Modified RMR Rock Mass Classification System for Preliminary Selection of Potential Sites of High-Level Radioactive Waste Disposal Engineering

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Abstract: This paper proposed a modified Rock Mass Rating (RMR) system, the RMR_{HLW} system, for evaluating the rock quality of High-level Radioactive Waste (HLW) geological disposal engineering. Some salient factors, including the weakening of groundwater and temperature on the uniaxial compressive strength, the continuity of index values, the geostress, the rock permeability, and the groundwater chemical properties, were further incorporated based on the widely used RMR system. The proposed RMR_{HLW} system was then verified by the case study of selection of nine candidate sites for HLW disposal engineering in China. The results indicated that the rock quality of the Xinchang site was the best and ranked as the most appropriate site, while the Jiujing site ranked the worst. Compared with the traditional RMR system, the proposed RMR_{HLW} system can further consider crucial factors related to the long-term safety of HLW disposal and better reflect the differences between the potential sites. It can facilitate engineers to preliminarily evaluate the rock quality of the potential sites for High-level Radioactive Waste geological disposal engineering.

Keywords: modified RMR system; high-level radioactive waste geological disposal; rock mass quality evaluation; site comparison and selection

1. Introduction

High-level Radioactive Waste (HLW) disposal engineering plays a decisive role as a deep underground scientific research facility worldwide [1,2]. Compared with traditional above-ground structures, it has many distinctive features, including a longer construction period, more complex project design, and many uncertain factors during the construction process. Hence, the rock mass quality evaluation is of great significance for safeguarding this type of underground construction [3–5].

The reasonable evaluation of rock mass quality [6] is vital and necessary to be carried out for the sake of underground engineering. This is because the evaluation results of rock mass quality not only affect their physical and mechanical properties, but also serve as a basis for the selection of mechanical parameters and stability analyses. To select the appropriate excavation method and support type, some traditional rock mass quality evaluation methods are commonly used, such as RMR [7], tunneling quality index (Q) classification systems [8], and BQ grading standards in engineering rock mass [9]. These methods are useful to assess the rock mass quality during the engineering construction stage. With the increasing need for national construction, numerous deep and even ultra-deep underground structures are frequently designed and constructed. However, accompanied by high geostress, high temperature, high water pressure, the influence of the excavation...
disturbance, and a time-dependent softening property of rock strength, there will be an increase in the deformation of the surrounding rock and rheological effects. Meanwhile, some unfavorable geological phenomena, such as rock bursts, also become critical engineering problems [10]. It is found that the direct application of the traditional rock mass quality evaluation method in those cases is limited. To overcome this dilemma, some scholars [11–13] tried to modify the RMR method or Q method, taking into account the influence of single or multiple factors, such as geostress, groundwater, and high ground temperature. Although these revised methods can guide the rock mass quality evaluation of underground structures to a certain extent, it is still necessary to establish an appropriate evaluation system, adequately considering the characteristics of specific projects of High-level Radioactive Waste (HLW) geological disposal.

Typically, the HLW geological disposal projects are accompanied by groundwater seepage, nuclide migration, and the degradation of engineering barrier facilities. As such, its surrounding rock is in a complex physical and chemical environment, coupled with heat, water, and force. These adverse conditions will affect the long-term stability and safety of the disposal project [14]; therefore, it is vital and necessary to establish a specific evaluation system of rock mass for HLW geological disposal. In this regard, Hagros [15] first proposed the Host Rock Classification (HRC) method, a rock classification method for HLW disposal. McEwen et al. [16] extended this method and established Rock Suitability Classification (RSC). However, most of the existing work qualitatively evaluated the rock mass conditions of candidate sites, which cannot reflect the difference in rock mass classification. Additionally, they generally ignored the factors of the waste decay heat release, which will affect the long-term mechanical properties of the surrounding rock. Nevertheless, Chen et al. [3] established the QHLW system classification method based on the Q system and conducted a comprehensive quality evaluation of HLW geological disposal rock mass. However, due to the limitations of the Q method, the influence of rock strength and joint density on the rock mass quality cannot be directly considered in QHLW. Oppositely, these factors can be further considered in the RMR system. Nevertheless, evaluating the rock mass of sites for high-level radioactive waste disposal engineering with an RMR-based system is rare.

The traditional RMR system failed to take into account some important factors affecting the mechanical properties and long-term safety performance of the surrounding rock for the HLW geological disposal project. In view of these limitations, a new revised RMR system named RMRHLW (RMR of High-level Radioactive Waste Geological Disposal) rock mass quality evaluation system has been established in this study. With the sites’ data, the modified RMRHLW system is verified and can be used for the preliminary evaluation of the rock mass quality of candidate sites to provide a reference for site investigations.

2. Introduction to Traditional RMR System

The Rock Mass Rating (RMR) classification system was firstly developed by Bieniawski in 1973 [7]; since then it has become a fairly complete and practical evaluation system after several modifications. The RMR system generally includes six evaluation indexes, namely uniaxial compressive strength ($R_1$), rock quality index RQD ($R_2$), joint spacing ($R_3$), joint state ($R_4$), groundwater state ($R_5$), and modification of joint orientation effect on engineering (tunnel, foundation, slope) ($R_6$). The total score of $RMR$ can be calculated by these six parameters [7] through the following equations:

$$RMR = R_1 + R_2 + R_3 + R_4 + R_5 + R_6.$$  (1)

The detailed scoring criteria for each index can be checked in Bieniawski [7] and the corresponding evaluation results of the rock mass quality are shown in Table 1.
Table 1. RMR system rock mass quality classification [7].

| Score (RMR) | 81–100 | 61–80 | 41–60 | 21–40 | <20 |
|-------------|--------|-------|-------|-------|-----|
| Grade       | I      | II    | III   | IV    | V   |
| Rock Mass Quality | Excellent | Good | Fair | Poor | Very poor |

3. Modification of RMR System

As mentioned above, compared to the general underground structures, HLW geological disposal has a complex physical–mechanical–chemical environment, including high geostress, high temperature, high water pressure, and the influence of the excavation disturbance. This thereby makes the stress state of the rock mass more complex and the deformation and failure form of the surrounding rock more variable. In this regard, rock bursts, water bursts, excavation section bucking, and other disasters occur more frequently, and their consequences seriously threaten the construction safety [10]. Moreover, for HLW geological disposal, the surrounding rock is not only the stress medium but also the last barrier to blocking nuclide migration [3]. Therefore, in addition to the safety and stability of the engineering construction, the long-term mechanical and security properties of the surrounding rock are also the core concern. However, the RMR system has significant limitations. Some indices in the system tend to be discrete, which cannot objectively and thoroughly reflect the differences between the rock masses. In order to reasonably conduct the rock mass quality evaluation of HLW geological disposal, a new revised RMR system, namely $RMR_{HLW}$, is developed in this study to better evaluate the rock mass quality of the candidate sites.

3.1. Rating Modification of Uniaxial Compressive Strength $\sigma_c$

Generally, the score of $R_1$ in a traditional RMR system is obtained according to the laboratory uniaxial compressive strength test, which reflects the rock strength in its natural state. Nonetheless, the water seepage is severe for the project with a burial depth of approximately 500 m. The geothermal energy can be higher than 90 °C for HLW disposal projects due to the heat emission from nuclear waste decay [17]. In this regard, a significant deviation will be caused when the uniaxial compressive strength $\sigma_c$ measured in the laboratory tests is applied directly to the rock mass quality evaluation of the HLW disposal engineering. Therefore, the value of $\sigma_c$ has to be modified taking into account the influence of water and thermal environment on rock strength.

3.1.1. Modification of Groundwater Weakening

Deep underground engineering is mainly surrounded in the water-bearing environment. The physical and chemical effect of groundwater on rock can be amplified by the influence of geostress, resulting in the actual strength of the rock mass being lower than the strength measured in laboratory experiments [13]. Kang [18] and Liu and Dang [19] pointed out that rock strength was strongly affected by its water state. The research results of Kwon et al. [20] showed that the rock strength of hard granite is significantly weakened under the influence of groundwater. Therefore, the water weakening coefficient $\lambda_w$ is introduced in this study to modify $\sigma_c$ by the groundwater. Referring to the research results of relevant scholars [12,13,19], the rock mass strength of the weakening coefficient $\lambda_w$ can be defined as follows:

$$\lambda_w = \sigma_{cw} / \sigma_c,$$

where $\sigma_c$ is uniaxial compressive strength in the laboratory, $\sigma_{cw}$ is uniaxial compressive strength under different water content states. For the rock in the form of the water saturation, $\lambda_w$ can be approximated as the softening coefficient $\eta$ of the rock. For other rocks with water content, the corresponding $\lambda_w$ should be measured by the test.
3.1.2. Modification of Temperature Weakening

The HLW geological disposal projects are inevitably affected by the ground temperature due to their large burial depth. In particular, the HLW disposal projects are also affected by the heat released from the decay of nuclear waste. The thermo–physico–mechanical and thermo–chemical effects under the action of temperature will significantly affect the physical and mechanical properties of the rock, especially the long-term mechanical properties [10,13,21]. Kranz et al. [22], Kinoshita et al. [23], and Chen et al. [24] pointed out that the rise in temperature would weaken the rocks’ strengths and accelerate rock failure. Lin et al. [17] came to the conclusion that when the temperature increased from room temperature (here, it approximately refers to 23 °C) to 90 °C, the long-term strength of the rock will decrease significantly. Therefore, the weakened strength index of the rock mass should be modified by the temperature. In this study, the weakening coefficient of the rock mass by geothermal $\lambda_t$ is defined as follows:

$$\lambda_t = \frac{\sigma_c}{\sigma_{ct}},$$  

(3)

where $\sigma_c$ is the uniaxial compressive strength after different temperatures weaken it. At the same time, Martin and Chandler [25] pointed out that the long-term strength of the rock is directly related to the damage stress $\sigma_{cd}$. Compared with the long-term strength of the rock under different temperatures, the damage stress $\sigma_{cd}$ of the rock under these conditions is easier to be measured by laboratory tests. In this study, $\lambda_t$ was approximated as the ratio of the damage stress $\sigma'_{cd}$ of surrounding rocks at different temperatures to the damage stress $\sigma_{cd}$ at room temperature:

$$\lambda_t = \frac{\sigma_{cd}}{\sigma_c} = \frac{\sigma'_{cd}}{\sigma_{cd}},$$  

(4)

Considering groundwater and geothermal factors that weaken the strength of rock mass, the revised compressive strength $\sigma'_c$ can be derived based on Equations (2) and (4), as shown below:

$$\sigma'_c = \lambda_w \times \lambda_t \times \sigma_c,$$  

(5)

3.2. Continuously Modification of Scoring Values

In the RMR system, the rock uniaxial compressive strength $\sigma_c$, the rock quality index RQD, and joint spacing $S$ are divided into several intervals. The same index score value is used for each interval. The value of the endpoint is calculated by jumping. For example, when $\sigma_c$ is 100.01 MPa and 249.99 MPa, the difference between them is 149.98 MPa. However, their corresponding index scores $R_1$ are all 12. In addition, for different intervals, e.g., when $\sigma_c$ is 99.99 MPa and 100.01 MPa, the difference is only 0.02 MPa. However, their corresponding index scores $R_1$ are 7 and 12, respectively, because they are in two intervals bounded by 100 MPa. As mentioned above, such discrete values are unreasonable and cannot objectively reflect differences between rock masses. In order to avoid the jumping motions of the RMR rating value, a continuous method should modify the scoring values of the above three indicators. The corresponding numerical points and regression curves are shown in Table 2, Figures 1–3, respectively. The calculation Equation of $R'_1$, $R'_2$, and $R'_3$ after continuous modification is as follows:

$$R'_1 = \begin{cases} 15 & \sigma'_c \leq 250 \text{ MPa} \\ 10^{0.6343\log_{10}\sigma'_c-0.3627} & \sigma'_c > 250 \text{ MPa} \end{cases},$$  

(6)

$$R'_2 = \begin{cases} 0.1958\text{RQD} + 0.6484 & \text{RQD} < 250 \text{ MPa} \\ 20 & \text{RQD} = 250 \text{ MPa} \end{cases},$$  

(7)

$$R'_3 = \begin{cases} 20 & S < 2 \text{ m} \\ 10^{0.1799(\log S)^2+0.3834(\log S)^2+0.4462\log S+1.125} & S \geq 2 \text{ m} \end{cases}.$$  

(8)
Table 2. Curve fitting points of $R_1$, $R_2$, and $R_3$ for continuity correction.

| Rock Burst Grade | The Corresponding Numerical Points for Regression Curves |
|------------------|--------------------------------------------------------|
| $c'_c$ /MPa      | 3           | 15      | 37.5    | 75       | 175      | 250      |
| $\lg(c'_c)$      | 0.477       | 1.176   | 1.574   | 1.875    | 2.243    | 2.398    |
| $R_1$            | 1           | 2       | 4       | 7        | 12       | 15       |
| $\lg(R_1)$       | 0.000       | 0.301   | 0.602   | 0.845    | 1.079    | 1.176    |
| RQD/%            | 12.5        | 37.5    | 62.5    | 82.5     | 100      | -        |
| $R_2$            | 3           | 8       | 13      | 17       | 20       | -        |
| Joint spacing S/m| 0.03        | 0.13    | 0.4     | 1.3      | 2        | -        |
| $\lg(S)$         | -1.523      | -0.886  | -0.398  | 0.114    | 0.301    | -        |
| $R_3$            | 5           | 8       | 10      | 15       | 20       | -        |
| $\lg(R_3)$       | 0.699       | 0.903   | 1.000   | 1.176    | 1.301    | -        |

Figure 1. The continuous regression curve of scoring of index $R_1$ related to the uniaxial compressive strength.

Figure 2. The continuous regression curve of scoring of index $R_2$ related to the rock quality index.
The failure of deep rock masses under the influence of high geostress usually occurs suddenly without warning and results in vital destruction. As a common and serious dynamic failure phenomenon in deep underground engineering, rock burst tends to occur in hard rock strata with high strength and thickness [26]. At present, granite, as the rock mass of HLW geological disposal sites in China, is affected by geostress and poses a risk of rock burst. Since the influence of the in situ stress on the rock mass quality is not considered in the RMR system, the in situ stress modification index is proposed based on rock burst intensity grade and strength–stress ratio \( \sigma_i' / \sigma_1 \) as the grading standard.

The research results of Barton [27], Grimstad [28], Zhang et al. [29], and The Engineering Rock Mass Classification Standard [4] are adopted to determine the rock burst intensity grade of the rock mass. When \( \sigma_i' / \sigma_1 > 7 \), it is considered that there is almost no rock burst. A slight rock burst may occur when \( 7 \geq \sigma_i' / \sigma_1 > 5 \). A moderate rock burst may occur when \( 5 \geq \sigma_i' / \sigma_1 \geq 2.5 \). When \( \sigma_i' / \sigma_1 \) is less than 2.5, a severe rock burst is likely to occur. As for the corresponding scoring value \( R_i \) (I, II, III, and IV), the value \( R_i \) was modified by referring to the influence of joint orientation on engineering in the RMR system, and the evaluation standard of the impact of ground stress on the rock mass quality evaluation of the undersea deposit considered by Liu and Dang [19]. The established criteria for the geostress correction \( R_7 \) are shown in Table 3. For the rock mass quality evaluation of the site, the ground stress modification value \( R_7 \) is to be defined as follows:

\[
R_7 = \sum R_i \times \text{Per}(i),
\]

where \( \text{Per}(i) \) is the percentage of different rock burst grades.

**Table 3. Criteria for geostress correction \( R_7 \).**

| Rock Burst Grade | Rock Burst Intensity      | Criteria          | \( R_i \) |
|------------------|--------------------------|-------------------|----------|
| I                | No rock burst            | \( \sigma_i' / \sigma_1 > 7 \) | 0        |
| II               | Slight rock burst        | \( 7 \geq \sigma_i' / \sigma_1 > 5 \) | –4       |
| III              | Moderate rock burst      | \( 5 \geq \sigma_i' / \sigma_1 \geq 2.5 \) | –8       |
| IV               | Severe rock burst        | \( \sigma_i' / \sigma_1 < 2.5 \) | –12      |

\( y = 0.1799x^3 + 0.3834x^2 + 0.4462x + 1.125 \)

\( R^2 = 0.9998 \)
3.3.2. The Rock Mass Permeability Index

For HLW geological disposal, groundwater seepage will bring erosive materials into the disposal project, resulting in buffer and canister damage. Meanwhile, pollutants from the near field may be carried into the far-field rock mass and even into the biosphere. In this regard, the groundwater will significantly impact the long-term safety of the waste disposal. The permeability of rock mass is one of the core factors controlling the groundwater seepage rate. Therefore, in this work, the influence of rock mass permeability is considered in the rock mass quality evaluation system of HLW geological disposal engineering and the correction index $R_8$ of the rock mass permeability is proposed.

SKB \cite{30,31} pointed out that the rock mass with permeability $\leq 10^{-8}$ m/s was suitable for HLW disposal in the early safety evaluation. However, later research suggested that this limit was overly optimistic. Against this background, Nagra \cite{32} pointed out that when the permeability coefficient of the rock mass was within the range of $10^{-11}$ m/s–$10^{-9}$ m/s, the degree of erosion of engineering barrier materials could be significantly weakened, which was conducive to the long-term safety of the disposal repository. In order to ensure the long-term safety of waste disposal, this work adopts $10^{-9}$ m/s as the limit value to establish the rock mass permeability correction standard. The value of $R_8$ is 0 as $Per (\leq 10^{-9} \text{ m/s}) = 1$ when the rock mass permeability coefficient within the site study scope is $\leq 10^{-9}$ m/s. Moreover, $R_8$ is $-12$ when $Per (\leq 10^{-9} \text{ m/s}) = 0$. For other conditions, the value of $R_8$ can be derived through the linear interpolation according to Equation (10):

$$R_8 = -12 \times \left(1 - Per (\leq 10^{-9} \text{ m/s})\right), \tag{10}$$

3.3.3. The Groundwater Chemistry Index

Andersson et al. \cite{33} and SKB \cite{31} all found that the chemical environment of groundwater would affect the long-term performance of canisters and buffer backfill materials, finally affecting disposal safety. However, there are too many factors controlling the chemical environment of groundwater. For instance, Hagers et al. \cite{34} had sorted out 33 factors, such as the hydraulic conductivity, the rock mass permeability, the strength–stress ratio, the fracture zones (length, thickness, and transmissivity). However, it is uneconomical and unrealistic to consider so many factors in the initial site evaluation stage, hence it is necessary to analyze the influence of underground chemical characteristics on disposal safety according to the controlling factors. Wang \cite{1}, Nagra \cite{32}, Posiva \cite{35}, and SKB \cite{36} all pointed out that pH directly affected the degree of erosion of the disposal tank and a moderately alkaline environment was conducive to the long-term safety of the disposal project. Andersson \cite{33} and Vieno \cite{37} found that total dissolved solids (TDS) would weaken the performance of buffer materials and enhance their permeability. SKB \cite{30} pointed out that when TDS > 50 g/L, the expansion performance of bentonite buffer material would decline and its permeability would be strengthened, which was not conducive for the long-term safety of the disposal project. Therefore, the TDS of the groundwater has to be controlled. Andersson et al. \cite{33} pointed out that high Cl$^-$ concentration would weaken the engineering barrier’s performance and accelerate its degradation. Thus, after the TDS has been controlled, the concentration of the Cl$^-$ must also be controlled; the relevant studies of SKB \cite{31} and Andersson \cite{38} showed that the concentration of the Cl$^-$ ion should be controlled under 20 g/L to ensure the performance of buffer backfill material. Combined with the above analysis, this paper introduced the correction index $R_9$ of groundwater chemical characteristics. It used the pH value, TDS, and Cl$^-$ ion concentration as the control index to evaluate the influence of groundwater chemical characteristics on disposal safety. The established value standard of $R_9$ is presented in Table 4.
3.4. Modified Rock Classification System RMR$_{HLW}$ for HLW Geological Disposal

For the HLW geological disposal project, the influence of the physical and chemical environment on the long-term mechanical properties of surrounding rock and disposal safety is considered based on engineering construction safety. Finally, the RMR$_{HLW}$ rock mass quality evaluation system is established as follows:

$$RMR_{HLW} = R'_1 + R'_2 + R'_3 + R_4 + R_5 + R_6 + R_7 + R_8 + R_9$$

(11)

4. Applications of Modified RMR Rock Mass Classification Systems in China

It has been nearly 30 years since China started the site selection of high-level radioactive waste disposal. It generally went through four phases: national investigation, regional investigation, lot investigation, and site investigation. Jiujing, Xinchang, Shazaoyuan, and Suanjingzi in Beishan of the Gansu Province; Yamansu, Tianhu, and Aqishan in the Xinjiang Uygur Autonomous Region; and Tamusu and Nuorigong in the Inner Mongolia Autonomous Region were finally selected as the candidate sites for HLW geological disposal in China (see Figure 4). The rock mass of each candidate site is mainly granite [39].

Figure 4. Schematic diagram of candidate sites for HLW geological disposal in China (not in scale).

In this study, the site with an area of 10 km$^2$, consisting of Jiujing, Xinchang, Shazaoyuan, Suanjingzi, Yamansu, Tianhu, Aqishan, Tamusu, and Nuorigong, is used as the evaluation object. At the same time, the burial depth of the disposal repository is taken into account and the value of the evaluation parameters of each site is determined based on the data from the borehole within the burial range from 400 m to 600 m [3].

4.1. Determination of Evaluation Parameters for Each Site

4.1.1. Determination of $R'_1$

Considering that the HLW geological disposal is below the groundwater level [40], the rock mass is believed to be in a state of water saturation. $\lambda_w$ can be approximated as the soft-
ening coefficient \( \eta \) of granite. In the uniaxial compression test, the peak strength of granite under the saturated conditions is about 84.41% of it under dry conditions [41]. The softening coefficient of granite generally ranges from 0.71 to 0.92 [42] and \( \lambda_w \) is approximately as 0.84 in this paper.

As for the weakening of rock strength by temperature, Liu et al. [21] and Wang et al. [43] studied the variation characteristics of fracture damage stress in granite at Jiujiang and Xinchang of Beishan under the conditions of 23 °C (room temperature) and 90 °C (ground temperature and HLW decay heat release) through indoor creep tests. The measurement results of borehole samples in Jiujiang (confining pressure 0 MPa) and Xinchang (confining pressure 0.5 MPa) are shown in Figure 5. According to Equation (4), the values of \( \lambda_t \) at 90 °C are calculated as \( \lambda_{90} = 0.88 \) for Jiujiang and \( \lambda_{90} = 0.83 \) for Xinchang. There is no high-temperature mechanical test data of drill cores at other sites. Considering that all sites are granite rocks, the mean values, i.e., \( \lambda_{90} = 0.85 \), of Jiujiang and Xinchang are used as the temperature weakening coefficients of other sites.

![Figure 5. Crack damage stress of Beishan granite at different temperatures [21,43].](image)

Based on the measurement results of granite \( \sigma_c \) (see Figure 6) in the site investigation technical report [38], combined with the values of \( \lambda_w \) and \( \lambda_t \), the corresponding revised score \( R'_1 \) are calculated by Equations (5) and (6), respectively. The results are as shown in Table 5. It is noted that there is no measured value for Shazaoyuan and Suanjingzi, so the value of \( \sigma_c \) is the mean value of data from Jiujiang, Xinchang, and Suanjingzi. The mean values of relevant indices of Akishan, Tamusu, and Nuorigong are extracted.

| Candidate Sites | \( \sigma_c/\text{MPa} \) | \( \lambda_w \) | \( \lambda_t \) | \( \sigma'_c/\text{MPa} \) | \( R'_1 \) |
|-----------------|----------------|--------|--------|----------------|--------|
| Jiujiang        | 141.7          | 0.84   | 0.88   | 104.7          | 8.3    |
| Xinchang        | 183.8          | 0.84   | 0.83   | 128.1          | 9.4    |
| Shazaoyuan      | 169.8          | 0.84   | 0.85   | 121.2          | 9.1    |
| Suanjingzi      | 169.8          | 0.84   | 0.85   | 121.2          | 9.1    |
| Yamansu         | 173.2          | 0.84   | 0.85   | 123.7          | 9.4    |
| Tianhu          | 182.1          | 0.84   | 0.85   | 130.0          | 9.6    |
| Aqishan         | 120.4          | 0.84   | 0.85   | 86.0           | 7.3    |
| Tamusu          | 107.8          | 0.84   | 0.85   | 77.0           | 6.8    |
| Nuorigong       | 140.0          | 0.84   | 0.85   | 100.0          | 8.0    |
temperature and HLW decay heat release) through indoor creep tests. The measurement results of borehole samples in Jiujing (confining pressure 0 MPa) and Xinchang (confining pressure 0.5 MPa) are shown in Figure 5. According to Equation (4), the values of $\lambda_{90}$ at 90°C are calculated as $\lambda_{90} = 0.88$ for Jiujing and $\lambda_{90} = 0.83$ for Xinchang. There is no high-temperature mechanical test data of drill cores at other sites. Considering that all sites are granite rocks, the mean values, i.e., $\lambda_{90} = 0.85$, of Jiujing and Xinchang are used as the temperature weakening coefficients of other sites.

Figure 5. Crack damage stress of Beishan granite at different temperatures [21,43].

Based on the measurement results of granite $\sigma_c$ (see Figure 6) in the site investigation technical report [38], combined with the values of $\lambda_w$ and $\lambda_t$, the corresponding revised score $R'_1$ are calculated by Equations (5) and (6), respectively. The results are as shown in Table 5. It is noted that there is no measured value for Shazaoyuan and Suanjingzi, so the value of $\sigma_c$ is the mean value of data from Jiujing, Xinchang, and Suanjingzi. The mean values of relevant indices of Akishan, Tamusu, and Nuorigong are extracted.

Figure 6. Measured values of the uniaxial compressive strength $\sigma_c$ for some candidate sites.

4.1.2. Determination of $R'_2$

The value of $R'_2$ is calculated using Equation (7) according to the RQD value of each site in the site investigation report [39]; the calculated values are shown in Table 6.

Table 6. RQD and $R'_2$ values of candidate sites.

| Candidate Sites | RQD  | $R'_2$  |
|-----------------|------|---------|
| Jiujing         | 76.7 | 15.7    |
| Xinchang        | 97.6 | 19.8    |
| Shazaoyuan      | 96.5 | 19.5    |
| Suanjingzi      | 80.4 | 16.4    |
| Yamansu         | 95.2 | 19.3    |
| Tianhu          | 79.9 | 16.3    |
| Aqishan         | 98.4 | 19.9    |
| Tamusu          | 89.6 | 18.2    |
| Nuorigong       | 94.1 | 19.1    |

4.1.3. Determination of $R'_3$

Joint fractures will reduce rock mass strength, while the connected fracture network will become a potential channel for nuclide migration, seriously affecting the disposal safety of HLW [44–46]. This study calculated the average crack spacing according to each borehole's rock mass crack density [39]. The revised $R'_3$ was determined based on Equation (8) and is shown in Table 7.
Table 7. The average crack spacing and $R'_3$ values of candidate sites.

| Candidate Sites | Average Crack Spacing/m | $R'_3$  |
|-----------------|-------------------------|---------|
| Jiujing         | 0.5                     | 10.3    |
| Xinchang        | 1.4                     | 16.0    |
| Shazaoqian      | 1.5                     | 16.7    |
| Suanjingzi      | 0.8                     | 12.4    |
| Yamansu         | 0.7                     | 11.6    |
| Tianhu          | 0.2                     | 8.9     |
| Aqishan         | 1.2                     | 14.4    |
| Tamusu          | 0.9                     | 13.0    |
| Nuorigong       | 2.0                     | 19.9    |

4.1.4. Determination of $R_4$

The joint conditions and their scoring value $R_4$ of each site are shown in Table 8, which are based on the scoring criteria of joint disorders in the RMR system and combined with the geological survey data of boreholes at each site [39].

Table 8. Joint conditions and $R_4$ values of candidate sites.

| Candidate Sites | Descriptions of Joint Conditions | $R_4$ |
|-----------------|----------------------------------|-------|
| Jiujing         | Rough joint surface; Slight metamorphism; Joint opening < 1 mm | 25    |
| Xinchang        | The joint surface is closed tightly; Unweathered; Discontinuity | 30    |
| Shazaoqian      | The joint surface is closed tightly; Unweathered; Discontinuity | 30    |
| Suanjingzi      | The joint surface is closed tightly; Unweathered; Discontinuity | 30    |
| Yamansu         | Rough joint surface; Slight metamorphism; Joint opening < 1 mm | 25    |
| Tianhu          | Rough joint surface; Slight metamorphism; Joint opening < 1 mm | 25    |
| Aqishan         | Rough joint surface; Slight metamorphism; Joint opening < 1 mm | 25    |
| Tamusu          | The joint surface is closed tightly; Unweathered; Discontinuity | 30    |
| Nuorigong       | The joint surface is closed tightly; Unweathered; Discontinuity | 30    |

4.1.5. Determination of $R_5$

The site investigation technical report [39] indicated that the site’s groundwater at the candidate sites consists mainly of bedrock fissure water and the rock mass permeability of each site was low. Therefore, it is preliminarily concluded that the hydrogeological conditions of each site are simple and the water bearing and permeability of the rocks are low. Based on the scoring standard of groundwater conditions in the RMR system, the overall state of groundwater conditions in each site is set as wet, thus $R_5$ is set as 10.

4.1.6. Determination of $R_6$

The revised RMR system is mainly used for the preliminary evaluation of rock mass quality of candidate sites, which can be adopted as a reference for site selection. Therefore, the joint orientation is considered to have a general influence on engineering and the value of $R_6$ is determined as $-5$.

4.1.7. Determination of $R_7$

Based on the geostress correction criteria shown in Table 3 and the strength–stress ratio shown in Figure 7 [39], the geostress correction value $R_7$ for each site is calculated using Equation (9) and they as shown in Table 9.
Figure 7. The strength-stress ratio \(\sigma_c'/\sigma_1\) values of candidate sites [39].

Table 9. Geostress correction values \(R_7\) of candidate sites.

| Candidate Sites | Per(i)% (i = I, II, III, IV) | \(R_7\) |
|-----------------|------------------------------|-------|
| Xinchang        | 100.0                        | -     |
| Shazaoyuan      | 33.3                         | 66.7  |
| Suanjingzi      | 58.3                         | 41.7  |
| Yamansu         | 72.2                         | 11.1  |
| Tianhu          | 90.9                         | 9.1   |
| Aqishan         | 100.0                        | -     |
| Tamusu          | 50.0                         | 50.0  |
| Nuorigong       | 33.3                         | 66.7  |

4.1.8. Determination of \(R_8\)

The measured value of the rock mass permeability coefficient at each site are shown in Figure 8. Based on the value standard of \(R_8\), Equation (10) is used to calculate the correction value \(R_8\) of the rock mass permeability at each site. The corresponding results are shown in Table 10.

Table 10. Rock mass permeability correction values \(R_8\) of candidate sites.

| Candidate Sites | \(Per < 10^{-9}\) m/s | \(R_8\) |
|-----------------|------------------------|-------|
| JiuJing         | 0                      | -12.00|
| Xinchang        | 100%                   | 0     |
| Shazaoyuan      | 69%                    | -3.72 |
| Suanjingzi      | 100%                   | 0     |
| Yamansu         | 95%                    | -0.60 |
| Tianhu          | 56%                    | -5.28 |
| Aqishan         | 67%                    | -3.96 |
| Tamusu          | 30%                    | -8.40 |
| Nuorigong       | 60%                    | -4.80 |
Figure 8. Permeability coefficient values of rock mass of candidate sites [39].

4.1.9. Determination of $R_9$

According to the site investigation report [39], the pH value, TDS value, and Cl$^-$ concentration value of groundwater at each site are listed in Table 11, which determines the correction value $R_9$ of the groundwater chemical characteristics. Still, it is challenging to obtain groundwater-related parameters due to the extremely low permeability of the BS06 borehole in Xinchang. Therefore, referring to the groundwater chemical analysis results of BS05 and BS15 boreholes in the same section, the mean value is approximated as the measured value of the BS06 borehole. For Shazaoyuan, Suanjingzi, and Yamansu, which have not obtained groundwater chemical indexes, the approximate weights of similar sites with corresponding indexes have been received by referring to the same pre-selected area, respectively.

Table 11. Correction values of groundwater chemical characteristics $R_9$ of candidate sites.

| Candidate Sites | pH   | TDS/(g·L$^{-1}$) | Cl$^-$/g·L$^{-1}$ | $R_9$ |
|-----------------|------|-----------------|------------------|------|
| Jiujing         | 9.55 | 3.96            | 1.31             | 0    |
| Xinchang        | 7.65 | 3.33            | 0.99             | 0    |
| Shazaoyuan      | 8.60 | 3.46            | 1.06             | 0    |
| Suanjingzi      | 8.60 | 3.46            | 1.06             | 0    |
| Yamansu         | 8.53 | 14.63           | 5.00             | 0    |
| Tianhu          | 8.87 | 7.66            | 2.54             | 0    |
| Aqishan         | 8.18 | 21.60           | 7.46             | 0    |
| Tanusu          | 7.95 | 2.80            | 1.21             | 0    |
| Nuorigong       | 8.23 | 0.57            | 0.18             | 0    |

4.2. Evaluation of Rock Mass Quality of Each Candidate Site

Based on the values of each index, Equation (11) is used to calculate the corresponding $RMR_{HLW}$ values for the rock mass at each candidate site, as shown in Table 12. From the perspective of long-term safety of HLW geological disposal, the evaluation results indicate that the Xinchang site has the best suitability with the highest score, while the Jiujing site has the worst suitability with the lowest score. The other two sites in the top three are the Nuorigong site and Shazaoyuan site. The results based on the modified $RMR_{HLW}$ system are essentially consistent with the evaluation results of the individual sites from a geological point of view in the site investigation report.
Considering the constructability and long-term safety of HLW disposal engineering, the proposed RMR<sub>HLW</sub> system ulteriorly incorporates the weakening of groundwater ability, and the groundwater chemical properties. Meanwhile, in order to avoid the jumping motions of the RMR rating value, the scoring values related to the uniaxial compressive strength, the rock permeability, and the groundwater chemical properties. The proposed evaluation system has been successfully applied to the comparison and selection of potential sites for HLW disposal in China. Based on this study, the following insights were gained:

(1) Considering the constructability and long-term safety of HLW disposal engineering, the proposed RMR<sub>HLW</sub> system can more objectively reflect the differences in the rock mass quality of each candidate site. It has a specific practical value and provides a meaningful reference for site selection of the HLW geological disposal.

5. Conclusions

Consequently, the established RMR<sub>HLW</sub> system can more objectively reflect the differences in the rock mass quality of each candidate site. It has a specific practical value and provides a meaningful reference for site selection of the HLW geological disposal.
comprehensive strength, the rock quality index, and the joint spacing are revised in a continuous way.

(2) The proposed $RMR_{HLW}$ system is applied to thoroughly assess the rock quality of nine candidate sites for HLW disposal in China. The evaluation results show that Xinchang has the best rock quality, followed by Nuorigong, Shazaoyuan, etc., while Jiujing is the worst.

(3) Compared with the traditional $RMR$ system, the proposed $RMR_{HLW}$ system can reflect the differences in the rock mass quality of the individual sites more objectively. The proposed modified $RMR$ system can be used to more comprehensively evaluate the rock quality of the HLW geological disposal engineering and has a higher reference value for similar construction projects worldwide.

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