste in China. Beijing: CAEA; 2006 (in Chinese).

Chen L, Wang J, Liu YM, Collin F, Xie JL. Numerical thermo-hydro-mechanical modeling of compacted bentonite in China-mock-up test for deep geological disposal. Journal of Rock Mechanics and Geotechnical Engineering 2012;4(2):183–92.

Chen L, Liu JF, Wang CP, Liu J, Su R, Wang J. Characterization of damage evolution in granite under compressive stress condition and its effect on permeability. International Journal of Rock Mechanics and Mining Sciences 2014;71:340–9.

Chen L, Wang CP, Liu JF, Liu J, Wang J, Jia Y, Shao JF. Damage and plastic deformation modeling of Beishan granite under compressive stress condition. Rock mechanics and Rock Engineering 2015a;48(4):1623–33.

Chen L, Wang J, Zong ZH, Liu J, Su R, Guo YH, Jin YX, Chen WM, Ji RL, Zhao HG, Wang XY, Tian X, Luo H, Zhang M. A new rock mass classification system Q_{HLW} for high-level radioactive waste disposal. Engineering Geology 2015b;190:33–51.

Chen L, Wang CP, Liu JF, Li Y, Liu J, Wang J. Effects of temperature and stress on the time-dependent behavior of Beishan granite. International Journal of Rock Mechanics and Mining Sciences 2017a;93:316–23.

Chen SW, Yang CH, Wang GB, Li EB, Chen L. Experimental study of acoustic emission monitoring in situ excavation damage zone of Beishan exploration tunnel. Rock and Soil Mechanics 2017b;38(Supp.2):349–58 (in Chinese).
Deere DU. Geological consideration. In: Stagg KG, Zienkiewicz OC, editors. Rock mechanics in engineering practice. New York: John Wiley & Sons; 1968. p. 1–20.
Delay J, Lebon P, Robours H. Meuse/Haute-Marne center: next steps towards a deep disposal facility. Journal of Rock Mechanics and Geotechnical Engineering 2010;2(1):52–70.
Fairhurst CE, Hudson JA. Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. International Journal of Rock Mechanics and Mining Sciences 1999;36(3):279–89.
Grimstad E, Barton N. Updating of the Q-system for NMT. In: Proceedings of the international symposium on sprayed concrete. Fagernes, Norway 1993:46–66.
Haimson BC. The hydrofracturing stress measurement method and recent field results. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 1978;15(4):167–78.
Hoek E. Practical rock engineering. Evert Hoek Consulting Engineer Inc; 2007. http://www.rocscience.com.
Hoek E, Kaiser PK, Bawden WF. Support of underground excavations in hard rock. Rotterdam: A.A. Balkema; 1995.
Ji RL, Zhang M, Zhou ZC, Li JB. Research on in situ hydraulic test method in Beishan pre-selected area. Uranium Geology 2018;34(1):53–9 (in Chinese).
Kickmaier W, McKinley I. A review of research carried out in European rock laboratories. Nuclear Engineering and Design 1997;176(1–2):75–81.
Liu J, Chen L, Wang CP, Li YW, Wang J. Effect of distance measures and validity indices on clustering of joint orientation data. Chinese Journal of Rock Mechanics and Engineering 2015;34(Supp.1):3151–9 (in Chinese).
Liu YM, Ma LK, Ke D, Cao SF, Xie JL, Zhao XG, Chen L, Zhang PP. Design and validation of the THMC China-Mock-Up test on buffer material for HLW disposal. Journal of Rock Mechanics and Geotechnical Engineering 2014;6(2):119–25.
Luo H, Wang J, Jiang S, Chen WM, Zhao HG, Jin YX. Study on 3D geological modeling of Xinchang potential underground laboratory site for high-level radioactive waste disposal. Uranium Geology 2017;33(3):178–83 (in Chinese).
Ma HS, Yin LJ, Gong QM, Wang J. TBM tunneling in mixed-face ground: problems and solutions. International Journal of Mining Science and Technology 2015;25(4):641–7.
Ma HS, Gong QM, Wang J, Yin LJ, Zhao XB. Study on the influence of confining stress on TBM performance in granite rock by linear cutting test. Tunnelling and Underground Space Technology 2016;57:145–50.
Mejías M, Renard P, Glenz D. Hydraulic testing of low-permeability formations: a case study in the granite of Cadalso de los Vidrios,. Spain. Engineering Geology 2009;107(3–4):88–97.
National Cooperative for the Disposal of Radioactive Waste (Nagra). Kristallin-I safety assessment report. Nagra Technical Report NTB-93–22. Wettingen, Switzerland: Nagra; 1994.
Nuclear Energy Agency (NEA). The role of underground laboratories in nuclear waste disposal programmes. Paris, France: Organisation for Economic Co-operation and Development (OECD); 2001.
Swedish Nuclear Fuel and Waste Management Co. (SKB). Processes in the repository evolution. SKB Technical Report TR-99–07. Stockholm, Sweden: SKB; 1999.
Su R, Zong ZH, Ji RL, Chen WM, Xu J, Wang J, Guo YH. Application of integrated borehole measurement techniques to hydrogeological characteristics evaluation of water-conductive fault. Chinese Journal of Rock Mechanics and Engineering 2007;26(Supp.2):3866–73 (in Chinese).
The State Council of China. The medium- and long-term plan of China nuclear power development (2011–2020). Beijing: The State Council of China; 2012 (in Chinese).
Tian X, Wang J, Chen WM, Jin YX, Luo H. Research advances and prospects of geochemical studies of fracture mineral for high level radioactive waste disposal. World Nuclear Geoscience 2014;31(Supp.1):268–74 (in Chinese).
Wang GB, Chen SW, Liu PJ. Research on the technology for EDZ evaluation, groundwater monitoring and fractured zone supporting. Wuhan, China: Institute of Rock and Soil Mechanics, Chinese Academy of Sciences 2017:11–55 (in Chinese).
Wang J. Key scientific challenges in geological disposal of high-level radioactive waste. Engineering Sciences 2007;5(4):45–50.
Wang J, Fan XH, Xu GQ, Zheng HL. Geological disposal of high-level radioactive waste in China: progress in the last decade (1991–2000). Beijing: Atomic Energy Press; 2004 (in Chinese).
Wang J. High-level radioactive waste disposal in China: update 2010. Journal of Rock Mechanics and Geotechnical Engineering 2010;2(1):1–11.
Wang J. On area-specific underground research laboratory for geological disposal of high level radioactive waste in China. Journal of Rock Mechanics and Geotechnical Engineering 2014;6(2):99–104.
Wang J, Chen WM, Su R, Guo YH, Jin YX. Geological disposal of high-level radioactive waste and its key scientific issues. Chinese Journal of Rock Mechanics and Engineering 2006;25(4):801–12 (in Chinese).
Zhang CL, Wang J, Su K. Concepts and tests for disposal of radioactive waste in deep geological formations. Chinese Journal of Rock Mechanics and Engineering 2006;25(4):750–68.
Zhao HG, Shao H, Kunz H, Wang J, Su R, Liu YM. Numerical analysis of thermal process in the near field around vertical disposal of high-level radioactive waste. Journal of Rock Mechanics and Geotechnical Engineering 2014a;6(1):55–60.
Zhao XG, Cai MF, Cai M. Considerations of rock dilation on modeling failure and deformation of hard rocks – a case study of the mine-by test tunnel in Canada. Journal of Rock Mechanics and Geotechnical Engineering 2010;2(4):338–49.
Zhao XG, Cai M, Wang J, Ma LK. Damage stress and acoustic emission characteristics of the Beishan granite. International Journal of Rock Mechanics and Mining Sciences 2013a;64:258–69.
Zhao XG, Wang J, Cai M, Ma LK, Zong ZH, Wang XY, Su R, Chen WM, Zhao HG, Chen QC, An QM, Qin XH, Ou MY, Zhao JS. In situ stress measurements and regional stress field assessment of the Beishan area, China. Engineering Geology 2013b;63:26–40.
Zhao XG, Wang J, Cai M, Cheng C, Ma LK, Su R, Zhao F, Li DJ. Influence of unloading rate on the strainburst characteristics of Beishan granite under true-triaxial unloading conditions. Rock Mechanics and Rock Engineering 2014b;47(2):467–83.
Zhao XG, Wang J, Qin XH, Cai M, Su R, He JG, Zong ZH, Ma LK, Ji RL, Zhang M, Zhang S, Yun L, Chen QC, Niu LL, An QM. In situ stress measurements and regional stress field assessment in the Xinjiang candidate area for China's HLW disposal. Engineering Geology 2015;197:42–56.
Zhao XG, Wang J, Chen F, Li PF, Ma LK, Xie JL, Liu YM. Experimental investigations on the thermal conductivity characteristics of Beishan granitic rocks for China's HLW disposal. Tectonophysics 2016;683:124–37.

Dr. Ju Wang obtained his BS degree from the Nanjing University in 1984, majored in Uranium Geology and Geochemistry. He started his career at the BRIUG in 1987, and then held a PhD degree in Geology from the BRIUG. Dr. Wang is now the Vice-President of the Beijing Research Institute of Uranium Geology (BRIUG), as well as the Head of the CNNC Key Laboratory on Geological Disposal of High-level Radioactive Waste. He is responsible for R&D project management and international cooperation. His current research focuses on geological disposal of high-level radioactive waste. He also held various positions for BRIUG's Environment Research Center as vice-director, senior scientist, project head and chief scientist from 1995 to 2004. Dr. Wang is currently the president of Commission on Radioactive Disposal of International Society for Rock Mechanics and Rock Engineering (ISRM), and the president of Commission on Waste Underground Disposal of the Chinese Society for Rock Mechanics and Engineering (CSRME).