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Research paper

Rock mass classification in highway tunnel engineering during exploration phase and case study

Du Yanqiang[1], Xie Bing[2]

Abstract: It is the foundation of tunnel engineering to classify the rock mass surrounding tunnels. However, it is not easy to precisely determine the class of rock mass in practice as sufficient geological exploration need to be completed before rock mass classification, and there exists some disputes referring to the rationalization of dozens of methods for rock mass classification through the world. The principles and procedures of the basic quality method, which are widely used in China, are presented in this paper, and the application process of the basic quality method is showed with a project case of Zhongnanshan highway tunnel which has operated in safety for nearly a decade. Then, both the advantages and disadvantages of the basic quality method are analyzed in terms of practical engineering applications. In consideration of the defects of the basic quality method, the concept of the subclassing of surrounding rock in grade III–V is developed in the end and the criterion is given to determine the subclass of rock mass. This study is aimed at providing some useful ideas and a reference for rock classification in highway tunnel engineering.

Keywords: tunnel engineering, rock mass classification, earth pressure, the basic quality method

[1]PhD., China., Luoyang Institute of Science and Technology, School of Civil Engineering, No. 90 Wangcheng Avenue, Luoyang, China, e-mail: cquduyq@163.com, ORCID: 0000-0001-5385-5617
[2]Prof., PhD., China., Luoyang Institute of Science and Technology, School of Civil Engineering, No. 90 Wangcheng Avenue, Luoyang, China, e-mail: rs425@126.com, ORCID: 0000-0003-1934-7859

1. Introduction

Rock mass classification is an essential issue in tunnel engineering as surrounding rock or soil types strongly affect how a tunnel is designed or built. However, there exists some problems to correctly determine the types of rock mass due to the variation of rock or soil properties such as the presence of fractures (which govern the stability of surface structures) and in-situ stress conditions (which govern the stability of deep structures) in rock mass [1, 2]. Furthermore, groundwater, squeezing and swelling or stability conditions of rock mass, and filling materials in joints will scale their effects. Dozens of approaches, qualitatively or quantitatively, were developed to evaluate rock mass quality of underground or slope engineering or worldwide in recent decades [3, 4]. Surrounding rock classification is carried out by means of field or laboratory tests during the investigation phase of a tunnel, and provides the essential foundation for subsequent tunnel design and construction. Different factors, such as rock mass structure, joint plane and rock strength, are taken into account to evaluate the quality of rock mass in these approaches. Once rock mass types are identified, it is accessible to determine the load of tunnel lining [5] and select an appropriate support pattern, lining thickness, and construction method for tunnel engineering, making surrounding rock mass classification to be the primary work of tunnel construction.

Nowadays, developing a simple and accurate surrounding rock classification method has become a common aspiration for experts and scholars worldwide [6]. Currently, surrounding rock classification methods are categorized into three types, namely, qualitative methods, quantitative methods, and methods combining the qualitative and quantitative methods. Qualitative methods mean a few qualitative-described factors which are deemed to have an influence on rock mass are used to assess the rock mass quality. The Terzaghi method [7], which considers the structure and geological characteristics of the rock mass as a major issue, is representative of qualitative methods and widely used in Europe and America. However, qualitative methods have strong subjectivity and largely depend on the knowledge and experience of evaluators; therefore, the classification of surrounding rock is occasionally inconsistent with reality. Unlike qualitative methods, quantitative approaches typically consider a few indicators as the factors affecting the rock mass quality. Then, the quantized value of these indicators is obtained by laboratory or in-situ tests to access the final index for rock mass evaluation. Some representative approaches are the Protodyakonov coefficient method [8], rock tunneling quality index (Q) method [9, 10], geological strength index (GSI) [11], rock mass rating (RMR) [12], rock quality designation (RQD) method [13], and Japanese surrounding rock classification method [14]. In addition to traditional methods, some artificial intelligence methods such as neural network [15], support vector machine and deep learning [16, 17] for evaluating rock mass quality have been proposed in recent years. The artificial intelligence methods [18] also try to explore the relationship between the factors and the performance of rock mass and reach a decision efficiently and accurately. Owing to the great difference in the rock mass' occurrence conditions and the many variables [19] affecting the stability of rock mass, it is difficult to find an ideal approach for accurately evaluating the quality of surrounding rock only by using a mathematical formula with several parameters. Moreover, it is impossible to implement a quantitative classification approach that is universally accepted. Because

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the two above-mentioned method types possess individual advantages and disadvantages, a method combining quantitative and qualitative approaches to determine the rock mass quality is typically selected in most practical situations.

In recent decades, a large thousands of tunnels have been built in China, forming teams with experienced and mature professionals. So, in this study, we aim to introduce widely-used basic quality [BQ] method in China. To be specific, in Section 1 the background and major approaches around the world for rock mass classification is introduced. In Section 2 and Section 3, the classification criteria of rock mass and its implementation method is introduced theoretically. Then, in the next Section 4, the procedures of BQ method are demonstrated combining a concrete case in China. Section 5 of sub-grading for rock mass in grade III–V. In the end, Section 6 gives the summarize of the whole study.

2. Methodology

The classification of rock surrounding highway tunnels has transitioned from qualitative assessment to quantitative assessment through its development over almost 100 years. In the early stage of tunnel engineering, qualitative analysis was dominant because geological exploration and testing methods had not developed sufficiently. As the understanding of rock mass was enriched by experience accumulated from mountain excavation for tunnel construction, it was recognized that some quantitative parameters, such as the rock mass elastic wave velocity, rock strength, rock mass integrity, and joint number in unit volume, should be introduced into the surrounding rock evaluation system. Assisted by increasingly advanced exploration technology, many of the above-mentioned factors can be accessed at low cost and high efficiency. The BQ method is a typical example of such methods.

In China, the Code for Design of Highway Tunnels adopts the BQ method [20], which combines qualitative and quantitative approaches, to classify the rock mass surrounding tunnels. In this method, two factors, namely, the rock strength and rock mass integrity, serve as the primary factors influencing the rock mass quality index, BQ. In the first step, the preliminary classification of surrounding rock is carried out based on qualitative analysis. Subsequently, three secondary factors, namely, the groundwater level or pressure, weak structural plane, and geostatic stress state, are considered to reduce BQ so as to determine the corrected BQ value. The final score for identifying the rock mass grade is denoted by [BQ] (Table 1).

Table 1. Qualitative classification of rock or soil surrounding tunnel [20]

Rock or soil mass grade	Structural characteristics and compressive strength of rock or soil mass	BQ
I	Hard rock: intact rock mass, giant monolith or thick layered structure	> 550
II	1. Hard rock: less intact rock mass, block, or thick layered structure 2. Less Hard rock: Intact rock mass, block structure	450~550

Continued on next page

Table 1 – *Continued from previous page*

Rock or soil mass grade	Structural characteristics and compressive strength of rock or soil mass	BQ
III	1. Hard rock: the rock body is quite fragmented, and the massive (stone) broken (stone) mosaic structure 2. Less hard rock: less Intact rock mass, block structure or medium-thick layer structure	450~350
IV	Rock: 1. Hard rock: cataclastic structure 2. Less hard rock: less cataclastic structure or mosaic structure 3. Soft rock: soft and hard rock are interbedded, and soft rock is the main part, and less Intact rock mass with medium-thin layered structure	350~450
	Soil: 1. Compacted or diagenetic clay and sandy soil 2. Loess (Q_1 or Q_2) 3. General calcareous, iron cemented gravel soil, pebble soil or blocky rock-like soil	
V	Rock: Less Soft rock: cataclastic structure; soft rock: more cataclastic structure; all kinds of rock mass are extremely cracked featured by loose structure	250~350
	Soil: 1. Generally Quaternary semi-dry hard to hard plastic clay soil and slightly wet to wet gravel soil, pebble soil, round gravel, breccia soil and loess 2. (Q_3, Q_4). Non-cohesive soil has a loose structure, clay soil and loess are soft	
VI	Soft plastic clay and wet, saturated fine sand layer, soft soil, etc.	

Note: This table is not applicable to swelling rock, permafrost, and other special types of rock or soil.

3. Process of surrounding rock classification

3.1. Determination of Rock Strength Index, R_C

The strength index of rock is denoted by R_c, which represents the uniaxial compressive strength of saturated rock, as expressed by Equation (3.1). The value ofR_c can be obtained directly by uniaxial compression testing in the laboratory or indirectly by a point load test as expressed by Equations (3.1) and (3.2).

$$R_c = P_c/A \tag{3.1}$$

$$R_c = 22.82 I_{s(50)}^{0.75} \tag{3.2}$$

where: P_c is the load value when the rock sample fails – cracks (kN); A is the cross-sectional area of the rock sample (mm^2); $I_{s(50)}$ is the strength of the standard sample with a diameter of 50 mm in the point load test (MPa).

3.2. Determination of Rock Mass Integrity Index K_V

The integrity coefficient is also called the fissure coefficient which is a quantitative index to describe the degree of rock's reduced performance resulting from cracks in rock mass. It is denoted as K_v which represents the square of the ratio of the longitudinal elastic wave velocity of the rock mass to that of rock, as follows:

$$K_v = (v_{pm}/v_{pr})^2 \tag{3.3}$$

where: v_{pm} is the longitudinal elastic wave velocity of rock mass (km/s); v_{pr} is the longitudinal elastic velocity of rock (km/s). In practice, the integrity coefficient can also be derived according to the number of joints in the unit volume of rock mass.

3.3. Calculation of Basic Quality Index BQ of rock mass

The basic quality index BQ of rock mass is determined according to the uniaxial compressive strength R_c of saturated rock and the integrity coefficient K_v of rock mass. The calculation formula is expressed as follows:

$$\mathrm{BQ} = 90 + 3R_c + 250K_v \tag{3.4}$$

In Equation (3.4), the unit of R_c should be converted to MPa and K_v is a nondimensional parameter. To calculate the final BQ value, in Equation (3.4), when $R_c > 90K_v + 30$, we set $R_c = 90K_v + 30$; when $K_v > 0.04R_c + 0.4$, we set $K_v = 0.04R_c + 0.4$.

3.4. Correction of BQ value

In fact, there are many factors affecting the quality of the rock surrounding a tunnel, and the rock mass is subjected to various geological conditions. Although the rock strength and rock mass integrity are considered as the two most important factors affecting the quality of surrounding rock, other factors should not be ignored when evaluating the stability of rock mass. In many cases, the groundwater level or pressure, occurrence of a weak structural plane, and initial stress state of surrounding rock can also strongly affect the rock mass quality and reduce the stability of the tunnel's surrounding rock to varying degrees. In quantitative terms, the influence of these factors on the quality of surrounding rock can be expressed as follows:

$$[\mathrm{BQ}] = \mathrm{BQ} - 100\,(K_1 + K_2 + K_3) \tag{3.5}$$

where: K_1 is the influence coefficient of groundwater level or pressure; K_2 is the influence coefficient of the occurrence of the main weak structural planes; K_3 is the influence coefficient of the initial in-situ stress.

4. Project case

4.1. Tunnel overview

Zhongnanshan tunnel (Fig. 1) is located between Shixieyu Township and Yingpan Town of Xi'an City, in Northwest China. This tunnel is a highway tunnel that crosses the Qinling mountain, which separates China into the northern and southern regions. The tunnel is 18-km long and located at a depth of 500–1350 m below the mountain. The tunnel consists of two separate holes with a distance of 30 m, and both of them have two monodirectional lanes. The shape of the tunnel cross-section resembles a three-center circular vault with a curvy wall. The width of the tunnel is 10.5 m and the height limit is 5 m. The speed limit is 80 km per hour. The tunnel construction started in 2001 and was completed in 2007.

Fig. 1. The entrance of Zhongnanshan tunnel

4.2. Application of the bq method

4.2.1. Investigation and test results

The geological exploration was conducted in the km 79 + 580 – km 75 + 180 section to determine the lithology of the tunnel's surroundings. According to the exploration results, the surrounding rock mass of the tunnel is mainly composed of mixed gneiss, which is slightly weathered and has a high compressive strength. Additionally, not too many joint fissures exist. The groundwater level or pressure is not sufficient and some seepage water or trickles exist only in a few areas. The saturated uniaxial compressive strength tests were carried out between the km 78 + 980 and km 77 + 176 sections and the maximum compressive strength of mixed gneiss was determined as 140.1 MPa. The wave velocity investigation, conducted via velocity measuring instrument (Fig. 2), revealed that the longitudinal wave velocity of rock mass was 3765 m/s, and the rock's longitudinal wave velocity was 4882 m/s. The maximum initial stress in the vertical direction of the tunnel axis was obtained by in-situ stress measurement, and the experimental results of stress relief technique revealed that the maximum initial stress, expressed as $\sigma_{\max}$, was 34.05 MPa.

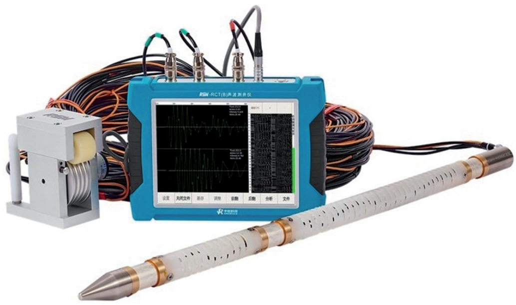

Fig. 2. Velocity measuring instrument used in investigation: RSM-RCT series

4.2.2. Basic Quality Index of rock mass

According to the test data, the saturated uniaxial compressive strength of rock, R_c, is 160 MPa, and the integrity coefficient of rock mass $K_v = (v_{pm}/v_{pr})^2 = (3765/4882)^2 = 0.595$.

Because $R_c = 160 > 90K_v + 30 = 90 \times 0.595 + 30 = 94.5$, R_c was set to 94.5 MPa. Additionally, Because $K_v = 0.595 < 0.04r_c + 0.4 = 0.04 \times 160 + 0.4 = 6.8$, K_v was set to 0.595. Thus, $\text{BQ} = 90 + 3R_c + 250K_v = 90 + 3 \times 94.5 + 250 \times 0.595 = 522$

4.2.3. Correction of Basic Quality Index

The three coefficients can be deduced from the investigation results and Tables 2, 3, and 4, respectively. The influence coefficient of groundwater level or pressure, K_1, was set to zero, which means that the impact of groundwater level or pressure on the rock mass can be ignored. The influence coefficient of the main weak structural plane K_2 was set to 0.3.

Table 2. Influence coefficient K_1 of groundwater level or pressure [20]

State of groundwater level or pressure \ BQ	> 450	450~350	350~250	≤ 250
The surrounding rock or soil is damp or water drips down in tunnel	0	0.1	0.2~0.3	0.4~0.6
Like rainfall, water pressure lower than 0.1 MPa or hydraulic discharge less than 10 L/(min·m)	0.1	0.2~0.3	0.4~0.6	0.7~0.9
Like rainfall, water pressure greater than 0.1 MPa or hydraulic discharge more than 10 L/(min·m)	0.2	0.4~0.6	0.7~0.9	1.0

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Because the value of strength–stress ratio $R_c/\sigma_{\max}$ was 4.11, the corresponding influence coefficient of the initial in-situ stress K_3 was set to 0.5 according to Table 4. Hence, the corrected value of the basic quality index is expressed as follows:

$$[\mathrm{BQ}] = \mathrm{BQ} - 100\,(K_1 + K_2 + K_3) = 522 - 100 \times (0 + 0.3 + 0.5) = 442 \tag{4.1}$$

Finally, it can be determined that the grade of the rock mass surrounding this section is grade III according to the assessment criteria in Table 1.

Table 3. Influence coefficient K_2 of occurrence of main weak structural planes [20]

The occurrence of structural plane and its relation with tunnel	The angle between the strike of structural plane and tunnel axis is less than 30° and the dip angle of structural plane lays between 30° and 75°	The angle between the strike of structural plane and tunnel axis is greater than 6° and the dip angle of structural plane greater than 75°	Other situations
K_2	0.4~0.6	0~0.2	0.2~0.4

Table 4. Influence coefficient K_3 of initial in-situ stress [20]

BQ / Initial state of geostatic stress	> 550	550~450	450~350	350~250	< 250
Very high geostress ($R_c/\sigma_{\max} < 4$)	1.0	1.0	1.0~1.5	1.0~1.5	1.0~1.5
High geostress ($4 \leq R_c/\sigma_{\max} < 7$)	0.5	0.5	0.5	0.5~1.0	0.5~1.0

Note: $\sigma_{\max}$ is the maximum initial stress perpendicular to the tunnel axis.

4.2.4. Use of rock mass grade identification

The rock mass class should be identified to cope with follow-up issues. Particularly, the pressure of the surrounding rock mass can be calculated according to empirical formulas based on the surrounding rock grade and the tunnel's cross-section size. In fact, the calculation of rock pressure provides the basis for resolving several key issues, such as selecting the support form, lining thickness, construction method, and others.

5. Discussion

5.1. General comparison with other methods

The classification of rock mass is the precondition for tunnel engineering. the RMR method and the Q method are the most widely adopted approaches in rock mass classification in geotechnical engineering worldwide, while the BQ method is the recommended one in China. In fact, the RMR method and the Q method are quantitative, while the BQ method [21] is an integrated approach combining qualitative and quantitative analysis. These methods were developed to evaluate the quality of rock mass to prepare for tunnel excavation and support. In fact, these methods have much in common, yet some differences may also exist in details. For the RMR method, seven indicators are identified to determine rock mass quality [18], while there are six indicators in the Q method [9]. As to the BQ method, there are two basic indicators and three other modification indicators to calculate the index of rock mass quality. By comparison, it can be concluded that these three methods all regard rock strength and joint plane as the principal factors influencing rock mass performance, and it can reach a consensus that weathering, geo-stress and groundwater level or pressure also degrade rock mass quality. These methods differ in how to quantify the influence of the above-mentioned factors. Instead of several joint-related parameters, the BQ method proposes a compositive factor, the integrity coefficient, to assess the impact of joints in rock mass. Compared with joint-related parameters, the integrity coefficient can be easily obtained by ultrasonic investigation, greatly reducing the geological exploration work. When it comes to rock mass classes, the BQ method and the RMR method classify rock mass into five levels, while the Q method classifies them into nine levels.

5.2. Advantages of the BQ method

The BQ method combines quantitative calculation and qualitative analysis, while the RMR method and the Q method are quantitative approaches. The integrity and strength of the rock mass are considered as the principal factors affecting the quality of rock mass. Moreover, the influence of three other factors, namely, the groundwater level or pressure, initial stress state of surrounding rock, and occurrence of main weak structural plane, are also considered in the BQ method. Therefore, a geological factor, mechanical factor, and construction factor were introduced in this method based on a large number of highway tunnel data, and the formula of the basic quality index of the surrounding rock was established by regression analysis. This method clearly shows the factors influencing the rock mass quality and how the rock mass quality may be affected. Moreover, reliable results can be obtained through investigation and lab testing at low cost and high efficiency. Finally, the formula involves simple calculation and can be easily understood by engineers. Hence, it is concluded that this method has a strong practicability, which is helpful in establishing it as the general method for evaluating the rock mass of tunnels in China.

5.3. Disadvantages of the BQ method

The BQ method has the following disadvantages:

1. The qualitative classification results may be inconsistent with the quantitative results

As presented in Table 1, the qualitative characteristics of the surrounding rock should be consistent with the quantitative characteristics obtained by calculation for each rock mass grade. Notably, some unexpected cases may occur. For example, for integrated hard-rock mass, the surrounding rock should be qualitatively classified as grade I. From a different quantification viewpoint, if R_c is set to 85 MPa and K_v is set to 0.76, which matches the qualitative attributes of the above-mentioned rock mass, the value of BQ is assumed to be 535, according to Equation (4.1). Therefore, quantitatively, the surrounding rock mass should be classified as grade II. Hence, different conclusions are obtained by the qualitative analysis and quantitative calculation. Generally, the quantitative evaluation is more conservative compared with the qualitative analysis according to thousands of practical cases. However, the code also mentions that "when the qualitative classification is inconsistent with the [BQ] value, the reliability of the qualitative descriptions and quantitative indicators should be re-examined". Engineers tend to prefer the quantification results over clear and reliable quantitative indicators and qualitative indeterminate indicators, which may lead to the conservative classification of the surrounding rock mass and result in economic waste. To address this issue, it is recommended that the qualitative evaluation be conducted before the quantitative evaluation. Additionally, measures should be taken to ensure that the qualitative evaluation result is reasonable, which is key for ensuring the validity of rock mass grade identification. The guiding principle is that the quantitative evaluation should comply with the qualitative evaluation when the two evaluations are contradictory.

2. Wide range of correction coefficient

As presented in Tables 2, 3, and 4, the determination of parameters K_1, K_2, and K_3 has a wide range, which may result in the deviation of the [BQ] value to various degrees. Consequently, this may lead to different surrounding rock mass assessment results. Considering the impact coefficient of groundwater level as an example, if the state of groundwater in the tunnel is similar to spraying and the water pressure is less than 0.1 MPa, under the condition that the BQ value falls in the range of 350–250, the correction coefficient should be set in the range of 0.4–0.6 according to Table 2. Correspondingly, the difference between the calculated [BQ] values reaches up to 20, which accounts for 25% of the interval value of BQ. Thus far, the influence of the other two correction parameters has not been considered. In fact, the influence on the rock grade under the combined action of K_1, K_2, and K_3 will be much greater. Therefore, the calculated value of [BQ] may change in a wide range, determining an inconsistent rock or soil grade from what is based on the qualitative method as shown in table 1. In particular cases, the difference between qualitative method and quantitative one can be as many as two grades.

3. Grade determination when [BQ] value falls near boundary

When determining the rock mass grade, the [BQ] value often falls near the boundary of two contiguous intervals. Consequently, engineers find it difficult to decide whether to select the lower grade or higher grade. If the higher grade is selected, the final grade may be two levels higher than the initial grade, which may be very confusing to engineers. Obviously, this situation is not only unreasonable but also unacceptable in highway tunnel engineering.

5.4. Sub-grade of surrounding rock mass

Based on the above analysis, it is understood that the range of the BQ value of the same grade is too wide for determining the rock mass grade, which may result in unreasonable conclusions. Rock mass rated as the same grade may differ considerably in terms of rock

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strength, integrity, and wave velocity. Finally, unreasonable assessment will affect the calculation of rock or earth pressure and pressure-related support parameters. Therefore, the grading of surrounding rock mass using the BQ value method has certain shortcomings, such as randomness and uncertainty, and should be further refined in future work.

For surrounding rock mass with superior or inferior rock quality and stability, such as rock mass grades I, II, and VI, there are fewer disputes in the field of tunnel engineering. Additionally, the percentage of rock mass belonging to these three grades is relatively low. In engineering practice, grades III, IV, and V of surrounding rock mass are most common and the majority of disputes exist with regard to these three rock mass types. Hence, it is necessary to refine the rock mass of grades III, IV, and V. Rock mass of grades I, II, and VI do not require further refinement. The recommended refined criteria for the classification of surrounding rock mass is presented in Table 5.

Table 5. Subclass of surrounding rock mass for highway tunnels

Rock mass		The range of [BQ] value
General grade	Sub-grade	
I	–	≥ 551
II	–	450~550
II	III_1	390~450
	III_2	350~390
IV	IV_1	310~350
	IV_2	275~310
	IV_3	250~275
V	V_1	210~250
	V_2	≤ 210
VI	–	–

6. Conclusions

The grading of surrounding rock mass is the foundation of tunnel design and tunnel lining construction. However, it takes a large amount of geological exploration to grade rock mass rationally, and that a broad classification is inadequate to conduct succeeding activities, especially the earth pressure calculation. Hence, this paper focuses on rock mass classification and introduces the BQ method which is widely used to a large number of tunnel cases in China. The contrast analysis shows that the RMR method, the Q method and the BQ method follow the same principle to evaluate rock mass quality. Specifically, the three methods all believe that several factors like rock strength, structural planes, geo-stress and underground water are the main considerations in rock mass evaluation. The differences lie in how to quantize the influences of these rock mass related indicators. In addition, the advantages and disadvantages of this method are analyzed by case study and an improved diagram of rock mass sub-grades with quantized data is proposed to detailing classification of rock mass. In this study, the idea of sub-classification for rock mass in grade III–V is presented and the threshold value is also suggested due to the issue of the broad range of the BQ value. This improvement of the BQ method serves the purpose of determining the type of rock mass and subsequent earth pressure accurately.

This method considers the strength of rock and the integrity of surrounding rock mass as the main factors affecting the stability of the surrounding rock mass, and that the influences of groundwater level or pressure, initial geo-stress and attitude of main structural planes are also considered in evaluation. Although this method provides an available means to avoid contradictoriness caused by qualitative and quantitative evaluations, it is still in improving process, and there exists some deficiencies in the BQ method such as the rough classification, inconsistency between the qualitative and quantitative classification, and the large deviation of the correction coefficient. The rationality of sub-grading is still to be subject to verification by practical engineering under diverse conditions. Hence, with more engineering data, the BQ method can be ameliorated by means of detailed classification in years to come. Meanwhile, the threshold values for rock mass of various types are bound to be more accurate.

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