Article

Application of Integrated Geophysical Methods for Site Suitability of Research Infrastructures (RIs) in China

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Abstract: Research Infrastructures (RIs) are essential to achieve excellence in innovative scientific research. However, because of limited land availability and specific geological requirements, evaluating the viability of a site for a new RI can be a challenging task. Stringent safety construction requirements include developing site-specific architectural and geoengineering solutions, minimizing construction disturbances, and reinforcing rock and soil in a timely fashion. For successful development of the RIs in China, such as the Daya Bay Neutrino Laboratory (DBNL) and the China Spallation Neutron Source (CSNS), an integrated approach of joint geophysical methods including the electrical resistivity tomography (ERT), controlled-source audio-frequency magneto telluric (CSAMT), gravity and seismic refraction methods, and geological mapping and surveys were carried out. Geophysical parameters, such as electrical resistivity, density, and seismic velocity, show inverse proportion to the degree of rock fracturing or weathering. The results show that the low values of geophysical parameters suggest the weathered/fractured rock, while high values reveal the fresh bedrock. The Engineering Geological Suitability Index (EGSI) value can represent the individual EGSI values at a constant and summed over varying depths. EGSI methodology is an improvement on the existing siting process and has been applied to CSNS. Our integrated approach provides clearer insight into the subsurface for site suitability of RIs in challenging geological engineering conditions and removes any ambiguity caused by a single geophysical parameter. The obtained geological knowledge of the area not only provides engineers with much-needed information about the construction conditions of a potential site but also gives scientists the opportunity to explore the local geology. In this study, we demonstrate our innovative approach for siting RIs, as demonstrated by the synthetic evaluation of the site location and utilization for two established RIs (DBNL and CSNS).

Keywords: research infrastructures (RIs); engineering geological conditions; integrated geophysical methods; Daya Bay neutrino laboratory (DBNL); China spallation neutron source (CSNS)

1. Introduction

This article is about large scientific research centers using high-tech and sensitive equipment, not “standard” research infrastructure available at universities, and gives a short definition in the sense of “facilities” that provide resources and services for the research communities to conduct research and foster innovation in their fields.

Research Infrastructures (RIs) play an important role in exploring the unknown geological conditions of the subsurface and represent an incomparable research asset [1].

While some smaller RIs are built by individual institutions, some instruments or facilities are large enough that they must be constructed and maintained by one or more national organizations [2–4]. These large-scale RIs (for distribution, see Figure 1a) provide many countries and scientists with the opportunity to explore both specialized and interdisciplinary topics [5–7]. During the planning stages for RIs, such as Homestake [8] and the Jinping Underground Laboratory (CJPL) [9], one of the main issues engineers faced was selecting a location site with the appropriate geological characteristics. Despite the fact that a lack of local geological knowledge can be problematic for RI developers, few studies have analyzed the siting of RIs from a geoenvironmental sustainability perspective [10].

Figure 1. (a) Distribution of RIs worldwide (location data from [11]). Some of the Chinese RI locations are labeled with numbers (1–9). The investigated sites DBNL and CSNS are labeled with numbers 1 and 3, respectively. (b) The view of the DBNL site environment before construction. (c) The view of the far hall in the DBNL site during construction. (d) The view of the CSNS site during construction. (e) The view of the CSNS site before construction.

Given the complex and variable geological conditions observed throughout China, an RI site assessment is not complete without subsurface geological data [11]. The local subsurface geological information is vital since it provides the site selection, which can, in turn, affect the ability of those using the RI facilities to achieve their scientific objectives [12,13]. In 1984, the results of the survey conducted at the Babaoshan active fault zone [14] played a role in determining the site of the Beijing Electron Positron Collider (BEPC), which opened in October of 1988 [15]. The China initiative Accelerator Driven System (CiADS) core device location and the High Elevation Cosmic Ray Observatory (LHAASO) site (see 5-2 in Table 1) were both moved to avoid fault zones and the corresponding complex hydrological conditions.

Because China is cognizant of social changes and developments, the country is investing heavily in strategic long-term scientific programs [21]. During the XI Five-Year period (2006–2010), China built twelve major science and technology RIs. China has 32 RIs that are either being constructed or are fully operational [22]. The XIII Five-Year Plan for the National Major Science and Technology Infrastructure Construction (2016–2020) proposes that by 2020, 55 major science and technology infrastructures will be either be up and running or in the process of being built [23]. Due to China's rapid socio-economic development, infrastructure is expected to grow strongly in the near future [24]. As such, there are very few ideal and fully appropriate sites with simple geological conditions that can meet the RI engineering requirements. During site selection of nine large-scale

RIs in areas with relatively complex geological conditions, it was a challenging task for the planners to efficiently obtain the local geological data that would determine whether the site was an appropriate RI location (Table 1 and Figure 1a). In the recent past, China has made much-needed scientific advancements for a large number of RIs having been planned recently [24].

Table 1. The nine large-scale RIs (corresponding to the RIs labeled with numbers in Figure 1a) in various stages of completion in China.

No	Name	Geological Characteristics	Location	Site Selection Periods	Investigation Result	Evaluation Result	Construction Period and Operation Result	Ref.
1	Daya Bay Neutrino Laboratory (DBNL)	Granite tunnel and hall	Daya Bay, Shenzhen	2005–2006	South limb of Paiyashan syncline, granite contact with Devonian sandstones. Four weathering troughs, 3 faults	Site suitability	2007–2011, 2013; innovative scientific outcomes	[16]
2	Jiangmen Underground Neutrino Observatory (JUNO)	Sandstone inclined shaft, granite shaft, and hall	Kaiping, Jiangmen	2011–2013	Granite contact with sandstone having complex fold	Site suitability	2014–2020, under construction	[17] et al.
3	China Spallation Neutron Source (CSNS)	Buried tunnel and basement in compound gneiss and granite	Dalang, Dongguan	2006–2009	Weathering profile with 50 m thickness troughs, and 4 faults	Site suitability	2010–2016, in operation	[10,17]
4	High Energy Photon Source Test Facility (HEPS)	Buried tunnel and basement in sandy gravel layer	Huairou, Beijing	2011–2017	300m sandy gravels over granite and fractured pyroclastic rocks in west of Gaoliying active fault	Site foundation (medium complex)	Abandoned due to granite margin, afterward, a site was selected 5 km north ward with larger area of granite in 2018, currently under construction	[17,18]
5-1	High Altitude Cosmic Ray Observatory (LHAASO)	Mudstone, limestone basement, and slope	Zhongdian, Yun'nan	2013	Over 118 sinkholes, 12 water-accumulating depressions, landslides and sand slopes, 4 uphill routes	unsuitable	Abandoned due to karst development	[18]
5-2	High Altitude Cosmic Ray Observatory (LHAASO)	Granite basement and slope	Daocheng, Sichuan	2013–2014	Glacier remnants of plateau ice cap, riverside beach	Medium suitable	2016, currently under construction	[17]
6-1	High-Intensity Accelerator Facility (HIAF) and Accelerator Driven System (ADS)	Sandstone basement and slope	Dongsheng, Inner Mongolia	2012	Strong permeability of rock mass, storage of surface flood	unsuitable	To consider other places, including Shandong, Jiangsu, and Guangdong	[17]
6-2	High-Intensity Accelerator Facility (HIAF) and Accelerator Driven System (ADS)	Dacite, Pyroclastic rocks basement, and slope	Huizhou, Guangdong	2014	Strong permeability of rock mass and 40m weathering profile	Medium suitable	Under construction	[19]
7	Circular Electron-Positron Collider (CPEC)	Granite tunnel	Zhangjiakou, Chengde, qinghuangdao, Guangdong	2013–present	Soft Foundation, Uneven Settlement and Moving Head Treatment	Funing granite in Qinhuangdao, Huizhou granite	Site selection	[17]
8	Five-hundred meters Aperture Spherical Telescope (FAST)	Limestone basement	Pingtang, Guizhou	2006–2007	Karst depression with a diameter of 500 m	Basement stability and runoff discharge	2008–2013, in operation	[20]
9	Jinping underground laboratory(CJPL)	Marble tunnel	Jinping, Sichuan	2008	High geostress and rock burst	2400 m deep incomplete marble	2009–2010, in operation	[9]

To visualize geological structures and identify harmful geological bodies in advance, engineers often develop geological planes and section drawings in order to properly site the RIs. For capturing some of the key risk factors for the purposes of a comparison of

repository sites, a brief commentary highlighting contrasts between onshore and offshore locations in relation to multiple factors has been a primary issue [25]. With high-quality geological site data, a crystalline rock mass for hydraulic stimulation experiments can be evaluated [19]. The digital elevation models (DEMs) and spatial resolution are important issues in geomorphic studies. However, the highest accuracy can be attained from the sampled 30 m LiDAR DEM derivatives, indicating that fine-resolution topographic data do not necessarily achieve the best performance [26]. We introduce a variable weight-analytical hierarchy process-comprehensive index model to evaluate the land suitability for agriculture and construction, which can provide some geological basis to utilize the regional zoning in the future [27].

Integration of two or more geophysical methods coupled with local geological data has proved to be very successful in geotechnical investigations. Our main goal is the integral evaluation of two construction sites (e.g., Daya Bay Neutrino Laboratory (DBNL) and the China Spallation Neutron Source (CSNS)) through several geophysical methods (e.g., electrical resistivity tomography (ERT), controlled-source audio-frequency magneto telluric (CSAMT), gravity and seismic refraction methods), supported by the classical geological surveys including digital drilling analyses, geological structural modeling, engineering testing, and the problematic geological subsurface imaging.

2. RIs Requirements and Approaches

Site selection for large RIs requires geotechnical analyses that ensure the long-term stability of the area beneath and around the RI site. Site selection has been an important topic for the setup of new RI [28]. Previous RI plantings have applied standard geological and geophysical methods and may have followed the systematic procedures by adhering to industrial defined norms. However, this is a rare study reported in China that provides site suitability for RIs development using a systematic methodology via integration of four geophysical methods and systematic parameters describing the suitability by indices. This new field of inquiry will require comprehensive case studies at multiple locations before the methodology is robust enough for wider application worldwide.

Our RI site selection investigation was applied at two Chinese RIs (e.g., the Daya Bay Neutrino Laboratory (DBNL) and the China Spallation Neutron Source (CSNS)). The study of two RIs sites revealed that the geological structure and the structural plane of the rock mass could disturb the mechanical balance of the geological body, which may result in weakening of the geological body and in reducing the stability of the engineered structures at the sites.

From the approach called jade carving in China (i.e., maximum utilization of a highly heterogeneous site) to deal with unfavorable constraints, we incorporated geological surveys, geophysical exploration, and information system technologies into the project analysis at two sites. The geotechnical analysis was undertaken for siting purposes prior to the construction of the main facilities. Table 2 shows the timeline for engineering site selection of the RIs.

Table 2. Timeline for engineering site selection of the RIs.

Phase	Name	Evaluation	Objectives	Main Problems
1	Site selection	Suitability	Geological model	Discontinuity
2	Plan and design	Feasibility	Parameters	Discrete layers
3	Construction	Disturbance	Materials	Unfavorable geological body
4	Operation	Reliability	Rebalance	Complex site evolution

3. Geological Conditions

Geomorphologically, the RIs potential sites (CSNS, DBNL, JUNO, HIAF and ADS, HEPS, and LHAASO) can be categorized as consisting of plains, hills, mountains, or plateaus, with elevations a.s.l ranging from tens of meters to more than 4000 m. The geology of these sites is typically composed of sandy gravel soil, volcanic rocks, granite,

gneiss, and marble. The host rocks were identified with problematic geological bodies, such as saprolites (i.e., residual soils and completely decomposed granites), fractured rocks, and mud layers. Additionally, intermediate acidic dykes are susceptible to fracturing under weathering and geostress.

The DBNL site is composed of Yanshanian (Cretaceous) medium-coarse grained granite and Devonian sandstone. The former occurs as one shallow intrusion at the north wing of one anticline, whereas the sandstone appeared as a capping layer sporadically exposed on the top of granites. The DBNL site is found at the southern slope of the mountain and anticline in the east–west. Several faults of small scale occur in the DBNL site trending in the east–west and south–north [29]. The CSNS site is composed of Yanshanian (Cretaceous) coarse-grained granite (northern part) and Sinian gneiss (Southern part). The intrusive contact between these rock bodies is located in the east–west, where diorite porphyrite intrusion is found along the contact zone. Small scale faults in the direction of east–west are seldom seen [30].

For a better understanding of the host rocks, we conducted microscopic, textural [29,30], physical, mechanical, and hydrogeological sample analysis from the two RI sites. Moreover, we drilled some boreholes for granites (from DBNL and CSNS sites) and gneisses (CSNS site) to acquire the local geological knowledge. Long borehole cores, up to 1.7 m in length, ensured that we were reliably obtaining the essential subsurface characteristics for each RI site (Figure 2). The examples of encountering the underlying complex geological bodies during the RIs development (Table 1 and Figure 1a) include karst caves (LHAASO site) moving from the Shikashanin Yun’nan Province to Daocheng in Sichuan Province [31], large uneven subsidence (HEPS site) moving northward by nearly 5 km to the plain area at Huairou [18], and water-rich fracture zones (ADS site) moving with tens of meters towards the north [19]. As the host rocks of the two sites (CSNS and DBNL) are mainly granite and gneiss, the subsurface geology is more complicated. The case studies of these two sites were undertaken in an effort to better understand the complex geological settings in order to facilitate the RI siting process. We used integrated geophysical techniques at the DBNL site because boreholes are unsuitable for assessing the deep geologic structures in a steep slope area. Similarly, we employed the EGSi index to analyze the shallow subsurface at the CSNS site. Our interpreted model results show a strong correlation with the local geological conditions, and our recommendations were implemented in the construction of these two sites.

Figure 2. Drilled cores from borehole ZZK23 used to locate the ring accelerator at the CSNS site.

4. Methods

Engineering geologists deal with nature in its intrinsic variability and complexity; thus, geologic uncertainties should be recognized and quantified, and considered in engineering design and construction with the help of advanced technical tools [12]. High-resolution 3D geological models corresponding to the numerical simulations are crucial for underground development projects [19]. In addition to the existing maps, the use of remote sensing data is very helpful to investigate the topographic and geomorphological conditions of potential RI sites. The site suitability for siting the RI at DBNL was performed by the geophysical methods, such as ERT, Seismic refraction, gravity, and CSAMT. Whereas the CSNS site for the RI development was assessed using the rock mass integrity indices, such as rock quality designation (RQD), rock core index (RCI), and the Engineering Geological Suitability Index (EGSI).

4.1. Geophysical Surveys

We used electrical resistivity tomography and seismic refraction techniques to evaluate the shallow subsurface formations, whereas the CSAMT and gravity techniques were performed to assess geologic formations at large depths. The joint geophysical approach of gravity and seismic reflection methods for the fast, large-scale characterization of hydrogeological potential was used in the Ain El Beidha plain (central Tunisia) [32]. The geophysical methods such as gravity and magnetic are usually implemented by the 2D grid because they use simple equipment and are the cheapest. The inversions of these methods were developed in 2D and 3D framework architecture [33]. ERT and CSAMT measure electrical resistivity with a unit of Ωm . Electrical resistivity is often employed to differentiate subsurface rocks from one another because it is sensitive to changes in the composition, clay content, water content, porosity, and degree of fracturing in different rock samples. Furthermore, low resistivity values are closely associated with weathering troughs and fractured rocks, which may indicate the presence of significant groundwater resources, whereas high resistivity suggests fresh rock [34–38]. Compared to the traditional electrical methods, the ERT provides higher resolution results at shallower depths. The ERT was conducted using a McOHM 21 (produced by the OYO Company of Japan), and the data were processed with the Gauss–Newton least squares method. ERT was performed along a profile from south to northwest with a total of 381 electrodes, spread length of 1900 m, and electrode interval of 5 m (Figure 3a). ERT evaluated the subsurface layers with a maximum depth of 300 m. The seismic refraction provides insight into the seismic velocities (in m/s) of the rocks sampled by the seismic waves. The seismic velocity is inversely proportional to the degree of rock fracturing or weathering. Thus, high seismic velocity suggests the unweathered rock, whereas low seismic velocity reveals the rock mass of poor quality. The seismic refraction data were acquired using a 24-channel McSeis-F170 (OYO Company of Japan) with 1.024 sampling points, a sampling interval of 0.05 ms, a geophone interval of 5 m, and a shot point interval of 30 m. The seismic refraction survey was carried out along two profiles with a total length of 690 m and an investigation depth of 100–150 m (Figure 3a). Gravimetric data provide information about the rock densities (in g/cm^3) in the gravity survey. The high precision gravity survey was performed along the ERT profile using the CG-3 gravity meter manufactured by Scintrex (Canada) to acquire gravitational data at seven repeated observation checkpoints with a data point distance of 10 m. The 2D gravity model of 1820 m exploration length provides investigation depth over 400 m (Figure 3a). The weathered/fractured rock is delineated by a low value of density, while the fresh rock is evaluated by high density. The electrical resistivity tomography data and the gravimetric data were collected along the center line of all tunnels with a horizontal position error of less than 3 m (mostly within 50 cm) and an elevation error of less than 5 cm.

Figure 3. Geophysical exploration surveys and interpreted profiles at the DBNL site. (a) Layout of the geophysical exploration profiles along the tunneling line. (b–f) Interpreted profiles using different geophysical methods, such as seismic refraction analyses of the (b) mid hall and (c) far hall, (d) electrical resistivity tomography analyses of the west and far halls, (e) gravimetric analyses, and (f) electromagnetic resistivity analyses (CSAMT).

CSAMT is a frequency domain electromagnetic (EM) method that uses a grounded dipole or loops to generate repetitive signals. CSAMT data were obtained from electric and magnetic fields oriented along and perpendicular to the traverse line, respectively. Originally, we planned to use CSAMT to acquire data along the ERT profile; however, because of the sensitivity of the instrument to the high voltage power lines (present in the southern region of our study area), we only conducted the gravity survey along all of the tunnel lines. Therefore, the CSAMT profile was performed with a short length of 720 m on the north side of the ERT profile (Figure 3a). We assessed the surface and subsurface conditions using geophysical exploration techniques before borehole drilling. With a variety of geophysical exploration methods available, the feasibility, cost, and data quality must be considered prior to the use of geophysical surveys in order to identify problematic geological bodies that could impact the siting or engineering design of the RI site.

4.2. Site Suitability Evaluation Based on Multi-Factors

We can quantify the required engineering adaptability, as characterized by RI structural matching. Ideally, we identify areas that can be built and reinforced efficiently with stable rock masses that are minimally disturbed by problematic geological bodies. The timely reinforcement countermeasure test [39] steers our analysis away from areas with a high likelihood of irreversible deformation and failure, which is vital in the planning and construction of large scientific installations. By combining the data from the geological surveys, digital drilling analyses, geological structural modeling, and problematic geological body mapping, as well as engineering testing, we created a scaled 3D model of CSNS that demonstrates how the engineering structural layout is affected by changes in geological conditions [40,41] such as weathering and rock mass integrity.

The rock mass integrity was classified based on Rock Quality Designation (RQD) and Rock Core Index (RCI). RQD is measured in percentage from the core samples of a borehole, in which the combination of core pieces of solid rock over 10 cm (4 in.) is divided by the core run length. Thus, RQD is actually a measure of the percentage of the solid rock mass. In addition to calculating the RQD values for the rock masses in samples from the drilled cores, we also employed the Rock Core Index (RCI) as a way to describe the integrity of the cored samples [42]. The RCI defines the continuity of the core sample (and the rock mass it sampled):

$$RCI = 1 \times Cr_1 + 3 \times Cr_3 + 10 \times Cr_{10} + 30 \times Cr_{30} + 50 \times Cr_{50} + 100 \times Cr_{100} \quad (1)$$

where Cr is the core acquisition rate for different drilled core lengths [31]. Cr_1 , Cr_3 , Cr_{10} , Cr_{30} , Cr_{50} , and Cr_{100} represent the proportion of the core sections with lengths that fall into intervals of 1~3 cm, 3~10 cm, 10~30 cm, 30~50 cm, 50~100 cm, and greater than 100 cm, respectively. For example, if the total core length is 250 cm, and 100 cm of that core is in sections with lengths that fall in the 10~30 cm interval, and the remaining 150 cm of the core has lengths that are greater than 100 cm (i.e., the remaining 150 cm of the core is completely intact), then Cr_{30} is 0.4 and Cr_{100} is 0.6, and the final, RCI value is 72. The numerical constants in the RCI equation are effectively weights so that cores with longer intact sections will have higher RCI values.

We also tested the water sensitivity and dynamic disturbance response of some problematic geological bodies (e.g., fault gouges, weathered rocks, etc.) at the CSNS site; both characteristics can greatly affect the site stability, the construction quality control measures, and the engineering reinforcement implementation. Each of these analyses represents a single factor in the calculation of the Engineering Geological Suitability Index (EGSI):

$$EGSI = \sum w_i f_i(x, y) \quad (2)$$

where w_i is the weight ratio of influential factors, $f_i(x, y)$ is the normalized single factor influential function value, which ranges from 0 to 1, and each factor is evaluated at geographical coordinates (x, y) . In plane map models, an EGSI value can represent the individual EGSI values at a constant (x, y) and sum over varying depths. EGSI takes its role as one important parameter for quantifying rock mass quality in the Hoek–Brown criterion [43]. The EGSI chart is based on qualitative geological observations regarding the degree of fracturing and surface condition of joints. The software GOCAD (Geological Object Computer-Aided Design) Version 2011 provides a powerful geostatistical analysis module. GOCAD is a registered trademark (GOCAD (TM) (Mira Geoscience Ltd., Montreal, QC, Canada) [44,45]. It uses the measured data as the attribute volume, assigns each point in 3D space, and then carries out appropriate interpolation for the establishment of 3D attribute volume to assist in the 3D visual query [46].

We comprehensively use the EGSI to evaluate the geological conditions and determine how they might affect the engineering site. The EGSI quantifies the suitability of the conditions for construction and operation of the RI facility at a given site [47]. Using the EGSI methodology is an improvement on the existing siting process, which relies heavily

on subjective data and impressions. We can calculate the *EGSI* on large spatial scales (to identify RI locations) and small spatial scales (to identify where certain instruments should be located within the RI site) [48]. If the geotechnical parameters are sound, we can reasonably expect the long-term, stable, and efficient operation of the RI facilities. The purpose of normalization is to eliminate the unbalanced contributions of different factors to the ultimate result in order to make the data statistically comparable. Using the *EGSI*, the CSNS site was evaluated for suitability zonation, geohazards susceptibility, basement stability, standard penetration, weathered rock thickness, quaternary thickness, main lithology, and the slope gradient (Figure 4).

Figure 4. Geological suitability zonation at the CSNS site for different indices, such as (a) suitability zonation, (b) geohazards susceptibility, (c) basement stability, (d) standard penetration, (e) weathering thickness, (f) quaternary thickness, (g) main lithology, and (h) slope gradient at the CSNS site.

5. Results and Discussion

We investigated six RI sites in different parts of China. Currently, most of the RI sites are being built according to our recommendations. In this study, we focused on two sites (DBNL and CSNS) where construction is complete, and the RIs are now fully operational. Because each site has its own complexities, we investigated these two locations using slightly different approaches. We used integrated geophysical techniques at the DBNL site because boreholes are unsuitable for assessing the deep geologic structures in a steep slope area. Similarly, we employed the EGSI index to analyze the shallow subsurface at the CSNS site. Our interpreted model results show a strong correlation with the local geological conditions, and our recommendations were implemented in the construction of these two sites. The results of the investigations at each site are summarized below.

5.1. DBNL Site

DBNL is an RI site that focuses on neutrino research. The four laboratories (East Hall, Central Hall, West Hall, and Far Hall) of the Chinese Academy of Sciences at the DBNL site are connected by tunnels (Table 3). Because these tunnels are located underground, it was vital to understand the subsurface geological structures prior to tunnel design and construction. The electric resistivity, gravity, and seismic refraction results for this site, including the different lithologies and faults, are shown in Figure 3. The seismic refraction and high-density electrical analyses reveal information about the surficial and sub-surficial geologic features, while gravimetric and CSAMT data are employed to draw conclusions about geological features at depth. However, because of the limitations inherent in these different geophysical methods, the shallower subsurface data are more robust than the data gathered at deeper depths.

Table 3. Location of observation laboratory halls and boreholes at the DBNL site.

Lab Hall	Bottom/Surface Elevation (m)	Buried Thickness (m)	Point Distance-DaYa/Left Central Point (m)	Line Distance-LingAo/Left Central Point (m)	Drilling Depth (m)
West	−23.00/88	121	361.071/E41	—	ZK4 133
Central	−20.57/198	218	1155.604	871.340	ZK2 210.6
East	−19.17/98	117	—	445.35/W52	ZK3 130.3
Far	−17.87/347	364	1985.697	1598.572	ZK1 213.1

The results obtained from the two seismic refraction profiles, the CSAMT profile and the gravity profile, confirm the electrical resistivity tomography observations, where the low resistivity values are found in the low velocity/density layer (Figure 3). The comparison between the quantitative inversion gravity profile and the electrical resistivity tomography profile shows that the central section at the location of the Kaishuiyan ditch (located at a distance of 1.200 m on the profiles) includes a high-angle fault (F6 in Figure 3); however, the ditch is revealed at depth by the electrical resistivity tomography. The faults (F1, F5, and F6 in Figure 3), weathering troughs (2, 3, and 4 in Figure 3), and rock contact locations constrained by ERT are consistent with those indicated by the Bouguer anomalies on the gravity profile. However, the location of F₆ and weathering troughs 2 and 3 on the gravity section is further north than it is on the electrical section; this is because of the different nature of these parameters (density and resistivity). The maximum depth of the weathering troughs is only 120 m below the surface. The rock mass passing through the tunnel at depth is generally slightly weathered or fresh rock. The 1500 m difference between the depth of the sedimentary rocks on the original anticline covering the granite and the granite outcrop in surface maps represents the erosional thickness, or the difference between the physical depth and the geological depth [49]. The two geophysical methods (CSAMT and ERT) indicate the contact belt between the Devonian sedimentary rock and

the granite intrusion with inclined angle (or steeper depth), as shown in Figure 3d,f). Therefore, at an elevation of -17 m within the granite intrusion about 50 m south of the contact belt, most of the rocks are found highly resistive and dense, which was designed for sitting in the far hall. The seismic velocity varies between 300 and 3.000 m/s, and the weathering troughs 2 and 3 were delineated with a seismic velocity of less than 2500 m/s. Electrical resistivity in the ERT model ranges from 10 to 13,500 Ωm , and the weathering troughs and faults were detected with a resistivity less than 500 Ωm . Density in the gravity profile varies from 1.9 to 2.7 g/cm^3 , and the fault is delineated by density less than 2 g/cm^3 and the weathering troughs with density between 2.3 and 2.4 g/cm^3 . Electrical resistivity along the CSAMT profile varies from 200 to 27,000 Ωm , and the weathered/fault zones are revealed with a resistivity less than 500 Ωm . Our integrated geophysical exploration results indicate that several laboratories are located on sites with favorable geological conditions, but the conditions of the tunnels connecting the labs fall along faults and weathering troughs and may experience a small amount of water seepage. Compared to the known existing conditions at this RI, our assessment is more than 85% accurate, demonstrating that our analyses can provide information relevant to laboratory design and tunnel construction safety.

We also determined the geotechnical composition and static and dynamic mechanical parameters of the granite and gravel soil both in situ and in the laboratory; knowing these parameters can prove helpful when it comes to engineering designs and instrument debugging. After monitoring the long-term deformation of the problematic geological body, our proposed engineering countermeasures mitigated any possible deformation from the tunneling process to the point where the safety and stability of the project are not threatened in the future. In order to avoid the fault zone and its corresponding stress concentration zone, we recommended that the remote observation hall (far hall) of the DBNL be located at least 50 m away from the contact belt, leaving a section of the tunnel terminal with a length of nearly 30 m, where a slight rock burst occurred during the excavation (Figure 3f).

5.2. CSNS Site

The rocks exposed at the surface of the 400 mu (266,800 m^2) site, known as the SIA (Site Installation Area), are mainly composed of unconsolidated Quaternary sediments, Cretaceous granite, and Sinian gneiss. The potential geotechnical issues for this RI consist of slope instability and uneven foundation settlement. After dividing the 400 mu area (the SIA) of the CSNS site into 12,086 sub-units, we calculated the *EGSI* value for each sub-unit. Using the standard mining method, we used the *EGSI* value and the size of each sub-unit to divide the SIA into engineering geological suitability zones per the natural breaks (Jenks) method in ArcGIS [50]. An example of this approach for the CSNS site is shown in Figure 4, guided by the *EGSI* index.

We used the ArcGIS software to quantify the factors that might affect the area's stability and suitability, such as potential geohazards (mainly landslides), suitability zonation, basement stability, standard penetration, weathering thicknesses, unconsolidated Quaternary sediment layer thicknesses, rock lithologies, and slope gradation (Figure 4). ArcGIS is a registered trademark of ESRI (Environmental Systems Research Institute) (ArcGIS (TM) [51]). This zoning map incorporates various influencing factors of the potential RI site; these factors provide actionable advice for designing and constructing the RI. As shown in Figure 4, the engineering geological suitability of the south-central and southeastern parts of the SIA is better than it is for the northern part of this study area. Based on this information, we see that the northern half of the SIA is more unstable than the southern half because of the presence of thick, highly weathered and/or unconsolidated Quaternary sediment layers that are highly fractured or have low mechanical strength. The southern half of the SIA resides on exposed bedrock and is more stable from a geoengineering perspective. However, the combination of steeper slopes and the soft, fractured rocks located near the line accelerator indicates that this part of the RI could be threatened by the instability of the

high-cut slope (Figure 4b). Taken together, the stability of the foundation and the disaster susceptibility of the installation area determine the engineering geological suitability. Based on these data, we recommended that the CSNS ring accelerator and the target zone device (middle position in Figure 4a) should be placed in south-central and southeastern parts of the site, rather than the northern part of the SIA. This recommendation was implemented during the construction of this part of the RI [34]. The CSNS borehole weathering shells are shown in Figure 5a. In the southern part of the site, the thickness of the weathered crust is small, extending to a depth of ~10 m. In the auxiliary area, which is located in alluvial soil, the Quaternary unconsolidated sediment layer and completely weathered granite layers are thicker and are visible throughout the entire borehole. The rock core index (RCI) increases with depth (Figure 5b) and generally corresponds to the different weathering zones. The RCI of the underground cores throughout the entire CSNS site ranges from 0 to 30, and the RCI value of the borehole that samples fracture zone in the main device area is 10. The RCI of the Quaternary alluvial and completely weathered granites is about 0, while the RCI of the strongly weathered granite, slightly weathered granite, and fresh granite are 0~3, 8, and 13, respectively. The RCI values of the rock layer are generally less than 30 at depths less than 100 m.

Figure 5. Geological modeling (using GOCAD software) of (a) weathering, (b,c) the RCI values, and (d) the RQD values. Note: for the RCI, The light blue layer represents a problematic geological body (e.g., fractured rocks or displaced soils).

The RCI results for the linear accelerator section of the site show distinct variations with depth and fracturing degree (Figure 4c). The two red regions highlighted in Figure 4c represent moderately weathered and slightly weathered granite with low RCI values; these zones are consistent with the actual fracture distribution in the area, as revealed by drilling (such as borehole ZZK94). In the RCI and RQD models of the fracture zone (Figure 4c,d), there is an anomalous area in the exposed section that is similar to the “Syncline” structure exhibited by the ZZK94 and ZZK94B boreholes. However, the RQD values, which range from 0 to 40 for the completely weathered and strongly weathered granites, are not as well constrained as the RCI results (Figure 4d). While the completely weathered granite has an RQD value that is close to 0, other RQD results for strongly weathered and moderately

weathered granites range from 0 to 100. Because *RQD* is defined using the cumulative borehole length (which is greater than 10 cm) and cores are discretized into smaller units, the *RQD* may be affected by sudden changes at different rock layer interfaces. Unlike the *RQD* value, the *RCI* value can be calculated at multiple scales (1 cm, 3 cm, 10 cm, 30 cm, 50 cm, and 100 cm); thus, layer discontinuities are not an issue. At lower *RCI* values, the *RCI* value is more informative than the *RQD*; at high *RCI* values, the correspondingly high *RQD* values give us confidence in our *RCI* analyses (Figure 4c,d). The *RCI* values, in conjunction with the *RQD* values, provide detailed information about the underground rock mass structure.

While potential rock weaknesses induced by chemical alteration are minimal (affecting less than 1 m of some boreholes), the deep drilling boreholes revealed potential stability issues in the layers beneath the CSNS main equipment areas, such as broken or fractured rocks (boreholes ZZK99, ZZK94, and ZZK88), water table changes (boreholes ZZK104 and ZZK105), moderate weathering at deeper depths than expected (boreholes ZZK94 and ZZK94B), and water leakage greater than 5 L/min (boreholes ZZK99 and ZZK104). The water leakage signifies that the fractures created by extensional joints are highly developed and penetrate deeply into nearby rock units [52]. In borehole ZZK94 (at depths of 40–50 m), part of the core was filled with mud. In order to better understand the distribution of this mud unit, we drilled additional boreholes, such as borehole ZZK94B, in a grid around ZZK94 at intervals of 10 m. From these boreholes, we determined that the fractured zone is not a band but is concentrated in a nest-like formation. Because the rock both above and below the mud layer is pristine and unfractured, we eliminate weathering and faulting as potential causes for the infiltration of mud into these rocks and instead decided that the mud layer represents a compositional and stress-related transition zone.

When determining the stability and suitability of an RI site, we often investigate problematic geological bodies more thoroughly so that we can quantify both the horizontal and vertical extent of the body, as well as the potential effects this body will have on the engineering and architectural design of the RI. Our results were particularly instructive during the construction of CSNS. Between the potentials for slope failure and the desire to avoid the intrusive contact zone between the gneiss and granite layers, the institute's orientation was shifted by 180°. The linear accelerator is located in the sloped area, and the target station, which requires a safe and stable foundation, is located at the top of a hill composed of slightly weathered granite from which 40 m of the weathered cover was excavated.

Based on this analysis, the layout of the SIA at CSNS, including the layout of the main instruments, was altered. The final position of the ring accelerator was moved ~150 m to the southwest. While the original target site was located on a steep slope, the adjusted target station was located at more stable granitic bedrock, a change that is conducive to the stable operation of the RIs equipment.

6. Conclusions

It is vital to understand the impact that complex geological conditions will have on the planning and designing of RI sites, as demonstrated by so many RIs that are currently in various stages of completion in China. There are clear advantages to investigate the geotechnical parameters of an RI site prior to the design, construction, or operation process, as we have demonstrated with the DBNL and CSNS RI sites in this current study. Using a jade carving technique composed of non-invasive, preliminary approaches, such as geological surveys, geophysical surveys, and targeted borehole drilling, we identified problematic geological bodies and quantitatively modeled the geotechnical parameters at two RI sites (DBNL and CSNS) that provided valuable insight into the optimal construction and geoengineering conditions during the RI site development. These techniques represent an affordable alternative to more extensive (and expensive) borehole studies. By conducting rigorous geological and geophysical analyses, we submitted our recommendations to the

engineers who designed the RI sites and planned the RI construction process. In this study, we assessed two RI sites in China, which are being built according to our recommendations.

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