Classification and engineering application of tunnel surrounding rock based on the relationship between rock mass quality index and rock firmness coefficient

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Abstract. The evaluation of rock mass integrity is of great significance to tunnel engineering. In addition to the number of volumetric joints, the quantitative classification of rock mass integrity mainly relies on wave velocity test to obtain Kv for quantitative classification. As a statistical method to evaluate the quality of rock mass, RQD is also a quantitative analysis method of rock mass integrity. With the development of the Belt and Road construction project, the contradictory situation of different specifications put forward a serious examination of the construction. This paper is based on the principle of volumetric joint equivalence, the empirical formula of volumetric joint coefficient expressed by integrity coefficient(KV)and rock quality index(RQD)was used, and the relationship between KV and RQD was deduced. Based on the principle of equivalent uniaxial compressive strength, used to rock firmness coefficient(f)and rock mass basic quality index(BQ)respectively the rock uniaxial compressive strength of empirical formula, obtained in this paper, the relationship between BQ and f suggested in this paper is obtained, and the corresponding table of the relationship between F Methods and BQ Methods is established. The research results have been successfully applied in the scheme modification and optimization design of the south-north trans-ridge tunnel in Kyrgyzstan, it provides reference for tunnel construction in countries along the"Belt and Road".

Keywords: Tunnel engineering; Rock mass classification; Basic quality of rock mass; Rock firmness; Relational equation; Parameter estimation.

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1 Introduction

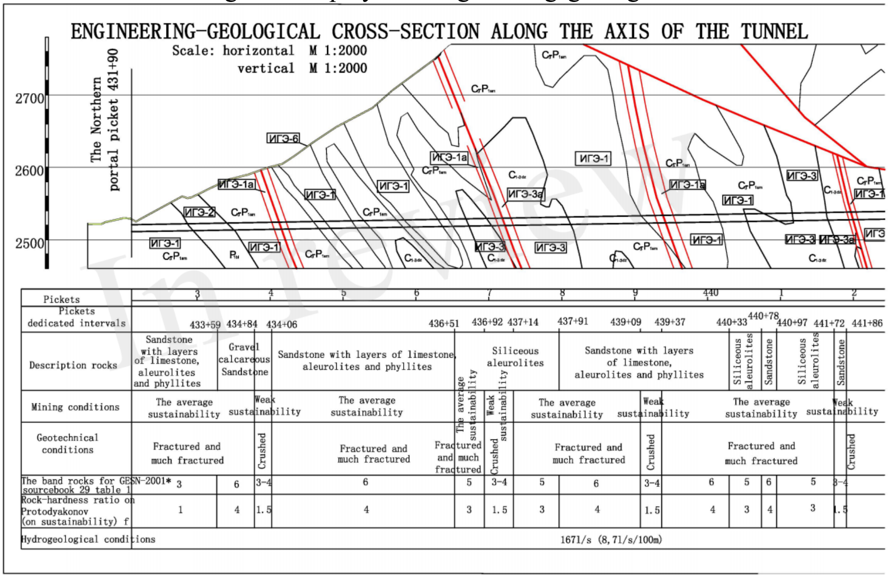
There is currently no globally accepted international standard for classifying engineering rock masses and selecting relevant indices.The traditional construction of rock classification is mostly based on the stability of rock[1].Some examples of rock classification methods include the Rock Quality Index Classification(RQD Methods)[2], Platts Rock Firmness Coefficient(F Methods)[3], Barton Rock Mass Quality Classification(Q System)[4], RMR Methods[5], and Engineering Rock Mass Classification(BQ Methods)[6].Among them, BQ methods has been widely applied and studied in China.Fan Xinran[7] and Zhu Xunguo[8] conducted a comparative analysis of the relevant contents of the Standard for Engineering Classification of Rock mass(GB/T 50218-2014)and derived a simplified calculation method for the basic rock mass quality index(BQ).Wu Aiqing[9]put forth a rock mass classification method for rock slope engineering that builds on the BQ approach.This method was developed after conducting in-depth research and carefully analyzing the existing rock mass classification results in slope engineering.

With the deepening of research and the emergence of a large number of international projects, many scholars try to establish the relationship between rock mass classification in various countries. Barton[10] studied the relationship between *RMR* and *Q*. CAI Bin[11] analyzed the relationship between BQ Methods, Q System and RMR Methods through the statistical analysis of hundreds of field measured data. Jiang Ping and Meng Ping[12] analyzed the measured data of slope rock mass in the middle section of Yixing Road of Ning-Hang Expressway, and obtained the correlation between *RMR* and *BQ*. Guo Chenye[13] regressed the test results of firmness coefficient (*f*) and uniaxial compressive strength (*UCS*) of different rocks, and obtained a linear correlation between them. The above studies on the relationship between various rock classification systems focus on RMR Methods, Q System and BQ Methods, and do not involve the studies on F Methods and BQ Methods.

In this paper, the relationship between BQ methods and F methods was studied based on the south-north trans-ridge tunnel in Kyrgyzstan, and the gap in this research field was also made up. It provide theoretical reference for reconciling the differences of different surrounding rock classification, and provide reference for tunnel engineering construction in countries along the "Belt and Road". With the implementation of the “Belt and Road” initiative, countries of the Central Asia along the “Belt and Road” such as Kyrgyzstan and Tajikistan will have a large number of tunnel projects designed in accordance with Russian norms and constructed by China[13].

2 Project

The second north-south Road construction project of Kyrgyzstan (phase I) is composed of road tunnel and service guide tunnel, excluding composite buildings at the entrance. The total length of the tunnel is 3750m. Tunneling is carried out over Paleozoic strata with sedimentary rocks of moderate strength and fragmentation. The tunnel passes through several tectonic faults and rock fragmentation zones are widely distributed near faults. Figure 1 displays the engineering-geological cross-section.



(a) Tunnel profile

(b) Tunnel entrance

Fig. 1. Engineering-geological cross-section along the axis of the tunnel.

Kyrgyzstan north-south trans-ridge tunnel designed the Russian standard design, according to China's tunnel construction concept, Kyrgyzstan as the state supervision of the road tunnel. The original design of the tunnel involved the utilization of a cantilever tunnelling machine for construction. Because hard sandstone and limestone are unsuitable for mechanical excavation. Sandstone is affected by sedimentation and diagenesis, and there are a large number of bedding structural planes within the rock mass. So it is an important reason for the deterioration of rock mechanical properties and even rupture[14].And the 20km area near the cave entrance is a restricted zone, it is not favorable for extensive mechanical construction. Hence, it is essential to modify the original design's construction method to drilling and blasting.

3 Analysis of the relationship between *BQ* and *f*

Despite the notable distinctions between BQ Methods and F Methods, the use of UCS in both suggests a definite link between the two classification approaches. Based on the above content, this paper demonstrates the correlation between BQ Methods and F Methods.

3.1 Rock firmness

The firmness of rock is indicative of its ability to withstand damage when subjected to external forces. The f is determined by various methods, such as compressive strength method, crushing method, etc. Prototyakonov[2] revised the previous calculation method of f based on years of accumulated experience and proposed to use *UCS* to calculate f, as shown in Formula (1).

$$f = \frac{UCS}{10} \tag{1}$$

By performing regression, Guo Chenye[13]derived a linear relationship between the experimental results of f and UCS for various rocks.

$$UCS = 19.078f + 18.361 \tag{2}$$

The striking feature of rocks compared with other materials is that the data vary greatly when the firmness is repeatedly measured. Therefore, the Formula (1) and (2) is quite different. This paper takes into account the challenge of dealing with the inherent variations in the objective existence of rocks and the discrete nature of measured data.It considers the differences between these factors and uses them as the foundation for its analysis.

3.2 Engineering rock mass classification

According to the Standard for Engineering Classification of Rock mass(GB/T 50218-2014), the rock is qualitatively divided according to its hardness, integrity, weathering and combination degree of structural planes.The rock is divided into different sections based on the UCS and integrity coefficient(KV)in a quantitative manner. The calculation formula is as follows.

$$BQ = 90 + 3R_C + 250K_V \tag{3}$$

In the sentence, "Where, RC represents the uniaxial compressive strength of rock."When applying Formula(3), it is important to consider that when RC exceeds 90 · KV+30, RC should be set at 90 · KV+30, and KV should be used in the formula to calculate BQ. Similarly, if KV is higher than 0.04 · RC+0.4, KV should be replaced-with 0.04 · RC+0.4 and RC should be utilized to calculate BQ.

3.3 The relationship between BQ and f

Both classification methods use the index of uniaxial compressive strength of rock, so the relationship between *BQ* and *f* can be established according to the principle of equivalent *UCS*. By substituting Formula(1)and(2)into Formula(3), we obtain the following equation.

$$BQ = 90 + 30f + 250K_V \tag{4}$$

$$BQ = 145.1 + 57.2f + 250K_V \tag{5}$$

Formula (4) and (5) obtained the relation between *BQ* and *f* through *UCS* equivalent substitution, but *BQ* still cannot be obtained.In combination with the study of Jiang Zhaohui[15], Merritt A H[16]and WANG Shi-chun[17], as well as Formula(4)and(5)obtained above, and based on the principle of equivalent substitution, the following eight formulas are finally obtained.

$$BQ = 182.3 + 30f + 1.205RQD \tag{6}$$

$$BQ = 79.51 + 30f + 2.335RQD \tag{7}$$

$$BQ = 237.40 + 57.2f + 1.205RQD \tag{8}$$

$$BQ = 137.61 + 57.2f + 2.335RQD \tag{9}$$

$$BQ = 80.36 + 30f + 2.283RQD \tag{10}$$

$$BQ = 88.36 + 30f + 2.335RQD \tag{11}$$

$$BQ = 135.5 + 57.2f + 2.283RQD \tag{12}$$

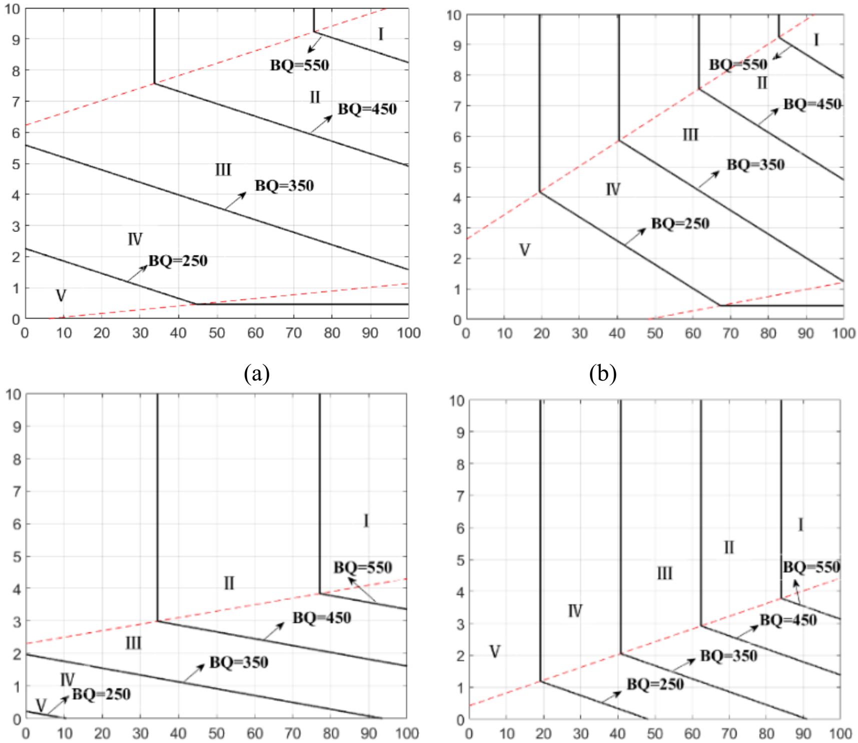
$$BQ = 143.5 + 57.2f + 2.335RQD \tag{13}$$

4 Discussion

In this paper, according to the *BQ* limit value of each surrounding rock grade, the stability of rock mass is considered to be poor when *f* value is too large *and RQD* is too small, *f* is too small and *RQD* value is too large. Upper and lower limit conditions are set for rock mass classification.

The contour map of BQ is drawn in Figure 2 using the mapping method of limiting conditions. RQD is used as the abscissa and f is used as the ordinate to aid in choosing the appropriate rock mass classification basis. Generally speaking, when $RQD \leq 25$, the integrity of surrounding rock is very poor, which is not conducive to tunnel excavation. The grade of the surrounding rock cannot be raised, even if the rock is harder. The stability of tight clay, gravel, and sand texture layers is poor when the value of f is less than or equal to 1, despite having good integrity. Thus, the upper and lower limits for RQD are set at 25 and f is set at 1. A clear correspondence between F methods and BQ methods can be observed from Table 1. The main difference between the two methods is that the quantitative classification index of rock firmness is only represents rock strength, while BQ Methods uses both *UCS* and K_V. In recent years, engineering accidents caused by insufficient stability of surrounding rocks are common[18].

According to Figure 2, Figure (f) corresponding to Formula (17) can best reflect the classification characteristics of rock mass, so Formula (17) is selected in this paper as the basis for qualitative classification. In the application, it should be noted that when $f > 0.08 \cdot RQD + 2.94$, $f = 0.08 \cdot RQD + 2.94$ and RQD should be substituted into the formula to calculate BQ; When the $RQD > 42.46f + 41.77$, $RQD > 42.46f + 41.77$ and f should be substituted into the formula to calculate BQ.



(a) (b)

(c) (d)

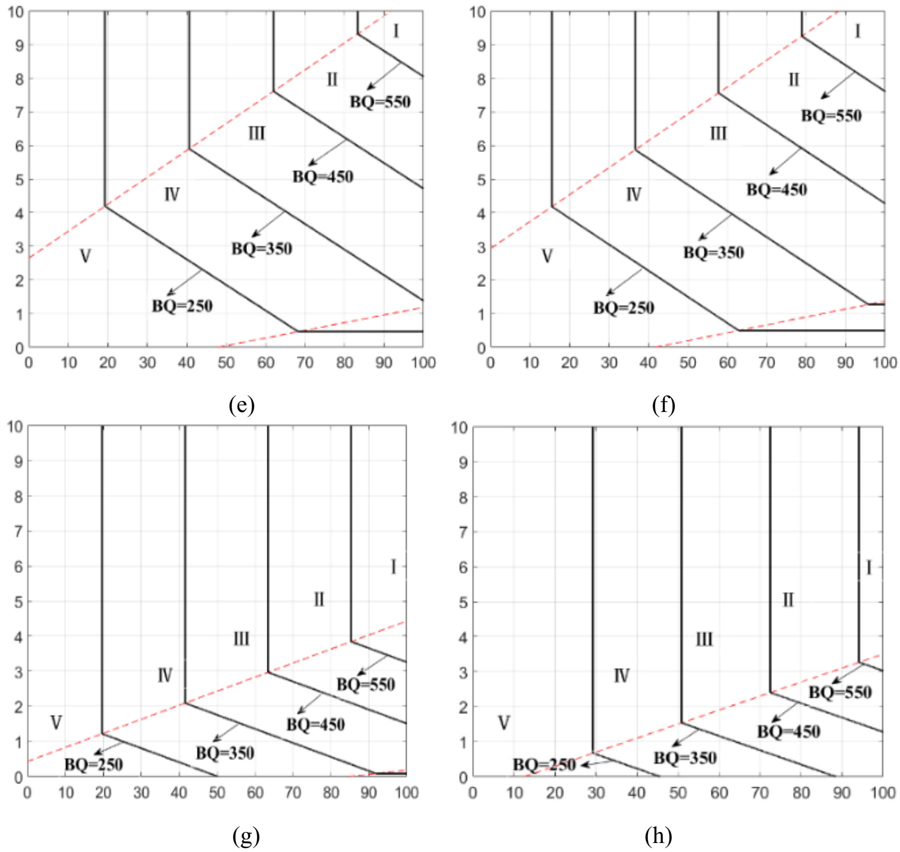


Fig. 2. Classification diagram of rock mass quality.

5 Application

Based on the Kyrgyzstan north-south trans-ridge tunnel, F method and BQ method are used to classify surrounding rock and estimate the physical and mechanical parameters. Table.1 gives the classification of tunnel surrounding rock of typical tunnel sections.

According to the classification results of surrounding rock and the corresponding mechanical parameters of rock mass, the tunnel entrance section is determined as the construction risk area, and the corresponding construction scheme is formulated.

Table 1. classification of tunnel surrounding rock and estimation of rock parameters.

Pile no.	*RQD*/%	*f*	F Methods	*BQ*	BQ Mehods	γ/kN·m^{-3}	*c*/MPa	φ/°	*E*/GPa	μ
K431+90~K433+59	2.74	1	VII	124.7	V	18.59	0.04	15.96	0.32	0.41
K433+59~K433+84	5.84	4	V	222.0	V	21.29	0.15	24.58	1.12	0.37
K433+84~K434+06	2.11	1.5	VIa	138.2	V	18.99	0.05	17.01	0.38	0.41
K434+06~K436+51	5.46	4	V	221.1	V	21.27	0.15	24.49	1.11	0.37
K436+51~K436+92	3.74	3	Va	187.0	V	20.36	0.10	21.21	0.72	0.38
K436+92~K437+14	2.64	1.5	VIa	139.5	V	19.02	0.05	17.11	0.39	0.41

6 Conclusion

In order to meet the needs of engineering change, the relationship between BQ Methods and F Methods is studied in this paper.

(1) Based on the principle of equivalent volume joint coefficient and uniaxial compressive strength, eight relation formulas between B*Q* and *f* were established. The proposed expression between *BQ* and *f* is obtained.

(2) According to the results of this study, it is found that the F Methods' grade IV corresponds to the BQ Methods' grade IV, and the F Methods' grade V - VII corresponds to the BQ Methods' grade V. The F Methods is not corresponding to the BQ Methods, but corresponds to different engineering rock classification according to different *RQD*.

(3) According to the classification results of surrounding rock and the corresponding mechanical parameters of rock mass, the tunnel entrance section is determined as the construction risk area, and the corresponding construction scheme is formulated.

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