Study on Rock Mass Classification Methods Used in the Geological Disposal of High-level Radioactive Waste

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Abstract. The conventional methods of rock quality classification mainly focus on the constructability of rock mass, while the long-term safety requirements of the high-level radioactive waste (HLW) disposal are not considered. Therefore, two rock suitability classification methods for geological disposal projects, the Rock Suitability Criterion (RSC) and the $Q_{HLW}$ methods were systematically compared by evaluating the rock suitability of the ONKALO site for geological disposal in Finland. The suitability of the ONKALO site was analyzed by evaluating the permeability, geochemical condition, and integrity of rock mass, according to the RSC method. Meanwhile, the $Q_{HLW}$ method was used to evaluate the rock mass suitability by analyzing the fault zone influence, hydrogeochemical characteristics, temperature influence, permeability, strength-stress ratio, and integrity of rock mass. Then, the advantages and disadvantages of the two methods were discussed. We found that the results obtained with RSC are consistent with those with $Q_{HLW}$. While RSC gives more detailed chemical properties of groundwater and mechanical characteristics of rock mass, $Q_{HLW}$ performs better in evaluating the permeability of rock mass. Besides, RSC is a qualitative or semi-qualitative method with some site-specific criteria, while the $Q_{HLW}$ is a quantitative method with higher universality. Based on the above results and conclusions, a new version of $Q_{HLW}$ at the tunnel scale was finally proposed by incorporating the advantages of RSC.

1. Introduction

Nuclear industry generates some high-level radioactive waste (HLW), which is extremely difficult to dispose-off because it contains nuclides with high radioactivity, long half-life, high toxicity, and high heat release rate. At present, deep geological disposal is the most feasible method for the safe disposal of HLW and is well-approved by many countries and international communities. Deep geological disposal generally adopts the “multi-barrier system” design with the host rock as the last barrier \cite{1}. It is required to systematically investigate the geological, hydrological, and geochemical conditions of the host rock and accurately evaluate its suitability for geological disposal.

For traditional underground engineering, the rock mass suitability is generally evaluated by using the rock mass classification methods, such as $Q$ \cite{2}, RMR \cite{3}, and BQ \cite{4}, mainly focusing on the constructability of rock mass. However, the service period of the geological disposal repository is much longer than the traditional underground engineering, thus, some long-term safety requirements should be considered additionally. In line with this, T. McEwen et al. \cite{5} established the RSC (Rock Suitability Classification) rock mass classification method, which has been used in the rock suitability
analysis of ONKALO Underground Research Laboratory (URL) in Finland. According to the R&D requirements of China’s geological disposal project, Chen L et al. [6] proposed the Q_{HLW} suitability classification method, and it has been successfully applied to the site selection of China’s URL for geological disposal. The two methods, RSC and Q_{HLW}, were proven to be effective in the development of the URLs in Finland and China, respectively. However, these two methods have not been used at the same site and the universality of the two methods has not been well discussed yet.

Therefore, for comparison at the same site, RSC and Q_{HLW} methods were applied in the rock mass suitability analysis of the ONKALO site in this paper. The advantages and disadvantages of the two methods were identified and analyzed. Finally, some optimizations in Q_{HLW} were recommended.

2. Rock Suitability Classification (RSC) [5]

The RSC covers four stages (Figure 1). The suitability evaluation starts at the beginning of the layout of the repository, goes through the determination processes of the disposal area and disposal tunnel, and ends with the determination of the disposal hole layout position.

![Figure 1. The application of RSC](image)

RSC evaluates the suitability of the rock mass for geological disposal based on three aspects, the rock mass stability, conductivity, and chemical characteristics of groundwater. The contents of RSC are shown in Table 1.

| Scales                  | Chemical composition of the groundwater | Mechanical stability of the rock. | Mass permeability of the rock |
|------------------------|------------------------------------------|----------------------------------|------------------------------|
| Reposition scale       | 6pH<1; Cl<2 M; Total charge equivalent of | Avoid the influence zones of the site-scale Brittle Fault Zones. | Avoid the influence zones of the site-scale hydrogeological zones. In general, 20 m is considered an adequate distance |

Table 1. Rock suitability criteria in RSC [5]
Deposition tunnel scale

- cations, $\sum q[Mq+] > 4$ mM; $TDS < 35$ g/L;
- Avoiding Layout Determined Features (LDFs).

Deposition hole scale

- Strictly avoid fracture longer than 50 m in length; The deposition hole must not intersect an FPI fracture; a preliminary respect distance of 0.5 m is suggested.
- Deposition hole cannot intersect minor brittle deformation zones and the influence zones of these must be avoided.
- Deposition hole cannot be positioned within the influence zone of a hydrogeological structure (a zone or a fracture); The maximum allowed inflow to a deposition hole is 0.1 L/min.

3. Rock classification system $Q_{HLW}$

$Q_{HLW}$ includes three scales: the repository, tunnel, and hole scales. $Q_{HLW}$ generally evaluates the rock mass suitability in six aspects: the influence of fault zone, the chemical characteristics of groundwater, temperature influence, rock mass integrity, rock mass permeability, and strength-stress ratio of the rock mass. The method considers the complex condition of the thermal-hydro-mechanical-chemical coupling environment in the near field of the repository and quantitatively evaluates the rock mass suitability of the geological disposal.

At the site scale, the classification is divided into two steps. Firstly, the candidate sites are selected based on the principles and requirements for avoiding large-scale faults. The classification criteria of the fault zones are shown in Table 2.

| Types | Length | Position requirement | Respect zone (m) | Note |
|-------|--------|----------------------|------------------|------|
| A     | Length $\geq 10$ km | Intersecting any part of the repository is prohibited. Intersecting the disposal tunnel and disposal hole is prohibited. | $> 100$ m | $L_A, L_B,$ and $L_C$ are the length limits, determined according to the region-special seismic activity, geological conditions, and the design of the engineered barriers. |
| B     | $2$ km $\leq$ Length $\leq 10$ km | Intersecting the disposal tunnel and disposal hole is prohibited. | $> 100$ m |
| C     | $100$ m $\leq$ Length $\leq 3$ km | Intersecting the disposal hole is prohibited. |

Then, the selected candidate sites are evaluated quantitatively based on the long-term safety requirements of geological disposal. The calculation formula for the evaluation index at the site scale is as follows:

$$Q_{HLW}^R = C_{chm}^R \times C_T^R \times Q \times \frac{J_{w,HLW}^R}{SRF_{HLW}^R}$$

(1)

where $C_{chm}^R, C_T^R, J_{w,HLW}^R,$ and $SRF_{HLW}^R$ represent the indexes of groundwater chemistry, thermal effect, hydraulic conductivity, and strength/stress ratio, respectively.

The determination criteria of $C_{chm}^R$ are shown in Table 3.

| Description of groundwater chemistry. | $C_{chm}^R$ |
|--------------------------------------|-------------|
| $6 < pH < 10$, TDS $< 50$ g/L, Cl$^- < 20$ g/L. | 1.0 |
| 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 |

The calculation formula of $C_T^R$ is as follows:

$$C_T^R = \frac{\sigma_{cd}^{max}}{\sigma_{cd}}$$

(2)
where \( \sigma_{cd}^{T_{max}} \) represents the crack damage strength of the surrounding rock at the maximum temperature on the canister exterior surface; \( \sigma_{cd} \) represents the crack damage strength at room temperature.

The calculation formula of \( Q' \) is as follows:

\[
Q' = \frac{RQD J_n}{J_r J_a}
\]

where \( RQD \) is the Rock Quality Designation (Deere, 1964), \( J_n \) is the joint set number, \( J_r \) is the joint roughness number, and \( J_a \) is the joint alteration number.

The rating of hydraulic conductivity index is given in the following:

\[
J_{u,HGW}^r = \begin{cases}
1.0 & Per(K < 10^{-6} \text{ m/s}) \geq 90\% \\
0.66 & 70\% \leq Per(K < 10^{-6} \text{ m/s}) < 90\% \\
0.33 & 50\% \leq Per(K < 10^{-6} \text{ m/s}) < 70\% \\
0.1 & Per(K < 10^{-6} \text{ m/s}) < 50\%
\end{cases}
\]

where \( K \) is the conductivity of rock mass tested with the double-pack system in a borehole, \( Per(x) \) is the number percentage of the test results satisfying the condition \( x \).

The rating of strength/stress ratio is given in the following:

\[
S_{HLW}^R = \begin{cases}
0.5 & Per(\sigma_{UCS} / \sigma_1 > 5) \geq 90\% \\
1 & 70\% \leq Per(\sigma_{UCS} / \sigma_1 > 5) < 90\% \\
5 & 50\% \leq Per(\sigma_{UCS} / \sigma_1 > 5) < 70\% \\
20 & Per(\sigma_{UCS} / \sigma_1 > 5) < 50\%
\end{cases}
\]

where \( \sigma_{UCS} \) is the rock uniaxial compressive strength, and \( \sigma_1 \) is the maximum horizontal in-situ stress.

The \( Q_{HLW} \) index value is finally obtained according to formula (1) and the evaluation result is divided into three categories: suitable, moderately suitable, and unsuitable (Table 4).

**Table 4. Suitability classification of sites at the repository scale \([6]\)**

| \( Q_{HLW} \) | Class | Suitability       | Comments                                                                 |
|---------------|-------|-------------------|--------------------------------------------------------------------------|
| (40, 1000)    | I     | High suitability  | The evaluated rock volume is quite suitable for repository construction, and the following tunnel construction can be executed at this site. |
| (10, 40)      | II    | Moderate suitability | The evaluated rock volume is suitable for repository construction, but some engineering measures will be necessary to ensure the long-term stability and safety of the repository. |
| \( \leq 10 \) | III   | Low suitability   | The evaluated rock volume should be avoided in the construction of a repository. |

4. Suitability Classification of ONKALO

4.1. Overview of the ONKALO URL

The ONKALO URL for geological disposal is located on the island of Olkiluoto on the west coast of Finland, and it is being expanded into the world's first permanent HLW disposal repository. It was built in 2004–2012 at a depth of 450 m. After detailed exploration and demonstration in the URL, it is concluded that the rock mass 400–500 m below the surface of Olkiluoto Island is quite suitable for permanent disposal of HLW \([7]\).

4.2. Application of RSC method at ONKALO Site
(1) Groundwater chemical index

The groundwater chemical characteristics of the ONKALO site are investigated based on groundwater samples from borehole KR6 (Table 5). All the water samples are neutral or weakly alkaline (pH 7.2–7.5). The main chemical types of groundwater are Na-Ca-Cl and Na-Cl. The main cations are Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), and the main anions are Cl\(^-\) and SO\(_4^{2-}\) [8]. It indicates that the molar concentration of cations, chloride ions, pH, and total dissolved solids (TDS) of the ONKALO site comply with RSC requirements on the chemical characteristics of groundwater [8].

| Parameter | Type of cation | Concentration of cation (mmol/L) | Cl\(^-\) (mol/L) | pH | TDS (g/L) |
|-----------|----------------|---------------------------------|-----------------|-----|-----------|
| Standard  | Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\) | Ave 148.75 Ave 0.175 Max 7.5 | Ave 3.1 | Ave 3.1 |
|          | Min (Na)       | 3.42 | 7.2 | 6-11 | <35 g/L |

As mentioned above, the chemical properties of groundwater, the mechanical stability, and the water conductivity of the rock mass meet the RSC requirements, and the site is considered “suitable” for geological disposal.

4.3. Application of \(Q_{HLW}\) method at ONAKLO Site

(1) Fracture zone influence

Posiva conducted a detailed geological investigation in the Olkiluoto Island. According to the geological survey results of the deep boreholes, the fault zone in the Olkiluoto area is mainly formed by the previously formed SE immersion thrust fault with some NE-SW faults [5]. The geological conditions and the distribution of fault zones in the Olkiluoto area are shown in Figure 3. There is no fault larger than 3 km within the scope of the site, making it a suitable candidate for \(Q_{HLW}\) as per its classification criterion of fracture zones (Table 2).
(2) Groundwater Chemical Index

The chemical characteristics of groundwater are summarized in Table 5. The chemical condition of the groundwater meets the requirements of $Q_{HLW}$ (Table 3), and the groundwater chemical index $C_{chm}$ of the ONKALO site is taken as 1.0.

| Parameters | Deep (m)                  |
|------------|----------------------------|
|            | 98.5-100.5 | 125-130 | 135-137 | 422-425 |
| TDS/(g·L⁻¹) | 4.76       | 7.3     | 7.25    | 10.54   |
| pH         | 7.4         | 7.2     | 7.5     | 7.5     |
| Cl⁻ (mg·L⁻¹) | 2580       | 4120    | 4040    | 6150    |

(3) Hydraulic conductivity index $J_{Rw,HLW}$

The test results of conductivity from long-term monitoring (2008–2015) at the ONKALO site within 200–340 m are shown in Figure 4. 97% of the site had a conductivity of less than $10^{-9}$ m/s with the hydraulic conductivity index of 1.0 according to formula (4).

(4) Strength/stress ratio index $SRF_{HLW}$

![Figure 3. Fault zone distribution in Olkiluoto area [5]](image)

![Figure 4. (a) Hydraulic conductivity and (b) strength-stress ratio distribution of ONKALO sites [9-11]](image)
According to the distribution characteristics of the strength and in-situ stress of the surrounding rock within the depth of 150–450 m at the ONKALO site, 76% of the site showed strength/stress ratio greater than 5 is (Figure 4). According to formula (5), the value of the index $SRF_{HLW}$ is 1.0.

\begin{equation}
SRF_{HLW} = \frac{Q'}{Q_{HLW}}
\end{equation}

Table 7. Determination of the $Q'$ value of the ONKALO sites \(^{[12-14]}\)

| Deep boreholes | RQD   | $J_n$ | $J_r$ | $J_a$ |
|----------------|-------|-------|-------|-------|
| KR44           | 95.68 | 1.69  | 3.42  | 1.24  |
| KR45           | 94.19 | 2.08  | 3.43  | 2.09  |
| KR48           | 91.46 | 2.33  | 3.27  | 2.24  |
| KR57           | 96.50 | 2.05  | 3.52  | 1.54  |
| Average        | 94.46 | 2.03  | 3.41  | 1.78  |

All the above indexes are summarized in Table 1 and the final evaluation index $Q_{RHLW}$ of the ONKALO site is obtained according to the formula (1). The ONKALO site is regarded as “suitable” for geological disposal according to the $Q_{HLW}$.

Table 8. Results of suitability evaluation on sites

| Site       | $C_{frz}^{R}$ | $C_{Rchm}^{R}$ | $Q'$ | $J_{w,HLW}^{R}$ | $SRF_{HLW}^{R}$ | $Q_{RHLW}$ | Suitability |
|------------|---------------|----------------|------|----------------|----------------|------------|-------------|
| ONKALO     | 1.0           | 1.0            | 89.15| 1.0            | 1.0            | 89.15      | Suitable    |

5. Discussion

The evaluation results from $Q_{HLW}$ were found to be consistent with those from RSC. It shows that $Q_{HLW}$, successfully used in the site selection of China’s URL, is also valid for the ONKALO site.

According to $Q_{HLW}$, the faults greater than 3 km must be avoided and a respect distance should be defined. While no detailed characteristics are required in the $Q_{HLW}$, RSC includes a detailed study of the hydraulic activity and mechanical strength of the fault zone.

The ONKALO site is near the sea. The content of Mg\(^{2+}\) and Ca\(^{2+}\) in groundwater is high, possibly affecting the long-term performance of canister and buffer materials. However, the geochemical index is taken as 1.0 according to $Q_{HLW}$. Besides, the concentration of cations can effectively slow down the corrosion of buffer materials according to the RSC, a point not considered in $Q_{HLW}$.

In RSC, the rock mass with the transmissibility coefficient $T \geq 10^{-6}$ m\(^2\)/s is regarded as a water-conducting zone, which should be avoided. In contrast, $Q_{HLW}$ quantitatively evaluates the permeability of the rock mass by taking $K \geq 10^{-9}$ m/s as the reference threshold, rather than avoiding the “unavailable” areas directly. The above criteria of $Q_{HLW}$ help identifying more “available” areas, enhancing the utilization rate of the site.

In conclusion, RSC provides more detailed and specific information on fracture zones and groundwater chemical conditions while $Q_{HLW}$ consists of more indicators, such as temperature, in-situ stress, and rock mass constructability index. Besides, $Q_{HLW}$ is a quantitative evaluation method, and thus, it can be easily applied to different sites. Based on the above results and conclusions, a new version of $Q_{HLW}$ method is proposed by incorporating the advantages of RSC:

\begin{equation}
Q_{HLW}^T = C_{frz}^T \times C_{Rchm}^T \times Q \times \frac{J_{w,HLW}^T}{SRF_{HLW}^T}
\end{equation}

where $C_{frz}^T$, $C_{Rchm}^R$, $J_{w,HLW}^T$, and $SRF_{HLW}^T$ represent the indices of fracture zones, groundwater chemistry, hydraulic conductivity, and strength/stress ratio at the tunnel scale, respectively.
6. Conclusions
The following conclusions can be drawn based on the rock mass suitability evaluation with RSC and Q\textsubscript{HLW} methods.

(1) The suitability evaluation of the ONKALO site by Q\textsubscript{HLW} is consistent with that of RSC. For the first time, Q\textsubscript{HLW} method is applied at a foreign site, proving the feasibility and universality of the method.

(2) RSC provides more detailed and specific information on fracture zones and groundwater chemical conditions while Q\textsubscript{HLW} consists of more indicators, such as temperature, in-situ stress, and rock mass constructability index. Moreover, Q\textsubscript{HLW} is a quantitative evaluation method and it can be easily applied to different sites.

(3) A new version of Q\textsubscript{HLW} is proposed by absorbing the advantages of RSC, making it an effective tool in the site selection and evaluation of geological disposal projects.

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